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Acclaimed photographer Jean-François Dars took this picture late last summer when visiting SCGP. Dars and his partner Anne Papillault are working on a special book about the Center titled “The Spirit of the Place.” It will be published in 2020 for the Center’s 10th year anniversary. Based in Paris, Dars and Papillault have been Documentarians-in-Residence for the French National Center for Scientific Research (CNRS) since the 1980s.
A Note from the Director

By Luis Álvarez-Gaumé

Director, Simons Center for Geometry and Physics

We began the year by congratulating Sir Simon Donaldson for being awarded the Oswald Veblen Prize in Geometry, together with Xiuxiong Chen and Song Sun, and we close it by congratulating Sir Donaldson again on being elected a Foreign Member of the prestigious Russian Academy of Sciences.

This summer, the annual meeting String 2019 took place in Brussels from July 9-13. It is every year’s high point of the string theory community. It was a pleasure to see that four presentations were made by members of the Simons Center—one by SCGP faculty, Zohar Komargodski, and three by Research Assistant Professors, Dalimil Mazac, Mark Mezei and Kentaro Ohmori. The week before another SCGP faculty, Nikita Nekrasov, lectured at String Math 2019, in Uppsala, Sweden. The year has also been bustling with activity as the Center tackles a wide range of topics in workshops and programs. Indeed, it was a successful year of research.

The immediate goal for next year is to fill the two open faculty positions at SCGP. We endeavour to have all professor lines occupied, with the Center operating at full capacity. We are also restructuring and optimizing the visitor program, inspired in part by methods at other research institutions, while tailored to our special needs and characteristics. Recognizing we operate within a state university, there are elements that add both unexpected complexity and reward.

The number of requests for visits, from short term to sabbatical stays, is rapidly increasing and we continue to refine a flexible and well-structured program in line with our resources. We are actively seeking proposals to run programs in the next few years, and also planning to organize a summer workshop in mathematics, to increase the presence of mathematical activity.

In the fall of 2020, we will celebrate the tenth anniversary of the opening of the Simons Center building. We are preparing a number of special publications, talks and exhibits for this occasion. It will be interesting to reflect with our community on the impact the Simons Center has had in its twelve years of existence, ten of which in our distinctive building. Among the planned activities, we will have a retrospective exhibition of M.C. Escher’s work in our gallery starting in September. We will also continue to expand the SCGP’s Art and Outreach program on campus and for the local community. Please stay tuned in the coming months for information regarding the 10 year commemoration.
Milestones and Prizes

In June, the Simons Center celebrated the retirement of Founding Director, John Morgan. A reception was held in his honor where many friends, colleagues and members of the Stony Brook community joined together to acknowledge Morgan for his pivotal role in the growth and development of the Simons Center. As Founding Director, Morgan served from 2009–2016, and was instrumental in the early stages of establishing the Center. It was under his leadership and guidance that the Center’s structure of visiting faculty programs and workshops was developed, as well as many of the data, administrative and building processes the Center continues to operate on today. We are grateful for Morgan’s important contributions and wish him continued success.

In August, it was announced that Dr. Peter van Nieuwenhuizen, Distinguished Professor of Physics in the C.N. Yang Institute for Theoretical Physics at Stony Brook University, and long-time friend and collaborator with the SCGP, was awarded the Special Breakthrough Prize in Fundamental Physics. Van Nieuwenhuizen shares the prize with Sergio Ferrara of CERN and Daniel Z. Freedman of MIT and Stanford University* for their “invention of supergravity, in which quantum variables are part of the description of the geometry of spacetime.” Ferrara, Freedman and van Nieuwenhuizen are the architects of supergravity, a highly influential 1976 theory that successfully integrated the force of gravity into a particular kind of quantum field theory (a theory that describes the fundamental particles and forces of nature in terms of fields embodying the laws of quantum mechanics). As an integral member of the Stony Brook community, the Simons Center is pleased to congratulate van Nieuwenhuizen on this distinguished achievement.

As mentioned in the Director’s Note, Sir Simon Donaldson was elected as a Foreign Member of the Russian Academy of Sciences (RAS) in fall 2019. Founded in St. Petersburg on the order of Peter the Great and by Decree of the Senate in 1794, the RAS is known for its world excellence of research in basic and applied science. Election to membership is based on the significance of the member’s scientific contribution. This well-deserved prestigious acknowledgment provides yet more recognition of the deep impact Simon’s work has on the sciences.

* At the time of the discovery in 1976, Freedman was on the faculty at Stony Brook University.

Peter van Nieuwenhuizen, Sergio Ferrara and Daniel Freedman at a meeting at CERN in 2016 to celebrate 40 years of supergravity. Photo courtesy CERN

Simon Donaldson
Photo: Jean-François Dars
Hitchin systems have found remarkable applications in many different areas of mathematics and physics. In particular, Hausel and Thaddeus related Higgs bundles to mirror symmetry, and in the work of Kapustin and Witten, Higgs bundles were used to give a physical derivation of the geometric Langlands correspondence. Moreover, in the last year many advances were made in the study of branes inside the moduli space of Higgs bundles, opening paths to promising new research directions.

The overall goal of the program was to bring together mathematicians and physicists working on areas close to Higgs bundles. The four interrelated themes of the program were; Higgs bundles and geometric structures; Higgs bundles and representation theory; Higgs bundles and mirror symmetry; and Higgs bundles and singular geometry. During the course of the program there were three associated workshops: Holomorphic Differentials in Mathematics and Physics from February 4–8, 2019; Challenges at the Interface of Hitchin Systems and String Theory from March 18–22, 2019; and Graduate Summer School on Mathematics and Physics of Hitchin Systems from May 27–31, 2019. There were also two independently funded graduate workshops on Geometry and Physics of Higgs Bundles IV from March 16–17, 2019 and Current Trends on Spectral Data for Higgs Bundles V from May 25–26, 2019. The program hosted two regular weekly seminar series; a Journal Club every Friday, coordinated by participant Paul Oehlmann, and a weekly seminar every Thursday.

171 participants from 88 different universities visited the Simons Center as part of either the Hitchin Systems program or associated workshops. Nigel Hitchin, whose seminal work launched this subfield, presented a lecture during the program seminar series titled "Subintegrable systems and their special Kahler metrics." Other seminar speakers who addressed topics that represent interesting and rapidly developing fields in physics and mathematics were Philip Boalch (on the topic of Wild Higgs Bundles), Andrew Sanders (on Opers), and Andres Collinucci and Fernando Marchesano (on T-branes).

AUTOMORPHIC STRUCTURES IN STRING THEORY
Program: March 4–April 5, 2019
Workshop: March 4–8, 2019
Organized by Daniel Persson, Terry Gannon, David Ginzburg, Axel Kleinschmidt, Stephen Miller, Boris Pioline
Recent work has uncovered connections between the theory of automorphic structures and string theory. Automorphic representations are a crucial component of the description of the Langlands program and play a crucial role in understanding scattering amplitudes in string theory. There has also been a recent surge of interest in analyzing the integrands of string theory amplitudes, which have led to studies of “modular graph functions.” This program was designed as an interdisciplinary program to foster the exchange of ideas and perspectives from participants from a wide range of different fields.

The program began with a week-long workshop designed to introduce the key topics and facilitate interactions and novel collaborations. The workshop was organized into four overall themes, each introduced by a two-hour lecture, followed by a selection of shorter, related research seminars throughout the week. The first theme was automorphic forms and representation theory, introduced by Paul Garrett. The second theme, BPS-states and modular forms, was introduced by Shamit Kachru. The third theme, string theory and automorphic representations, was introduced by Henrik Gustafsson, and the final theme, introduced by Pierre Vanhove, was multi-zeta values and modular graph functions.

The remaining weeks of the program allowed for more specialized discussions of the themes presented at the workshop. Several topics were featured prominently; in the context of small representations, Aaron Pollack presented his recent work on automorphic forms in exceptional groups of quaternionic type, emphasizing those associated to the quaternionic discrete series. Due to the physics interest of the subject, particularly the conjectured relation of the quaternionic discrete series to non-perturbative effects in certain Calabi-Yau compactifications of string theory, this talk prompted many discussions amongst participants. Another prominent topic was the Fourier expansions of special automorphic forms in the case of split real groups, focusing both on general results and cases relevant to string theory. Several publications related to this collaboration involving Dmitry Gourevitch, Henrik Gustafsson, Axel Kleinschmidt, Daniel Persson, and Siddhartha Sahi are expected soon. Boris Pioline discussed the generalization of modular graph functions to higher loops. Alejandro Ginory discussed congruence subgroups of Affine Lie Algebras, their Weyl reflection groups and modular invariants.

In addition to the aforementioned talks and collaborations, discussions between Howard Garland and some of the physicists about string theory and affine symmetric spaces led to a plethora of interesting ideas and fruitful exchanges. The program resulted in a number of collaborations between participating mathematicians, including ongoing and renewed existing collaborations, in addition to new ones. The subject of these collaborations include quaternionic discrete series, theta lifts and Poincaré series representation, and new perspectives on the Chinta–Gunnells action and multiple Dirichlet series.

OPERATOR ALGEBRAS AND QUANTUM PHYSICS
Program: June 3–30, 2019
Workshop: June 17–21, 2019
Organized by Stefan Hollands, Vaughan Jones, Gandalf Lechner, Roberto Longo

Nearly 100 years ago, in 1925, Heisenberg, Born, and Jordan formulated the “matrix mechanics” representation of quantum mechanics, which motivated the mathematical research into operator algebras. Later, in 1932, von Neumann used operators to develop the first rigorous mathematical framework for quantum mechanics. Today, the developments of these fields have led to the discoveries of connections between operator algebras and knot theory, free probability, K-theory, quantum field theory, quantum statistical mechanics, and, most recently, quantum information theory. The link between these two fields has led to one of the most fruitful interdisciplinary research programs in the past century.

In the collaborative spirit of the history of these subjects, this program sought to unite established experts and young researchers to discuss developments in and new approaches to quantum field theory, subfactor theory and quantum information theory.

Throughout the program, there were daily talks on various topics that related operator algebras and quantum physics. The first week included a visit from Edward Witten and featured talks by Martina Lanini, Makoto Yamashita, Tom Faulkner and Sebastiano Carpi. Intense discussions centered around entropy and quantum energy inequalities. In the second week, the focus of discussion shifted to conformal field theories, subfactors and other related structures. Talks were given by Yoh Tanimoto, Mihaly Weiner, Luca Giorgetti, Ulrich Penning and Giovanni Landi.

The third week featured the week-long workshop associated with this program. The key topics of the workshop focused on the mathematical treatment of quantum field theories (especially conformal field theories), quantum information theory, and condensed matter physics with operator-algebraic methods. Notable speakers included Feng Xu, Masaki...
Izumi, Vaughan Jones, Dietmar Bisch, Detlev Buchholz, James Tener, Karl-Hermann Neeb, Terry Gannon, Dan-Virgil Voiculescu and Yasuyuki Kawahigashi. The talk schedule was designed to be light, and therefore facilitated many productive discussions amongst the participants.

The final week of the program featured three talks given by Albert Schwarz, Marcel Bischoff and Mayuko Yamashita. Schwarz’s lecture on scattering theory resulted in discussions about the relation of scattering theory to algebraic quantum field theory and subfactors.

This program was a successful interdisciplinary effort to exchange ideas and update the state of the art across the two general fields. Several teams of collaborators met for continuing joint research projects, and ideas and directions for new research projects emerged.

