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The Magazine of the Society of Physics Students

Benjamin Franklin: Natural Philosopher, Statesman, America's First Physicist

— by Dwight E. Neuenschwander, Department of Physics, Southern Nazarene University, Bethany, OK

Students of American history remember Benjamin Franklin because he edited and signed the Declaration of Independence, served the Colonies before the Revolution as an ambassador to England, served the newly declared United States during the Revolution as its ambassador to secure a treaty with France, and participated in drafting the U.S. Constitution. And, of course, Franklin *should* be remembered for these accomplishments of diplomacy and statesmanship!

But have students of U.S. History ever wondered *why* Franklin enjoyed the name recognition in England and France that made him welcome there among people of influence? They knew of Franklin because he was America's first physicist of international reputation. Franklin transformed the subject of electrostatics from a parlor amusement into a science, with a vast body of careful observations and a theoretical organizing principle that forms an integral part of physics to this day. His contemporary Joseph Priestly (who discovered oxygen) wrote that Franklin's work on electricity would "be handed down to posterity as expressive of the true philosophy of electricity just as Newtonian philosophy is the true system of nature in general."

Franklin was a fun-loving, yet practical man who knew his own mind and could articulate his thoughts with humor as well as pointed argument. As a postmaster, newspaper publisher, and printer, he knew the power of communicating ideas. Franklin should be the poster child for the Enlightenment. Thomas Jefferson's first draft of the Declaration of Independence began, "We hold these truths to be sacred and undeniable..." Franklin changed it to read, "We hold these truths to be self-evident..."

(continued on page 2)

ADOPT-A-SCIENTIST PROGRAM TAKES OFF

— by Kendra Rand, American Physical Society

This is the first year I haven't been in school in 19 years. It almost seems like cheating not to have finals and homework hanging over my head all of the time. Instead of studying and working in a windowless basement lab, I've spent this year in the airy office

(continued on page 5)

Kendra, right, working with the glass designer who designed the physics glass wall art. For story see: www.physicsmatters.com

–Photo courtesy of Kendra Rand, APS.

GREETINGS FROM THE SPS PRESIDENT

G'day Everyone!

This is my first opportunity to greet all of you as SPS President. I have greatly enjoyed serving on the National Council as a Zone Councilor and now as President. This is a great organization to be a part of! As SPS President I get to meet so many of the interesting people who keep fanning the flames of interest in physics. Marvelous! I am amazed over and over by all the cool activities involving SPS chapters from all over. The latest adventure to tickle me is the saga of Mojo, the motorized couch created by the Purdue University (West Lafayette) SPS Chapter. They were even invited to go to New York to appear on Good Morning America! You can check out the story on their chapter web page, http://www.physics.purdue.edu/sps, which includes photos and short videos.

Now, you might be thinking that Purdue's chapter can pull off stuff like that because they are a big chapter. But I have seen amazing stuff done by SPS chapters at two year community colleges, where the advisor has to teach 18 credits or more every semester! Size is not irrelevant, but it isn't everything. You can do wonders with a good core of excited people.

A short while ago, I was talking with a chapter advisor who said his chapter was very small, usually only 12 to 15 members, and so he downplayed their ability to get things done. His comment got me wondering about the size of a "typical" chapter. I took a quick peek at all 702 SPS chapters, just a snapshot of the official rosters as of February 7, 2006. The distribution is not at all Gaussian, the average chapter size was 5.4 members with a mode of 3 members. (If you are curious: in that snapshot, Purdue did have the largest membership, with 42 members.) Of course, there are always constituents, folks who actively participate in your chapter but never get around to coughing up the $20 to actually join. So in terms of the number of people who participate, your chapter might be even "larger" than the official roster would suggest. I think you might agree that 12 to 15 members is actually a "big" chapter. But I know that even with 6 or 7 excited members, you CAN do great things! So, don't bemoan your limited size, you are only limited by your own imagination. Go for it! — Earl Blodgett, SPS President, University of Wisconsin-River Falls

AIP Member Societies: American Physical Society • Optical Society of America • Acoustical Society of America • The Society of Rheology • American Association of Physics Teachers • American Crystallographic Association • American Astronomical Society • American Association of Physicists in Medicine • AVS, The Science and Technology Society • American Geophysical Union ***Other Member Organizations:*** Sigma Pi Sigma, Physics Honor Society • Society of Physics Students • Corporate Associates

Benjamin Franklin: Natural Philosopher, Statesman, America's First Physicist

(continued from page 1)

Franklin lived and breathed science; for example, his were the first charts of the Gulf Stream (Fig. 1), which he put together from his own observations—and conversations with sailors—while making a trans-Atlantic voyage in 1775. He was intrigued by the calming effect of oil on water, and in his study of these thin films came very close to measuring an upper limit on the size of atoms. His interest in electricity was sparked while visiting Boston in 1743, where he heard the Scottish itinerant lecturer, Dr. Archibald Spencer, present a program of demonstrations on static electricity. Intrigued, Franklin arranged for Spencer to bring his show to Philadelphia, and afterwards bought Spencer's apparatus. Having achieved sufficient success from his printing and newspaper businesses to retire from active involvement in them, and with a solid study of experimental mechanics and Newton's *Optiks* already behind him, he turned his full attention to research in electricity.

Fig. 1. Benjamin Franklin's chart of the Gulf Stream.

Image credit: National Oceanic and Atmospheric Administration/Department of Commerce.

Little was known about it at the time; electricity was a parlor game, such as the activity shown in Fig. 2. The young woman stands on an insulated step, with her hand on the brass rail. Her accomplice (left) turns the crank on a large electrostatic generator (a non-conducting wheel in contact with brushes, that have leads going to the rail). When the young man on the right—who is grounded—leans up to receive a sweet kiss from the young lady, he gets an electrical shock! Franklin and his colleagues began to study electricity in earnest. Shortly thereafter the Library Company of Philadelphia (one of many civic organizations co-founded by Franklin) received a gift of electrostatic equipment from one of Franklin's London friends, the merchant Peter Collinson. Franklin began corresponding with Collinson about the Philadelphia research. One of Franklin's letters first describes the principle that we call today "conservation of electric charge." Before Franklin's researches, it was known that the "electrical fire" exhibits both attraction and repulsion; so it had been supposed two kinds of "electrical fire" existed, called "vitreous" and "resinous," after the kinds of materials one rubbed to generate the electrified state. Franklin was the first person to realize that "vitreous" and "resinous" electricities were additive inverses of one another: positives and negatives. The electrostatic generator in the parlor amusement apparatus and the rubbing of glass with fur did not *create* the charges; it merely *separated* them. Thus all matter contained electric charge. In Paragraph 6 of a 1749 letter to Collinson, in experiments with Leyden jars (early capacitors, consisting of a glass bottle layered inside and outside with foil), Franklin described how:

> *In this experiment the bottles are totally discharged; the equilibrium within them is restored. The abounding of [electrical] fire in one of the hooks (or rather in the internal surface of one bottle) being exactly to the wanting of the other: and therefore, as each bottle has in itself the abounding as well as the wanting, the wanting and abounding must be equal in each bottle.*

Franklin also discovered the phenomena we now call the polarization of dielectrics, and at the same time invented the parallel plate capacitor by showing that planes of glass separated by lead sheets could also hold the electrical fire as well as cylindrical Leyden jars:

> *17. ...To find out, then, whether glass had this property merely as glass, or whether the form contributed anything to it; we took a pane of sash-glass, and laying in on the hand, placed a plate of lead on its upper surface; then electrified that plate, and bringing a finger to it, there was a spark and shock. We then took two plates of lead of equal dimensions, but less than the glass by two inches every way, in doing which, what little fire might be in the lead was taken out, and the glass being touched in the electrified parts with a finger, afforded only very small pricking sparks, but a great number of them might be taken from different places. Then dexterously placing it again between the leaden plates, and compleating a circle between the two surfaces, a violent shock ensued-which demonstrated the power to reside in glass as glass, and that the non-electrics [the conductors] in contact served only...to unite the force of the several parts, and bring them at once to any point desired: it being the property of a non-electric, that the whole body instantly receives or gives what electrical fire is given to or taken from any one of its parts.*
>
> *18. Upon this we made what we called an electrical-battery, consisting of eleven panes of large sash-glass, arm'd with thin leaden plates, pasted on each side, placed vertically, and supported at two inch distance on silk cords, with thick hooks of leaden wire, one from each side, standing upright, distant from each other, and convenient communications of wire and chain, from the giving side of one pane, to the receiving side of the other; that, so the whole might be charged together, and with the same labour as one single pane; and another contrivance to bring the giving*

(continued on page 3)

Benjamin Franklin: Natural Philosopher, Statesman, America's First Physicist

(continued from page 2)

sides, after charging, in contact with one long wire, and the receivers with another, which two long wires would give the force of all the plates of glass at once through the body of any animal forming the circle with them...

