PHYSICS NEWSLETTER

University of California Santa Cruz
Physics Department

Summer 2022

COVER STORY

UCSC and The Webb Telescope

UC SANTA CRUZ

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FACULTY & ALUMNI NEWS in PHYSICS, 2021-22

FACULTY NEWS

Assistant Professor **Aiming Yan** was awarded a 2022 Hellman Fellowship. The Hellman Fellows program was created by Chris and Warren Hellman to support junior faculty. Started in 1995 at UCSD and UC Berkeley, and since expanded to 10 UC campuses, the program strives to augment startup resources for junior faculty at the critical pre-tenure time in their career. Typical grants range between $10,000 and $50,000. Read about Professor Yan's research in the article "New Directions in Materials Science."

Associate Professor **Michael Hance** was awarded a campus Excellence in Teaching Award for the 2020-2021 academic year. Typically honoring to 8-10 professors each year for exemplary and inspiring teaching, this award is the result of student nominations and further considerations by the selection committee.

Assistant Professor **Aris Alexandradinata** joined the physics department at UCSC after completing his PhD at Princeton and a postdoctoral stint at the University of Illinois at Urbana-Champaign. His interests cover a broad range of theoretical topics involving topological materials and their applications. For more information, see the article "A Quantum Leap in Photovoltaics."

Professor Emeritus and former chair **Michael Dine** has published a book on particle physics and cosmology aimed at a general audience.

Professor **Anthony Aquirre**, the Faggin Presidential Chair for the Physics of Information, has taken a leave of absence in order to serve as Executive Vice President for the Future Of Life Institute. The FLI supports initiatives for understanding the interplay of human life and the environment, both natural and technological.

Edgar Shaghoulian, a Fellow at the Center for Particle Cosmology at the University of Pennsylvania, will be joining our faculty as Assistant Professor in fall 2022. His interests include quantum information, quantum gravity, and cosmology.

ALUMNI NEWS

Risa Wechsler (Ph.D. Physics 2001) was awarded as the Distinguished Graduate Student of UCSC's Physical and Biological Sciences Division. Dr. Wechsler is a professor at the Stanford Linear Accelerator and Stanford University and is also Director of the Kavli Institute for Particle Astrophysics and Cosmology at Stanford. Wechsler was a student of Professor **Joel Primack**, and also worked with Professors **Sandra Faber** and **George Blumenthal**. Her dissertation "Dark Halo Merging and Galaxy Formation" was concerned with dark matter "halos", which are basic units of cosmological structure.

Letter from the Chair

Greetings to the UCSC Physics community at the end of the 2021-2022 academic year!

First, I'd like to give our warmest welcome to our newest faculty member, Aris Alexandradinata, who joined us from the University of Illinois, Urbana Champaign. Aris's field of expertise is Theoretical Condensed Matter Physics, with an eye towards bending what appear to be abstract approaches to understanding the workings of matter to the development of novel materials with a broad array of possible applications, including renewable energy. With the arrival of Aris, our numbers within the inter-disciplinary Materials Science and Engineering initiative (led by our own David Lederman) is truly notable, comprising half-a-dozen faculty split between theory and experiment, and an ever-growing technical infrastructure at the Westside Research Park on the West Side of town (near Natural Bridges State Park). To all this, we soon hope to add an expert in the actual synthesis of these novel materials – so stay tuned! As you'll see in one of the articles in the newsletter, we are slowly becoming a major presence in the area of Materials Science, and expect great things from the group over the next few years.

In the area of teaching and learning, a number of things are underway. We are in the process of searching for our first "Teaching Professor" whose efforts will be singularly devoted to the development and delivery of instruction at the introductory level. At the same time, the existing faculty are devoting a lot of time to re-imagining the nature of our introductory teaching, both for our majors (Physics 5) and for those in other fields of science (Physics 6). Another development that's in the works, but also fairly far along, is the creation of a Computational Physics track within the Applied Physics major. We hope to offer this track next year, and are confident that its graduates will be well prepared to hit the ground running when it comes time to pursuing careers in technology.

Another thing we're very excited about is our just-completed faculty search in the area of Theoretical Particle Physics and Cosmology, and we will welcome Edgar Shaghoulian to campus this fall. Edgar's expertise bolsters a long-standing area of strength in the department, and opportunities for rejuvenating our particle theory group abound. With the "departure" of several senior faculty (all of whom continue to advise students and churn out papers and books) within the last few years, this group has become a home to some of the leading "next-generation" particle and cosmological theorists of our day, including Stefano Profumo, Anthony Aguirre, Stefania Gori and Wolfgang Altmannshofer. The addition of a fifth colleague to this dynamic and impactful group has us all quite excited.

Despite the now-perennial-seeming pandemic, our community remains strong. Even in the face of the Omicron wave, we have successfully offered our advanced laboratory classes in person, and have worked with the administration to put safeguards in place that will keep everyone – students and instructors – safe. But the situation remains uncertain, as I'm sure you know. In addition our research labs are open and many students find themselves able to get valuable hands-on laboratory experience in the exciting context of original research. The department continues to develop ways to ease the path into research for undergraduate students for those that seek such an experience (which we encourage all students to consider!). In any regard, you'll find an even more in-depth update in the pages of this newsletter that follow. You'll hear about some of the most visible scientific thrusts of the day (the James Webb Telescope, and a discussion of the profound fundamental questions that pique our curiosity), a wonderful new course opportunity for students (the Advanced Optics Lab), of our department's influence in many types of physics research, and much more. So grab a cup of your favorite beverage, sit back in a comfortable chair, peel back the next page of the newsletter, and enjoy the ride!

Best Wishes,

Bruce Schumm
Chair and Professor of Physics

UCSC and The Webb Telescope

by Garth Illingworth

The giant 6.5 meter "origami" that is the James Webb Space Telescope (JWST) was folded up and carried aloft from Kourou, French Guiana in a spectacular, flawless launch on a French Ariane 5 rocket early Christmas morning 2021. This remarkable launch was the culmination of over 30 years of effort on JWST. Webb had its genesis at the Space Telescope Science Institute (STScI) in Baltimore in the mid 1980s, even before Hubble was launched in 1990, as a large ~8-10 meter passively-cooled infrared telescope located far from earth. Prior to coming to UCSC Astronomy in 1988, I worked on this concept as Deputy-Director at STScI under the subsequent Nobel-Prize winning Director Riccardo Giacconi. This 8-10 meter concept, called the Next Generation Space Telescope (NGST), became the focus of the first science and technical workshop that was held in 1989 at STScI. See https://www.ucolick.org/~gdi/early_jwst/. I chaired this workshop and some subsequent activities, and went on to play a larger role in the late 2000s until the launch of the renamed NGST -- now JWST, or Webb as it is now often known to the public. The deployments, as well as the cryogenic nature of Webb, made for engineering and management challenges well beyond those demanded by Hubble, even given the advances in technology from the 1970s to the 2000s. As a result, the decades since the early-mid 1990s saw a huge technical, scientific, and political effort by scientists and engineers across the country, particularly at NASA and at Northrop Grumman (the prime contractor). That commitment and effort by many thousands of dedicated and extremely capable people brought the JWST observatory to completion and launch. Webb was shipped by boat, fully folded up for launch, from Northrop Grumman Redondo Beach in Los Angeles and arrived in Kourou mid-October 2021.

Me in front of the JWST mirror in 2016 (called OTIS for the cold optical telescope and instrument system – the "Observing Side" components) in the clean room at Goddard Space Flight Center in Maryland in 2017, but without the warm spacecraft (the "Sun-Facing" components are all part of the spacecraft) or the sunshield. The spacecraft and sunshield were being built at Northrop Grumman in Redondo Beach at that time.

The JWST mirror, called OTIS (optical telescope and instrument system), was planned to operate in space at ~35 to 50 Kelvin (-400 to -379 Fahrenheit). To ensure its ability to work cryogenically, OTIS was shipped in 2017 to Johnson Space Flight Center (JSC) in Houston for testing to <50 Kelvin in the largest cryogenic vacuum chamber ever used for a space science mission. From JSC, OTIS traveled to Northrop Grumman in Redondo Beach for integration with the spacecraft and the sunshield. The spacecraft is where Webb's control, communications, propulsion, data handling and power systems reside, as well the cryogenic cooler for the mid-infrared instrument. The sunshield sits just below OTIS, above the spacecraft, and allows the actual telescope and instruments to cool passively to an operational temperature of 35 to 50 Kelvin by radiating into our ~3 Kelvin Universe!

Webb's deployment complexity was driven in part by the need to fit a 6.5 meter mirror in available rocket fairings. The mirror itself had to be folded, but the most challenging deployable aspect resulted from the need to passively cool the entire optical system and instruments to ~45K, which demanded a huge multi-layer sunshield. The engineering, integration, and test requirements for the sunshield, combined with requirements for the other deployables, set Webb apart from all prior and current space missions. Webb certainly made history as a uniquely complex mission. Webb's challenges were increased still by the fact that Webb could *not* be fully system-level tested on the ground due to its 20+ meter physical scale and thermal range of over 300K. There was no practical, cost-effective way to "Test as You Fly". Therefore, subsystem testing and models constituted Webb's verification path.

The sunshield and spacecraft systems had been under development and construction at Northrop for many years when OTIS arrived from JSC after its cryogenic testing. The integration to a full observatory, and the subsequent extensive test program to verify that all the deployment systems worked, were then carried out over the next several years at Northrop. It is essentially impractical to replicate the zero-gravity situation in space with the full range of temperatures from the hot spacecraft side approaching 100 Celsius to the cold telescope side of -230 to -240 Celsius (35 to 45 Kelvin). This called for a very comprehensive test program for all the deployments with gravity offloading and the use of complex models to validate much of the thermal and structural behavior. This allowed the JWST project to gain confidence that Webb's deployments would work as required, but never with an explicit fully-realistic demonstration. The testing was extremely comprehensive for each of the key deployable systems, but it was with some trepidation that we all approached the launch and deployments in space!

The launch was followed by two weeks of complex, nail-biting deployments, of which the most scary was the sunshield -- a rolled-up, 14 x 21 meter, 5-layer structure of specially-shaped 25 micron thick Kapton layers (50 microns for the hottest and lowest layer). Its deployment and tensioning required the release of 139 non-explosive actuators (NEAs), 70 hinge assemblies, 8 deployment motors, ~400 pulleys, and 90 cables totaling approximately 400 meters in length. All in all, there were about 50 major deployments, involving 178 NEAs amongst the nearly 300 potential mission-ending single-point failures. And everything worked! Within two weeks we had a deployed observatory, with the telescope and its complex set of instruments beginning their cooldown, but no optical system yet. Another two weeks of nervous anticipation occurred while the 18 mirror segments and the secondary mirror were being moved from their launch stops, which was by a very macroscopic 12.5 mm adjustment using 132 precision actuators. These remarkable actuators can move the individual mirrors in microscopic 8 nanometer steps for mirror phasing, and are powered by their 20 cryogenic electronic control boxes. This series of mirror moves, done one actuator at a time, was not quite as obviously major as the initial telescope deployments, but were equally crucial for a working Webb telescope!

During this month-long series of deployments, three carefully calculated thruster burns were also made to ultimately put Webb into its halo orbit about the quasi-stable Sun-Earth Lagrange point, L2, which is 1.5 million kilometers from Earth. Ariane did such a remarkable job with its extremely precise insertion into its trajectory towards L2 that Webb required minimal accelerations to reach L2. In addition, due to Webb's orientation relative to the sun, Webb can only

The smooth release of Webb from the Ariane 5 upper stage, and the subsequent early deployment of the solar panels, was captured by the first flight of an on-board video camera.

be accelerated pointing away at all times so as not to overheat. As a result, every chosen maneuver had to "undershoot" the required acceleration, or else Webb faced the risk of being accelerated at a velocity that would drive it beyond L2. Webb's lifetime is limited by the fuel available for L2 station-keeping and the fuel used to offset momentum buildup from normal operations and solar wind pressure. The three performed thruster burns resulted in far less onboard propellant use than "expected" to get Webb to L2. As a result, Webb, instead of having a 5 year life as required, or even its 10 year goal, now amazingly has at least 20 years of life from its onboard propellant.