WORKSHOPS

TTBAR AND OTHER SOLVABLE DEFORMATIONS OF QUANTUM FIELD THEORIES
April 8–12, 2019
Organized by Mark Mezei, Stefano Negro, Alexander Zamolodchikov, Zohar Komargodski

Deformations of quantum field theories can be sorted into three classes: relevant, marginal, and irrelevant. Although relevant and marginal deformations have been studied at length, irrelevant deformations have not, due to the great difficulty involved in computing physical quantities from infinite counterterms. However, recently it has been shown that certain irrelevant deformations are solvable in two-dimensional space-time. Therefore, solvable examples of two-dimensional irrelevant deformations, such as TTbar deformations and their generalizations, have attracted significant recent attention in high energy theory.

This workshop brought together experts from different fields of integrable field theories, conformal field theory, and quantum gravity to review recent developments, exchange ideas, encourage interdisciplinary collaboration, and establish new directions of research.

Due to the variety of approaches to this topic, this workshop consisted of both longer introductory lectures and research talks. The research talks focused on the status of irrelevant deformations of two-dimensional quantum field theories, specifically those affected by conserved currents. Noteworthy lectures were given by John Cardy, Sergei Dubovsky, David Kutasov, Eva Silverstein, Roberto Tateo and Herman Verlinde. The workshop also featured an open discussion moderated by a panel of these speakers, chaired by Alexander Zamolodchikov.

GRADUATE SCHOOL ON GEOMETRY OF TEICHMULLER SPACE
April 15–19, 2019
Organized by Samuel Grushevsky, Babak Modami, Leon Takhtajan

Teichmuller theory and moduli spaces of Riemann surfaces play a central role in modern mathematics. They have been a fruitful playground for ideas and methods from complex and algebraic geometry, topology, analysis, and more recently, dynamical systems. They also have been used to explain physics theories.

The main goal of this graduate school was to introduce students to the various geometric structures on Riemann surfaces and their moduli and related concepts in Teichmuller theory. Four mini-courses were taught by expert mathematicians Richard Canary, Carlos Matheus, Yair Minsky and Scott Wolpert.

In his mini-course, Canary introduced higher Teichmuller spaces and pressure metrics, which are natural generalizations of some aspects of Teichmuller theory. Matheus gave a course on totally geodesic subvarieties in the moduli space and Hodge bundles, and applications to dynamics of SL(2,R) action on moduli spaces and dynamics of billiards. Minsky’s mini-course focused on the coarse geometric aspects of metric structures on Teichmuller space and mapping class groups of surfaces. Wolpert gave his mini-course on some classic aspects of variations of Riemann surfaces and derived geometric formulas such as the curvature of the Weil-Petersson metric on the moduli space.

In addition to the mini-courses, this graduate school hosted three talks, given by David Aulicino, Jason Behrstock and John Loftin. Aulicino’s talk focused on platonic solids and used ideas from Teichmuller theory to study period orbits on the solids. Behrstock’s talk was complementary to Minsky’s mini-course and focused on the generalization of coarse techniques to geometric group theory and so-called hierarchically hyperbolic spaces. Loftin discussed cubic differentials and the deformation of projective structures that are related to some ideas introduced in Canary’s talk.

The graduate school hosted over 40 participants, the majority of which were graduate students from a vast range of universities in the United States who are working in areas related to Teichmuller theory and moduli space. The graduate students were given the opportunity to interact with each other and with experts and learn about their work. Some participants had the chance to
work on ongoing projects with their collaborators who were present at the school. Several graduate students from the Stony Brook Math Department also participated in talks. Participation in these talks gave the graduate students a unique opportunity to gain insight into the subject, which informed their research and possible future directions.

CONVERGENCE AND LOW REGULARITY IN GENERAL RELATIVITY
April 29–May 3, 2019
Organized by Philippe LeFloch, Jeff Jauregui, Mike Anderson, Christina Sormani

Many open questions in general relativity (GR) explore solutions that go beyond the notion of strong convergence, and that are not solely geometrically characterized by smooth metrics. Weak notions of convergence must be applied to deal with sequences of manifolds that arise naturally when studying notions of mass. Weak convergence is also needed to rigorously define stability in both Riemannian and Lorentzian GR. It is also increasingly necessary to explicitly define low regularity metrics and how they solve the Einstein Field Equations and therefore specify spacetime geometry.

Over 30 geometers and mathematical physicists with various levels of experience in GR came together at this workshop to share results and ideas and to discuss problems. The workshop began with a talk by organizer Christina Sormani, which introduced different areas of research studied by the participants, followed by research talks. The first two days consisted of talks that related to intrinsic flat convergence and the mass of spacelike manifolds that satisfy the positive energy condition. Notably, Anna Sakovich gave a talk on low regularity aspects of initial data sets and the Jang Equation, and Andrea Mondino presented a new optimal transport approach that might allow one to define a metric measure spacetime in the style of RCD spaces. Philippe LeFloch gave the weekly colloquium on low regularity solutions to the Einstein equations. Stephanie Alexander, Stacey Harris, Clemens Saemann and Eric Ling presented metric geometric approaches to Lorentzian geometry, and David Maxwell discussed Sobolev approaches to spacetimes defined by low regularity metrics. Later in the conference, talks were geometrically-focused, with notable talks on Ricci and scalar curvature given by Chao Li, Shouhei Honda and Guofang Wei. The final day focused on black holes and apparent horizons. These talks were presented by Theodora Bourni, Marcus Khuri, and A. Shadi Tahvildar-Zadeh. Two additional talks were delivered virtually by Dan Lee and Lan-Hsuan Huang, who could not attend the workshop in person.

Throughout the week, attendees engaged in discussions and exchanged ideas that resulted in a greater collective understanding of low regularity metrics and weak convergence in mathematical GR. Several of these discussions flourished into ongoing collaborations that are expected to produce enlightening results.

STRING FIELD THEORY, BV QUANTIZATION, AND MODULI SPACES
May 20–24, 2019
Organized by Kenji Fukaya, Owen Gwilliam, Stephan Stolz, Peter Teichner, Mahmoud Zeinalian

The Batalin-Vilkovisky (BV) formalism plays an important role in many aspects of theoretical physics. Namely, it plays a prominent role in both the mathematical description of quantum field theory and in certain aspects of topological string theory. Recent work on BCOV theory has given a BV perspective to large N limits of gauge theories and the corresponding relationship with string field theory. Such a relationship suggests that some methods from higher category theory and higher algebra might be applicable to large N limits via factorization algebras. Additionally, a new relationship between factorization algebras and functorial field theories indicates how these developments fit together. By exploiting their shared language of BV formalism, this workshop sought to expand the dialogue between string field theory and quantum field theory.

Workshop participants consisted of mathematicians and physicists whose work fused higher algebra with physics, to various degrees. To foster interactions between participants, this workshop was anchored by two lecture series focusing on topics at the interface of the various communities.

The first lecture series was given by Kai Cieliebak. This lecture series explained the homotopical algebra—the strong homotopy version of involutive Lie bialgebras—that appears in symplectic field theory. The second lecture series was given by Kevin Costello. In this series, Costello explained holomorphic twists of well-known string theories and analyzed the anomalies to quantization.

In addition to the lecture series, the workshop hosted a ‘gong show,’ which consisted of speakers from each of the communities giving short talks back-to-back. This gave everyone, especially younger participants, the opportunity to advertise their different interests, leading to frequent discussions.
The latest edition of the annual Simons Summer Workshop titled “Cosmology and String Theory” was the 12th hosted by the Simons Center for Geometry and Physics, and 17th in the history of the Summer Workshop series. The unique and impactful four-week long workshop has been a highlight of Stony Brook’s scientific summer scene since 2003, and a flagship event of the Simons Center, that has been hosting the workshop since 2008, the first year of the Center’s existence. The Center is joined by the Stony Brook scientific community, the YITP, the Math and Physics Departments and neighboring institutions in welcoming over 120 participants from around the world in what is in no way a traditional meeting of the experts. The Summer Workshop is a place where the world-renowned specialists in the most exciting areas of string-related science are mixed together with junior faculty, students, and first-time postdocs, thus creating a unique and broad perspective. As always, organized by Cumrun Vafa (Harvard) and Martin Röček (YITP), but joined this year by YITP’s Marilena Loverde, the workshop welcomed 21 distinguished speakers, including Juan Maldacena (IAS), Paul Steinhardt (IAS), Cora Dvorkin (Harvard), David Spergel (Princeton) and Adam Riess (STSCI) whose public talk was also part of the Della Pietra Lecture Series.

Dedicating the workshop to a very exciting area in observational physics—the interface between cosmology and string theory—the organizers hoped to generate new ideas possibly leading to new stringy predictions for the dark sector. The status of observational data was reviewed, both in the context of the very early universe, as well as more recent epochs, with particular focus on the observational data on dark energy and dark matter. Moreover, various theoretical ideas in cosmology were discussed, such as inflationary models and the associated challenges in their realization in string theory, as well as novel stringy inspired approaches to solving cosmological issues. All this while having fun, enjoying sandy beaches of Long Island’s ocean shore, an array of banquets and receptions, weekly concerts and more,

I myself was very inspired by listening and talking with people, and I am working on a couple of projects already, motivated by the ideas that were discussed during or after the talks. I, and from what I gather from other participants, many others certainly found the atmosphere very inspiring.

--Cumrun Vafa
providing an excellent variety of subjects, locations, and inspiration for scientific discussion.

Exciting experimental results in cosmology, both for the early universe and the universe as we experience it today, are coming out, beginning with the discovery of dark energy in 1998 by two international teams that included American astronomers Adam Riess (the Summer Workshop participant and Della Pietra Lecture Series speaker) and Saul Perlmutter and Australian astronomer Brian Schmidt. This brought about many changes, with results about the early universe becoming more precise. The fact that we observe fluctuations in CMB (cosmic microwave background) at more and more precise levels tells us more about primordial fluctuations, and to a great extent puts strong constraints on early universe models. All these facts should somehow connect with string theory, and the workshop participants were looking into stringy attempts to confront these issues, trying to explain the early and the late universe cosmology and what challenges there are.

“During the workshop we have seen that many new discoveries are happening in the cosmology domain, which are challenging for the standard model of cosmology,” says Cumrun Vafa. “This is bringing the Lambda-CDM, the standard model for cosmology, into question, and on the other hand the usual solutions within string theory of having inflationary phase at the beginning and dark energy at the end seems to be very difficult. The constant dark energy inflation at the beginning is also very difficult to realize in the string theory as well, if not impossible. Those are the aspects that people are trying to find connection between.”

In a way this year the Summer Workshop continued some of the last year’s topics, dedicated to the recent developments in the swampland. In this context a cosmological model that people are trying to get from string theory in the standard cosmology, as well as early inflation and late cosmological constant are challenging in string theory, and that was the swampland idea. Some aspects of that were discussed during the workshop, and new ideas were presented, however we are still in the same situation as we were last year, namely we don’t exactly know whether string theory can produce the things that observations seem to support: dark energy and early period of inflation.

Trying to connect the two scientific communities was one of the main aims of the workshop. In order to see the interaction between them it was necessary to get them on the same page in terms of what are the phenomena that we are seeing, the experimental consequences and the theoretical ideas to explain those. Given the exciting talks given during the workshop,
especially about the unfolding experimental results that are coming out as we speak and challenging the standard cosmological paradigm, we can hope for it being not just a small step, but a truly fascinating and exciting move forward. “Many people I talked with during the workshop, were convinced that we now are entering the era where the standard cosmological model is not going to survive,” Vafa says. “We don’t know yet if it is the case or not, but it is beginning to look like that.” So, new theoretical ideas coming from fundamental physics, presumably where the string theory may help, is the kind of exciting development that might be leading us to the future, and this is what the workshop was trying to initiate.