With these observations, and the theoretical concept of charge conservation to provide an organizing principle and direction for further research, Franklin was far ahead of everyone else. In London, Franklin's researches were published in 1751 under the title *Experiments and Observations on Electricity, Made at Philadelphia* (See figure 3). In 1756 (one year before he arrived in England as an ambassador of the Pennsylvania Colonial Assembly), Franklin was elected as the first American member of the Royal Society, having been awarded the Society's Copely Gold Medal in 1753, which at the time represented the highest scientific honor awarded in England. The *Experiments and Observations* book went through five editions in English, and was translated into French, Italian, and German. In 1772 the French Academy of Sciences elected Franklin a Foreign Associate, of which there could exist only eight at one time.

Thus we can understand Franklin's fame when he was sent to France as an ambassador of the fledgling United States of America, in 1776. At age seventy, with his two grandsons to accompany him, Franklin landed in France at the tiny village of Auray. He tried to keep a low profile, "thinking it prudent first to know whether the court [of Louis XVI] is ready and willing to receive ministers publicly from Congress." Walter Isaacson, one of his biographers, notes, "France was not a place, however, where the world's most famous American would find, nor truly seek, anonymity. When his carriage reached Nantes, the city feted him at a hastily arranged grand ball, where Franklin reigned as a celebrity philosopher-statesman and Temple [one of the grandsons] marveled at the height of the women's ornately adorned coiffures. After seeing Franklin's soft fur cap, the ladies of Nantes began wearing wigs that imitated it, a style that became known as *coiffure à la Franklin.*"

Fig. 2. Electrostatic generator for parlor amusements, ca. 1750. This apparatus is on display at the Smithsonian Institution's American History Museum, Washington, DC.

Photo by: D. E. Neuenschwander

The scientific accomplishment for which Franklin was best known to French society, and to every American schoolchild to this day, was drawing the "electrical fire" from a kite flown in a thunderstorm. In the course of his researches in Philadelphia, Franklin had discovered how a grounded conductor sharpened to a point would draw the charge off a nearby electrically charged object; and inversely, how charge could be drawn from the point of an isolated but electrified pointed rod (in modern terms we see this as the electric field being especially strong around the sharpened point). From these insights he was led to the study of lightning: Is lightning merely a colossal spark of "electrical fire?" He hypothesized that thunderstorm clouds become charged (their charges separated) through their turbulence; and if so then one could draw from them an electric spark using a grounded, pointed rod placed at a great height. The spire of Christ Church in Philadelphia was under construction, and Franklin planned to build a sentry box on top of the spire, where a grounded sharpened rod, held by a well insulated observer, would attempt to draw off the electrical fire. Before the sentry box could be completed, the experiment was done in France, confirming Franklin. Waiting no longer for the sentry box in order to do the experiment himself, Franklin improvised the kite experiment. He described the experiment in an article of 19 October 1752, in the *Pennsylvania Gazette*:

A frequent mention is made in public papers from Europe of the success of the Philadelphia experiment for drawing the electric fire from clouds by means of pointed rods of soft iron erected on high buildings &c. It may be agreeable to the curious to be informed that the same experiment has succeeded in Philadelphia, though made in a different and more easy manner, which is as follows:

Make a small cross of two light strips of cedar, the arms so long as to reach to the four corners of a large thin silk handkerchief when extended; tie the corners of the handkerchief to the extremities of the cross, so you have the body of a kite; which being properly accommodated with a tail, loop, and

(continued on page 4)

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Benjamin Franklin: Natural Philosopher, Statesman, America's First Physicist

(continued from page 3)

> *string, will rise in the air, like those made of paper; but this being of silk, is fitter to bear the wet and wind of a thunder-gust without tearing. To the top of the upright stick of the cross is to be fixed a very sharp pointed wire, rising a foot or more above the wood. To the end of the twine, next [to] the hand, is to be tied a silk ribbon, and where the silk and twine join, a key may be fastened. This kite is to be raised when a thunder gust appears to be coming on, and the person who holds the string must stand within a door or window, or under some cover, so that the silk ribbon may not be wet; and care must be taken that the twine does not touch the frame of the door or window. As soon as any of the thunder clouds come over the kite, the pointed wire will draw the electric fire from them, and the kite, with all the twine, will be electrified, and the loose filaments of the twine will stand out every way, and be attracted by an approaching finger. And when the rain has wet the kite and twine, so that it can conduct the electric fire freely, you will find it stream out plentifully from the key on the approach of your knuckle. At this key the phial may be charged; and from the electric fire thus obtained, spirits may be kindled, and all the other electric experiments performed, which are usually done by the help of a rubbed glass globe or tube, and thereby the sameness of the electric matter with that of lightning completely demonstrated. —B.F.*

Jacob Bronowski notes, "Franklin loved fun (he was a rather improper man), yet he took electricity seriously; he recognised it as a force in nature. He proposed that lightning is electric, and in 1752 he proved it—how would a man like Franklin prove it?—by hanging a key from a kite in a thunderstorm. Being Franklin, his luck held; the experiment did not kill him, only those who copied it."

Franklin was indeed a mischievous, flirtatious, and fun-loving man who enjoyed life. At the close of his 29 April 1749 letter to Collinson, he combined humor with physics in describing the termination of the season's electrical experiments:

> *Chagrined a little that we have been hitherto able to produce nothing in this way of use to mankind; and the hot weather coming on, when electrical experiments are not so agreeable, is proposed to put an end to them for this season, somewhat humorously, in a party of pleasure, on the banks of the Skuylkil. Spirits, at the same time, are to be fired by a spark sent from side to side through the river, without any other conductor than the water; an experiment which we some time since performed, to the amazement of many. A turkey is to be killed for our dinner by the electrical shock, and roasted by the electrical jack, before a fire kindled by the electrified bottle: when the healths of all the famous electricians in England, Holland, France, and Germany, are to be drank in electrified bumpers, under the discharge of guns from the electrical battery.*

Benjamin Franklin, 1706-1790: his 300th birthday occurred on January 17, 2006. We remember the anniversary of his birthday to honor him as a sage of the Enlightenment, philosopher of science, communicator of ideas, jolly good fellow, Framer of American democracy, and America's First Physicist.

— by Dwight E. Neuenschwander

Acknowledgements

The assistance of Bo Hammer and Virginia Ward of the Franklin Institute is greatly appreciated.

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2005-06 Marsh W. White Award Recipients

BALL STATE UNIVERSITY

Fisiks is Phun

During the past two years, the Ball State University Society of Physics Students Chapter has been actively involved in the community, taking physics demonstrations to the local middle schools in a program called "Fisiks is Phun." In addition, we set up a table at the Indiana State Fair in August of 2005. There, many people, young and old, showed a great deal of interest in physics. Due to the success, we would like to incorporate other topics such as magnetism and sound and we have been requested by local teachers to include optics. With new equipment, we will be able to expand our programs to include optics as well as demonstrate sound and magnetism.

Principal Proposers: Courtney Rowe-Bultinck & Melissa Bitters
Faculty Advisor: Dr. David Grosnick

BRIGHAM YOUNG UNIVERSITY—UTAH

Society of Physics Students Outreach Program

We propose to create additional physics demos for our outreach program. There is a demand for demos that correlate with the K-12 curriculum and demos for assemblies. We believe that the demos will not only teach kids how physics is fun, but will also reinforce concepts taught in the classroom.

Principal Proposers: Michael Clemens, William Ashby, Benjamin Wheaton & Justin Paul.
Faculty Advisor: Dr. Bret Hess

(continued on page 6)

ADOPT-A-SCIENTIST PROGRAM TAKES OFF

(continued from page 1)

building located at One Physics Ellipse—home to the American Physical Society and SPS, among others. Here surrounded by books, posters, diffraction gratings, and homemade Leyden jars, I create physics-based outreach projects for middle school and high school students.

One of my main projects has been Adopt-a-Scientist, a program that connects high school classes with scientists through e-mail interviews. Conceived by former American Physical Society intern Jennifer Fischer and developed by former Society of Physics Students intern Mika McKinnon, the goal of this project is to expose high school students to the variety of careers available in science. The "scientists" in Adopt-a-Scientist range from undergraduate science majors to retired industry workers. It includes science policy workers and teachers, engineers and biologists, minorities and women.

Mika recruited scientists by sending e-mails to companies, universities, and organizations across the country, and the response was overwhelming. We had to cap registration at 600 scientists because that was all that we could handle. Similarly, we had to turn teachers away because we only had room for 400 classrooms.