In the months since Webb reached L2, its 18 mirror segments have been aligned and phased, and its instruments brought online, as Webb's operational temperature of ~35-45 Kelvin was reached. The fine phasing steps revealed that Webb not only achieved its requirement of being diffraction-limited at a wavelength of 2 microns, but in fact was diffraction-limited at ~1 micron. In essentially all aspects — e.g., optical, stability, instruments — Webb is performing substantially better than its requirements. A significant micrometeorite hit on a primary mirror segment in May degraded its optical performance, but fortunately only slightly (now diffraction-limited at ~1.1 microns). The first science images have been released, community science observations have begun, and the first science results have begun to appear on the pre-print server astro-ph. This included a first record-breaking redshift of 13, just 4 days after the first science image data became available, for a very early galaxy just 300 million years after the Big Bang. Redshift records are dropping every few days now, with a claim of a redshift near 17. These all remain to be confirmed by spectroscopy, but the photometric information is very robust. This blog has many images and more details about the launch and its aftermath. Progress can be seen in the periodic updates from NASA.

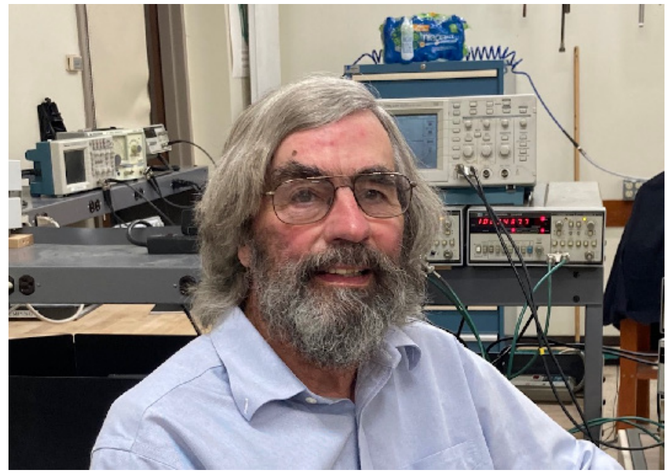
Garth Illingworth is a Distinguished Professor/Astronomer Emeritus in the Astronomy department.

This image of glittering stars is actually the edge of a nearby, young, star-forming region called NGC 3324 in the Carina Nebula. Captured in infrared light by NASA's new James Webb Space Telescope. From https://www.nasa.gov/webbfirstimages

Optics in Undergraduate Education

by George Brown

Light is remarkable. It is something we take for granted every day. It is needed for life as we know it—our biological systems are wired for it. It is both wave and particle—it is energy moving through space. The study of light, including the nature of, production, control, and harvesting (see the article on topological photovoltaics in this issue), is of central importance in science and technology. Optical science underlies photosynthesis, photovoltaic energy transference, long-distance telecommunications, technologies of image acquisition, including medical diagnostics and night vision, and is the primary tool of astronomy. In fact, UCSC's Center for Adaptive Optics (CfAO) is a pioneer of adaptive optics, which considers the atmosphere a fluctuating, disordered medium that can be compensated for by a distortable mirror, thus dramatically enhancing spatial resolution. In this article, we describe two projects, one completed and one aspirational, that provide enhanced educational opportunities for undergraduates interested in optical science.



George Brown, Professor of Physics

A new course in Optics

The Physics Department takes great pride in its laboratory course offerings. Beyond the introductory physics labs, the department offers Intermediate Laboratory (Physics 133), Advanced Laboratory (Physics 134), and Astrophysics Advanced Laboratory (Physics 135). Now, thanks to the initial work of Professor Onuttom Narayan, support form generous donors combined with state funding and course relief funds, the Physics Department has inaugurated an undergraduate Advanced Optics Laboratory course, Physics 137. Our new course teaches the fundamentals of optics, and applications to advanced research in the physical and biological sciences.

Among the experiments to be offered in Physics 137, students will manipulate polymers with optical tweezers, correct fluctuating optical distortions with adaptive optics, excite surface plasmons in thin gold films, measure molecular radii using dynamic light scattering, and analyze frequency-filter optical images using the methods of Fourier optics.

The course plan begins with a two-week boot camp, where students learn basic optical concepts; construct a telescope and a microscope; and study more advanced topics, such as interferometry, birefringence, and optical polarization. Upon completion of the boot camp, students may then choose three experiments from a menu of eleven advanced experiments.

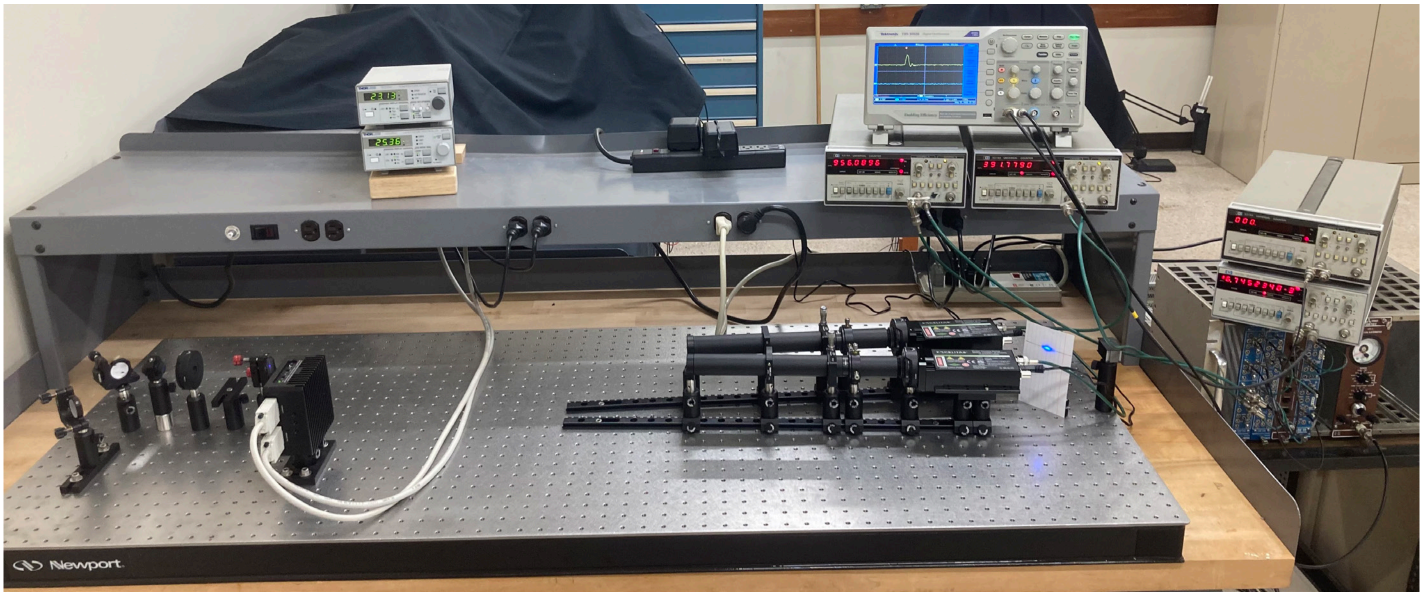
Perhaps the most interesting experiment is a demonstration of Bell's theorem, first proposed by John Bell in 1964 and demonstrated by Alain Aspect and colleagues in 1982. Bell's theorem addressed an idea proposed by Einstein, Podolsky, and Rosen in 1935, speculating that the uncertainty inherent in quantum mechanics (e.g. Heisenberg's uncertainty principle) was a consequence of "hidden variables". By contrast, demonstrating Bell's theorem validates the fundamental postulates of quantum theory. In our experiment, students shine an intense 405 nanometer blue diode laser beam onto a pair of nonlinear crystals, producing a polarization-entangled pair of 810 nanometer red photons. The relative polarization of the two photons can be shown to contradict all local, deterministic theories. The results are in full agreement with the fundamentally non-deterministic quantum theory of radiation.

The course was inaugurated in the fall of 2021, and will continue to be offered every fall quarter. The present capacity of the course is 18 students, and the department will continue to introduce additional experiments over the course of the next few years.

Call for Alumni participation

The Physics Department newsletter has, so far, focused on the work of students and researchers on campus.

We expect that some alumni also have physics news of general interest. So, if you have something to contribute to the next issue - or you know of a fellow alumni who might - please contact Professor Arthur Ramirez (apr@ucsc.edu) to discuss developing a possible article.



The Bell Inequality Experiment. A laser diode, shown on the left, shines linearly polarized 405 nm light onto a pair of beta-barium borate crystals (center). Two entangled 810 nm photons emerge, each at three degrees from the axis of the primary beam. To the right are polarization analyzers and avalanche photodiode detectors.

UCSC and The Higgs Boson

by Stefania Gori

This July marked the tenth anniversary of the discovery of the Higgs boson at the Large Hadron Collider (LHC) at CERN, the European Organization for Nuclear Research. The LHC is the world's largest and most powerful particle accelerator. It collides protons with a speed up to 99.999999% the speed of light, and consists of a 27 kilometer ring of superconducting magnets with a number of accelerating elements to boost the speed of the protons.

It is difficult to overstate the importance of the Higgs boson, which was predicted in 1964 by Peter Higgs of the University of Edinburgh. Its discovery provides a glimpse into how the mass of elementary particles is generated. Elementary particles feel the presence of the Higgs field that permeates all of space. The stronger a particle interacts with the Higgs field, the more it resists acceleration (somewhat similar to an object moving through molasses). The "resistive force" of the Higgs field is mediated by the Higgs boson.

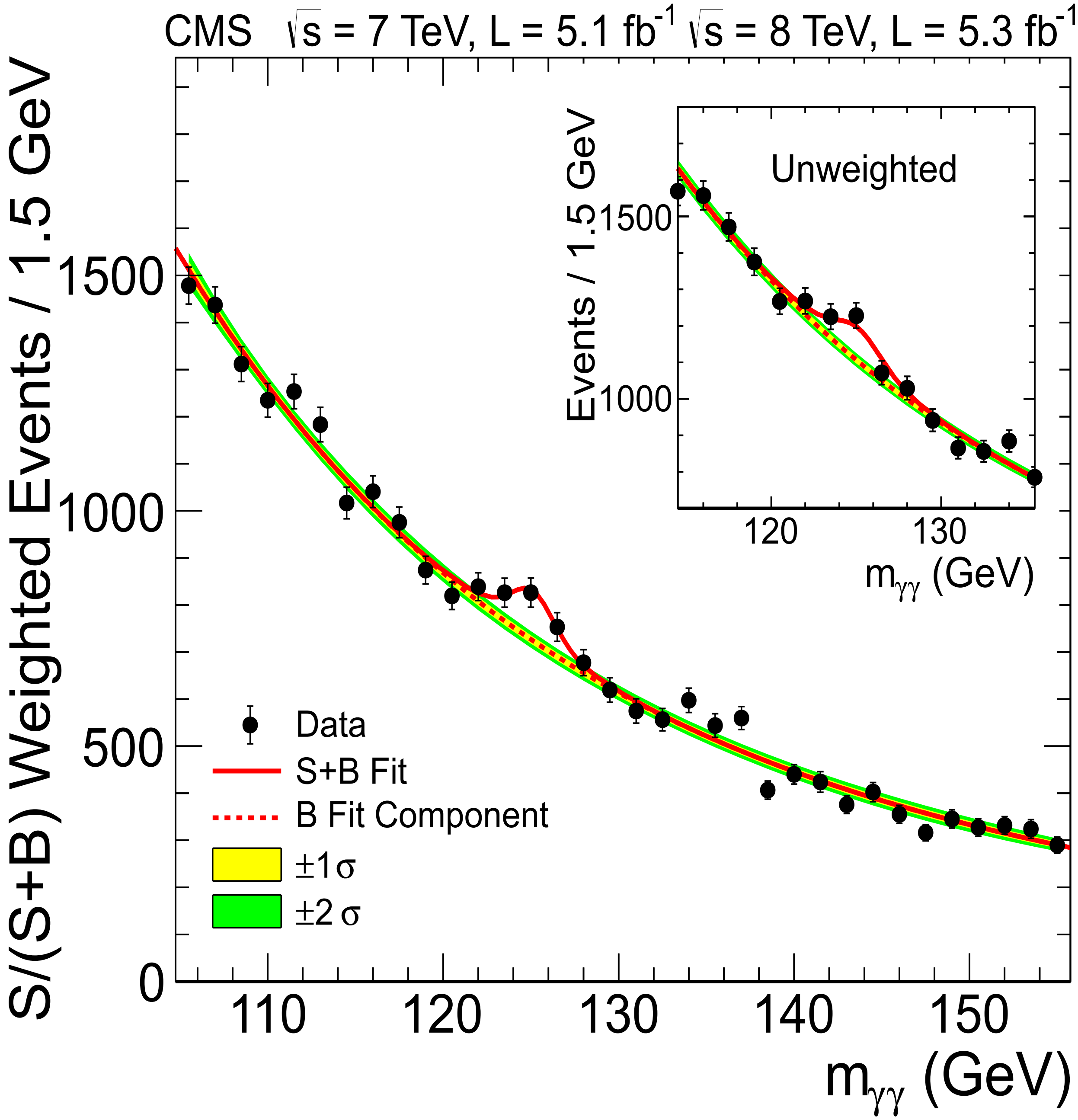
The Higgs boson is one of a kind. It is the only known elementary particle that does not have spin. By now, we know that the Higgs has properties similar to those predicted by the Standard Model (SM) of particle physics, and is responsible for giving mass to the heaviest SM particles. New measurements and discoveries of Higgs properties are regularly pursued by the ATLAS and CMS collaborations at the LHC. These are the two largest LHC experimental collaborations counting each more than 4000 members, including physicists, engineers, and technicians worldwide. Most recently in 2020, the two collaborations found the first evidence for the Higgs coupling to muons, the heavier partners of the electrons.