The Simons Center and the Summer Workshop organizers would like to show appreciation to Michael and Victoria Bershadsky for their generous support that enabled several younger Summer Workshop participants to be invited to Stony Brook. The long-time donors were celebrated at a special banquet given at the Simons Center in their honor. More banquets allowed for great socializing and fun, including the special barbeque hosted by Luis-Alvarez-Gaume and Cinzia DaVia at the Simons Center Café, a wonderful banquet generously hosted by Simons Foundation at the Avalon Park and Preserve, and at Martin Roček’s residence who every year opens his home to all the workshop participants and locals.

For video recordings of all the talks given during the Summer Workshop, program, photos and more, please go to the 2019 Summer Workshop’s home page at www.scgp.stonybrook.edu/archives/28200.
The Della Pietra Lecture Series, now in its eighth year, brings world-renowned scientists to the Simons Center for Geometry and Physics for the purpose of increasing awareness of recent and impactful scientific discoveries. Funded by a generous donation from brothers Stephen and Vincent Della Pietra, and their spouses Pamela Hurst-Della Pietra and Barbara Amonson, the lectures are presented to a wide audience, and accessible to the University faculty and students, as well as the Long Island community. A component of the Center’s annual outreach efforts, the series also includes a special presentation specifically for local high school students with an interest in the sciences. A goal of the series—and the Center at large—is to promote interdisciplinary education, interaction and collaboration. This past spring, the Center was honored to host a lecture series by Dr. Charles L. Kane of the University of Pennsylvania, followed by a second series by Dr. Adam Riess of Johns Hopkins University and the Space Telescope Science Institute (STSCI).

Kane, theoretical condensed matter physicist and Christopher H. Browne Distinguished Professor of Physics at the University of Pennsylvania, delivered three lectures at the Simons Center on May 7 and 8, 2019. With a research background focused on the theory of quantum electronic phenomena in solids, Kane is best known for theoretically predicting the quantum spin Hall effect and what would later be known as topological insulators.

On May 8, he presented a public lecture titled "The Emergence of Topological Quantum Matter," during which he explored the different ways matter can be arranged, and the role quantum mechanics plays in the existence of electronic phases of matter. This same lecture was also presented to a select group of local high school students with a strong background in physics. To close out the series, Kane delivered a third lecture for advanced graduate students and faculty as part of the SCGP Weekly Colloquium titled "Topological Superconductivity from Majorana to Fibonacci." He discussed topological superconductivity and its potential for providing a method to reliably store and manipulate quantum information. For a more in depth review of Kane’s research see the article on page 12.

In August, the Simons Center welcomed Dr. Adam Riess, astrophysicist and Bloomberg Distinguished Professor at Johns Hopkins University and STSCI. Riess is widely known for his research using supernovae as cosmological probes. He shares both the 2006 Shaw Prize in Astronomy and the 2011 Nobel Prize in Physics with Saul Perlmutter and Brian P. Schmidt for providing evidence that the expansion of the universe is accelerating. Riess delivered a public talk on August 5 titled "Supernovae and the Discovery of the Accelerating Universe," in which he described how his team discovered the acceleration of the Universe, and why understanding the nature of dark energy presents one of the greatest remaining challenges in astrophysics and cosmology. His second lecture of the series was a technical talk for faculty and advanced graduate students in conjunction with the 2019 Simons Summer Workshop, titled "The Present Expansion Rate of the Universe, Evidence of New Physics?" The focus of this talk was the Hubble constant which remains one of the most important parameters in the cosmological model, setting the size and age scales of the Universe. Riess explained how steadily improving the precision and accuracy of the Hubble constant has led to new evidence for significant deviations from the standard model, and thus the exciting chance—if true—of discovering new fundamental physics.

By Maria Guetter
Matter can arrange itself in the most ingenious ways. In addition to the solid, liquid and gas phases that are familiar in classical physics, electronic phases of matter with both useful and exotic properties are made possible by quantum mechanics. In the last century, the thorough understanding of the simplest quantum electronic phase—the electrical insulator—enabled the development of the semiconductor technology that is ubiquitous in today’s information age. In the present century, new “topological” electronic phases are being discovered that allow the seemingly impossible to occur: indivisible objects, like an electron or a quantum bit of information, can be split into two, allowing mysterious features of quantum mechanics to be harnessed for future technologies.

The building blocks of matter are largely known. Matter is composed of fundamental particles with electric charges that are precisely quantized in units of the indivisible fundamental charge e, and whose behavior is governed by the laws of quantum mechanics. In an atom, electrons with charge -e orbit the positively charged nucleus, similar to planets orbiting the sun. However, according to quantum mechanics, electrons can only exist in orbits with discretely quantized energy. This can make atoms electrically inert. Electrons are locked in place like legos: dislodging them requires a big enough kick to overcome the energy gap to the next discrete energy level.

This simple picture allows a cartoon-like understanding of the insulating phase. In a crystal of inert atoms, all of the electrons are stuck on their home atom as in Fig 1a, allowing no flow of electric charge. There is a sense in which the insulating state is the most boring state: nothing happens. But if you add an electron to an insulator, that added electron can move around and conduct electricity. Alternatively, you can remove an electron. The missing electron, known as a “hole,” can also move when another electron takes its place, as in Fig 1b. Holes behave just like fundamental particles with charge +e, but they are not among the original building blocks. They are emergent particles that are fundamental excitations of the insulating state. They are also useful: most of modern electronics technology is founded on our exquisite control over electrons and holes. A semiconductor, like silicon, is an insulator to which electrons and holes can easily be added.

Of course, real materials are more complicated than the above cartoon picture. One of the triumphs of 20th century physics was the quantum theory of solids, which provides a detailed understanding of materials like silicon. However, there are things that the cartoon gets right. There is still an energy gap in silicon, and the fundamental excitations are still charge -e electrons and charge +e holes. The sense in which the cartoon “gets it right” leads to the deep and beautiful idea of topology. In your mind’s eye,
you can imagine smoothly transforming a silicon crystal into a trivial atomic insulator by, for example, slowly moving the atoms apart. If along the way it remains an insulator with a finite energy gap, then there is a sense in which it has stayed the same. Topology is the mathematical study of objects that can be continuously deformed. The classic example for topology is the sense in which a doughnut is the same as a coffee cup. If they were made out of clay, you can imagine continuously molding one into the other. The thing that stays the same is the number of holes: the hole in the doughnut turns into the handle of the coffee cup. But not everything is the same. You can’t mold a ball into a doughnut without poking a hole in it—and you can’t do that smoothly. Insulators that can be continuously deformed into one another are topologically equivalent. Thinking about this way poses a very interesting question that was overlooked for decades in the quantum theory of solids. Are there “topological insulators” that can not be smoothly deformed into trivial atomic insulators? The remarkable answer is yes, and they have fascinating, and potentially useful properties.

The simplest version of a topological insulating phase occurs in a one-dimensional (1D) polymer called polyacetylene, which is an electrical insulator that consists of a chain of atoms with alternating strong and weak bonds. However, there are two possible configurations (“strong-weak-strong-weak” and “weak-strong-weak-strong”) which are topologically different in the above sense. The cartoon picture for this insulator is that there are twice as many spaces for the electrons than there are electrons, so in the A-phase (B-phase) the electrons occupy only the black (red) sites in Fig. 1c. Importantly, there are just enough electrons to exactly compensate the positive charge of the nuclei, so that with half the spaces filled the system is overall electrically neutral.

Now, something magic happens when you add an extra electron, say, to the A-phase. In Fig. 1c there is one added electron, so the net charge is -e. In Fig. 1d, by simply shifting electrons over one space, that added charge -e splits in half! The only places where there is any net charge is in the regions where the electrons are bunched together. Since there are two of them they each have charge precisely -e/2. These -e/2 charges can move and are emergent particles in the same way that holes are.

How can this be? The electron is indivisible and can’t be split. But notice that between the -e/2 charges the insulator is in the B phase. The “impossible” -e/2 charges exist on the boundary between topologically distinct insulators. This is the essence of topological phases of matter. They allow the indivisible to be split by putting the “impossible” on the boundary. There are many examples of this general phenomenon, and the “impossible” things that they allow are truly remarkable.

Our first example is motivated by a problem: the flow of electrons in conductors is disorganized. It’s not that the electrons are moving chaotically, but rather that they are not moving at all. In the case of a conductor, the electrons are free to move, but the flow is not organized. In the case of an insulator, the electrons are locked to their home atoms and cannot move, but extra electrons or missing electrons (holes) can be added and (b) can move. (c) In a simple picture for polyacetylene, electrons occupy every other site with two possible configurations A and B (figure A is shown). An added electron has charge -e, but in (d) by shifting electrons over that added charge splits into two charge -e/2 particles at the boundary between the A and B phases.

Figure 1.
A cartoon picture of an insulator: (a) Electrons are locked to their home atoms and cannot move, but extra electrons or missing electrons (holes) can be added and (b) can move. (c) In a simple picture for polyacetylene, electrons occupy every other site with two possible configurations A and B (figure A is shown). An added electron has charge -e, but in (d) by shifting electrons over that added charge splits into two charge -e/2 particles at the boundary between the A and B phases.
like trying to navigate a crowded hallway. You are constantly bumping into people, which makes it hard to get where you are going. This problem gets worse when the conductors are smaller, so this poses a serious obstacle to the miniaturization of electronics technology. How can we make the flow more organized? To organize traffic, we build divided highways. Can we do the same for electrons?

There exists a topological phase, called the quantum Hall state, that accomplishes this. This is the “mother of all topological phases:” the one we understood first and the one we understand the best. It was discovered in the 1980’s, when experimentalists making electrical measurements on semiconductor devices found a striking quantization of the Hall resistance when electrons were confined to a 2D plane in the presence of a strong magnet. This prompted theoretical physicists to think deeply about how that could be and to introduce the notions of topology that now underlie the field.

The quantum Hall state has an energy gap in the 2D interior, so the electrons are locked in place like in an insulator. However, it is topologically distinct from a trivial insulator. It necessarily has a “one-way” electrical conductor on its 1D boundary. These one-way edge states are remarkable because an electron in them has no choice but to go forward. This makes the electrical conduction perfect and leads to an electrical Hall resistance that is precisely quantized in units of the fundamental constant $\hbar/e^2$ ($\hbar$ is Planck’s constant). Experimentally, this quantization is measured to one part in a billion. It is so accurate, that these measurements now serve to define the standard unit of resistance called the Ohm, which is a key part of the international system of units used by physicists.

The one-way edge states are also remarkable because they are impossible. If they were to exist in isolation, deep principles of charge and energy conservation would be violated. An ordinary 1D conductor allows motion in both directions, with counterpropagating lanes that are inextricably tied to each other. The quantum Hall state allows those indivisible lanes to be split, as shown in Fig. 2a. Once you have a one-way edge state it is impossible to get rid of it. If you did, then the other edge would be an impossibly isolated one-way conductor. Thus, the edge states are topologically protected.

The one-way edge states could be useful for organizing the flow of charge in tiny electrical conductors. However, a difficulty is that using present technology a strong magnet is required to create them. There is another topological phase called a three-dimensional topological insulator (3D TI), which could provide a route towards that goal without the magnet.