Each participating classroom "adopted" five scientists and received a brief description of them as well as contact information. The students are responsible for contacting their scientists via e-mail, and finding out what it's like to be a scientist. Students are given a list of recommended questions to ask, such as:

◆ How would you describe your job? What do you do in a typical day?

◆ What type of organization do you work for? Is this unusual for someone with your background? Why did you choose to work there?

◆ Do you think that your educational background prepared you for your current occupation? What would you change?

◆ When you were 18, what did you want to do when you grew up? How has that changed? Why?

Many of the scientists have copied their answers to us, and I get the great job of reading through them. I am surprised by how much I am learning; in fact, I found that many of them have helped me understand myself better.

The first thing I noticed was just how much scientists love their jobs. One scientist compared trying to name her favorite part of work to trying to name her favorite part of ice cream. Another said his 80 hour work weeks in graduate school were an "amazingly wonderful time" because the experiment was like one big hobby. This love isn't always evident when funding falls through. It's rarely evident in scientific journals. And it can be hard to recognize in yourself after being up all night doing homework and knowing you still have the wrong answers. But it's there. These e-mails were a great reminder of why we do what we do—we love it.

Also evident in these responses is the persistence (some might call it stubbornness) and passion that makes our advisors spend all their free time in the lab and expect us to do the same. "To do research, you must be willing to try something new, every day, for years on end," said one scientist, "And, after all of that effort, a long career might only result in one or two major accomplishments." In the end, I think, for most scientists it's not the *accomplishments* that make their life's work worthwhile, but the *search* for understanding. "There is a wonderful feeling of satisfaction in being able to look at the world and realize that you actually understand it," according to another scientist. That was what drew me to physics in the first place, and I think that I'm drawn to physics outreach because I want other people to feel that satisfaction too.

I am also struck by the honesty with which the scientists respond to the students. "It feels lonely at times," said one scientist on being a woman in her field, "like an outsider most of the time, and uncomfortable at other times." Another scientist explained his experience with such a demanding career, "Balancing work and family is difficult. Long hours limit the opportunity to do ordinary things, like repairing my house, which is becoming a bit of a dump…I have had to travel over my children's birthdays, my wife's birthday, my own birthday."

One scientist told students about the need, in science, to move away from searching for the "right" answers. "Always step back," he said, "ask yourself what really matters, how accurate you really need [an answer] and if the gains from the additional effort is worth it. This wisdom separates the practitioners from the students." As I thought about that statement I realized that's not a bad way to live—whether you're thinking about your future or about finishing that last quantum problem, focusing too much on the "right" answer may actually keep you from realizing the big picture.

The real value, I think, in programs like Adopt-a-Scientist is that they connect real people. More than fancy posters and guidance counselors, I think that honest, personal interactions like these will help students decide if a career in science is right for them—and will show them that you don't have to be an Einstein to succeed in science. One teacher wrote to me, "My students (and myself) have enjoyed hearing about REAL people." In a field where equations and technical terms can seem to be everything, I do too.

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KENDRA'S STORY

I became a "scientist" sort of by accident. After entering college as an undecided major, I vividly remember my freshman advisor asking me, "If I put a gun to your head and told you that you had to pick a major, what would you pick?" My response was, "umm, math?"

So math it was—until I took an astronomy class taught by the Physics Department Chair, who also happened to be the Society of

(continued on page 6)

Kendra sits at her desk in the APS offices.

-Photo courtesy of Kendra Rand, APS.

ADOPT-A-SCIENTIST PROGRAM TAKES OFF

(continued from page 5)

Physics Students advisor. He talked me into taking more physics classes, becoming involved in outreach using the Science Outreach Catalyst Kit (SOCK) and our school planetarium, and doing research for a summer. The rest is history…here I am years later with a masters degree in physics working in physics outreach.

I decided to leave research and work in public outreach because it allows me to combine my passions for science, communication, and education. I'd much rather spend my time learning about many different fields instead of specializing in just one. In addition, I enjoy putting journal articles and science results into language that non-scientists can understand and I believe strongly that the general public should be scientifically literate. My physics training gave me the background, as well as the critical thinking skills and creativity that I need to see how the technical details fit in with the big picture.

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2005-06 Marsh W. White Award Recipients

(continued from page 4)

CALIFORNIA STATE UNIVERSITY—CHICO

The Rocket Trike: A Dramatic Outreach Demonstration

The CSU-Chico chapter of the Society of Physics Students would like to resurrect our once-renowned "Rocket Trike." We propose demonstrating the Rocket Trike at multiple upcoming K-12 outreach events. We believe the Rocket Trike's dramatic illustration of Newton's Laws is a highly entertaining and effective tool for increasing student interest in science.

Principal Proposers: Joel Amato & Justin Stimatze.
Faculty Advisor: Dr. David Kagan

UNIVERSITY OF CENTRAL FLORIDA

Reel Physics

A continuation of the previous year's outreach program aimed at exciting high school and middle school students about physics. This program will use clips from popular movies to explain physical concepts and determine the validity of the "science" presented by the entertainment industry. This investigation will be supplemented with demonstrations.

Principal Proposer: Erik Riley
Faculty Advisor: Dr. Costas Efthimiou

UNIVERSITY OF COLORADO—COLORADO SPRINGS

Light and Liquid Crystals: A Panoply of Color

One of the best ways to get younger students interested in science and more specifically, physics, is to bring exciting demonstrations into their classrooms. We plan to develop a program to bring exciting knowledge about liquid crystals and liquid crystal displays to elementary, middle school, and high school classrooms. The program will be based on our faculty advisors research in liquid crystal displays and will include hand out materials, overhead presentations, and experiments.

Principal Proposer: Diana Haskins
Faculty Advisor: Dr. Anatoliy Glushchenko

UNIVERSITY OF CONNECTICUT

UConn Physics Olympiad

The SPS Chapter of the University of Connecticut is collaboratively working with the Physics Department in organizing a Physics Olympiad. The event will invite local high schools to attend a full day program at the University where students will compete in different tasks involving Physics concepts. The goal is to involve high school students in an intellectually stimulating and fun event involving Physics and to spark their interest and broaden their view of the field.

Principal Proposers: Carolina Artacho Guerra & Kurt Doughty
Faculty Advisor: Dr. Philip Best

UNIV. OF CONNECTICUT (L-R) Wesley Gohn, Dr. Barry Wells, Cecile Stanzione, Carol Artacho Guerra, Dr. Phil Best, JC Sanders, Nicole DiNicola, Nolan Samboy and Anne Wrigley.

MARQUETTE UNIVERSITY

Honoring Telsa's Dream of Wireless Electricity

Each year, members of the Marquette University Society of Physics Students visit inner-city elementary schools for High Interest Days. The goal is to promote interest in the sciences, and motivate students to continue their education. A Tesla coil provides a dramatic and memorable demonstration that will provoke student curiosity.

Principal Proposer: Jennifer E. Bustamante & Eric Breitbach
Faculty Advisor: Dr. Andrew Kunz

(continued on page 15)

LOOKING BACK ON THE SUCCESS OF THE WORLD YEAR OF PHYSICS 2005

— by Christy Hyde, University of Alabama, Associate Zone Council Representative of SPS/Sigma Pi Sigma Executive Committee, 2004-05

As scientists, our primary job is to find the basic principles that give rise to our human-inspired laws of physics. This is what so many of us are deeply passionate about; professionals describe physics as beautiful and artful. But our secondary charge is of the utmost importance. It is our job to publicize and help educate the masses as to what physics and science are really all about, sharing both the beauty and responsibility for technology with others.

This was the job of the World Year of Physics; this is why it was so important to so many of us. We measure the success of the WYP by how many people now have an appreciation for some area of physics, be it static electricity from the Van de Graff generator, electrical impulses from the lie detector test or the beauty and fun of stargazing. I very much enjoyed the numerous events I attended that celebrated the WYP.

The highlight that everyone is still talking about was the Sigma Pi Sigma Congress which was one of several WYP kickoffs. There were ethics talks and round table discussions, Einstein talks, student research and outreach, the American Physical Society (APS) Four Corner's meeting and a zone meeting. There were also excellent speakers, including Carl Wieman, Mildred Dresselhaus and Jocelyn Bell-Burnell, just to name a few. It was the Associate Zone Councilor's (AZC) privilege to introduce and talk with these distinguished speakers. My personal favorite was Jocelyn Bell-Burnell, who I introduced and then later had the amazing opportunity to sit with at dinner. She gave an excellent talk as well as very sound advice to an up-and-coming astronomer such as myself. I was very impressed with the caliber of speakers, especially the international representation. You really missed a spectacular physics party if you did not have the chance to attend this Congress. The next one should be at the top of everyone's to-do list in 2008! Because it is being held at FermiLab in Chicago, it is sure to be an even bigger hit than this one was.