UCSC physicists – faculty, postdocs, and students – are taking a leading role in the study of the Higgs boson properties and of the possible existence of new Higgs bosons (as predicted by several beyond-the-Standard-Model theories), from both the experimental (Marco Battaglia, Michael Hance, Jason Nielsen, Bruce Schumm) and theoretical (Wolfgang Altmannshofer, Howard Haber, and myself) sides. My research group explores new theories beyond the SM with modified Higgs properties to shed light on several theoretical open questions, such as the nature of Dark Matter and the origin of mass. Although my work is theoretical in nature, I work hand-in-hand with experimentalists on the frontline at the LHC and other accelerator experiments, such as so-called fixed-target experiments. For example, I initiated the "DarkQuest" experimental collaboration at Fermilab, working on a new proton fixed-target experiment that has the potential to discover new particles and, possibly, new Higgs bosons with a mass close to or below the proton mass.

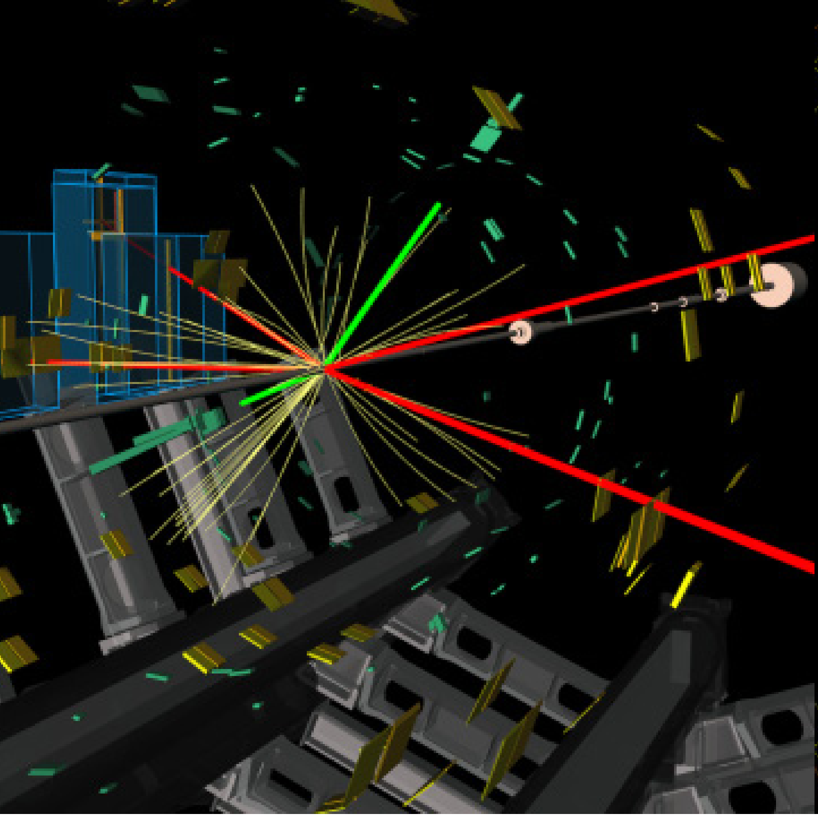
Stefania Gori, Professor of Physics

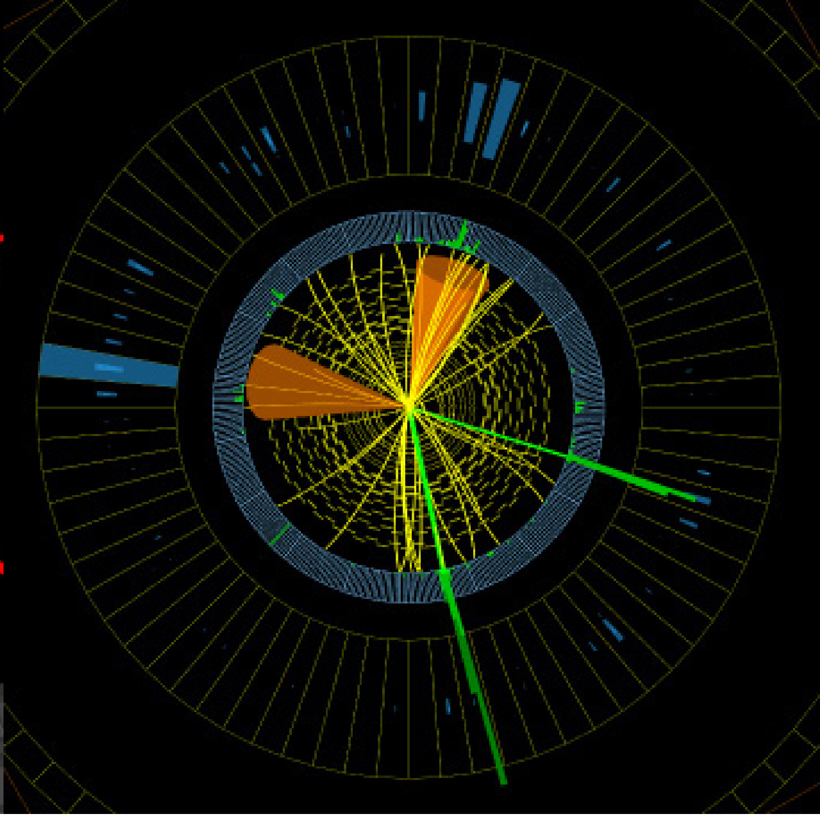
What are open questions about the Higgs boson?

The Higgs is still the least known among all elementary particles. Many of its properties are not yet understood. For example, we do not know if the Higgs is responsible for giving mass to all massive SM particles or if new not-yet-discovered Higgs bosons participate in the mechanism of mass generation. We don't know yet how strongly the Higgs interacts with itself. The way the Higgs transforms under charge (C) and parity (P) reversal is still unexplored, i.e., we do not yet know if the Higgs interacts in the same way with matter and antimatter. Recently, I focused on this latter question. Together with Wolfgang Altmannshofer, my Ph.D. student Nick Hamer, and a former postdoc of the group Hiren Patel, we studied how to test the CP properties of the Higgs using experiments that measure the precession of electrons in an electric field. Furthermore, with Nick Hamer, I am now exploring possible new CP signatures that can be searched for in the upcoming runs at the LHC.



Above: The CMS Higgs discovery plot. The bump at around 126 GeV shows evidence for the existence of the Higgs boson with a mass of 125 times the proton mass.





These are two actual pictures of "Higgs events" recorded by the ATLAS and CMS collaborations at the LHC. On the left, the Higgs decays to two muons (represented as red lines); on the right, the Higgs decays to charm quarks (represented as orange cones).

Although the Higgs boson discovery completes the experimental verification of the Standard Model, it may provide one of the key conduits that will lead to more discoveries and a deeper understanding of Nature at the most fundamental level. Several open problems in particle physics and cosmology cannot be addressed by the Standard Model and might be naturally connected to the Higgs boson. For example, the origin of the observed imbalance between matter and antimatter in the observable Universe is not yet understood. Theories with more than one Higgs boson could address this puzzle. My Ph.D. student, Pankaj Munbodh, is taking the lead on this and is presently studying how the Higgs potential energy evolved between a time shortly after the Big Bang and the present day. He predicts this evolution in models with more than one Higgs boson to shed light on the matter-antimatter asymmetry problem.

Many physicists are searching for a connection of the Higgs to one of the most pressing issues facing particle physics and cosmology, namely the origin of Dark Matter (DM). Dark Matter is thought to be responsible for adding gravity to big objects in our Universe, like galaxies or galaxy clusters, but has so far escaped direct detection. Weakly interacting massive particles (WIMPs) with a mass close to the Higgs boson mass have been one of the leading candidates for DM in the last decades. These last several years have seen tremendous progress in experimental searches for WIMPs. The non-discovery and overall stringent constraints have led the community to explore novel theories beyond WIMPs, particularly theories in which DM belongs to an extended "dark sector" consisting of particles that do not interact with any SM force. Many new theoretical ideas have been put forth in the last few years. Dark sector particles can be studied at a broad range of different accelerator experiments, ranging from high-intensity fixed-target experiments, neutrino experiments, electron-positron colliders, and the LHC. My research group is taking the lead in proposing new experimental strategies to discover dark particles at these experiments. Due to its unique properties, the Higgs boson can provide a portal between the SM and the dark sector. The Higgs interactions with the dark sector could lead to new exotic decays of the Higgs to dark sector particles that could be searched for by the LHC. Very recently, I have completed a review on Higgs exotic decays, collaborating with M. Cepeda (CMS, U. of Madrid), V. Martinez Outschoorn (ATLAS, U. of Massachusetts at Amherst), and J. Shelton (theory, U. of Illinois, Urbana-Champaign).

We look forward to learning much more about the Higgs boson in the coming years!

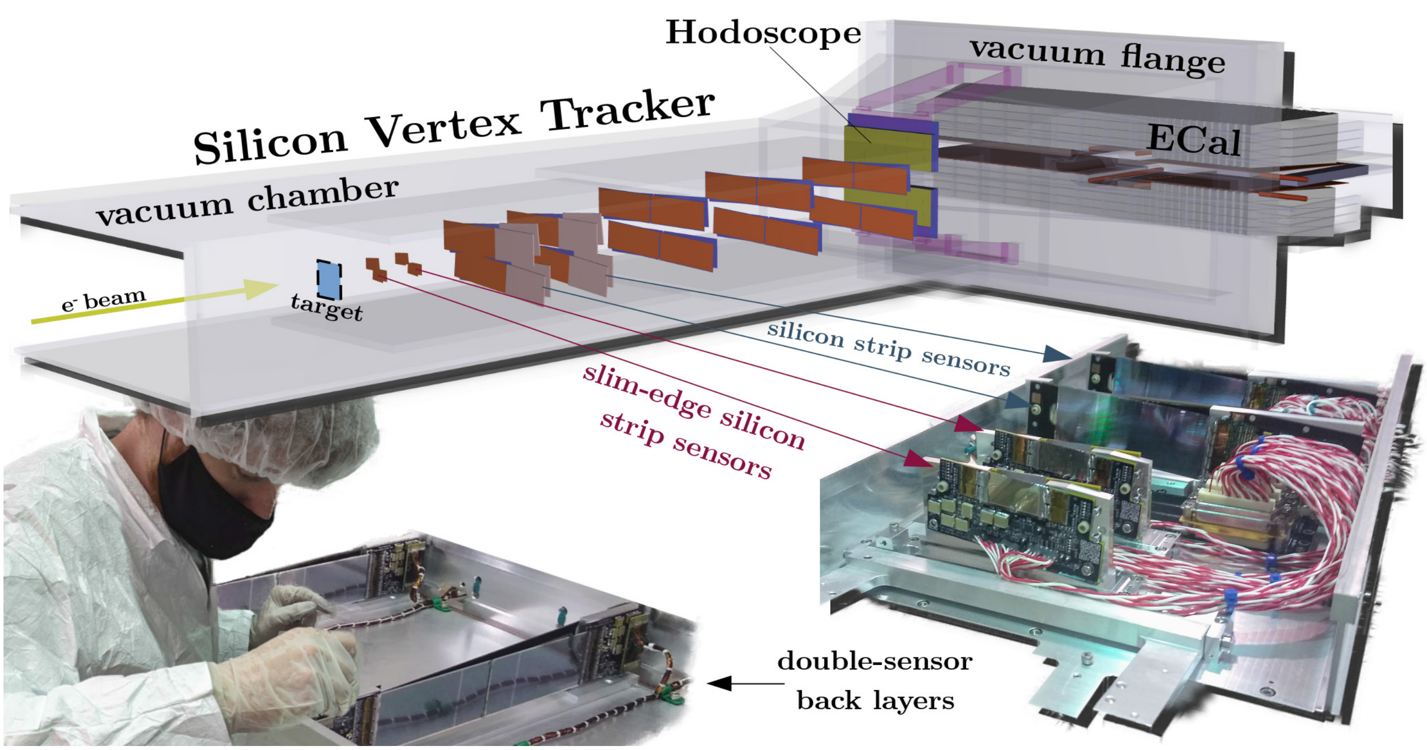
The Heavy Photon Search

by Alic Spellman

Physicists and astronomers have made many observations over the last century that strongly suggest that 85% of the universe is comprised of "dark matter". The evidence for dark matter comes from several sources: an unidentified gravitational interaction among the visible masses; the inability to explain galaxy formation and rotation using only visible matter; gravitational lensing; the structure of the universe itself. Clearly, the inability to detect dark matter hints at a very weak interaction with other matter and one scenario envisions that billions of dark matter particles may be passing through each of us every second. If, as many physicists believe, that dark matter is comprised of massive elementary particles, their existence poses a problem for the Standard Model (SM) of elementary particles, into which they don't seem to fit. Therefore, physicists have developed various models "beyond the SM" to explain the nature of dark matter, each with its own set of assumptions, motivations, underlying physics, and detectable signatures.