A 3D TI is a material that is an insulator on its interior, but is a very special kind of electrical conductor (called “helical”) on its 2D surface. The helical surface conductor can be viewed as splitting an ordinary 2D conductor into two pieces: one on the top and one on the bottom (Fig. 2b). These helical conductors are

Figure 2.

Splitting the indivisible: (a) a 1D conductor is split into two one-way conductors at the edge of a 2D quantum Hall state. (b) a 2D conductor is split into two helical conductors at the surface of a 3D topological insulator. (c) a qubit (i.e. a spin that can be up, down or both at the same time) is split into two “half qubits” at the ends of a 1D topological superconductor.
impossible in isolation. They possess a special property called a “single Dirac cone” that is impossible in a purely 2D system. Once you have them, though, they are impossible to get rid of. Like the edge states in the quantum Hall effect they are topologically protected.

Unlike the quantum Hall effect, 3D topological insulators were conceived of by pure thought. Theorists realized that such a phenomenon was possible, and developed techniques to predict specific materials where it would occur. Experimentalists then created the materials and performed measurements that verified their properties. For example, a landmark experiment in 2008 observed the single Dirac cone on the surface of a crystal of Bi₂Se₃, using a technique called angle resolved photoemission spectroscopy. This helped initiate a vast subfield of condensed matter physics with strong interplay between theoretical physics, computational physics and experiment. Nowadays there are many more materials that are known to be 3D TI’s and related topological states.

One of the potential applications of topological insulators is to use them to organize the flow of electric charge in the tiny conductors. A second, more speculative but also more ambitious, proposal is to use topological insulators and related materials to construct a quantum computer. This problem motivates our third example of a topological phase.

Ordinary computers perform logic operations on bits: the 0’s and 1’s that can be combined to encode binary numbers. A quantum bit (or qubit), can be 0 or 1 or both at the same time. This combination of 0 and 1 is enabled by a mysterious feature of quantum mechanics called superposition. This allows a quantum computer—a device that performs operations on qubits—to be much more powerful than an ordinary computer. Unfortunately, a quantum computer is very hard to make because qubits are fragile. If you measure a qubit, you lose most of the information that it encodes. The difficulty is therefore making sure that the quantum computer doesn’t accidentally measure itself. This fact makes constructing a quantum computer one of the grand technological challenges for the coming century. One approach is to try to make the qubits very well isolated. There is another approach which takes advantage of a topological electronic phase.

The idea is to split the qubit. Qubits are ordinarily pointlike (0D) objects, like atoms or spins, that can exist in two distinct states. However, just as a topological insulator can split an electrical conductor into two, there exists a related topological phase called a topological superconductor that can split a qubit into two pieces that reside at the two ends of a 1D material, as shown in Fig. 2c. The beauty of this is that the qubit is shared between the two ends and cannot be measured with any local measurement on one end. The quantum information is thus topologically protected, and immune from accidental measurement. One possible route to creating a topological superconductor is to combine an ordinary superconductor (which can easily be found) with a topological insulator, or a related topological material. There is promising experimental evidence that such topological superconductors can be created. Demonstrating that they have the capacity to store quantum information remains a challenge—but one which seems likely to be solved.

Knowing the fundamental building blocks of matter and the rules that govern them is only part of the story in physics. In 1687 Newton’s *Principia* laid out the fundamental rules of classical mechanics. It was much later that the concept of energy emerged as an organizing principle for understanding what matter that obeys Newton’s laws can do. Likewise, the rules of quantum mechanics were laid out in the early 20th century. Organizing principles, like topology, for understanding quantum matter are still emerging. This makes it an exciting time to be a physicist, because matter can arrange itself in the most ingenious ways!

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**Indivisible**

**Quantization of electric charge**

Matter is composed of fundamental particles with discrete, indivisible electric charges.

- electron: e
- proton: p
- neutron: n
- charge -e
- charge +e
- charge 0

**Quantum Mechanics**

- In an atom, electrons occupy discrete quantized energy levels.
- Electrons are “locked in place”: It requires a minimum energy to excite an electron.

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Slide from Dr. Kane’s public Della Pietra lecture

Image courtesy Charles L. Kane
Cosmologists are largely statisticians. We cannot directly observe the evolution of the Universe, but we can make maps of the Universe at different epochs in time and compare how the statistical properties have changed. Similarly, we cannot set up and perform cosmological experiments with different variables held fixed, but we can search for correlations between the things we observe and quantities that vary throughout space. In fact, much of observational and theoretical cosmology involves devising clever statistics to isolate physical relationships that cannot be measured directly.

Cosmologists make maps of the Universe through a variety of probes: the temperature and polarization of the cosmic microwave background radiation (CMB), the abundance of galaxies or the magnitude of their line-of-sight velocities, the ellipticities and brightnesses of galaxies, which can be used to infer the distribution of matter by gravitational lensing, and the strength of emission and absorption lines from atomic and molecular spectra in intergalactic gas. From these quantities we can extract information about both the initial distribution of different types of matter in our Universe and dynamical processes occurring through the history of our Universe. In this article, I give a brief description of some examples of both types of inferences.

To set the stage for this discussion, an image showing a map of the anisotropy in the temperature of the CMB as mapped by the Planck satellite [1], along with a map of the distribution of galaxies mapped by the Sloan Digital Sky Survey (SDSS) [2] is shown in Figure 1. The temperature and polarization anisotropies in the CMB provide a snapshot of the Universe at a fixed time about 380,000 years after the big bang. The galaxy surveys (and other methods) provide images of the Universe at a range of times in cosmic history, beginning with the faintest observable galaxies formed about a billion years after the big bang until today. In the coming years, new cosmological surveys will map out more and more of the observable Universe.

The most familiar examples of cosmological statistics are power spectra, the Fourier transforms of two-point correlation functions. For instance, if $\rho_m(x)$ de-
The matter density at position $\mathbf{x}$ in a volume $V$, then the fluctuations in the matter density are given by,

$$\delta_m(\mathbf{x}) \equiv \rho(\mathbf{x})/\bar{\rho}_m - 1,$$

(1)

with $\bar{\rho}_m$ the mean matter density in $V$. The power spectrum of matter fluctuations is estimated by

$$P_{mm}(k_b) = \frac{1}{V N_k} \sum_{\mathbf{k} \in k_b} |\delta_m(\mathbf{k})|^2$$

(2)

where $k_b$ is a bin in wavenumber and $N_k = \sum_{\mathbf{k} \in k_b}$ and I have adopted the cosmologist’s convention of distinguishing between real and Fourier space quantities only by their argument. Similarly, if $n_g(\mathbf{x})$ is the number density of galaxies, and then the matter-galaxy cross-power spectrum is given by

$$P_{gm}(k_b) = \frac{1}{V N_k} \sum_{\mathbf{k} \in k_b} \frac{1}{2} (\delta_g(\mathbf{k}) \delta_m(\mathbf{k}) + \delta_m(\mathbf{k}) \delta_g(\mathbf{k})) .$$

(3)

where $\delta_g(\mathbf{x}) = n_g(\mathbf{x})/\bar{n}_g - 1$, where $\bar{n}_g$ is the mean number of galaxies in $V$. Cosmologists measure the auto- and cross-power spectra of nearly any quantity they can measure! These are used for a variety of purposes. For instance, the matter power spectrum in Eq. (2) characterizes the typical amplitudes of fluctuations in the matter density on wavelength $2\pi/k$. More precisely, the variance of matter fluctuations on scale $k$ is given by $\Delta_{mm}(k) = 4\pi^2 k^3 P_{mm}(k)/(2\pi)^3$. In our Universe, $\Delta_{mm}(k)$ is an increasing function of $k$ so that the typical amplitude of density perturbations is larger on smaller scales. Equivalently, the Universe appears most inhomogeneous on small scales, and on large scales typical fluctuations in the density are very tiny. The variance of matter fluctuations in our Universe is shown in Figure 2. For comparison, Figure 3 shows a realization of the matter distribution taken from a snapshot of a cosmological simulation. By construction, the power spectrum of the matter distribution in the simulation will be consistent with Figure 2.

A working assumption in cosmology is that the particular realization of the distribution of different types of matter in our Universe is a random draw from some underlying probability distribution functional. I’ll call $\mathcal{P}[\delta_c, \delta_b, \delta_\nu, \ldots]$. In this expression $\delta_c$ indicates fluctuations in the cold dark matter density, $\delta_b$ indicates fluctuations in baryonic matter density\(^1\), $\delta_\nu$ indicates fluctuations in the photon energy density, $\delta_\nu$ indicates fluctuations in neutrino energy density, and the … allow for any other type of matter that may exist.

In this framework, if the “experiment” of our Universe were run many times we would expect to see different realizations of these fields $\delta_c(\mathbf{x}), \delta_b(\mathbf{x}), \delta_\nu(\mathbf{x}), \delta_\nu(\mathbf{x}), \ldots$. Yet, if one measured the power spectra and cross-power spectra of these fields in each realization via Eq. (2) and then computed the averages, we would recover the “true” power spectra, e.g.

$$P^{true}_{cc}(k) = \langle P_{cc}(k) \rangle, \quad P^{true}_{cb}(k) = \langle P_{cb}(k) \rangle \ldots$$

(4)

The angular brackets, $\langle \rangle$ above, indicate ensemble averages over realizations of the matter fields. The “true” power spectra are the functions that characterize the variances and co-variances of fluctuations in the probability distribution functional $\mathcal{P}[\delta_c, \delta_b, \delta_\nu, \ldots]$. A theory that provides a mechanism for the origin of the structure, or inhomogeneities, in our Universe should provide an explanation for both the form of the probability distribution functional $\mathcal{P}[\delta_c, \delta_b, \delta_\nu, \ldots]$ and for any quantities, e.g. power spectra or bispectra, needed to characterize it. A completely general probability distribution functional will depend on an infinite number of correlation functions, or higher-order polyspectra, of each independent quantity! Amazingly, our

\[\text{Figure 2: The power spectrum of fluctuations in the matter density throughout our Universe compiled from a variety of datasets, adapted from [1]. Data from the Planck satellite’s measurements of CMB temperature and polarization anisotropies determines the power spectrum on the largest scales (smallest $k$). The distribution of galaxies from SDSS is used on intermediate scales, while the smallest scale measurements come from maps made using the Lyman-$\alpha$ absorption line in intergalactic Hydrogen from BOSS, and correlated distortions to the shapes of galaxies caused by gravitational lensing, as measured by the Dark Energy Survey (DES). This plot uses cosmologist length units of Mpc ($\approx 3 \times 10^{22}$ meters) with the dimensionless Hubble parameter $h = H_0/(1000 km/s) \approx 0.7$ scaled out.}\]
MAPPING THE UNIVERSE

The universe appears much simpler. All data can be described if the initial values of each field are determined by a single random field $R(x)$, sometimes called the **primordial curvature perturbation**. That is, the initial spatial distributions of all quantities we have observed appear to be determined by $R$ through simple proportionality,

$$\delta_c(x) \propto \delta_b(x) \propto \delta_g(x) \propto \delta_n(x) \propto R(x).$$  

This is a special class of initial conditions called **adiabatic**. Relative fluctuations between different components are called isocurvature modes, and at present there is no evidence for any primordial isocurvature modes in our universe.