The excitement felt throughout this meeting was carried back to schools all over the country. My chapter hosted a WYP Zone Meeting in January that started a chain reaction in our zone. Hopefully other chapters will continue the tradition of having a zone meeting each year! We also had a very successful WYP tent on the quad before two of our home football games. We did physics demos and gave out tops, yo-yos and balloons. I was very happy with these events because of all the publicity we attracted. It was really wonderful to be able to talk with people about how the physics demos worked and about the World Year of Physics. Overall, I feel that our department has a much greater sense of community, which is one of the missions of SPS. I hope that all of our students share this feeling and that our school will send a large group to the next Congress.

Christy Hyde, of the University of Alabama, served as the AZC Representative, the student representative to the Executive Council of the Society of Physics Students.

Photo courtesy of Christy Hyde.

As the AZC representative, I also had a unique perspective on other schools' activities all over the country. It was invigorating to be a part of the large network of AZCs over the past year. Wonderful things happened as a direct result of both the Congress and the WYP. Several schools have had their own ethics discussions, outreach efforts have increased and the excitement has carried into the planning of the next Congress. One of my best friends, who is a car mechanic and also happens to be my brother, loves to wear his World Year of Physics t-shirt. He says that when people ask him about his shirt, he tells them about some of the events he enjoyed through his "silly physics major sister!"

As the World Year of Physics comes to an end, I reflect on how successful it was. So many people were reached through this effort and hopefully they will have gained a new enjoyment of the lighter side of physics. Without the knowledge and appreciation of the essentials of physics, the general populace cannot make informed decisions about the direction our technological society will take. I genuinely believe that the WYP has bolstered this effort and was therefore as successful as we would like to hope it was!

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PHYSICS NEWS UPDATE

The American Institute of Physics Bulletin of Physics News

by Phillip F. Schewe, Ben Stein, and Davide Castelvecchi

RARE $e^-/e^+/e^-$ STATE. The best study of the rare "atom" consisting of two electrons and one positron is being reported. Positronium (abbreviated Ps) is a very "clean" two-body object: it consists of an electron and a positron which after about 150 nanoseconds annihilate each other. For studying the theory of quantum electrodynamics (QED), Ps is in some ways better even than the hydrogen atom: with pointlike constituents and with no complicating nuclear forces (the size of the proton and its own internal structure interject uncertainties into QED estimates of H behavior), Ps is a simpler, albeit fragile, quantum system. An even more fragile "atom" is the tripartite object consisting of two electrons and one positron. Ps^-, as it is known, is less suitable for QED studies than Ps, but has the great virtue of being the simplest three-body system in physics. Again, it is simpler than H^-, H_2^+, and He because of its pointlike constituents and the absence of nuclear forces. Ps^- is, like Ps, a bound system with discrete quantum energy states, although only the ground state is calculated to be stable against dissociation into Ps and a free electron. Very little is known about Ps^- beyond its lifetime. Now, a new experiment carried out at the Max Planck Institute for Nuclear Physics in Heidelberg has measured the lifetime of Ps^- with a sixfold increase in precision (the new value is half a nanosecond). Ps^- is formed by shooting a positron beam into a thin carbon foil, and its size is actually a bit bigger than a hydrogen atom. (Fleischer et al., *Physical Review Letters*, upcoming article.)

RELATIVISTIC ELECTRON COOLING of an antiproton beam has been demonstrated at Fermilab. Increasing the density of antiprotons by reducing the spread in longitudinal speeds leads to a larger collision rate in particle colliders, producing more sought-after scattering events that contain rare particles and decays. Antiprotons, made artificially by smashing protons into a metal target, must be collected on the fly and focused before they can be accelerated and collided with opposite-moving batches of protons; such proton-antiproton smashups are the premier activity at Fermilab's Tevatron facility. The more compact and tightly focused the two beams are, the more desirable high-energy collisions there will be. The degree of focus and beam density is expressed in a parameter called luminosity. To achieve interesting results it is desirable to have both high collision energy and high luminosity. Taming swarming antiprotons, however, is difficult. One would like all the antiprotons to be co-moving at the same velocity, but because of the way they're made in the first place, they will be flying at high speeds through a beam pipe with a variety of motions, both longitudinal and lateral. The lateral motions can be largely suppressed by a process called stochastic cooling, in which electric signals are dispatched to various electrodes stationed around the Fermilab's three antiproton storage rings; the electrodes offer minor kicks which serve to lower the lateral "temperature" of the swarm. Reducing the spread in longitudinal speeds has been harder to accomplish, until now. In the new Fermilab process a continuous beam of electrons at an energy of 4.8 MeV is made to overlap with a beam of 8.9 GeV antiprotons which, because of their higher mass, move at the same speed as the electrons. The electron beam—in effect an electrical current of 0.5 ampere and 2 megawatts—removes some of the unwanted longitudinal velocity spread, increasing thereby the luminosity by a factor of 30 percent. E-cooling of this kind has been used before but only with much lower-energy particle beams. (Nagaitsev et al., *Physical Review Letters*, 3 February 2006.)

NUCLEAR MOLECULE: NATURE'S SMALLEST DUMBBELL. An oxygen molecule is a small dumbbell less than a nanometer across: two oxygen atoms with two electrons flying between acting as the bonding agent. Now, an international consortium has succeeded in making a dumbbell far smaller: a beryllium-10 nucleus consisting of two alpha particles (nuclear fragments containing two protons and two neutrons) with two neutrons flying between acting as a sort of nuclear bonding agency. This nuclear dumbbell is only a few fermis (10^{-15} m) across. These tiny oblong nuclei are made by colliding a beam of helium-6 nuclei into a gas of helium-4 atoms. (The He-6 nuclei, which are themselves a novelty, were made by shooting protons at lithium.) The Be-10 nuclei created in this way don't live very long. With a lifetime of about 10^{-21} seconds, they fly apart, usually back into He-4 and He-6 fragments. Martin Freer says that the beryllium results support the idea that nuclei sometimes behave like atomic systems in that they can be thought of as a core of particles with extra "valence" particles (electrons/neutrons) exchanged between cores. Several exotic shapes are thought to be possible among the light nuclei. Carbon-12, for instance, can exist as a triangular arrangement of three alpha particles and oxygen-16 as a tetrahedron of alphas. But these nuclei are tightly bound, so their exotic geometry cannot be discerned. But Be-10's prolate shape can be seen clearly through the rotational behavior of the decaying system. Freer is part of a team from the Universities of Birmingham and Surrey (UK), Universite Catholique de Louvain and University of Leuven (Belgium), Universite de Caen (France), and the Rudjer Boskovic Institute (Croatia). (Freer et al., *Physical Review Letters*, upcoming article.)

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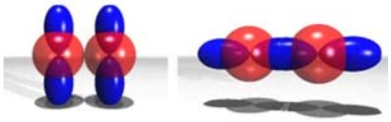
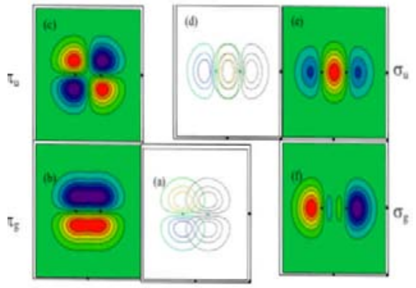
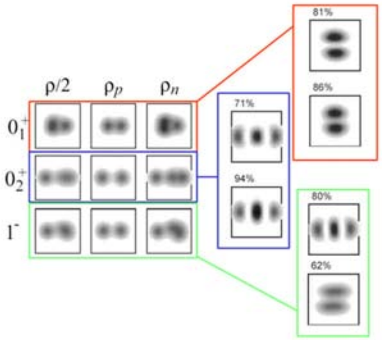
Dumbbell-Shaped Nucleus



Formation of molecular states in Be-10 based on the exchange of neutrons (blue) in p-orbits based on alpha-particle cores (red-spheres). The left-hand side shows the arrangement which gives rise to pi-bonds, the right-hand side sigma-schematic.



These are some antisymmetrized molecular dynamics calculations by Kanada En'yo et al. which show the proposed cluster structures in Be-10. On the left-hand side, the 3 panels show the total density, density of protons, and density of the neutrons. The 0+1 is the ground state, the 1- a negative parity structure and 0+2 the structure that we have measured. The right-hand side shows the calculated orbits of the 2 neutrons outside the 2 alpha-particle cores. For the 0+2 state it can be seen that the neutrons sit in sigma-type orbits. Reported by: Freer et al. in *Physical Review Letters*



2005-06 Sigma Pi Sigma Undergraduate Research Award Recipients

University of Texas—Arlington

Large Cloud Chamber Prototype at UT Arlington

We propose to construct a prototype for a large self sustaining cloud chamber. The prototype will be used to investigate the behaviors of proposed chamber materials at low temperatures, determine the most effective methods of maintaining a steep temperature gradient, and determine the best conditions to sustain chamber activity.