Here we will describe the "high-energy frontier" Heavy Photon Search (HPS) experiment, which seeks to identify the nature of dark matter through electromagnetic interactions. The theoretical motivation for this search is the postulate of a hidden sector (HS) of new particles, among them dark matter, that do not interact directly with those in the SM. This HS includes the heavy photon (called A') that interacts indirectly with electrically charged SM particles, and would therefore be produced through high energy electromagnetic interactions before ultimately decaying into an electron-positron pair that HPS can detect.

HPS is a multinational collaboration with a few dozen contributing members in Italy, France, and various institutions across the United States, notably SLAC National Accelerator Laboratory, Thomas Jefferson National Accelerator Facility (JLab), and University of California Santa Cruz (UCSC). The UCSC team is led by Professor Robert Johnson, who is my Ph.D. advisor.



Silicon Vertex Tracker (SVT) diagram. The electron beam strikes the target and generates particles that travel through the tracker within the uniform magnetic field, where electrons curve right and positrons left. Hits in the sensors are used to reconstruct charged particle tracks. External to the SVT is the Hodoscope, which is used to identify positrons, and the Electromagnetic Calorimeter (ECAL) that measures particle energy and triggers data collection.

HPS attempts to produce heavy photons by firing a high-energy electron beam, provided by the Continuous Electron Beam Accelerator Facility (CEBAF) at JLab, at a thin tungsten foil target. Interactions between the beam electrons and heavy nuclei in the target generate a maelstrom of SM particles, and at a considerably lower rate would also produce heavy photons. Unique among the background of uninteresting particles, a heavy photon will travel a crucial few mms beyond the target before decaying into an electron-positron pair. HPS detects this pair of particles, reconstructs their individual trajectories (called tracks), and then reconstructs the vertex from which the pair of tracks originated. We identify an A' candidate by finding such a vertex downstream of the target (called a "displaced vertex search"). Resolving the displaced A' vertex among the massive background of uninteresting events requires an advanced particle tracking system with ultra precise vertex resolution—this is where UCSC comes in.

All of the particle tracking detector modules used in HPS are assembled in part at the Santa Cruz Institute of Particle Physics (SCIPP) lab. These detector modules form the workhorse of HPS, the Silicon Vertex Tracker (SVT), shown in Figure 1. The SVT is split into two volumes, Top and Bottom, each composed of seven layers of detector modules. Each module is made of a pair of silicon strip sensors that together measure the position of charged particles passing through them (called hits). We use the hits to reconstruct tracks, and then try to find pairs of tracks that originate from the same vertex. Our ability to identify a displaced A' vertex candidate is dominated by our vertex position resolution, which is improved by placing the first few detector layers as close to the target and electron beam as possible—but too close and the intense beam can destroy the silicon sensors. My first graduate student research project was to help test and calibrate newly developed "slim-edge" sensors that can be placed substantially closer to the beam/target than past HPS runs, and through this work I became an active member in the HPS SVT group that prepares the tracker for taking data.

I traveled to JLab with the SVT group in the summer of 2021 to help upgrade and install the SVT just before the data run that fall. Under normal circumstances we would have had the SVT upgraded well ahead of time, but because of Covid-19 travel restrictions, it was left inaccessible at JLab for almost two years. Our scheduled first beam was fast approaching, and when an experiment requires an electron accelerator, everything revolves around beam time, because creating a beam requires a great amount of money. The process of upgrading, calibrating, and installing the SVT took over our lives for weeks (I spent my birthday working underground!) but as a team we managed to get the tracker operational just in time for the start of the run.

My first shift of the run started at midnight on September 6 in the Hall B Counting House, the first of a 10 day block of expert "Owl" shifts. Normally two people work a shift in the counting house, a more experienced "expert", and a "worker". However, because of international Covid-19 travel restrictions, our European collaborators, many of them true experts, were unable to take in-person shifts. Instead they assisted remotely over Zoom as "workers", and ready or not I was upgraded to expert. I found myself on the very first night, a few hours after stepping off an airplane, working in coordination with the Machine Control Center (MCC) and the acting HPS Run Coordinator trying to establish the first good beam of the months-long run.

The HPS experiment requires a significant calibration effort to steer the electron beam to the target. At optimal running position the first SVT layers are only 0.5 mm from the intense 3.7 GeV electron beam, so precision is essential. The beam enters the hall about 40 meters upstream of the HPS target and travels within a small steel beam-pipe through a series of steering magnets, passes through a 20 mm collimator (a metal plate with a 20 mm hole in it), and then a 2.82 mm collimator placed just before the target. Guided by the shift expert (me), MCC steers the beam by adjusting the magnets at various points along the beamline. If the beam scrapes anything inside of the beam-pipe, such as the edge of a collimator, or the walls of the pipe itself, it can scatter damaging radiation into our fragile silicon detectors. If the beam position is off by a few hundred microns, or isn't shaped correctly, or is too large (20 microns wide being optimal), it can damage the sensors (which are thankfully safely tucked away during this calibration process). Establishing "physics quality" beam is a meticulous game of taking frequent measurements of beam positions and widths by slowly scanning thin wires at various points along the beamline, calling MCC to make tiny adjustments to the steering magnets according to the scan results, and then taking more scans!

We did not establish physics quality beam on that first night—the first time is the most difficult and can take many shifts, but once we have a working configuration, it is usually easy to recover. Eventually my shifts became a routine of starting and stopping data runs (several hour long intervals of data collection), monitoring a few dozen computer GUIs and alarms, and waking up hardware/software experts at unconscionable hours of the night when more serious alarms were triggered, such as when the data acquisition system would inexplicably stop working. A few weeks after completing my shifts in the counting house I returned for ten days of "SVT Expert" shifts, where I got to be the victim of those unconscionable phone calls I once perpetrated.

When you're trying to detect the decay products of an invisible particle that barely interacts with the matter you're made of, and that may not even exist, you need as much data as you can afford! After roughly 70 days of running, taking data at a rate of 31 kHz, we recorded almost 73 billion events. With this volume of data, we expect to have sensitivity to A' production that goes far beyond what has been reached with previous explorations. The HPS collaboration is currently working on calibrating the data and detector geometry, and preparing to sift through that data, looking for any displaced vertices and mass resonances that could be a heavy photon. Discovery of this particle may be a long shot, but it would surely spawn a new era of physics, making the journey all the more exciting!

Alic Spellman, Physics Ph.D. Candidate

Dawn of the Topological Age

by Arthur Ramirez & Brian Skinner

Historians often label epochs of human history according to their material technologies—the bronze age, the iron age, and, most recently, the silicon age. From a physicist's perspective, the silicon age began with the theory, experiment, and device prototyping of a new type of material: the semiconductor. Although semiconductors had been known since the late 1800s as materials with unusual sensitivity to light, the direction of current flow, and the methods of synthesis, it was not until 1931 that Alan Wilson, working as a visiting scientist in Werner Heisenberg's theoretical physics institute in Leipzig, made a radical proposal to describe their electronic states. 1

At the time, the concept of energy bands, namely the set of energies and momenta that an electron can adopt within a solid, had been firmly established. (One can think of these bands as momentum-dependent versions of the atomic energy levels that we studied in the atomic spectra lab in Physics 133.) Conventional wisdom held that metals and insulators were just opposite limits of a continuum of states defined by a theoretical parameter that controlled the ability of electrons to "hop" from atom to atom. Wilson proposed a radical alternative. Instead of changing the energy bands, conduction could be altered by changing the population of electrons within a band – what we now call "doping". Insulators and metals correspond to filled and partially filled bands, respectively. Semiconductors are intermediate cases where introduction of dopants creates additional states in the forbidden region of insulators called the band gap. The fifteen years following Wilson's proposal witnessed advances in synthesizing and purifying elemental semiconductors silicon and germanium, leading to the discovery of transistor action at Bell Labs in 1947.

For semiconductors, the path from theoretical understanding to device implementation was neither linear nor easily predicted. If we fast forward to today, we see that physicists are making discoveries in the field of topological materials of such fundamental and practical importance that a comparison to semiconductor research in the 1930's and 1940's seems appropriate, suggesting the tantalizing possibility of being at the dawn of a topological age. Below, we give a glimpse of what it means for materials to be topological and how topology raises the prospect of revolutionary new devices.

Symmetry and invariance

Characterizing phases of matter by their symmetries is a central paradigm of physics. A magnet differs from inert iron because its internal magnetic moments consistently point in a particular direction rather than being isotropic. Similarly, a solid is different from a fluid because its atoms reside in fixed locations rather than moving freely. That prescription for understanding states of matter is usually referred to as the "Landau paradigm" after the pioneering Soviet physicist, Lev Landau. 2

The last decade, however, has seen a growing awareness that there is more to matter than the Landau paradigm. Researchers are uncovering an ever-larger class of materials for which answers to basic questions, such as whether the material conducts electricity, depend not on local symmetries but on nonlocal properties called topological invariants. In much the same way that one cannot tell whether a coiled rope will form a knot when pulled tight unless one examines the full length of the rope, the electronic properties of a topological material can only

Left: An example of topological equivalence, a coffee mug can be continuously deformed into a doughnut without cutting. Thus, from the standpoint of topology a coffee mug and a doughnut are the same thing.

be determined by examining the complete set of states in an electronic band. That topological nonlocality confers tremendous potential on topological materials: If a property is not defined locally, then it cannot be destabilized by local defects or fluctuations. Thus, the topological age promises a class of materials with unusually robust properties.

Topological electrons

The notion of a topological invariant comes from the mathematical subfield of topology, which concerns those properties of geometric objects that are conserved under continuous deformations. The most famous such property is the genus g, an integer that counts the number of holes in a three-dimensional shape. (So, $g = 0$ for a sphere, $g = 1$ for a donut, and $g = 3$ for a pretzel.) The genus is called a "topological invariant" because it cannot be changed by smoothly changing the shape.

What can be considered "topological" about electrons? To address this question one needs to describe momentum space. As mentioned above, the electron momentum, which is inversely related to its wavelength (in particle-wave duality language), can take only certain restricted values. In particular, since momentum describes hopping between neighboring crystal lattice sites, the wavelength cannot be shorter than the distance between neighboring unit cells of the crystal, thus placing an upper bound on the momentum. (A unit cell is the smallest set of atoms that when replicated periodically construct the crystal). Thus, the "space" defined by possible electron momenta is finite and the set of allowed energy-momentum states is described by surfaces within this space – surfaces to which ideas of topology can be applied. Closed surfaces in momentum space can be likened to geometric shapes that have an integer-valued index akin to the genus as defined above for shapes in position-space.

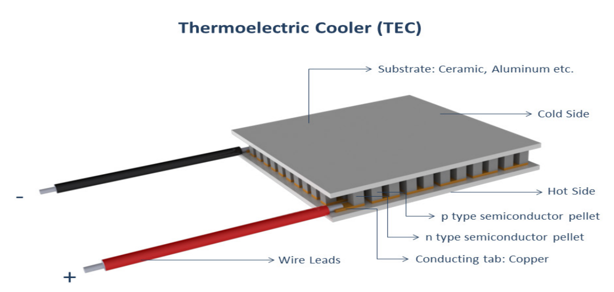
Now we need to get a little technical and, to make further progress, one defines the momentum-dependent center of the electron wave function, which is calculated as the expectation value of the position operator X. The operator X is not precisely defined, however – it is not gauge-invariant, similar to the vector potential A, in electromagnetism. However, $\Omega = \mathrm{curl} X$ is well-defined, just like the B-field in electromagnetism, and this curl is called the "Berry curvature," after Sir Michael Berry of Bristol University. The Berry curvature has the property that its integral across any closed surface in momentum space (the "flux" of Berry curvature) is an integer multiple of 2π, and this integer is a "topological invariant" called the "Chern number".