The properties of the field $R$ are also very special: $R$ is a Gaussian random field. This means that each Fourier mode $R(k)$ is statistically independent and the phases of each mode are drawn from a flat probability distribution. The two-point function completely characterizes the statistics,

$$\langle R(k)R(k') \rangle = (2\pi)^3 P_R(k) \delta_{Dirac}(k + k')$$  

where $\delta_{Dirac}$ is the Dirac-delta function and

$$\langle R(k_1)R(k_2)\ldots R(k_n) \rangle_c = 0 \quad \text{for} \quad n > 2.$$

The subscript $c$ in Eq. (7) indicates the connected part of the correlation function (i.e. subtracting all pairwise contractions, which are just determined by Eq. (6)). The amplitudes of the individual Fourier modes of $R(k)$ are drawn from a Gaussian distribution with a variance given by [3],

$$\Delta_{RR}(k) \equiv \frac{4\pi^2}{(2\pi)^3} P_R(k)$$  

$$\approx 2.1 \times 10^{-9} \left( \frac{0.05\text{Mpc}^{-1}}{k} \right)^{0.035}$$

From Eq. (9) we learn that the initial perturbations in the spatial curvature are very small and that the power spectrum is nearly scale-invariant but with slightly larger-amplitude perturbations on large scales ($k < 3 \times 10^{-4}$). At present, there is no evidence for any deviation from the functional form in Eq. (8), for instance any change in the power law index with $k$. Furthermore, there is no evidence for any non-trivial higher order correlation functions of $R$.

The initial conditions described above (adiabatic, Gaussian, and nearly scale-invariant) can be explained by one of the most popular theories for the origin of structure, cosmological inflation. Within inflation, the primordial curvature perturbations are generated by quantum mechanical fluctuations during a phase of exponential expansion in the very early universe. The near scale-invariance of the primordial curvature power spectrum is directly related to the near-constancy of the expansion rate. While we don’t know the precise time or energy scale during inflation, it could be as early as $10^{-36}$ seconds after the big bang when the typical energy scale was $10^{15}\text{GeV}$. Measurements of the statistics of $R$, therefore, provide a window into this era. Near-term experiments such as SPHEREx aim to detect higher-order correlation functions in $R$, which can provide information about the types of matter and interactions that were important during inflation – all at energy scales vastly beyond what is accessible by terrestrial particle colliders (see, e.g. [4], for a recent review).

Now, how do cosmologists actually determine the statistics of matter fluctuations? Traditionally, the simplest approach has been to use observations of the anisotropies in the CMB. As shown in Figure 1, these primarily give a map of our universe at a single snapshot in time. Dramatic improvements in our understanding of many aspects of our universe will require data from more epochs in cosmic history. One classic way of mapping the large-scale distribution of matter is via galaxy surveys – maps of the positions of galaxies across our universe. To interpret data from galaxy surveys, however, requires understanding how fluctuations in the distribution of galaxies relate to fluctuations in other types of matter, e.g. cold dark matter and baryons. Fortunately, these quantities are closely related. In Figure 3 two snapshots of simulations of structure in the universe are shown. The image on the left shows the distribution of dark matter, while the image on the right shows the distribution of galaxies. The galaxy distribution closely reflects some of the underlying structure in the matter distribution, but provide an incomplete picture where the matter is, particularly on smaller scales.

The correlation between large-scale fluctuations in the abundance of galaxies $\delta n_g(x)$ and large-scale fluctuations in the matter density $\delta \rho_m(x)$ quantifies how closely galaxies trace matter. The cross-correlation coefficient between these two quantities is referred to as **galaxy bias** $b_g$,

$$b_g \equiv \frac{P_{gm}(k)}{P_{mm}(k)}.$$  

This quantity is important for interpreting data from galaxy surveys because galaxies are much easier to observe than dark matter, which dominates the ma-
matter density \( \rho_m \) of our Universe, but the distribution of dark matter is a better diagnostic for addressing fundamental questions about cosmology. The galaxy bias in Eq. (10) is also interesting in its own right, it quantifies how the presence of long-wavelength matter fluctuations helps or hinders galaxy formation. This can be understood simply if we consider the number of galaxies in some region of space to be a functional of the matter densities in the same region of space,

\[
n_g(\mathbf{x}) = n_g[\rho_c(\mathbf{x}), \rho_b(\mathbf{x}), \ldots]. \tag{11}
\]

In Eq. (11), \( n_g(\mathbf{x}) \) should be understood to be the number of galaxies in some region around \( \mathbf{x} \) that is larger than the typical size of a galaxy, say \( R_{\text{gal}} \), and where the local values of the cold dark matter and baryon densities are \( \rho_c(\mathbf{x}) \) and \( \rho_b(\mathbf{x}) \) (as before we allow \( \ldots \) for any other quantity that may affect galaxy formation). Because galaxy formation is a process that occurs over a long period of time, the number of galaxies in some region will depend on the history of the local density fields, not just their values at a single instant in time. By cross-correlating Eq. (11) with the total fluctuations in the matter density \( \delta_m = (\rho_c + \rho_b)/\rho_0 \) we can extract the linear galaxy bias w.r.t. the total matter fluctuation defined in Eq. (10) via,

\[
b_g = \frac{1}{n_g} \left\langle \frac{\delta_m n_g[\rho_m]}{\delta m} \right\rangle = \frac{\delta \log n_g}{\delta \delta m}. \tag{12}
\]

Traditionally, the galaxy bias is studied under the assumption that only the total matter density affects galaxy formation and that all long-wavelength perturbations in the matter density \( \delta_m(k \ll 1/R_{\text{gal}}) \) evolve in the exact same way. While this is true in simple cases, for instance a Universe with inhomogeneities in only cold dark matter, it is violated in many interesting examples, including a Universe like our own! At Stony Brook, we have been pioneering the study of how the galaxy bias depends on the full evolutionary history of the local matter density. To do this, we have developed techniques to study dark matter halo formation in radically different environments. This, in essence, allows us to compute the functional derivative in Eq. (12) by computing the response of \( n_g \) to different evolutionary histories for \( \delta_m \). By doing this we have gained insight into the formation of structure in our Universe. Because the true evolutionary history of \( \delta_m \) will depend on the types of matter present in our Universe, as well as the initial conditions (e.g. Eq. (5) or violations of that form), these studies have produced new tests of properties of our Universe. In the coming years, these tools will be increasingly important for interpreting data from surveys of the galaxies and matter distributed throughout the Universe.*

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**References**


In July 2019, on behalf of the Simons Center for Geometry and Physics, Claude LeBrun, Stony Brook Mathematics Department, conducted an interview with Eugenio Calabi at the University of Pennsylvania Mathematics Department. Calabi is, of course, primarily famous for his pioneering work on Calabi-Yau manifolds, a class of solutions of Einstein’s equations that plays a central role in current research, both in mathematics (where they connect differential geometry and algebraic geometry in a remarkable new way) and in physics (where they are used to construct model universes via string compactification). This interview excerpt has been edited from a video interview that can be found on our website at scgp.stonybrook.edu/archives/31629. It is partly intended as a celebration of the recent award of the Veblen Prize to Simons Center and Stony Brook faculty members Simon Donaldson, Xiuxiong Chen, and Song Sun, for work answering questions first raised by Calabi. But, more specifically, it will also help us remember Calabi’s personal role in the story, both as Xiuxiong Chen’s thesis advisor, and as the mathematical grandfather of Chen’s student Song Sun.

CL: To begin, Gene, before we get to mathematics, could you say a little bit about your childhood and how you came to the United States?

EC: I grew up in Milan, Italy. My father was a lawyer. And he realized early on that I was gifted in mathematics. I remember when I was in first or second grade trying to memorize the multiplication table. My father taught me what a prime number was, and he told me, "your job is to find the law—how prime numbers succeed one another." And it was a standard question to me: "have you found the law of prime numbers?"

I went to public school in Milan, through what you might call tenth grade. I left when I was about 15, with my family, and we spent a year in France waiting for our American visas. This was 1938-1939, just before World War II broke out.

CL: So you had already been through the horror of Mussolini’s racial laws and so forth?

EC: Yes. It had just begun in 1938. My father had been getting alarmed and he started planning a possible exit from Italy around 1936, at the end of the Ethiopian war and the breakout of the Spanish Civil War, in which Italy and Hitler were allies. And when the racial laws came out he decided there and then, overnight, that he had to put the family safe. And, so, we eventually came here in the spring of 1939.

CL: Well done. And how old were you when you got to the United States?

EC: Sixteen. And I got admitted to MIT right away. It was a various "quirk" of scheduling—I had skipped a year both entering and another one exiting France. I majored in chemical engineering at MIT, but by the time I graduated I had decided to switch to mathematics. I applied for graduate school at both Harvard and Princeton in 1947. I was admitted to both, but at Princeton they offered temporary housing for graduate students so I went there.

CL: (Laughs) Important decisions are often made on the flimsiest basis, right?

EC: Oh yes.

CL: But you do have to have a place to live.

EC: I also spent two terms at the University of Illinois. That was my real start in pure mathematics. In 1947 for the winter and spring terms. Then that summer I moved to Princeton.

CL: Did you start working with Salomon Bochner immediately?

EC: About a year in—1948.

CL: So Bochner was the person that knew something about differential geometry. In particular, he worked on Ricci curvature and he proved an important theorem about harmonic forms. He seemed to be very skeptical in that article about the Hodge-de Rham theorem. He talks about harmonic forms but he doesn’t talk about how they’re related to topology at all.

EC: That I learned a little later. I was strictly studying...
differential geometry and the problem of selecting metrics—the manifolds of many possible metrics—and whether there are any problems about the function space of all metrics. Nonlinear analysis was still at its very infancy at the time. But it was the geometrical aspects that attracted me, and Kähler manifolds seemed to be the area to work in.

**CL:** I guess Bochner also started working on Kähler geometry not very long after his paper on harmonic one forms. But he always refers to them as "so-called Kähler metrics." He apparently knew that Kähler had been a Nazi and was very unhappy with the man over this.

**EC:** Well, I hadn’t noticed that. I had met Kähler when I just finished my doctorate in 1950, at the first International Congress of Mathematicians. I spoke with him briefly. My thesis was on Kähler metrics—the embedding problem. And I invented the word 'diastasis' in my thesis: the distance function. The normalized potential for Kähler metrics that works in the analytic case only.

**CL:** In 1954, you spoke at the next International Congress in Amsterdam, I believe? And that was when you first announced your entire program about representing Kähler classes on compact Kähler manifolds?

**EC:** Yes. I also wrote the first paper on the so-called generalization—on the theorem on the hessians, on real numbers—complex functions. At my first job at Louisiana State University, I bought a book on affine differential geometry, by Blaschke. And I was fascinated by it.

**CL:** So this work on real the Monge-Ampere equation—was this before or after you started thinking about the complex Monge-Ampere and Ricci flat Kähler metrics?

**EC:** Simultaneous. It was a step toward it. I was motivated by the other one but I also became interested in Affine differential geometry on its own right. And in fact, my current interest as it is—or at least pretends to be, at my age I can’t do much anymore—is still affine geometry.

**CL:** Still it’s quite amazing that you’re still doing mathematics. I saw you gave a very nice talk a couple of years ago. So how old are you now?

**EC:** 96

**CL:** 96. And still at it. That’s wonderful.
**EC:** The point is that you don’t learn during the course, you learn after, when mulling over the course. That has been my experience at least.

**CL:** Your paper on the Calabi conjecture is an amazing paper. It’s very, very impressive. But apparently you sent this to André Weil right? You must have been thinking that he was the expert on K3 surfaces?

**EC:** Well I asked him whether it was of any interest because I knew very little about algebraic geometry at the time. And he answered me very quickly and he said "how do you prove it?"