Principal Proposers: Kenneth Crawford, James Creel, Priya Mydur, Jacob Smith, Shane Spivey, & Sabine Sudduth
Faculty Advisor: Dr. Jaehoon Yu

University of Central Florida

The Ascending Double Cone: Verifying & Demonstrating the Motion of the Double Cone V-rail System

We propose here to construct the double-cone and v-rail system to the specifications required to verify the predictions made by S. Gandhi and C. Efthimiou for its motion. This construction will be designed so as to reveal features of the motion predicted by S. G. and C. E. that are not apparent in the conventional demonstration and to allow for the precise testing of the quantitative relations derived by them.

Principal Proposer: Sohang C. Gandhi
Faculty Advisor: Dr. Costas Efthimiou

Stephanie Sears and Jeremy McMinis, Eastern Michigan University

Eastern Michigan University

Investigating Experimental Parameters in a New Plasma Source

The objective of this research project is to investigate the properties of a prototype plasma source similar in nature to an ion thruster. We will build, operate and optimize the plasma generated by this source. We will build new plasma probes in order to study the properties of this plasma such as its size, density, and temperature. We will also update and enhance the equipment available in the plasma lab to encourage more active student research at Eastern Michigan University.

Principal Proposers: Stephanie Sears & Jeremy McMinis
SPS Advisor: Dr. Diane Jacobs
Research Advisor: Dr. James Carroll

University of Colorado—Colorado Springs

Stressed Liquid Crystals for Large Phase Shift Modulation

Historically, the last two decades have seen an explosion of interest in liquid crystal dispersions that has been encouraged primarily by the possibility of creating new display devices. Typical examples of liquid crystalline dispersions are polymer-dispersed liquid crystals (PDLC) and suspensions of micro-particles in liquid crystal matrices (filled liquid crystals). The common characteristics of these dispersions are random distribution of the phases and random orientation of the liquid crystal molecules. These systems scatter light but become transparent when an electric field is applied.

The effort of this project will be concentrated on ordered liquid crystal dispersions. We will be working with recently discovered stressed liquid crystals. They consist of interconnected liquid crystal domains and interpenetrating polymer chains. Shearing deformations impose a preferred orientation of the liquid crystal director and elimination of scattering, distinguishing the system in several fundamental ways from other known liquid crystal dispersions. This new type of material has great potential for use in numerous electro-optic device applications including flat panel displays, diffractive optical elements, and other light controlling devices.

Principal Proposer: Diana Haskins
Additional Proposers: Tim Fal, Mike Steinman Diana Qiu & Audra Tadevich Lee
Faculty Advisor: Dr. Anatoliy Glushchenko

Northern Virginia Community College

Applications of the Superconducting Meissner Effect

We plan to build and investigate the operation of three devices, all based on the repulsive force between a magnet and a superconductive diamagnet.

◆ Magnetic Flywheel Levitated Over a Superconducting Plate.

◆ Meissner Effect Heat Engine: a disc with superconductors on the rim and a magnet with nitrogen vapor at disc's bottom will rotate, absorbing heat from air.

◆ A superconducting simple pendulum as another form of a thermodynamic engine: it will swing in the field of gravity and in a magnetic field, while undergoing transitions between insulator and superconducting states.

Principal Proposers: John Jones, Pooya Azar, Daniel Gordon, Aziza Dang, Taha Ferozpuri, Adam Reed & Steven Hendrickson
Faculty Advisor: Dr. Walerian Majewski

North Dakota State University

Morphologies of Polymeric Membranes formed by Immersion Precipitation

The underlying dynamics of phase separation of a polymer-solvent solution by immersion precipitation will be studied. A thin layer of the polymer-solvent mixture is spread onto a substrate, which is then immersed in a non-solvent. The resulting morphology of the polymer is dependent on several parameters, which we intend to vary. The dependence of the structure morphology will be quantified and used to develop a theory to describe the process and create simulations to parallel the experimental results.

Principal Proposer: Adam Jones
Faculty Advisor: Dr. Alexander Wagner

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ELEGANT CONNECTIONS IN PHYSICS

Einstein on Atoms, Fluctuations, and Brownian Motion

— by Dwight E. Neuenschwander

"On the Motion of Small Particles Suspended in Liquids at Rest Required by the Molecular-Kinetic Theory of Heat"[1] was the third of Albert Einstein's celebrated five papers of his 1905 "miraculous year."[2] Building on his dissertation "A New Determination of Molecular Dimensions"[3] that was submitted on April 30, the "Small Particles" paper was received by *Annalen der Physik* only eleven days later, on May 11. Einstein resolved an enigma that had been around since 1827, and laid out a high-stakes alternative for physics:[4] *if* atoms are real, then the laws of thermodynamics are statistical; but if his theory did *not* compare favorably to reality, then the atomic hypothesis was in serious trouble.

Throughout the nineteenth century, the "atomic hypothesis" of Dalton (1808), Avogadro (1811), and Prout (1815) gained traction. By the 1880's and 90's, theorists such as Ludwig Boltzmann and J. Willard Gibbs were showing how the laws of thermodynamics could be understood in terms of atoms, by applying Newtonian mechanics to one atom then averaging over huge numbers of them. However, in 1905 several distinguished senior chemists and physicists still maintained that the atomic concept was useful in merely the same way that, say, complex numbers are useful. Into this unresolved discussion stepped the young Einstein. His May 11 paper was especially applicable to "Brownian motion," which takes its name from the Scottish botanist Robert Brown who discovered (or re-discovered) the phenomena in 1827.[5]

Looking through a microscope at pollen grains immersed in a drop of water, Brown noticed these visible grains jiggled erratically to and fro. Pollen grains are *alive*, so Brown further tested this strange phenomena with tiny grains that were manifestly dead, such as ground-up glass, granite, volcanic ash—even a powdered fragment of the Sphinx! These nonliving grains exhibited the same jiggling motions as the pollen. Clearly this was not a phenomena that depended on having life *in* the grains; rather some *physical* process was happening *to* the grains.

Several mechanisms were investigated and ruled out over the years, including capillarity, evaporation, convection currents, electrical forces, and light scattering. Many people realized that *if* the atomic hypothesis were true, *then* the jiggling might be understood in terms of collisions between the water molecules and a grain. Because the grains are so much larger (microns) than water molecules (nanometers), collisions with *individual* water molecules would have negligible effects on the grain. Most of the time the grain gets bombarded symmetrically from all directions by the water molecules anyway. But statistical fluctuations in the occurrence of these random collisions make it possible for a sufficiently large number of water molecules, by chance moving in concert ever so briefly, to impart a well-directed kick to the pollen grain. The problem was how to connect this *concept* to something actually *measurable* while squinting at those tiny grains through a microscope eyepiece.

Kinetic Theory vs. Thermodynamics

Because atoms would be independent of one another in the gaseous state, low-density gases provided the first theoretical workshops for connecting the atomic hypothesis to thermodynamic observables. From the macroscopic scale of pressure gauges, meter sticks, and thermometers, experiments with results that carry famous names such as "Charles' Law" and "Boyle's Law" and the "Gay-Lussac Law" show that, when in thermal equilibrium at absolute temperature T, the pressure P, volume V, and mass of gas (measured by the number of moles n) are related by the equation of state

$$PV = nRT\,. \tag{1}$$

Fit to data, R has the value 8.31 J/K-mol.

If this equation of state may be interpreted in terms of atoms, then the number of moles translates into the number of molecules N thanks to Avogadro's number, $N_A = 6.02\times10^{23}$ molecules per mole, so that $N = n\,N_A$. The convergence of independent experiments in the late 1800's and early 1900's that all gave essentially the same value for Avogadro's number contributed much to making the atomic hypothesis universally convincing. In his first three papers of 1905, Einstein envisioned three methods of measuring N_A, one of them the subject of this article. They played an important role in the demonstration that atoms are *real*. Einstein returned to the study of stochastic processes often over the next twenty-five years.[6]

To connect the equation of state of a dilute gas to the adventures of the microscopic atoms, let us model a single gas molecule as a structureless point mass m, whose only interactions are elastic collisions with the container walls. Apply Newton's second law, in the form $\mathbf{F}_{ave} = D\mathbf{p}/Dt$, to the particle as it makes collisions with one of the container walls. Assume for simplicity a cubical container, for which $V = L^3$. The velocity component v_x normal to the wall reverses; and for Dt we have the time $2L/v_x$ between successive collisions with this wall.