The Berry curvature acts in many senses like a physical magnetic field, although one whose value depends on the electron's momentum, and it gives electron states an orbital angular momentum. This orbital angular momentum interacts with the electron's intrinsic spin angular momentum via an effect called spin-orbit coupling. Since spin-obit coupling varies as the atomic number to the fourth power, the topology-induced magnetic field is most apparent in heavy metals, in particular some of the rarest elements such as Iridium, Ruthenium, Bismuth, and Tellurium.

Serendipity

If you own a thermoelectric car refrigerator, then you own a set of "topological insulator" crystals. These are materials whose electron energy levels are inverted due to a combination of Berry phase physics, discussed at left, and "spin orbit coupling" which is a relativistic effect that creates an interaction between an electron's spin and its orbital angular momentum. This inversion needs to be undone at the surface, where the levels must cross, leading to a several-atom-deep layer of metal enclosing the insulator in the interior. Spin orbit coupling varies as the fourth power of the atomic number and thus is largest in heavy elements. One of the first materials found to be a topological insulator by the observation of metallic surface states is bismuth telluride, Bi_2Te_3.

Purely by coincidence, Bi_2Te_3 is also the material of choice for thermoelectric cooling. It is a small-band-gap semiconductor with a large "thermopower", a quantity that expresses the temperature change induced by an applied voltage. Besides a large thermopower, thermoelectric coolers need a small thermal conductivity, which is achieved in Bi_2Te_3 by virtue of the heavy atomic mass of bismuth and tellurium. So the heaviness of its atoms serves two distinct purposes in Bi_2Te_3, modifying the electronic energy structure leading to topological insulating behavior, but also creating thermal conduction impedance via the heavy mass. Below is shown a typical thermoelectric cooling element, showing the Bi_2Te_3 blocks, referred to as "semiconductor pellets".



Technological prospects

Many materials derive their utility from their ability to either pass a current or prevent one from flowing. For example, the copper in a wire is useful because it allows electric current to flow freely, whereas the polymer encasing the wire stops the current from leaking out. Other materials pass or block heat currents, or filter light. From this perspective, the silicon age arose because doped semiconductors act as switchable valves for electrical current. Topological materials offer the promise of new type of filtering technology because their Berry curvature is a kind of handedness that breaks the symmetry between clockwise and counterclockwise motion.

One potential application is in spin filtering. The states in topological materials carry electrons with opposite spins in opposite directions. Such filtering is an essential ingredient for so-called spintronics, which aims to build electronic and computer technology based on currents of spin rather than charge. The Berry curvature also implies that circularly polarized light would couple differently to the two electron species, which could be used to create optical filters or logic circuits.

More generally, the topological stability of low-energy states in a topological electron band can be exploited in ways that would advantage them over conventional materials in which low energy states are often distorted by disorder. The protection of a material's electron band structure can cause its electrons to exhibit enormous mobility, causing each electron to make an outsized contribution to a current being carried. The class of topological materials called Weyl semimetals (after the German mathematician Hermann Weyl) are extremely sensitive to light, which may lead to a new generation of photodetectors and night-vision goggles. (See the next article for another example of topological materials interacting with light). Topological semimetals also exhibit an unprecedented thermoelectric effect or ability to convert waste heat into useful electric power. Finally, topological electrons are unusually sensitive to magnetic fields. For example, the quantum levels of the electron's magnetic field orbit—its Landau levels—are widely spaced, and applying a magnetic field along the current direction strongly reduces the material's electrical resistance, a phenomenon known as the chiral anomaly.

Whether topological materials will revolutionize our current electronic technologies remains to be seen. But ideas from topology have clearly established themselves in materials physics, and they have led to predictions and observations of new materials and phenomena. In this sense the topological era is already here.

Arthur Ramirez, Professor of Physics

Brian Skinner, Professor of Physics at Ohio State University.

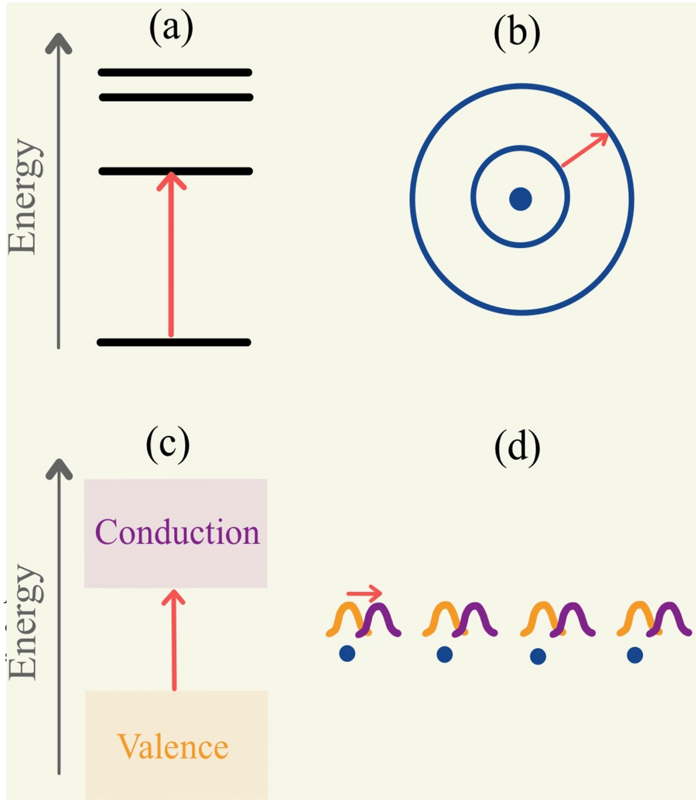
A Quantum Leap in Photovoltaics

by Aris Alexandradinata

Light harvesting accounted in 2020 for 11% of renewable energy consumption in the United States and is the fastest growing source of renewable energy. Silicon-based solar cells are the predominant method for converting light (photo-) into electricity (-volta). Its mechanism: an electron in the valence band absorbs a photon (the quantum of light) and is excited into the conduction band, leaving behind a 'hole' (an unoccupied state) in the valence band. In pure silicon, the electron and hole are bound together by electrostatic attraction, because the hole represents the absence of an electron and is therefore positively charged. What makes silicon special is that it can be engineered to achieve a precise impurity concentration. Specifically, we mean that a small fraction of silicon atoms can be substituted by other atoms having a different number of electrons per atom. This substitution process allows the formation of a 'p-n junction', i.e, an interface separating two regions of silicon where the substituted atoms are chemically distinct, thus forming an electric field across the junction. This electric field causes the light-excited electron-hole pair to separate, because (once again) the hole has an opposite charge with respect to the electron. This separation of charge constitutes the current that flows out of a solar cell and drives useful work.

There is, however, a disadvantage to the above mechanism. As a light-excited electron is accelerated by the electric field, it inevitably loses some of its energy by colliding with impurities and exciting lattice vibrations. By the time an excited electron is ready to do work, it has exhausted a substantial fraction of its initial energy of 2-3 electronvolts (eV)and lies near the "bottom" of the conduction band. This exhaustion is reflected in the maximum voltage generated by a silicon solar cell being 1.1V, where 1.1eV is the energy gap separating the conduction and valence bands of silicon. Moreover, the energy-conversion efficiency of silicon-based solar cells cannot exceed 30% - an upper bound derived from basic thermodynamic principles by Shockley and Queisser.

With the Shockley-Queisser constraint in mind, a perennial question has been: "How can voltages larger than the band gap be achieved?" A related question is whether it is possible to make an efficient solar cell based on a pure, undoped semiconductor, i.e. without the need to fabricate a p-n junction. To answer these questions, let us return to an early insight in quantum theory that was arguably the most contrary to classical intuition: Heisenberg's quantum leap. Heisenberg intuited that when an electron in a hydrogen atom absorbs a photon, the electron 'leaps' from one Bohr orbit to a different orbit. It is not possible to describe the leap by an intermediate classical trajectory. In one instant, the electron is in a Bohr orbit lying close to the nucleus; in the next instant, the electron is in a larger orbit situated further way from the nucleus. In this sense, a quantum leap is an instantaneous displacement (or 'teleportation') of an electron as it transits between stationary states.



Leaping electrons in atoms and solids (a) Light-induced excitation of atomic energy levels; the corresponding quantum leap between Bohr orbits is illustrated in panel (b). (c) Light-induced excitation between the valence and conduction bands of crystalline energy levels; the corresponding quantum leap of an electronic wave packet (within the crystal) is illustrated in panel (d).

Could we not design a solar cell in which a light-excited electron leaps over impurities and ions, thus minimizing the collisions that are so detrimental to silicon's performance as a solar cell? Could this leap occur even for a solar cell constructed from a homogeneous (undoped) crystal? The answers to both questions are yes, if the crystal is non-centric, i.e., it lacks a center of spatial inversion. This means that if space were to be inverted as (x,y,z) to (-x,-y,-z), the crystal and its inverted counterpart are not identical. If centrosymmetry exists, there can be no special direction along which an electron can quantum-leap toward, and no special direction for a light-excited current to flow. For instance, if one hypothesizes that a current flows in the x direction, centrosymmetry guarantees an opposite flow in the –x direction, resulting in no net current.

In high-energy terminology, centrosymmetry is known as parity symmetry, and is subtly violated for the weak interaction. However, it is not uncommon in solid-state crystals to find gross violations of centrosymmetry. The prototype of a homogeneous, noncentric crystal is a ferroelectric – the electrical analog of the ferromagnet that forms the basis of the compass. Just as a ferromagnet has a magnetization that picks out a special direction, a ferroelectric has a polarization (i.e., inhomogeneous charge distribution) that picks out a special direction, along which a light-excited current can flow. Ferroelectric-based solar cells allow for light-excited quantum leaps. Some of them allow for voltages of about 1000 eV, exceeding the band gap by three orders of magnitude. The efficiency of light-to-electrical energy conversion however remains modest, and cannot beat silicon. Why is that? For known ferroelectrics, the distance that an electron leaps is a modest fraction of the crystalline lattice period.

Here is where topological insulators come in. The term 'topological' suggests a robustness of certain properties against perturbations, as introduced in the previous article on topological materials by A. P. Ramirez and B. Skinner. A topological quantity is only allowed to take discrete values (e.g., integer values). I have theoretically discovered a class of topological insulators for which the quantum-leap distance is a topological quantity – it is only allowed to take values exactly equal to an integer multiple of the lattice period. This is large compared to ferroelectrics. For comparison, I have found that the conductivity (light-excited current divided by light intensity) of my model topological insulator to be at least three orders of magnitude larger than the conductivity of a prototypical ferroelectric (BaTiO3).

To demystify this 'quantum-leap distance', it is nothing more than the change in the expected value of the position operator between conduction and valence bands. In quantum mechanics, the non-commutivity of position and momentum implies that the position operator corresponds to a derivative with respect to momentum; this derivative of the wave function gives nothing more than the Berry phase. The wave function of an electron in a band can 'twist and turn' in momentum space, forming topological 'knots' which translate to the Berry phase being quantized to an integer multiple of 2π; if this integer differs between the conduction and valence band, then the leap distance is a nontrivial lattice vector.

The remaining missing piece is to find a material that might realize my vision. Fortunately, vast material databases now exist that will allow one to identify semiconductors with a non-centric crystalline structure and a band gap comparable to silicon, or larger. My hope is that among these materials there exists one that is manufacturable and enables the efficient harvesting of solar energy via topology!

Aris Alexandradinata
Assistant Professor of Physics

How Thermalization Arises from Fundamental Physics

by Joshua Deutsch

It is generally believed that all experimental observations can be completely understood by the application of fundamental physical laws. Aside from the issue of gravity, the behavior of almost all particles can be predicted from quantum mechanics using the "Standard Model" of particle physics. More complicated systems, such as humans, still obey the same equations, but are of course, much harder to analyze directly. Instead, laws at larger scales "emerge" from the more basic ones. It is generally believed that the issue of thermalization and the laws of thermodynamics are an example of such emergent behavior, but it is not clear how they can be derived. It is even possible that they are not in fact emergent, and that a clearer understanding of thermalization is key to enlarging our understanding of fundamental physics.

How and why is it that systems come to equilibrium, that is "thermalize"? Anyone who has taken a course in statistical physics has probably read a textbook with at least one explanation for this. But there are no explanations which start out with the most fundamental equation of quantum mechanics, the Schrodinger equation, and end up deriving thermalization and statistical mechanics. The arguments given have some degree of plausibility to them, but also have troubling aspects, with quite a few assumptions swept under the rug. For example, a lot of textbook explanations have the system of interest coupled to another much larger system, a "heat bath" that, by definition, is already thermalized. This is a "turtles all the way down" kind of logical fallacy.