**CL:** He was a very brilliant man but not known for generosity. He was a very smart guy who liked to show that he was the smartest guy in the room.

**EC:** Oh yes. I was intimidated by him, actually.

**CL:** So you were Bochner’s student. And you had just given a talk at the Lefschetz Festschrift. This makes me wonder... I’ve heard all of these stories about how Bochner basically would not talk to Lefschetz. I’ve been told in particular Bochner did not want to be in the same room as Lefschetz.

**EC:** That’s right. When we had invited speakers, Lefschetz liked to get the students acquainted with the speakers, so he encouraged them to have a reception for the speakers at the graduate college. And the usual routine was that Lefschetz would come very early. And leave early. And then we’d call Bochner.

**CL:** So it’s a mystery that they were both very major mathematicians.

**EC:** They respected each other. I mean, at least I’ve heard Bochner quoting Lefschetz. The other way around, I did not follow Lefschetz too closely, but I think it happened.

**CL:** There’s certainly many results proved by later mathematicians that use ideas from Lefschetz combined with ideas from Bochner. So, for the benefit of our audience, it might be good to review just a little bit about the statement of what’s now called the Calabi-Yau theorem. That if you have a compact Kähler manifold then if you specify any volume form, provided it has the right integral, that you can represent, in a given Kähler class, you could find a unique metric with that volume form. And then this has the consequence that if the first Chern class of the Kähler manifold is zero, you can prove that there is a unique Ricci flat Kähler metric in each Kähler class. So, in your paper in the Lefschetz volume you give a truly beautiful geometric proof of the fact that the solution, if it exists, is unique. And this is just a beautiful argument. Basically, a maximum principle argument.

**EC:** Sure, it’s the Bochner principle.

**CL:** I definitely think that your paper is still worth reading because the uniqueness is so beautifully explained there. And of course, as it turned out, in terms of proving existence, you had one of the key ideas of the continuity method. But in terms of actually showing that the set of parameters for which you have a solution of the perturbed equation is closed, you needed other ideas and that’s only solved by Yau in the 1970s.

**EC:** That’s right. That’s another dramatic episode because when he first announced it, he had earlier thought he had the counterexample. And that was wrong. He recognized it but then he announced the proof shortly after, maybe less than a year. There was a great deal of excitement. We had to hear the details, so we had arranged a meeting as soon as we could. The meeting took place on Christmas day in Nirenberg’s office in New York. We met there in his office and heard the first proof. Which I did not understand.

**CL:** So there’s a $C^0$ estimate which is done by iterating $L^p$ spaces. But there’s also sort of a key $C^1$ estimate that’s based on your earlier work in affine geometry. Did he discuss that in the same lecture?

**EC:** Yes he quotes it.

**CL:** You told me once that that was the first paper where you proved something with a priori estimates, right?

**EC:** That’s right. It was a celebration of the first understanding of analysis.

**CL:** So, with respect to your work on extremal Kähler metrics...Well actually one odd historical thing that some people even in the field may not know... There have been a lot of papers on Kähler-Einstein metrics with nonzero scalar curvature. And they have often put in the title that this is a proof of Calabi’s conjecture. Whereas you didn’t actually explicitly say that, although it follows from your assertions about constant scalar curvature.

**EC:** Oh yes. Well I realized only later that constant scalar curvature is obstructed in some manifolds.

**CL:** When did you first realize that?
EC: When the paper by Futaki appeared.

CL: Oh I see. So, you’d had these concerns about holomorphic vector fields - It’s there in your first article about constant scalar curvature Kähler metrics. You assume from the beginning that you’re on a manifold which supports no holomorphic vector fields, but you don’t say why that’s an important fact.

EC: Oh yes it was of interest to me as a variational problem. And then the first examples of extremal metrics in Ricci curvature is not constant. I even wrote a short paper announcing it.

CL: It’s a fairly long paper that’s in Yau’s conference volume. And there was a seminar on differential geometry and it’s a very beautiful article where you discuss the general variational problem, show what the Lagrange equations are, and then produce solutions on blow-ups. For example, CP2 blown up at a point supports solutions in every Kähler class, which have non-constant scalar curvature. When did you actually find those solutions? Was that just in the process of writing that paper?

EC: Yes. In the process, in the early 1980s.

CL: So those are now usually called extremal Kähler metrics, although it was not shown that they were minima for a long time. You had given a beautiful proof in the constant scalar curvature case that actually if you have a solution it is the minimum of the functional. It was, I think, your student Xiuxiong Chen that first proved that they were always minimizers in the general case.

CL: I’m just thinking back. You really made great strides in Kähler geometry as a branch of Riemannian geometry in the ’50s, ’60s, ’70s and ’80s. But back in the 1950s how well did people really even understand what a Kähler metric was?

EC: Well I understood it from the Bochner lectures. We asked him to give a course in differential geometry for the first time in my second year of graduate school, 1948-1949. And he defined it there.

CL: In particular it turns out that Kähler geometry is an example of Riemannian geometry of special holonomy. And that fact seems to have just been ignored by many people on the kind of algebro-geometric end of things.

EC: Well yes, it was really a remarkable discovery but it took years to focus from there—from its first announcement by Kähler.

CL: My colleagues Xiuxiong Chen and Simon Donaldson were kind enough to provide some questions that I should ask. One interesting question that Simon raises is that in some of your early papers you were interested in non-Kähler complex manifolds, in particular with Eckmann. You found a beautiful set of examples of complex structures on products of spheres which you know are on manifolds that certainly can’t admit Kähler metrics because their second cohomology is trivial. Have you followed these areas of non-Kähler complex geometry at all?

EC: No, just those questions that are on my mind, if there are any more examples other than the usual. Perhaps one being, after Milnor’s discoveries, whether you could also have twisted spheres?

CL: Well questions about complex structures on the sixth sphere are one of those annoying things that just won’t go away. It’s unfortunately one of those problems that is basically still quite out of range of any technology we have, and may always be.

EC: Yes, I’ve been bothered by that. But the obstruction to complex structures is basically unknown. Unless you have an almost complex structure. Obstruction to integrability.

CL: Another very interesting general question that Simon Donaldson proposed was, “when did you see analysis starting to have a major impact in differential geometry?”

EC: From the correspondence I had with André Weil.

CL: That’s when you realized that it was an essential thing?

EC: There was a problem. It was fundamentally analysis. I think that mathematicians very often what
they do at a later age was originally in their mind much earlier.

**CL:** Maybe with 20/20 hindsight though sometimes you know your ideas are so confused when you’re young.

**EC:** Well I know I’m certainly confused when learning things. Learning is a confusing process and the real learning takes place after you’ve sort of digested the information. Learning is a digestive process, in a creative way.

**CL:** So in your own case—we mentioned before this article on extremal Kähler metrics that came out in the 1980s. In a way, you’re writing about things that you had started to think about years before but actually being forced to sit down and write out the details you’ve discovered new things.

**EC:** That’s right. Well that’s the digestive aspect.

**CL:** So, in the course of your career you’ve seen these enormous changes in the way that mathematics is communicated. Looking back it seems like the number of mathematicians, particularly mathematicians that did something that would be relevant to your own area, would have been relatively small in fact, where you would have probably known almost everybody.

**EC:** I used to.

**CL:** So I mean mathematics was usually disseminated by mail and telephone. And in particular, anything that was in the direction of a collaboration, or dependent upon, had to be done in those ways. But also, you could only exchange ideas with people if you already knew them.

**EC:** That’s why we went to meetings. Meetings were useful. I think they still are.

**CL:** Some of your early work was on complex manifolds and you were asking questions that were alien to algebraic geometers. Were there ever any meetings where you would meet people that were interested in these topics?

**EC:** Very few. The only one I knew was Bochner and his other students.

**CL:** So when you collaborated with Eckmann. How did you meet Eckmann?

**EC:** Heinz Hopf was visiting Princeton, and I told him about the construction. And Bochner balled me out for doing so. But Hopf told me that Eckmann had just done the same thing. And so, he put us in touch. I met him later, shortly after. We decided to write jointly by correspondence.

**CL:** When you look back, was there a certain period of time when you really thought that what you were doing was particularly fun and exciting?

**EC:** No. I was just finding my way.

**CL:** I’m just wondering though, you’re now you at a point in your career when your name is famous. People probably don’t realize Calabi is a person. Calabi-Yau is a phenomenon. You were telling me earlier that there was a dance performance called Calabi-Yau in New York. And so, it’s kind of entered in popular culture. Do you ever have the experience that people want to come up and ask you about physics or something like that, or string theory?

**EC:** No. I’ve heard about them, of course. But no, my favorite slogan to explain mathematics to the layman is “it’s quintessentially science fiction.” I never quite understood the implications. But it was a piece of luck—unexpected.

**CL:** Well but on the other hand sometimes when you just do what comes naturally in mathematics it pays off, right?

**EC:** Yes. That’s my luck.

**CL:** Well, Gene it’s been wonderful interviewing you, I’m so glad that we could do this.

**EC:** Well, as I mentioned earlier it’s an ego trip for me.

**CL:** It’s a well-deserved one. I think that many people will find this interview interesting and I’m glad we were able to do it. Thanks a lot.

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*Illustration: Andrew J. Hanson / Color imaging by Lorraine Walsh*
A Dialogue Between a Struggling Student and his Advisor, Eugenio Calabi

By Xiuxiong Chen, Professor of Mathematics, Stony Brook University

I met Professor Eugenio Calabi in the Fall of 1989, a couple of months after I arrived on the University of Pennsylvania campus. We hit it off quite nicely, as he was a zealous lecturer and loved to go to the blackboard, while I was an eager listener and loathed to go in front of people, for fear that they might find out that I was not as good as my transcripts might have indicated. In retrospect, he must have found out early on, in his infinite wisdom, that I didn’t understand much of what he was talking about, but that apparently didn’t dampen an iota of his enthusiasm for talking to me. In my recollection, we spent 4-5 hours each day “talking” mathematics to each other—be it in his office, in the mailroom, or in our tea room. This is extraordinary luck for any graduate student to be blessed with. I endured growing pains for a long period of time after my graduation and Professor Calabi was with me during the whole process. His wit, humor and focus on the fundamentals have helped me regain balance in shaky times, and keep cool in sunny times. I cherish his invaluable teachings and wish to share these with the community. What follows are a few dialogues we have had over the years which hopefully will help elucidate the lasting wisdom of Eugenio Calabi.

Like any ambitious young person, I was curious about how to be famous:

XC: How many papers do I need to write in order to be famous?
EC: One.

Eugenio Calabi stresses the importance of being original and doing what you love:

XC: It seems to be relatively easy to write papers on a trendy subject?
EC: Be original and follow your own heart and intuition.

XC: How do I be original?
EC: Read classical papers which have withstood the test of time. Like a dog, smell the smell miles away before anyone else has noticed.

I often complained about the hardship of getting my papers published:

XC: Will being in a famous university help publish my papers?
EC: Maybe. Do you want your address to become famous because of you, or you to become famous because of your address?

When I was relatively young, I was shocked to find out that a friend had “cheated” on me. It was a tough pill to swallow, but Calabi steered me away from bitterness:

XC: A friend has stolen my idea. What should I do?
EC: Congratulations, now your idea is worth stealing!

XC: ???
EC: Will you have new ideas?
XC: Yes.
EC: Will you allow him to steal again?
XC: No.
EC: Then you win since you continue to have new ideas and he cannot continue to steal from you.