Average this result over all the particles, and note that, by symmetry, $\langle v_x^{\,2}\rangle = \langle v_y^{\,2}\rangle = \langle v_z^{\,2}\rangle = \tfrac{1}{3}\langle v^{2}\rangle$, where the brackets $\langle\,\rangle$ denote the average over the population of particles. Recalling that pressure measures average force per unit area, we obtain

$$PV = \tfrac{2}{3}\,N\,\langle \tfrac{1}{2}mv^2\rangle\,. \tag{2}$$

Comparing Eqs. (1) and (2), we conclude that

$$\langle \tfrac{1}{2}mv^2\rangle = (3/2)\,kT, \tag{3}$$

with proportionality constant k. Fit to data, k emerges with the value 1.4×10^{-23} J/K, "Boltzmann's constant." One mole of Boltzmann's constants equals the ideal gas constant $R = 8.31$ J/K-mol. Because the

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Einstein on Atoms, Fluctuations, and Brownian Motion

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internal energy of the gas $U = N\langle E\rangle$, from Eq. (3) we have a second equation of state for an ideal gas,

$$U = (3/2)\,NkT. \quad (4)$$

If the gas is made of atoms, then besides pressure due to atomic collisions, we also have a microscopic interpretation of temperature, as the average kinetic energy of the atoms. Other microscopic interpretations of thermodynamic state variables also follow from the more sophisticated methods of Maxwell and Boltzmann; notably, entropy as a measure of molecular disorder, the logarithm of the number of ways the atoms can be arranged to give the same macroscopic state.

The *kinetic* perspective sees matter as atoms in motion; in contrast, the *thermodynamic* approach relates various macroscopic state variables *to one another* through equations of state. Spelling out the nature of underlying microscopic reality does not appear in the "job description" of thermodynamics. Einstein realized that if the atomic picture was the ontological truth, then *statistical fluctuations* about the average values of thermodynamic observables *must* exist. In the May 11 paper, he laid out a high-stakes alternative for physics, for which Brownian motion would provide a test case with predictable consequences:

> *"In this paper it will be shown that, according to the molecular-kinetic theory of heat, bodies of a microscopically visible size suspended in liquids must, as a result of thermal molecular motions, perform motions of such magnitude that they can be easily observed with a microscope. It is possible that the motions to be discussed here are identical with so-called Brownian molecular motion...*
>
> *"If the motion to be discussed here can actually be observed, together with the laws it is expected to obey, then classical thermodynamics can no longer be viewed as applying to regions that can be distinguished even with a microscope, and an exact determination of actual atomic sizes becomes possible. On the other hand, if the prediction of this motion were to be proved wrong, this fact would provide a far-reaching argument against the molecular-kinetic conception of heat."*

Before re-creating Einstein's Brownian motion study, we must acknowledge an equation of state that holds for a dilute *liquid solution.* Consider a solvent (water, say) occupying some large volume. Into a sub-volume V one plops a solute (a spoonful of sugar) and lets it dissolve. Let this volume V be kept separate from the rest of the solvent by a semi-permeable membrane, such that solvent moves freely in and out of V but the solute molecules are confined inside V. Eventually an equilibrium becomes established; the solvent within V exerts a pressure P'' on the membrane from within, while the pure solvent exerts pressure P' from without. If we let P denote $P'' - P'$, the "osmotic pressure" (the pressure *excess* exerted by the solute above that of pure solvent), then one finds empirically an equation of state suggesting that the n moles of solute molecules behave strikingly similar to the molecules of an ideal gas:

$$PV = nRT, \quad (5)$$

where this R turns out to be the familiar ideal gas constant! This result, established empirically before Einstein's time, is known as van't Hoff's law.[7] Einstein invokes it in Section 1 of his paper:

1. On the Osmotic Pressure to be Ascribed to Suspended Particles

Einstein notes that a solution kept within volume V, and separated from pure solvent by the semi-permeable membrane, exerts the osmotic pressure $P = nRT/V$ on this membrane. In contrast to a dilute *solution*, to which van't Hoff's law applies, Einstein now asks us to consider a liquid that contains widely separated, undissolved *suspended bodies* such as Brown's pollen grains. As in much of his creative work, Einstein noticed two ways in traditional thinking that seem to be contrary.

On one hand, classical thermodynamics leads us to expect that these grains suspended *in* the fluid will contribute zero to the osmotic pressure exerted *by* the fluid. The reason, which Einstein recalls, requires a discussion of "free energy," to which we digress below. On the other hand,

> *"...a different interpretation arises from the standpoint of the molecular-kinetic interpretation theory of heat. According to this theory, a dissolved molecule differs from a suspended body only in size, and it is difficult to see why suspended bodies should not produce the same osmotic pressure as an equal number of dissolved molecules..."*

Einstein will provide additional support for this view by deriving the van't Hoff law from kinetic theory:

> *"It will be shown in the next section that the molecular-kinetic theory of heat does indeed lead to this broader interpretation of osmotic pressure."*

But first we must discuss why classical thermodynamics would lead us to expect zero osmotic pressure from the suspended grains. On this point Einstein only remarked, *"...according to the classical theory of thermodynamics, we should not expect...any pressure to be exerted on the wall; for according to the usual interpretation, the 'free energy' of the system does not seem to depend on the position of the wall and of the suspended bodies..."* This requires a small digression on "free energy." We will need it for other parts of the paper too.

The first law of thermodynamics says that the increase in a system's internal energy U equals heat dQ put *into* the system, minus work done *by* the system,

$$dU = dQ - PdV. \quad (6)$$

The second law of thermodynamics says that when a system receives heat dQ reversibly from the surroundings at temperature T, its entropy increases by the increment dS, where

$$dS = dQ/T\,. \quad (7)$$

Therefore, the combined first and second laws give

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Einstein on Atoms, Fluctuations, and Brownian Motion

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$$dU = TdS - PdV. \qquad (8)$$

If we add and subtract SdT, this becomes

$$dA = -SdT - PdV \qquad (9)$$

where

$$A \equiv U - TS \qquad (10)$$

denotes the "Helmholtz free energy." Note that $U = U(S,V)$ but $A = A(T,V)$, so that the pressure follows from

$$P = -(\partial U/\partial V)_S = -(\partial A/\partial V)_T \ . \qquad (11)$$

The introduction of the Brownian particles into the solvent is essentially adiabatic ($dS = 0$), isothermal ($dT = 0$), and the particles contribute neglible volume ($dV \approx 0$). Therefore, dU and dA are neglible, so that the Brownian particles might be expected to contribute zero osmotic pressure. Einstein argues a contrary view in Section 2.

2. Osmotic Pressure from the Standpoint of the Molecular-Kinetic Theory of Heat

In this section Einstein uses the statistical mechanics of Boltzmann to derive the van't Hoff equation of state f*or the suspended particles* in a liquid. He thereby provides an explicit demonstration for osmotic pressure exerted by Brownian particles.

Boltzmann developed two perspectives on statistical mechanics: a comprehensive kinetic theory (the Boltzmann transport equation) that deals with collision frequencies; and a program of probability distributions. In the latter calculus, when the microscopic molecule has kinetic plus potential energy $\mathbf{p}^2/2m + F(\mathbf{r})$, and that molecule finds itself in a macroscopic system in thermal equilibrium at temperature T, the probability of that molecule being in a state with energy E is

$$(1/Z)\exp(-E/kT),$$

where the "partition function" Z guarantees that all the probabilities add up to unity:[8]

$$Z \sim \int \exp(-E/kT)\, d^3p\, d^3r. \qquad (12)$$

Boltzmann connected macroscopic thermodynamics to the microscopic probabilities by identifying the Helmholtz energy A with the partition function through $Z = \exp(-A/kT)$, or

$$A = -NkT \ln Z. \qquad (13)$$

Using this machinery, Einstein imagines N Brownian particles suspended in the solvent and confined within a volume V by the semi-permeable membrane. The difficulty in calculating Z comes with our ignorance of the suspended particles' interactions with the solvent molecules. But arguing from the system's symmetry under translational invariance, Einstein shows that Z factors into the form $Z = JV$, where J is that part of the integral independent of V. Therefore

$$A = -NkT(\ln J + \ln V) \qquad (14)$$

and $P = -\partial A/\partial V$ gives the van't Hoff law.

"This analysis shows that the existence of osmotic pressure can be deduced from the molecular-kinetic theory of heat, and that, at high dilution, according to this theory, equal numbers of solute molecules and suspended particles behave identically as regards osmotic pressure."