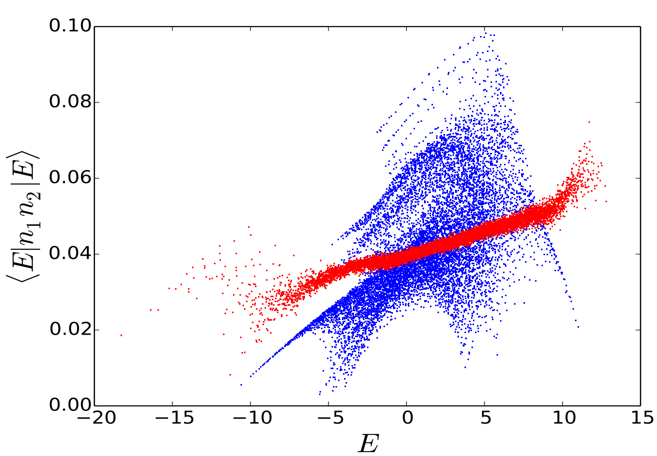
As time has progressed, the interest in these kinds of problems has spread from a fairly small circle of statistical mechanics specialists to people interested in areas as diverse as "cold atoms" and black holes. It turns out that a better understanding of thermalization is required in order to make progress in a lot of current research problems.

Until the 1990's, work on thermalization was mostly confined to classical mechanics, because as explained a bit later, quantum mechanics doesn't seem to mesh well with the concepts needed. One of them is the idea of "ergodicity". If a system is sufficiently chaotic, it will evolve to get arbitrarily close to any configuration, consistent with things like energy conservation. Using this idea and a few other properties, mathematicians and physicists were able to construct a good understanding of how classical systems thermalize. Ergodicity has only been proven for a handful of systems, but computer simulations and a lot of theoretical arguments make it plausible that systems in the real world have the requisite mathematical properties that allow for thermalization.

As just stated, the idea of ergodicity falls apart in quantum mechanics. You can put a system in an energy eigenstate, where the wave function is "stationary", which means that the system doesn't change in time. So how can a system like that thermalize? I worked on this in the physics department at UCSC in the late 80's and early 90's and came up with an answer. A few years later Mark Srednicki at UCSB independently came up with a similar explanation, and called this the "Eigenstate Thermalization Hypothesis" (ETH). We both recognized that in order to properly understand thermalization, one had to understand isolated quantum systems, and not appeal to the assumed thermalization of a larger system connected to it.

One clear distinction between the quantum and classical analysis of thermalization has to do with particle number. Although a classical mechanical system with one particle bouncing around can be shown to have the requisite properties in order to be ergodic, you always need to have a large number of particles in quantum mechanics in order to understand how thermalization can come about.

Another important concept is that of chaos. But this must be completely rethought from the way it is described in classical systems. Eugene Wigner in the 1950's, made the brilliant connection between generic quantum systems and random matrix theory. He applied his theory to energy levels in nuclei, but this random matrix description works equally well for the vast majority of physical systems. The



Numerical results showing the probability that two particles (hard core bosons) are next to each other, plotted against the system energy. The integrable case (blue dots) shows a poorly defined relationship between the variables plotted, whereas the non-integrable case (red dots) shows a much better defined one, consistent with thermalization.

exceptions are systems that are "integrable". Such systems possess a basis set of modes whose individual energy is conserved so they are not interacting. These systems are of much theoretical interest, but aren't the ones that we typically see in a lab. Sriram Shastry at UCSC is one of the world's leading experts on integrable quantum systems.

My own work applied ideas from random matrix theory to show that eigenstate thermalization does actually happen despite the counterintuitive nature of the claim. Although energy eigenstates are stationary in time, average values of quantities that are experimentally measurable, such as the position or momentum of a particle, will give the same answer that you would get for the more usual case where the system is time varying. This is due to the fact that in some intuitive sense, all of the other particles not being measured are acting as a "heat bath", or larger system, for the ones being measured.

Few paid attention to this work and both Srednicki and I spent most of our time on other things, but about 20 years later, with the advent of cold atom experiments and the increased power of computers, the question of how, precisely, quantum systems thermalize suddenly became of great experimental, as well as theoretical interest. Cold atom experiments are able to trap atoms to exceedingly low temperatures, and probe quantum phenomena with great precision in regimes that are virtually impossible to access any other way. This allows us to ask experimental questions about quantum thermalization and has led to a lot of fascinating new phenomena. At the same time, the increased power of computers meant that many particle systems could be investigated numerically to check to see if the eigenstate thermalization hypothesis was correct. It has worked out remarkably well, with the exception of systems that have been carefully designed not to thermalize such as integrable systems. And there is a new class of non-thermalizing systems that exhibit the phenomenon of "Many Body Localization" which are only expected to occur in one dimension, but currently have a large following among theorists.

Outside of condensed matter physics and cold atoms research, there has been a keen interest in ETH for studying a number of phenomena, such as quantum gravity, wormholes, and firewalls. It is useful in understanding quantum entanglement and how, for example, two black holes connected by a wormhole are related to their mutual entanglement. It is also used in quantum computing, for example, to understand the process of error correction.

As is evident experimentally, the vast majority of systems do thermalize, but to fully understand thermalization requires more than ETH. The second law of thermodynamics says that the entropy of a system increases, and this is an even harder problem to understand. More recently I have been collaborating with Anthony Aguirre and a former postdoc, Dominik Safranek to better understand the enigmatic concept of entropy and why it increases. They came up with a new approach to this problem called the "Observational Entropy", a general framework for understanding entropy in terms of "coarse grainings" of a system. It's already been taken up by other theoretical groups as well to further understand thermalization and a lot of progress in this area is ongoing.

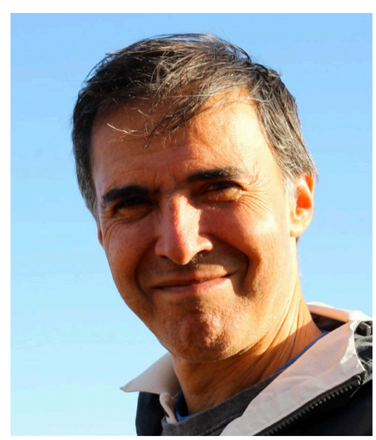
Quantum thermalization is closely related to the study of quantum chaos, which asks how the classical idea of chaos extends to quantum mechanics. At UCSC, physics faculty member Sergey Syzranov has been studying how to better understand quantum chaos using "out of time order correlators" which measure how fast systems with similar initial conditions diverge from each other. He and collaborators have recently connected this with the rate at which information is lost in observables.

At a classical level, another theorist at UCSC, Onuttom Narayan has done a large body of work studying how heat flows in one dimensional systems. It turns out that one dimensional systems, like carbon nanotubes, transport heat anomalously quickly, when the system size becomes large. In addition, he recently devised a one dimensional system where even classically, heat will not be able to flow through it, similar to the quantum phenomenon mentioned above of Many Body Localization.

Finally, Sriram Shastry made a significant contribution to the same general area of how heat flows, with his work on electrothermal transport coefficients using the Onsager reciprocity relations. This has proven very useful in analyzing a large class of condensed matter phenomena.

The fields of thermalization, quantum chaos, and quantum information are some of the most exciting and active areas of research in physics today.

Hopefully the above discussion has provided some idea of the exciting work done in this direction here at UCSC.



Joshua Deutsch, Professor of Physics

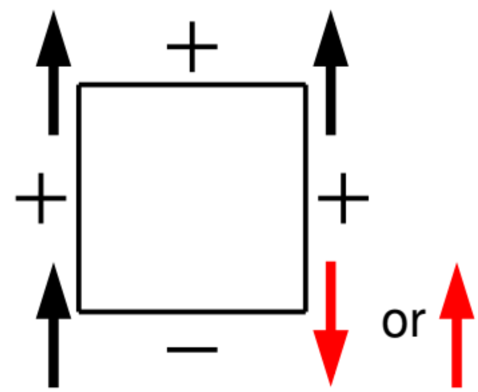
Spin Glasses and the 2021 Nobel Prize

by Peter Young

One half of last year's Nobel Prize in physics was awarded to Syukuro Manabe and Klaus Hasselmann "for the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming" and the other half to Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales". I am not specifically familiar with the work of Manabe and Hasselmann, but am familiar with the brilliant theoretical calculations of Parisi which are in a class of materials called "spin glasses". In this article I will try to explain what a spin glass is and Parisi's major contribution to the field.

In magnetic materials the atoms have individual magnetic moments. We are familiar with ferromagnets, such as iron, in which the magnetic moments of the iron atoms align parallel to each other, and give rise to macroscopic effects. There are actually many more so-called anti-ferromagnets, in which neighboring atomic moments align anti-parallel. We are less familiar with these since they don't display big magnetic effects because the magnetic fields generated by the atoms tend to cancel out. Materials become ferromagnetic below a certain temperature, T_c, called the transition temperature or critical temperature, because there is an interaction between neighboring atoms which lowers their energy when the magnetic moments of those atoms are parallel. This energy is called the "exchange" interaction referring to the quantum mechanical effect which is the origin of the magnetic interaction. At temperatures higher than T_c, thermal agitation destroys the alignment of the atomic moments. In anti-ferromagnets, the energy of two neighboring atoms is lowered because their magnetic moments are anti-parallel. Below T_c, a material has a non-zero magnetization if it is a ferromagnet, and a non-zero "staggered" magnetization if it is an anti-ferromagnet. More generally a quantity which becomes non-zero below a transition temperature is called an "order parameter".

It is common to refer more concisely to the magnetic moments of atoms as "spins", and I shall do this from now on. In spin glasses the interactions between the spins are random, and are so strongly random that even the sign of the interaction is random. Hence some pairs of atoms want locally to be an anti-ferromagnet and other pairs want locally to be a ferromagnet. Something interesting and non-trivial then happens, namely "frustration" (or competition) between different requirements so the system cannot minimize the energy of each pair for any spin configuration. This is shown in Fig. 1 for a toy example of a single square in which there is an odd number of negative interactions.



A toy example of a single square of spins, which in this case are constrained to only point "up" or "down" (so-called Ising spins). A "+" sign on the bond between two neighboring spins indicates a ferromagnetic interaction so those spins minimize their energy when they are parallel, and a "−" sign indicates an anti-ferromagnetic interaction so those spins minimize their interaction when anti-parallel. A moment's thought shows that no "up or down" orientation of the spins will minimize the energy of each of the four nearest-neighbor pairs around the square.

The result is that finding the grounding state configuration of spin glass with a large number of spins is non-trivial. In fact, it is an example of an "optimization" problem in which one has to minimize some function (here the magnetic energy) with competing requirements. Many important tasks, such as image recognition and speech recognition, are cast as optimization problems, which is why insights from spin glasses are useful far beyond the rather small domain of magnetic materials with competing interactions.

Not only is finding the precise ground state of a spin glass very difficult, but there are many ways of getting almost the best possible compromise in the spin orientations, that is to say there are many local minima of the energy, whose energy does not differ very much from that of the true ground state (the global minimum) but whose spin configuration is quite different from that of the ground state. Consequently, at low temperature the system gets stuck in local minima from which it is difficult to escape and the dynamics becomes very slow, so slow, in fact, that an experimental spin glass is never in thermal equilibrium at low temperature and one can only observe non-equilibrium phenomena. Slow dynamics is also a source of great difficulty in attempts to simulate models of spin glasses on a computer.

The first spin glass materials to be studied were metallic alloys in which a small percentage of magnetic atoms such as manganese are put at random in a non-magnetic host metal such as copper. It was observed that the magnetic susceptibility (the linear response of the magnetization to an applied magnetic field) shows a sharp cusp at a certain temperature, suggesting that there is some sort of magnetic phase transition at that temperature.

The seminal theoretical work which started the huge effort to understand spin glasses was by Sam Edwards and Phil Anderson in 1975 while both were at Cambridge University. They proposed a simple-looking model which they studied using a method of dubious mathematical validity called the "replica method". In calculating the thermodynamic functions, one needs to perform an average over the distribution of random interactions. This is normally a difficult mathematical task, but it is made tractable by calculating the thermodynamics of a system of n replicas of the original system and then letting n approach 0 to recover behavior of a single system. Edwards and Anderson found a transition at a non-zero temperature below which the system is characterized by a spin glass order parameter q.