For many, including myself, going to ICM is an ego trip. Calabi helped put it into perspective:

XC: I was invited to ICM 2002.
EC: Congratulations, it is important to you personally!
XC: Just personally?
EC: Yes. We will know if it is important to geometry in 10 years. Think about who you remember among ICM speakers in differential geometry in 1994 or earlier.

Ever since my student years, Eugenio Calabi has stressed to me over and over again that it is mathematical problems, not he, that is my teacher. I didn’t quite understand initially, but I have gradually gained an appreciation and become a faithful follower of his philosophy. Indeed, with limited talent myself, I was blessed with many extremely gifted students and hence opportunities to put his philosophy into practice. We find good problems together and learn mathematics from the problems we work on. As a side benefit, I have learned, though with some struggles, quite a bit from my students over the years. Calabi is correct that problems and gifted students are my teachers. This is the biggest secret of my moderately successful career and I wish to share it with future generations.
The Inscribed Rectangle is contributed by Sergei Maslov, Professor of Bioengineering and Physics, Bliss Faculty Scholar University of Illinois at Urbana-Champaign.

The solution will be published in the forthcoming SCGP News Volume XIV.

The Inscribed Rectangle

Prove that any non-self-intersecting loop on a plane has at least one inscribed rectangle. In other words, prove that one can find a set of four points on this curve that are the vertices of a rectangle. Hint: this problem has an elegant solution involving topology. Intriguing fact: a more restrictive problem to prove that any such loop has an inscribed square has not been solved. It is known as the Toeplitz’ conjecture or the square peg problem.
Simple Can Be Harder Than Complex: The Solution

Here is a least a partial answer to my question. Let’s start by solving the problem in an obvious physical way by writing the relevant 4-vectors in terms of the incoming and outgoing energies of particle 1, \( E \) and \( E' \) (primes will indicate outgoing here and below):

\[
P_1 = \left( E, \sqrt{E^2 - m_1^2} \right) \quad P_2 = (m_2, 0) \\
P_1' = \left( E', (\cos \theta \hat{x} + \sin \theta \hat{y}) \sqrt{E'^2 - m_1^2} \right)
\]

Then we can use

\[
(P_1 + P_2 - P_1') \mu \left( P_1 + P_2 - P_1' \right)_\mu = m_2^2 
\]

and write

\[
m_1^2 - EE' + \cos \theta \sqrt{(E^2 - m_1^2)(E'^2 - m_1^2)} + m_2(E - E') = 0
\]

Now we can solve this for \( \cos \theta \)

\[
\cos \theta = \frac{EE' - m_1^2 - m_2(E - E')}{\sqrt{(E^2 - m_1^2)(E'^2 - m_1^2)}}
\]

Now we can do the obvious thing to find the maximum \( \theta \). Find the value of \( E' \) for which the derivative of \( \cos \theta \) with respect to \( E' \) vanishes, substitute this value into (4), work very hard to simplify and find the simple result

\[
\cos \theta_{\text{max}} = \sqrt{1 - \left(\frac{m_2}{m_1}\right)^2}
\]

There are really two questions. Can we make it obvious that the result is independent of \( E \) without actually finding the explicit result? And can we find a simpler derivation? I am not sure that I have an answer to the second, but here is a nice answer to the first.

It seems clear that to avoid ratios of \( E/m \), we should use rapidity instead of energy, so write

\[
P_1 = m_1 \left( \cosh \eta, \hat{x} \sinh \eta \right) \quad P_2 = (m_2, 0) \\
P_1' = m_1 \left( \cosh \eta', (\cos \theta \hat{x} + \sin \theta \hat{y}) \sinh \eta' \right)
\]

Then (4) becomes

\[
\cos \theta = \frac{\cosh \eta \cosh \eta' - 1 - (\cosh \eta - \cosh \eta')m_2/m_1}{\sinh \eta \sinh \eta'}
\]

Now here is the trick. Look at the variable

\[
u = \frac{\cosh \eta - \cosh \eta'}{\sinh \eta \sinh \eta'}
\]

and notice that in terms of \( u \), (7) becomes

\[
\cos \theta = \sqrt{1 + u^2 - u \frac{m_2}{m_1}}
\]

Because (9) doesn’t depend on \( E \) but only on \( m_2/m_1 \), it is obvious that the maximum \( \theta \) is independent of \( E \). Does this give us a simpler derivation? I am not sure! Certainly, the last step where we find \( \theta_{\text{max}} \) from (9) is much simpler. But the key step is realizing that the substitution (8) is useful, and it is hard to compare the “simplicity” of this kind of inspiration with “simply” doing the straightforward but tedious calculus. This kind of apples and oranges comparison is one of the things that makes the math of physics so much fun.
ART & SCIENCE EXHIBITIONS

Last spring, the Simons Center was pleased to host the solo exhibition *Kolam: An Ephemeral Women’s Art of South India*, featuring photographs and video by Claudia Silva. The kolam is a geometrical pattern drawn on the ground with white rice flour, chalk, or colored powders. A custom common in many South Indian states, it is considered an auspicious symbol located at the entrance of a household.

This drawing ritual is practiced every morning before sunrise by millions of women in the South Indian state of Tamil Nadu. The transient designs are walked and rained on throughout the day, eventually disappearing. The activity begins anew the next dawn in a daily tribute to welcome all beings into one’s home.

On display in the gallery from March to July were photographs of various kolam schemas, including the continuous loop pattern characterized by one or more curved lines winding around a grid of dots, considered most traditionally Tamil. Silva also pictured elder female household members—adorned in exquisitely colored saris—patiently teaching children the art of drawing kolams. Thus passing on the practice to a new generation.

This time-honored tradition is considered ethnomathematical, a field of study that examines the mathematical accomplishments of different (typically nonwestern) cultural groups. Marcia Ascher,  

Professor Emerita of Mathematics at Ithaca College, notes that while cultural practices are often mathematically abundant, it is unusual for such cultural practices to be accepted and studied in-depth academically, as has been the case with kolam (Ascher, 2002). The historic roots of the kolam practice include studies tracing these threshold designs to approximately 2500 BCE in the Indus Valley Civilization (Pakistan and northwest India today). (See sidebar for mathematical connections.)

The artist Claudia Silva is a photographer and videographer. She developed *Kolam: An Ephemeral Women’s Art of South India* during travels to Tamil Nadu from 2012 to 2019. This work is part of her audiovisual research on the transmission of traditions in different cultures and their anthropological value.

Visual imagery and spatial reasoning are inseparable in the kolam activity. Reproducing the kolam from memory involves manipulation and rotation of the pulli (points) and kambi (curvilinear lines), and the ability to see geometric patterns and symmetry. The kolam creation is especially important for girls in India who learn complex spatial relationships through apprenticeship from their female relatives and community members. Spatial skills are developed through frequent exposure to certain tasks.

The creation of kolam designs requires algebraic as well as spatial reasoning. Many kolam designs are recursive families: a pattern can be generated in arbitrary sizes, by either extending the basic unit in a uniform way, or merging multiple copies of a smaller design to form a more complex one. The family of designs known as Anklets of Krishna (Asher, 2004, p. 173), shown in the figure above, is an example of a recursive family of kolam: design (b) consists of four copies of design (a), design (c) consists of four copies of design (b), and so on. The process can continue indefinitely, as the basic unit (a) can be translated repeatedly to obtain the more complex designs (b) and (c). The practitioner only needs to remember the basic design, and how to connect copies of the previous design to form the next one. Through this process, she is engaging in algebraic reasoning.

The solution to this mathematical problem and the creation of the Anklets of Krishna design are based on one of the foundational processes of algebra, if not all of mathematics — that of recognizing and generalizing patterns.

Other exhibitions of Silva’s kolam photographs include the Institute of Mathematical Sciences (ICMAT) Madrid, University of Porto, and Wolfson College, Oxford University. Originally from Bogotá, Colombia, she currently lives in Madrid, Spain.

**MUSIC**

Every summer the Art and Outreach Program hosts four concerts for the Simons Center Summer Workshop. This year, the series began with Stony Brook’s Three Village Chamber Players performing compositions from one of the most richest and distinctive eras in music history—the Baroque period. Playing the harpsichord was Dr. Joyce Chen. Alison Rowe played baroque cello, and Anna Tsukervanik, baroque violin. The trio played Vivaldi and Bach, as well as lesser-known baroque composers. All of the musicians are affiliated with Stony Brook University as either graduates or students enrolled in the Doctor of Musical Arts degree program.

The second concert was a jazz trio with an exciting surprise guest. Saxophonist Chet Doxas and bassist Dave Ambrosio invited the legendary jazz drummer Billy Hart to join them for the evening. Hart’s illustrious career includes collaborations with luminaries such as Miles Davis and Herbie Hancock. The group performed a selection of music in celebration of American popular song and jazz classics, adeptly proved what makes jazz so unique with excellent improvisation, syncopation and rhythm.

Grammy award winning performer Andrew York was welcomed back to the Simons Center for the next concert. Internationally acclaimed and one of today’s best-loved composers for classical guitar, York’s compositions blend the styles of ancient eras with modern musical directions. A highlight of the evening was York’s suite *The Equations of Beauty* in six movements, each named after a mathematical constant.

The Canadian musician Emmanuel Vukovich closed the series with a beautiful classical violin program. His masterly performance included Sonatas and Partitas for solo violin (BWV 1003) by Bach. Among his many accolades, Vukovich is the grand-prize winner of the Fischoff National Chamber Music Competition as first violinist. He is currently a candidate for the Doctor of Musical Arts degree at Stony Brook University, and working with the Emerson String Quartet.

**UNIVERSITY GALLERY TOURS**

The Stony Brook University Art Crawl opened its galleries across campus once more for all on March 27th. An increasingly popular event, the free tour commenced at the Simons Center Gallery. The artist Claudia Silva was in the Simons Center Gallery to greet visitors and talk about her photography. It was a special treat for attendees to hear firsthand descriptions about the artwork. The tour continued their excursion to the University Libraries Special Collections, the Charles B. Wang Center, and a final destination at the Zuccaire Gallery with a warm reception hosted by the Staller Center.
ROUND TABLE FOR MATH AND SCIENCE SUMMER PROGRAMS

This workshop was hosted at the Simons Center in February and brought together organizers of pre-collegiate math and science summer enrichment programs. The conference fostered connections among top programs, allowing the participants to share ideas, seek feedback from experts, and discuss opportunities for continued cross-program collaboration. There were 49 participants, including the leaders of 22 different programs, both from the U.S. and abroad. The workshop served as the first step in a long-term project to create a support network in which established programs can advise and support one another as well as the organizers of new programs, addressing the need for more access to research-oriented STEM education for talented students.

Over the course of three days of the workshop, many different topics were addressed including math and science curriculum and activities, as well as research with high school students; organizational structure, leadership, and transitions in the programs; staff recruitment, training, and retention; and funding and fundraising.

The topics were presented in a variety of formats: short lectures, panels, and roundtable discussions. The lectures and panels included presentations by program directors sharing best practices (such as Daniel Zaharopol, founder of BEAM, speaking on Recruiting and Supporting Students from Marginalized Communities) and by outside experts addressing specific topics of interest (including Joel Spencer, on behalf of the AMS Epsilon Fund, and Chris Peterson, on behalf of MIT Admissions). The roundtable discussions invited open dialogue on questions such as the admissions process, academic integrity issues, and supporting girls in pre-collegiate programs, as well as opportunities for participants to seek advice on logistical questions like insurance, visas, and legal compliance.