The Brownian particles exert osmotic pressure because they *move*. This propagation can be considered a diffusion process, and to that Einstein next turns his attention.

3. Theory of Diffusion of Small Suspended Spheres

In this section Einstein begins to develop the theoretical machinery that will provide a way to experimentally track the motion of a Brownian particle. For this swarm of particles to be in *mechanical equilibrium*, a pressure gradient that would otherwise make them disperse must be balanced by some as-yet-unidentified force exerted on them by the fluid. Let this force acting on a single suspended particle be denoted **K**, and let the number of suspended particles per unit volume be f; then for mechanical equilibrium we require

$$\mathbf{K}f - \tilde{N} P = 0\ . \qquad (15)$$

Taking for x-axis the direction of **K**, by van't Hoff's law this becomes

$$Kf = (RT/N_A)\, \partial f/\partial x \qquad (16)$$

where we have used $f = N/V = n N_A/V$.

To obtain this result Einstein said "*...in the case of thermodynamic equilibrium f is a function of x such that the variation of the free energy vanishes for an arbitrary virtual displacement* $\hat{I}$ *of the suspended substance*," and he writes the equivalent of Eq. (16). He is rather terse on this point, and it's fascinating to see how he obtains Eq. (16) from the free energy.

Because the volume and temperature of the system does not change, according to Eq. (9), $dA = 0$. The work PdV done *by* the system, though zero, has two contributions that cancel out: PdV includes the work done by the Brownian particle, and the work done by the rest of the system:

$$0 = PdV = dW_{\text{Brownian particle}} + dW_{\text{rest of system}}$$

and thus

$$dW_{\text{Brownian particle}} = -dW_{\text{rest of system}} \qquad (17)$$

which says, in words, that the work done *by* the Brownian particle equals the work done *on* the rest of the system. When a Brownian particle moves the distance $\hat{I}$, the work done by the Brownian particle equals $K\hat{I}$.

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Einstein on Atoms, Fluctuations, and Brownian Motion

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Consider now all the Brownian particles that find themselves in a slab of fluid of cross-sectional area A_o and thickness dx. The number of Brownian particles inside the slab is $f A_o\, dx$. The work done by all these Brownian particles is $(f A_o\, dx)(K\hat{I})$. The work done by the rest of the system comes from the force due to the difference in pressure on the two sides of the slab: $A_o\, dP\, \hat{I} = A_o\, (dP/dx)\, dx\, \hat{I}$. By virtue of Eq. (17), we therefore have

$$K f = dP/dx\,. \tag{18}$$

But $P = nRT/V$, or

$$P = f\, RT/N_A\,. \tag{19}$$

From Eq. (19) we have $dP/dx = (RT/N_A)df/dx$, that when carried over into Eq. (18) gives the result of Eq. (16).

Einstein identifies the force **K** with Stoke's law.[9] If the suspended particles are spheres of radius a moving with velocity $\mathbf{v}$ without turbulence, and the liquid has viscosity m, then Stoke's law says that each sphere experiences the viscous drag of magnitude $6pma|\mathbf{v}|$. This tells us that the suspended particles move at the speed $K/(6pma)$. Therefore, the flux of these particles (the number of particle that pass per second) through an area A_o perpendicular to the x-axis is $vA_o f = Kf A_o/(6pm\, a)$. Using Eq. (16), this becomes

$$flux = (RT/N_A)(\partial f/\partial x)\, A_o/(6pma). \tag{20}$$

Einstein also writes the flux (and thus the viscous friction) in terms of a diffusion coefficient, as follows. The gradient of the number density causes the current density $f\mathbf{v}$, so that

$$-D\, Ñ\, f = f\, \mathbf{v}, \tag{21}$$

which *defines* the diffusion coefficient D. For motion parallel to the x-axis, Eq. (21) gives

$$flux = A_o\, f\, v = D\, A_o\, \partial f/\partial x. \tag{22}$$

Comparing Eqs. (20) and (22) yields

$$D = (RT/N_A)/(6pma). \tag{23}$$

"*Thus, except for universal constants and the absolute temperature, the diffusion coefficient of the suspended substance depends only on the viscosity of the liquid and on the size of the suspended particles*."

These results will be used to make his main point, derived in Section 5. But first we must consider Einstein's next move: to go beyond *macroscopic* thermodynamics and consider *fluctuations* about the statistical averages that we identify as thermodynamic state variables.

4. On the Disordered Motion of Particles Suspended in a Liquid and Its Relation to Diffusion

"*We shall now return to a closer examination of the disordered motions that arise from thermal molecular motion and give rise to the diffusion investigated in the last section*." Einstein here introduces into physics the study of fluctuations in a form what would become the celebrated "fluctuation-dissipation theorem."

He assumes what would soon become known as a Markov process: "*...each individual particle executes a motion that is independent of the motions of all the other particles; the motion of the same particle in different time intervals must also be considered as mutually independent processes, so long as we think of these time intervals as chosen not to be too small*."

Towards this end Einstein introduces a time interval t that is small compared to the time an observer watches through the microscope, but large compared to the time between successive collisions suffered by the suspended particle and atoms of the liquid. Let N Brownian particles be suspended in the liquid, and let their number density in the neighborhood of a point on the x-axis, at time t, be denoted $f(x,t)$. During the time interval t just described, a particle will move from x to $x+s$, (all the while suffering numerous and frequent collisions with the much smaller solvent molecules), where s has a different value (positive or negative) for each suspended particle. The fraction of particles dN/N that experience *some* displacement between s and $s+ds$ in the time t defines a distribution function $j(s)$ according to

$$dN/N = j(s)\, ds \tag{24}$$

where the normalization

$$\int_{-\infty}^{\infty} j(s)\, ds = 1 \tag{25}$$

guarantees that $\int dN = N$. Because the Brownian particles are large and slow compared to the solvent molecules, we may assume the distribution function $j(s)$ to be sharply peaked about $s = 0$. With no preferred direction in the liquid (gravity being negligible because of the Brownian particle's buoyancy), we may take the distribution function to be symmetric: $j(s) = j(-s)$. Thus equipped, Einstein investigates the *time evolution* of the particle density f. For the number density $f(x,t+t)$ of Brownian particles in the neighborhood of x at the time $t+t$, given that the density near x was $f(x,t)$ at time t, Einstein postulates

$$f(x,t+t) = \int_{-\infty}^{\infty} f(x+s,t)\; j(s)\, ds. \tag{26}$$

Einstein's intuition makes sense: In words, it says that to find the updated particle density at a given location x, at a later time $t+t$, you look at what it was at some point located at $x+s$ (near x) at the earlier time t; then you multiply the old-but-nearby f by the fraction of the

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Einstein on Atoms, Fluctuations, and Brownian Motion

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particles that moved from x to $x+s$ in the time interval t. That fraction is of course the distribution function $j(s)ds$. You do this for all possible s, then sum over s. Einstein develops this into a differential equation for the evolution of f, by making use of both the smallness of t and the smallness of s (j is sharply peaked so only small s are important). First, on the left-hand side of Eq. (20) he expands f as a function of time:

$$f(x,t+t) = f(x,t) + t\,\partial f/\partial t + ... \tag{27}$$

Next, under the integral on the right hand side he expands f as a function of s:

$$f(x+s,t) = f(x,t) + s\,\partial f/\partial x + ½\, s^2\, \partial^2 f/\partial x^2 + ... \tag{28}$$

Now Eq. (26) says

$$f + t\,\partial f/\partial t \approx f\int_{-\infty}^{\infty} j\;ds + \int_{-\infty}^{\infty} s\;\; j\;ds \;+\; ½(\,\partial^2 f/\partial\, x^2)\int_{-\infty}^{\infty} s^2\; j\;ds. \tag{29}$$

Note that the second integral vanishes by virtue of being an odd function integrated over symmetric limits. Also, use the normalization of Eq. (25), and let D denote the rate of change of $\langle s^2\rangle$:

$$D \equiv ½(1/t\,)\int_{-\infty}^{\infty} s^2\; j(s)\;ds. \tag{30}$$

So now with Einstein we obtain the diffusion equation,

$$\partial\, f/\partial t = D\,\partial^2 f/\,\partial x^2. \tag{31}$$

Its solution is well known:

$$f(x,t) = N\,(4pDt)^{-½}\,\exp[-x^2/4Dt] \tag{34}$$

"*The probability distribution of the resulting displacement during an arbitrary time t is thus the same as the distribution of random errors, which was to be expected. What is important, however, is how the constant in the exponent is related to the diffusion coefficient. With the help of this equation we can now calculate the displacement* l_x *, in the direction of the x-axis that a particle experiences on the average, or, to be more precise, the root-mean-square displacement in the x-direction...*"

The root-mean-square, which is the square root of

$$\langle x^2\rangle \;=\int_{-\infty}^{\infty} x^2\, f(x,t)\; dx, \tag{35}$$

contains a well-known Gaussian integral,[10] which yields $\langle x^2\rangle = 2Dt$, and Einstein's main result of this paper:

$$l_x \equiv Ö\,\langle x^2\rangle = Ö\,(2Dt). \tag{36}$$

This result was perhaps the first example of a "fluctuation-dissipation theorem,"[11] where the *fluctuations* of a variable about its average are related to a *dissipative* influence. Einstein commented, "*The mean displacement is thus proportional to the square root of the time. It can easily be shown that the root mean square of the total displacements of the particles has the value* l_x/Ö 3." We have seen this before: the distance the particle travels will be the square root of $x^2 + y^2 + z^2$, and by symmetry, $\langle x^2\rangle = \langle y^2\rangle = \langle z^2\rangle$ leading to Einstein's conclusion. Next he puts numbers to his result and makes a testable prediction.