However, work by David Sherrington and Scott Kirkpatrick in 1975 at IBM Labs, and particularly by Jairo de Almeida and David Thouless in 1978 at the University of Birmingham, showed that the Edwards-Anderson solution could not be right, at least in the low temperature phase below Tc. But how to correct it? This is where Parisi entered the field with a series of papers beginning in 1979. He took the infinite-range version of the Edwards-Anderson model proposed by Sherrington and Kirkpatrick in which every spin interacts with every other spin and not just with its immediate neighbors. The reason for taking this unphysical limit is that one hopes to be able to find the exact solution of the model, and not just an approximation. Without anything to guide his intuition, using the same replica method, Parisi came up with a formidable scheme with an infinite number of order parameters, which is called "replica symmetry breaking" (RSB). For comparison, the original Edwards Anderson solution, which has just a single order parameter, is labeled "replica symmetric" (RS).

The replica method uses mathematics which is not strictly valid but, in 2003, nearly a quarter of a century after Parisi's ground-breaking paper, a mathematician called Talagrand, proved rigorously that the Parisi solution of Sherrington and Kirkpatrick's infinite-range spin glass model is exact.

But what about real spin glasses, which of course don't have infinite-range interactions? Does the spin glass state below Tc correspond to the replica symmetry breaking (RSB) picture of Parisi or something else, perhaps some version of a replica symmetric (RS) theory? The most detailed comparison is obtained by comparing predictions of RSB theory with simulations rather than experiments, since simulations can measure quantities that are not accessible experimentally. Simulations, however, are limited in the sizes which can be studied because of the slow dynamics mentioned earlier. The biggest simulations have used a specially built computer called JANUS, optimized for spin glass simulations, for which Parisi himself is the scientific leader. Recall that below Tc we have to study non-equilibrium effects, in which distance over which the system is locally equilibrated grows slowly with time. For length scales which can be probed in simulations, the behavior of the Edwards-Anderson model, which has short-range interactions, is found to resemble the RSB picture much more closely than an RS picture. Even in experiments on real materials the length scales which can be probed are not much larger than in simulations because of slow dynamics. Hence, the behavior over any feasible experimental measuring time resembles quite closely the RSB picture. If it were possible to wait a truly infinite amount of time, one can not rule out the possibility that one would recover a RS picture. However, for the purpose of explaining experimental data on real materials, Parisi's RSB picture seems to work the best.

Spin glass physics is particularly important because it models complex phenomena using simple models that are subject to experimental test. We have already mentioned that finding the ground state of a spin glass is an optimization problem. In particular, Parisi's RSB solution has led to a new paradigm for solving optimization problems called Survey Propagation. The applicability of Parisi's theory to other areas beyond spin glasses was emphasized in the Nobel Prize announcement.

Peter Young
Research Professor of Physics

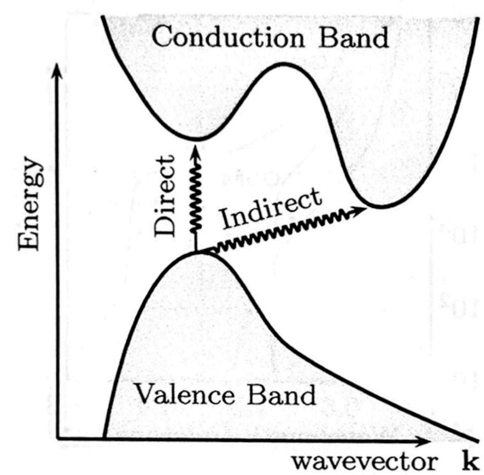
New Directions in Materials Science

by Aiming Yan

The advancement of materials plays an essential role in the development of technology in human society. Within the last century, the advent of Silicon opened the era of semiconductors and thus the Digital Age. As Moore's law predicts that the density of transistors in an integrated circuit doubles about every two years, this projection has shown signs of slowing down. The emerging field of 2D materials, one example of which is graphene, the subject of the 2010 Nobel Prize in Physics (see the article in the 2021 newsletter) provides what many researchers believe may offer a path beyond Moore's law.

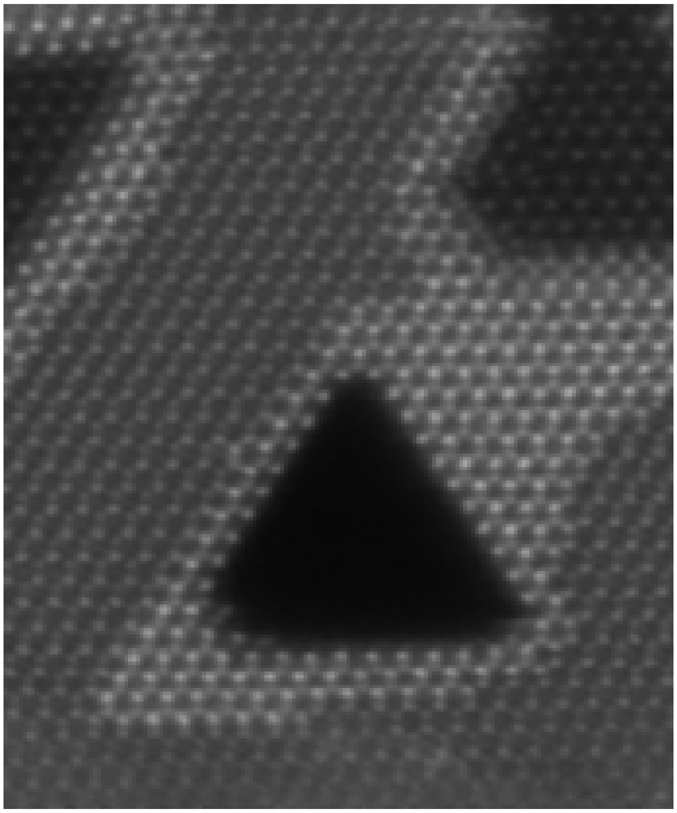
These atomically thin 2D materials possess many novel physical and chemical properties that their bulk counterparts do not. For example, single-layer molybdenum disulfide (MoS_2) is a direct-bandgap semiconductor and has a much higher photoluminescence yield compared to bulk MoS_2, which has an indirect bandgap (see sidebar for a discussion of the difference between direct and indirect in the context of photo-absorption). This distinction is important, as materials with direct bandgaps interact with light more efficiently. The ability to manipulate and control these properties and use them in real-life applications is of primary interest to scientists around the world. Because materials' chemical and physical properties are dependent on their microscopic structures, probing 2D materials' microstructure and understanding how the microstructure impacts their properties is a critical step towards the engineering and designing of such materials to achieve desired properties. In my research group, we use a state-of-the-art characterization method called scanning/transmission electron microscopy (S/TEM) to study the microstructure of 2D materials at atomic to nanometer length scales. Unlike a conventional optical microscope that uses light to "see" objects, a scanning/transmission electron microscope (S/TEM) uses an electron beam to "see through" a thin specimen. The atomic resolution of the S/TEM is enabled by the extremely small de Broglie wavelength of the electrons. The instrument our group members use for this purpose is called "TEAM 1/0.5", which is located in the National Center for Electron Microscopy at Lawrence Berkeley National Lab. This microscope can see features as small as 50 picometers, a size smaller than the radius of an atom. We use this microscope to study the atomic structure in 2D materials, for example few-layer MoS_2, shown on the next page, where individual atoms from different layers can be clearly distinguished.

Direct or Indirect?



Direct and indirect photo-induced transitions. While the indirect transition is lower energy, it is difficult for a photon to excite an electron across an indirect band gap because photons carry very little momentum. The absence of a direct band gap in silicon makes it, unfortunately, unable to be easily integrated into optoelectronic devices. Figure from *The Oxford Solid State Basics*, by S. H. Simon.

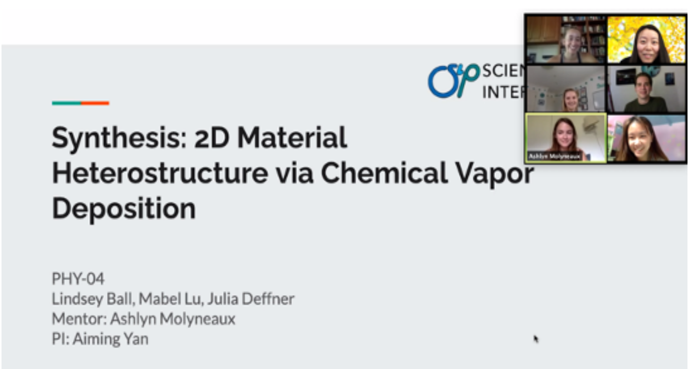
Left: Image of the "TEAM 1/0.5" S/TEM instrument located at the National Center for Electron Microscopy at the Lawrence Berkeley National Laboratory.



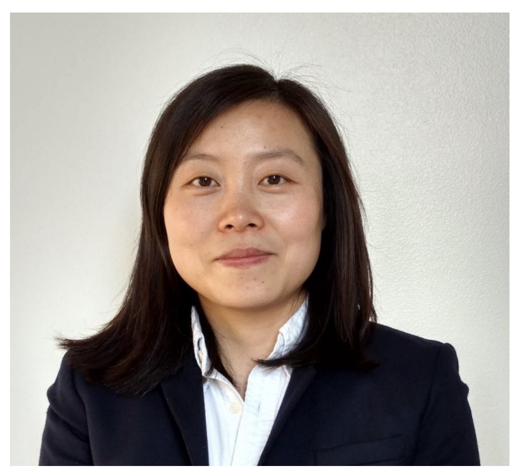
Atomic-resolution STEM image of a few-layer MoS_2, obtained by the Yan group working at the National Center for Electron Microscopy. The individual atoms are shown in bright contrast against the dark background. Different shading indicates different atomic weights, with the brightness corresponding to greater atomic wieght. Thus the brighter dots are molybdenum atoms and the darker dots are sulphur atoms.

Another major challenge of using 2D materials in real-life applications is the scalability of the synthesis of these materials. In order to integrate these materials into modern technologies, we need to be able to fabricate them at the wafer scale, which is presently 12" for silicon. One method that can be used to synthesize wafer-scale 2D materials is chemical vapor deposition (CVD) method. This method uses chemical gaseous precursors that carry the atomic species of the final product material and make them react at high temperatures in a tube furnace. We use this method to synthesize large-scale 2D materials of various kinds, including semiconducting (such as MoS_2, tungsten disulfide) and magnetic 2D materials (such as vanadium disulfide). In the future, my lab (the construction of which should be finished in July 2022) will focus on the CVD synthesis of novel 2D materials that are large-scale and possess new electronic and magnetic properties.

As one of the main focuses in my lab, CVD synthesis of 2D materials has been the project that most readily engages undergraduate students and high school students. Since my group started in 2019 at UCSC, we have been involved in various outreach programs, such as the National Science Foundation funded Research Experiences for Undergraduates (REU) program on "Sustainable Materials" (led by Prof. David Lederman in the UCSC physics department) that target late-college students and students from community colleges and the "Science Internship Program" (SIP) at UCSC that target local high school students. Through these summer programs, undergraduate students and high school students learn how to use the CVD method to synthesize different 2D materials and gain research experience in our lab- a materials science lab. Even during the pandemic, such activities still managed to take place, which we believe will have significant impact on the next-generation materials scientists and condensed matter physicists.



Above: Student interns practicing their final presentations for the SIP and REU programs in the summer of 2020, under the mentorship of Professor Yan (upper right corner) and Ashlyn Molyneaux (lower left corner), an undergraduate researcher.



Aiming Yan, Assistant Professor of Physics

Updates from SCIPP

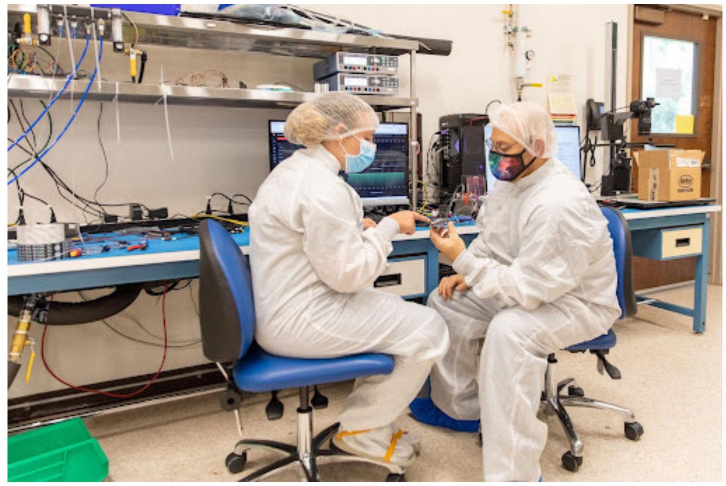
by Jason Nielsen

The Santa Cruz Institute for Particle Physics (SCIPP) is the home of research in particle physics and related areas, including particle astrophysics, cosmology, high-throughput computing, and particle detector development. As a research institute, SCIPP has close ties with researchers from several academic departments: Physics, Astronomy & Astrophysics, Computer Science & Engineering, and Electrical & Computer Engineering. About 75 faculty and students from the Physics Department are engaged with research at SCIPP.