SCHOOLNOVA

Last May, the Simons Center for Geometry and Physics along with the Department of Physics and Astronomy at Stony Brook University hosted SchoolNova’s third annual Math and Science Festival, which is free and open to the community.

The festival celebrates the intersection of math and science and their presence in our day-to-day lives. On May 5th, the Simons Center and the ground floor of the Physics building were turned into a math and science playground, where children and adults enjoyed numerous physics, chemistry and biology stations, as well as exciting math games and activities that they may have never seen before. For example, students conquered fun challenges such as engineering skyscrapers, blasting bottle rockets, and creating stunning spirographs. Many stations
also combined math—patterns, angles, and lines of perspective—with art.

Most stations were run by SchoolNova’s teachers and TAs, with help from parents, SigmaCamp, and Advanced Academic Programs of Roslyn.

SchoolNova is a local enrichment program that has served the community since 2004. It prides itself on going beyond classroom education in organizing events such as the Math and Science Festival that enrich not only SchoolNova students, but the entire community.

To learn more details about the festival and see announcements for future events, visit www.schoolnova.org/nova/festival

SIGMACAMP

SigmaCamp is a one-week residential summer STEM program for middle and high school students that aims to foster scientific inquiry and exploration through interactive experiments. University professors and researchers team up with graduate and undergraduate students for a multidisciplinary science experience. Students attend lectures by distinguished scientists who make advanced concepts accessible to young audiences. Speakers from past years include many guests and affiliates of the Simons Center of Geometry and Physics, such as Robbert Dijkgraaf, Michael Douglas, Maxim Kontsevich, Nikita Nekrasov and Zohar Komargodski. The wide range of courses offered cover physics of radioactivity, number theory, chemistry of scent and color, DNA barcoding, and computer vision. These diverse programs, along with an informal atmosphere, enable campers to explore, ask questions, and engage in discussions with active researchers in the field. Over 70 faculty, lecturers, and counselors volunteer their time each year to make SigmaCamp possible and are passionate about science, teaching, and community building.

While SigmaCamp is foremost a science camp, it is a camp nonetheless—with recreational activities such as swimming, sports, arts and crafts, and talent shows. Taking place in rural Connecticut, the location and setting are essential components for encouraging a sense of community. Interactions grow into real-life relationships, often resulting in academic collaborations. Several scientists, who originally met as faculty at SigmaCamp, have written papers together and created successful grant applications for further joint research. Current and former students organize discussions and meetings with each other outside of camp, where they not only socialize but often collaborate on school projects, and scientific endeavors beyond the classroom. Campers partner with the faculty and their colleagues to conduct research year-round and coauthor publications. Nearly all former campers are eager to return as Sigma counselors, to share their personal and academic growth as part of Sigma’s community. Returning from Sigma, students are energized to learn—both in school and independently. To maintain the learning momentum during the academic year, Sigma runs the Problem of the Month program, which is a free multidisciplinary STEM competition open to everyone in tenth grade or younger, regardless of the country in which they live. Each month, participants are offered a set of original problems created by the Sigma staff, enabling them to draw upon experiences and lessons learned during camp. As one campers adequately paraphrased, “Sigma is a week of summer that lasts all year.” Or perhaps a lifetime.

For more information visit: www.sigmacamp.org/2019

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### 2020 Upcoming Outreach Events

**Spring/Summer Art Exhibition**  
March 26–August 7, 2020

**Della Pietra Lecture Series by Dr. Elena Aprile**  
March 31–April 3, 2020

**Art Crawl – University Gallery Tours**  
April 2, 2020

**Science Playwriting Competition Staged Readings**  
April, 2020

**M.C. Escher, A Mini-Retrospective Art Exhibition**  
September 8–December 15, 2020

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SigmaCamp 2019  
Photo: Lev Bershadsky and Natalia Iлина
# 2020 Upcoming Programs and Workshops

## Programs

- **Lighting New Lampposts for Dark Matter and Beyond the Standard Model**: February 24 – April 8, 2020. Organized by Ranny Budnik, Rouven Essig, Maxim Pospelov

## Workshops

- **Floer Homology in Low-Dimensional Topology**: April 6–10, 2020. Organized by Matthew Hedden, Tom Mrowka, Olga Plamenevskaya, Jacob Rasmussen
- **Supersymmetric Black Holes, Holography and Microstate Counting**: April 20–May 1, 2020. Organized by Cyril Closset, Leopoldo Pando Zayas, Luigi Tizzano, Chiara Toldo, Alberto Zaffaroni
- **Many Faces of Renormalization**: June 1–5, 2020. Organized by Dzmitry Dudko, Mikhail Lyubich, Konstantin Khanin

For the most up-to-date schedule, please visit scgp.stonybrook.edu/science

The SCGP welcomes proposals for scientific programs and workshops. To submit a proposal, please visit: scgp.stonybrook.edu/science/call-for-proposals

For possible sabbatical stays, please contact: Alexander Abanov at aabanov@scgp.stonybrook.edu
The Simons Center Welcomes New Research Assistant Professors

Physics

Mykola Dedushenko received his undergraduate degrees in physics and mathematics in Ukraine and Russia: physics from Kyiv National University, and math from the Independent University of Moscow and the Math Department of the Higher School of Economics (Moscow). He pursued his PhD in physics at Princeton under the supervision of Edward Witten. Upon getting his degree, he moved to Caltech for a three-year postdoctoral position at the Burke Institute of Theoretical Physics and is now joining the SCGP. Dedushenko is interested in a wide range of topics in theoretical and mathematical physics, both of more physical (understanding dynamics of quantum field theories) and more mathematical flavor (extracting new mathematical structures from quantum field theory and string theory, understanding foundations of QFT). So far, he has mostly worked on exact results in supersymmetry and applications of QFT and string theory to topology, but he is eager to expand this list with new items.

Kantaro Ohmori graduated from the University of Tokyo in 2016, under the encouraging advice of Yuji Tachikawa, and worked at the Institute for Advanced Study at Princeton since 2016. His general interest of research is in quantum field theory and related topics, including string theory, quantum gravity, and condensed matter theory. One of his recent focuses is the symmetry and quantum anomaly of quantum field theory and its application. It has become clear that thorough investigation of these kinematic constraints can have a significant implication on the dynamics of various quantum field theories, including Yang-Mills theory and QCD. Ohmori is trying to expose the full power of these methods and find interesting applications.

Mathematics

Rodrigo Barbosa was born in Rio de Janeiro, Brazil. From 2014 to 2019, Barbosa studied at the University of Pennsylvania under the mentorship of Tony Pantev, receiving a PhD in mathematics in the Spring of 2019. Broadly speaking, Barbosa’s research is about applying string dualities to moduli problems in algebraic and differential geometry. In his thesis, he proposed a deformation family for certain G2-manifolds via unfolding of singularities and provided algebro-geometric descriptions of the G2 moduli space using mirror symmetry and certain analogs of Higgs bundles. More recently, Barbosa collaborated with physicists M. Cvetic, J. Heckman, C. Lawrie, E. Torres and G. Zoccarato to construct T-brane solutions for M-theory compactified on G2-manifolds. At SCGP, he plans to continue his work on G2-manifolds, Higgs bundles and mirror symmetry, and collaborate with other members to generate new ideas in geometry and string theory.
Catherine Cannizzo received her B.A. and Master of Mathematics from Cambridge University. She earned her PhD in mathematics in May 2019 at the University of California, Berkeley under Professor Denis Auroux. Her thesis was entitled “Homological mirror symmetry for the genus 2 curve in an abelian variety and its generalized Strominger-Yau-Zaslow mirror.” She is interested in mirror symmetry and symplectic geometry, homological mirror symmetry in particular. She plans to expand the types of symplectic manifolds which can be equipped with Fukaya categories and match them with B-model mirrors. Other work experience in graduate school includes co-organizing Kylerec 2018 and WiSCon 2019.

RTG (Jointly with the Mathematics Department, SBU)

Alena Erchenko obtained her PhD in mathematics at Penn State University in May 2018 under the supervision of Anatole Katok and spent the 2018-2019 academic year as a Zassenhaus Assistant Professor at Ohio State University. She is primarily working on the flexibility program in dynamical systems which was put forward in her joint work with Anatole Katok and studied further by herself and her collaborators in other settings. The aim of the program is to study natural classes of smooth dynamical systems and find constructive tools to freely manipulate some dynamical data inside a fixed class. Flexibility is a large area of dynamics which requires a combination of tools from various fields. During her time at the Simons Center and Stony Brook she is planning to consider new settings in dynamics, geometry, and topology to study from the flexibility and rigidity points of view.

Andrew Hanlon completed his PhD in mathematics at UC Berkeley in 2019 under the supervision of Denis Auroux while spending the last year on exchange at Harvard University. His research interests are in symplectic topology and homological mirror symmetry. In his thesis, he investigates certain aspects of Fukaya-Seidel categories of Laurent polynomials that are mirror to coherent sheaves on toric varieties. He is currently pursuing a further understanding of homological mirror symmetry in that setting as well as pushing the framework developed in his thesis beyond the toric case. While at the Simons Center and Stony Brook, Hanlon hopes to expand his research into other areas of symplectic geometry, particularly those involving the symplectic characteristics of singularities.

Kevin Sackel received his PhD from the Massachusetts Institute of Technology under the supervision of Emmy Murphy. He is interested in symplectic and contact geometry, in particular the ways in which flexible phenomena, typically via h-principles, and rigid phenomena, typically via pseudoholomorphic curves and related ideas, permeate these subjects, producing a stark dichotomy of results. His thesis describes the basic theory of handle decompositions for contact manifolds and is heavily related to open book decompositions and Weinstein manifold theory. As a Long Island native and Stony Brook alumnus, Sackel is excited to be back “home.”
Dear Friends and Members of the SCGP,

Since the launch of our Friends of SCGP program in early 2019, the Simons Center for Geometry and Physics is proud to welcome a number of new friends. We thank these members and donors for their generosity and commitment to advancing education in the sciences through lectures and cultural activities. We would like to take this time at the end of the year to share some of the special activities these donations helped make possible.

In May and August, we welcomed Della Pietra lecturers Charles Kane and Nobel Prize winner Adam Riess for a series of lectures and special events. Last summer, the Simons Center hosted the annual 4-week music series with performances that ranged from jazz to classical. These concerts are open to the entire community. There was also a special lecture that gave a brief history of the many accomplishments of the Nobel laureates from Bell Labs. Friends of various levels received information and private invitations to these events, and a mailed copy of SCGP News. In December, we will close out the year with another public lecture and private event for friends with Manjul Bhargava, Fields medalist and number theorist.

In 2020 the Simons Center will host many notable lectures and events, including a Della Pietra lecture series with particle physicist Elena Aprile; staged readings of the winning plays from our science-playwright competition; a mini-retrospective art exhibition featuring the work of M.C. Escher; and a number of special events in conjunction with the 10th anniversary of the building inauguration. Join our Friends of SCGP program to be the first to receive news and private invitations to these activities and more. Sign up before 2020 to receive a one-time special thank you gift!

Visit our website for more information and to make your tax-deductible gift: www.scgp.stonybrook.edu/friends.

The Simons Center for Geometry and Physics is extremely grateful for the steady and generous support of the Della Pietra families, without which many of the above activities would not be possible. We would also like to extend our gratitude to Robert Lourie and the Bershadsky family for their support.

We thank you,

Luis Álvarez-Gaumé
Director, Simons Center for Geometry and Physics
Stony Brook University

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