5. Formula for the Mean Displacement of Suspended Particles. A New Method of Determining the Actual Size of Atoms

In Section 3 Einstein found for a Brownian particle of radius a, suspended in a liquid of viscosity m, the diffusion coefficient

$$D = (RT/N_A)\,/\,(6pma). \tag{37}$$

Further, he found in Section 4 the root-mean-square value for its displacement, Eq. (36). By eliminating D between Eqs. (36) and (37), he gets

$$l_x = Ö\,[\,t\,(RT/N_A)/(3pma)]. \tag{39}$$

"*We will now calculate how large* l_x *is for one second if* N_A *is taken to be* 6×10^{23} *in accordance with the kinetic theory of gases; water at 17°C (* $m = 1.35\times10^{-2}$*) is chosen as the liquid, and the diameter of the particles is 0.001mm. We get* $l_x = 8\times10^{-5}$ *cm = 0.8 microns. Therefore, the mean displacement in one minute would be about 6 microns.*

"*Conversely, the relation can be used to determine* N_A*. We obtain*

$$N_A = (t/l_x^{\,2})(RT/3pma). \tag{40}$$

"*Let us hope that a researcher will soon succeed in solving the problem presented here, which is so important for the theory of heat.*"

In 1909, Perrin performed the experiment that confirmed Einstein. The reality of atoms was at last firmly established.

Acknowledgements

I wish to thank Don Lemons of Bethel College, North Newton, KS, for several enlightening discussions. Also, I thank Harold and Harriet Moran for their generous hospitality while work on this article was being completed.

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[1] A. Einstein, "On the Motion of Small Particles Suspended in Liquids at Rest Required by the Molecular-Kinetic Theory of Heat," *Annalen der Physik* **17** (1905), pp. 549-560. Because of symbols commonly used in today's textbooks often differ from those of Einstein's paper, I have taken the liberty to change some of them; for example, he used *P* for a radius, *k* for viscosity; he uses *n* and *B* where I use *N* and *Z*, etc.

[2] A translation of Ref. 1 consulted for this annotation is *Einstein's Miraculous Year*, J. Statchel, Ed. (Princeton Univ. Press, 1998).

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Einstein on Atoms, Fluctuations, and Brownian Motion

(continued from previous page)

[3] A. Einstein, "A New Determination of Molecular Dimensions," PhD dissertation, Bern, 30 April 1905. Our annotation of the dissertation appears in *The SPS Observer*, Spring 2005, pp. 10-15.

[4] John Rigden, *Einstein* 1905: *The Standard of Greatness* (Harvard Univ. Pr., 2005).

[5] For a lucid discussion of Brownian motion, and the study of stochastic processes of which Brownian motion forms one example, see *An Introduction to Stochastic Processes in Physics* by Don S. Lemons (Johns Hopkins Univ. Press, 2002). He relates how Brown (1773-1858) described the phenomena that bears his name in 1827, and that Jan IngenHousz (1730-1799) observed and described it in 1785. Lemons comments how this "is just one of many illustrations of *Stigler's Law of Eponymy*—which states that no discovery is named after its original discoverer." We concur, noting that ideas are sometimes "in the air," perhaps a condition created by the original discoverer, which helped prepare the minds of others who come later when, for them, the rediscovery was made at a time of abundant receptive minds.

[6] A. Pais, '*Subtle is the Lord...' The Science and the Life of Albert Einstein* (Oxford Univ. Pr., 1982), p. 58.

[7] ibid., p. 88.

[8] See "Elegant Connections in Physics: The Partition Function," *SPS Observer*, May 1996, pp. 8-11.

[9] Stoke's law can be derived from the Navier-Stokes equation by modeling the fluid in which the sphere moves as a *continuum*. But the main thrust of Einstein's paper looks at statistical fluctuations in the collision frequency between the suspended particles and the solvent's *discrete* molecules. However, the solvent molecules are assumed very small compared to the Brownian particles. This illustrates how physics is the art of using models *creatively*, as effective tools well fitted to the job, which requires a real craftsman's touch.

[11] "Elegant Connections in Physics: Brownian Motion and the Fluctuation-Dissipation Theorem," *SPS Observer*, Winter 2004, pp. 10-14.

[10] $\int x^2 \exp(-ax^{2})dx$ = ½ Ö (p/a^3), with limits from –∞ to + ∞.

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2005-06 Marsh W. White Award Recipients

(continued from page 6)

ITHACA COLLEGE

Creating an Ithaca College SPS Circus

The Ithaca College Chapter of the Society of Physics Students proposes the creation of a "Physics Circus" that will regularly visit local middle schools in the Fingerlakes Region. This will benefit not only the middle school students by teaching them physics in a hands-on manner, but will enable our SPS members to get valuable experience teaching and interacting with middle school students. Depending upon the audience there will either be numerous stations that small groups of people rotate between, or one stage that all the demonstrations are done on with one audience. The Physics Circus will cover topics in mechanics, optics, electricity and magnetism, fluid dynamics, and thermodynamics. All of these demonstrations will be in ready to go transportable crates. We will also develop instructional materials to make it easy for future SPS members to use the Circus materials.

Principal Proposer: Kevin Faehndrich
Other Proposers: Melissa Gilbert, Maksim Sipos, & Sweta Shah
Faculty Advisor: Dr. Michael Rogers

MISSISSIPPI STATE UNIVERSITY

Physics Focus on Mississippi

Our chapter proposes to use the awarded funds to expand and improve our physics outreach program geared towards high school physics students. This award would allow us to bring much-needed physics demonstrations to particularly resource-poor schools in east-central Mississippi and to strengthen the level of interest in physics in this area.

Principal Proposers: Brad N. Barlow & Ronald J. Unz
Faculty Advisor: Dr. James A. Dunne

MORNINGSIDE COLLEGE

Physics in the Community

The Chapter's proposed activity would involve physics students going into area schools and presenting an array of physics demonstrations and hands-on activities that would help to explain physics principles, both ones that are present in an everyday environment and also bring awareness to new ones. The target audience would be mostly within the fourth through twelfth grade range.

Principal Proposers: Brittany Cole & Elizabeth Kelly
Faculty Advisor: Dr. Gary Turner

SEATTLE PACIFIC UNIVERSITY

Engaging High School Culture... The Physics of Magic

The proposal seeks support for a statewide outreach project to encourage underrepresented science students to explore studying physics in college. Partnering with SPU's Office of Admission, Seattle School District, and the Northwest Urban Youth Leadership Conference, SPS members will present six workshops which include demonstrations, group discussions, and a Q&A panel.

Principal Proposer: Taryn Arslan
Faculty Advisor: Dr. Lane Seeley

SEATTLE PACIFIC UNIV. (L-R) Allie Hedges (Secretary), Kyle Igarashi (VP), Andrea Vermeer (President), Derek Cox (Treas.), Dr. Lane Seeley (Advisor), Asher Danner (Web master).

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INSIDE THIS ISSUE

1 Benjamin Franklin: Natural Philosopher, Statesman, America's First Physicist
— *by Dwight E. Neuenschwander*

1 Adopt-a-Scientist Program Takes Off
— *by Kendra Rand, American Physical Society*

1 Greetings from the SPS President
— *by Earl Blodgett, Univ. of Wisconsin-River Falls*

4 2005-06 Marsh W. White Award Recipients

7 Looking Back on the Success of the World Year of Physics 2005
— *by Christy Hyde, University of Alabama*

8 Physics News Update

9 2005-06 Sigma Pi Sigma Undergraduate Research Award Recipients

10 **ELEGANT CONNECTIONS IN PHYSICS:** Albert Einstein's Dissertation
— *by Dwight E. Neuenschwander*

INSIDE THIS ISSUE

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