Some long-term projects are passing important milestones. The Rubin Observatory, which will host the Legacy Survey of Space and Time (LSST), celebrated the [integration of the LSST Camera's three primary structures]() for the first time. Physics Professor Steve Ritz was named recently as Project Scientist for Rubin Construction. The ATLAS Inner Tracker detector upgrade project moved into production phase, in which more than 3000 electromechanical silicon detector modules will be produced at SCIPP, and the Dark Energy Spectroscopic Instrument has completed the first year of its five-year redshift survey, [mapping 12.8 million galaxies and quasars]().

Two exciting student training programs in high-energy particle detector instrumentation were launched recently with support from the US Department of Energy. Only two programs were funded nationwide, and SCIPP is involved with both. The HEPIC (high-energy physics and integrated circuits) program aims to train students in integrated circuit (IC) design with applications in high-energy physics (HEP). Electrical & Computer Engineering Professor Shiva Abbaszadeh is leading the UCSC part of that program. The HEP Consortium for Advanced Training (HEPCAT) focuses on the next generation of HEP instrumentalists, working on quantum devices and silicon detectors. Physics graduate student Adam Molnar is one of the first cohort of HEPCAT graduate fellows.

There are two big events for particle physics this summer. The first is the 10th anniversary of the Higgs boson discovery, which celebrated July 4 at CERN and around the world. Over the past decade the Higgs boson has become a useful probe of particle couplings and possible signature for new physics. The second event is the Snowmass community summer study workshop, the culmination of the community planning process on the future of particle physics. SCIPP members have been convening various working groups and preparing quantitative studies of future experiments. The information will be summarized in a series of reports later this year.



Grad student Hava Schwartz and postdoc Giordon Stark examine a readout board for the ATLAS ITk Pixel project in the SCIPP clean space in Natural Sciences 2. The project is part of the ATLAS experiment upgrade to be installed at CERN (photo credit: Carolyn Lagatutta).

The particle physics outreach program has had a busy year, welcoming visiting students in the [QuarkNet Particle Physics Masterclass](), hosting high school classes interested in science careers, and visiting local schools to demonstrate data analysis techniques.

Some of you may have seen [the excitement]() about [the W boson mass measurement]() from the [CDF experiment at Fermilab](). The W boson's importance stems from its role in radioactivity, mediating the weak force between quarks, and from its tight coupling to the Higgs boson. The new measurement is significantly different from previous measurements, as well as the predictions from the Standard Model. Is this another hint of new physics? What does it tell us about the mysterious Higgs sector and the nature of dark matter? Mysteries abound.

The Outreach Task Force

by Pierce Giffin

The Outreach Task Force (OTF) is a group of physics graduate and undergraduate students which takes direct action to make physics more accessible. We also serve as a volunteer force for organizations that aims to increase representation of groups historically sidelined in physics, such as racial minorities (Black, Indigenous, Latinx, and Pacific Islander people), women-identifying people, queer people, people with low income, people with disabilities, people from rural communities, and first generation students. This task force intends to achieve its goal of greater accessibility through developing a long term, continuous outreach program aimed towards current university students, high schoolers, and middle/elementary school students at schools and in areas that serve the groups we intend to aid. By focusing on students at three different educational levels, the task force hopes to induce ongoing interest in science and physics and provide continual support for educational growth. Our program will incorporate flexibility in the activities, modality, and structure, such that the program may be adapted and more robust in the long term.

Left: The OTF's first "Dumb Questions Night," which was a highly successful in bringing UCSC's physics community together.

Last year the Outreach Task Force started the No Jargon Talks series, inspired by CU-Prime Talks at CU Boulder and The Compass Lectures at UC Berkeley. We believe that these talks have been a great opportunity for students to showcase current research in physics and physics education in an accessible way as well as offering advice on careers in physics. In addition, these talks help to foster an inclusive community in the physics department through interaction and discussion. This year, we featured speakers with a wide variety of backgrounds, experiences, and research focuses that highlight the unique paths people take in becoming physicists.

In the Spring quarter, the Outreach Task Force hosted the first Dumb Questions Night at Woodstock's Pizza, pictured below. UCSC students, faculty, and other members of the Santa Cruz community joined to anonymously ask any questions about physics to our panel of professionals: Anthony Aguirre, Jason Nielson, Raja Guhathakurta, and Jairo Velasco Jr. This event was intended to encourage audience members to become more comfortable asking questions about physics. We had a lot of success with this event and plan to repeat it in the future.

As our community has continued to return to in-person activities, the Outreach Task Force has many plans for the upcoming year. We aim to continue our No Jargon Talk Series and Dumb Questions Night in the fall in addition to other new programs that will aid in engaging the physics community of Santa Cruz both from within and beyond the University. In order to do so, we need more students and faculty willing to participate and support these events, and we would very much appreciate the interest and support of UCSC Alumni.

If you are interested in joining the Outreach Task Force or would like to offer your support, please email ucsc-otf-group@ucsc.edu.

Thank You Cathy and Amy!

Cathy Murphy

Cathy Murphy has been the physics department's head administrator since 2016, having previously been the College Academic Manager at Crown College. In May 2022, she announced her retirement from the university. The widely held view among physics faculty is that Cathy's expertise, energy, and positivity will be sorely missed and not easily replaced. The newsletter staff wishes Cathy a well-deserved and happy retirement, and thanks her for her hard work and passion for our physics department.

Amy Radovan

The department is also saying goodbye to Amy Radovan. Amy has been assistant department administrator since 2016 and then last year took over the Graduate Student Administrator position. Amy is highly regarded by all, students and faculty, and has helped to make the department run smoothly for several years. She will be missed not only for her effectiveness in solving problems, but also for her enthusiasm and kindness. Her dedication to physics student groups has been much appreciated as well, and her offering of a smile and snacks while visiting her has been much appreciated. She will bring these qualities to her new job as Executive Assistant for the Chancellor's Office in Kerr Hall, and she has our best wishes with this new position.

Undergraduate Award Winners

Deans', Chancellor's, and Steck Undergraduate Awards

- Nina Blanch
- Austin Dymont
- Jialin Li
- Elizabeth Yunerman

Kenneth and Ann Thimann Scholarship: Undergraduate

- Jialin Li
- Austin Dymont

URST (Undergraduate Research in Science and Technology) Awards-PBSci Division

- Ava Webber
- Fenix Lopez
- Keanu Graham

Marilyn Stevens Award: Undergraduate

- Verenise Martinez

Ron Ruby Research Awards

- Zach Dethloff
- Xander Vriesman
- Siuling Pau Sanchez
- Sam English
- Max Silverstein
- Luis Bautista
- Lillian Santos-Olmsted
- Len Morelos-Zaragoza
- Jianhong Zou
- Eva Schmidt
- Bryn Lonsbrough
- Alberto Baez

Graduate Award Winners

Chancellor's Dissertation-Year Fellowship

- Daniel Davies
- Zhehao Ge

ARCS Award

- Clayton Strawn
- Nolan Smyth

Outstanding TA Award

- Sedik Elsayed
- Evan Frangipane
- Pierce Giffin
- Jordan Scharnhorst

Marilyn Stevens Award-Graduate

- Gabriela Huckabee

Bruce Lane Memorial Scholarship

- Heather Mentzer

Elmer A. Fridley Scholarship in the Physics Sciences

- Nolan Smyth

Long Ph.D. Dissertation Award

- Patrick LaBarre

Congratulations to all award winners!
See the following two pages for key information about each award.

Information About Awards

UNDERGRADUATE

Deans', Chancellor's, and Steck Undergraduate Awards

These awards recognize exceptional achievements in research projects or other creative activities, in order to both encourage outstanding scholarship and promote research as an important part of undergraduate education. In the Physical and Biological Sciences, the students submit a completed thesis, usually a senior dissertation.

Undergraduate Research in Science Awards: sponsored by the PBSci Division

These awards recognize undergraduate research in science and technology administered by the Physical and Biological Sciences Division. Multiple awards may be issued ranging from $500 to $2000. There are three sources for the funds behind this call: one is designated for research in coastal sustainability (Gunderson Family Student Research in Coastal Sustainability Award), one is designated for research in Earth and ocean sciences (Kathryn D. Sullivan Award), and the largest is open to projects in any discipline that uses the scientific method (Undergraduate Research in Science and Technology Award).

Koret Scholars Program

The Koret Scholars Program provides funding for a variety of undergraduate research projects and experiences. The program supports scholarships for undergraduate research projects with faculty and graduate student mentors, undergraduate and graduate student research internships with the Student Success Evaluation and Research Center, and expansion of the year-long College Scholars research development program.

Marilyn Stevens Memorial Scholarship

The Marilyn Stevens Memorial Scholarship is an award designed to honor the former Department Manager of Physics, Marilyn Stevens. It is given to a current upper-division physics undergraduate student and a current physics graduate student. Fellow students, faculty, or staff nominates prospective recipients. The award considers academic excellence, community service, service in and out of UCSC, and any outstanding contribution made to the Physics Department.

Ron Ruby Memorial Scholarship

Ron Ruby was a founding faculty member of the Physics Department. A memorial scholarship for undergraduates was set up in his memory. The Ron Ruby Scholarship is intended to reward the most promising young physicists while also honoring Ron's vision of providing greater access to quality college education. Both merit and financial need are considered in making the award. The department considers diversity an important academic value, so the Ron Ruby Scholarship shall be awarded preferentially to one or more students who have demonstrated potential for leadership in promoting cross-cultural understanding and/or those who have an outstanding record of service dedicated toward helping educationally disadvantaged students. However, recipients will be selected without regard to their race, gender, color, ethnicity, or national origin. U.S. citizenship is not required.

Kenneth and Ann Thimann Scholarship

1984 Dr. Kenneth Thimann, founding Dean of the PBSci Division, and his wife, Ann, established this award. Scholarships are awarded at the end of the academic year to a graduating UCSC senior, who has been accepted to graduate school and shows the most promise as a future scientist in one of the disciplines of biology, chemistry, physics, and earth sciences.

Elmer A. Fridley Award

This is a merit-based scholarship and is awarded to a continuing student in the physical sciences (chem, math, physics, astro, etc), either graduate or undergraduate. The winner is selected on academic merit, faculty support and recommendations.

Goldwater Scholars Award

The Goldwater Scholarship is a prestigious national competition for undergraduates in the fields of mathematics, science, and engineering. The scholarships provide up to $7,500 per year for sophomores and juniors from across the country to cover the costs of tuition, fees, books, and other expenses.

GRADUATE

ARCS Award

A national organization, the ARCS (Achievement Rewards for College Scientists) Foundation provides funds for scholarships to deserving graduate students in the fields of natural science, mathematics, medicine, and engineering. Departments submit their single best student for consideration for the 10 awards.

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President's Dissertation-Year Fellowship and Chancellor's Dissertation-Year Fellowship

Dissertation-Year Fellowships (DYFs) are state-funded, merit-based fellowships awarded on a competitive basis to doctoral graduate students who have overcome significant social or educational obstacles to achieve a college education, and whose backgrounds equip them to contribute to intellectual diversity among the graduate student population. The President's and Chancellor's DYFs are quarterly or year-long fellowships that provide a stipend of approximately $21,000 plus payment of resident tuition for the academic year.

Outstanding TA Award

This is the annual award for recognition of their outstanding performance as a Teaching Assistant during the Fall 2019, Winter 2020, and Spring 2020 quarters. Faculty and staff nominate students who are evaluated based upon the faculty endorsement and their teaching evaluations.

Stay Connected

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Like us on facebook: https://www.facebook.com/ISB211/.

Stay updated on our latest department news here: https://www.physics.ucsc.edu/news-events/news/index.html.

Department Facts & Figures

Undergraduate Students	247 declared
	155 proposed
	11 minors
Graduate Students	73 PhD
	5 BS/MS
Ladder Rank Faculty	22
Adjunct Faculty	10
Lecturers	3
Research Faculty	8
Postdocs	14
Department Staff	5

Giving

Gifts of any size to the physics department are deeply appreciated. Even small gifts into the **general fund** will help to support our student programs and student groups, as well as resources for graduation, our annual picnic, and other social gatherings, which we are looking forward to once the pandemic subsides. Please see the website link below for more information. Thank you!

Attribution and Acknowledgments: *This newsletter was assembled and designed by student Ava Webber and Professor Arthur P. Ramirez. We would like to thank the Physics Department staff for their assistance, and the students and faculty who contributed articles, photos, and other content.*