IAS

The Institute Letter

Institute for Advanced Study Fall 2015

A Global Politics of Knowledge

Doing social science across different worlds

ANDREA KANE

The Summer Program brings together its participants for two-week sessions each summer for three years.

BY DIDIER FASSIN

Let us imagine a conversation between a literary scholar from Palestine interested in the reception of Ibn Ruschd's commentary on Aristotle, an anthropologist from Iraq examining the experience of exiles fleeing the war, an economist from the Ivory Coast assessing the impact of microfinance projects, a sociologist from Benin investigating gas smuggling across the border, a political scientist from Brazil analyzing clientelism in local elections, and a legal scholar from Chile studying anti-discrimination laws. This conversation did take place at the Institute for Advanced Study as part of the Summer Program in Social Science that was launched in September 2015. Other scholars involved in the program were conducting research on environmental conflicts in Buenos Aires, crack use in Rio de Janeiro, income inequality in Egypt, water shortage in rural Iran, corruption practices in the Cameroonian health system, debates over the age of sexual consent under South African law, and negotiations at the World Trade Organization—among other themes.

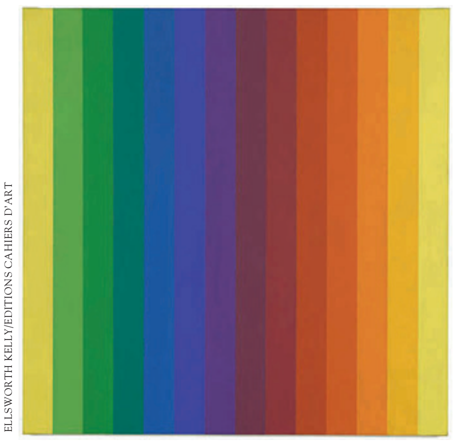
The idea of this special program was born from the observation that certain regions of the world are poorly represented among the Members who are selected each year to participate in the regular program of the School of Social

(Continued on page 21)

Ellsworth Kelly: Volume I

Cataloguing unexpected avenues of inquiry

BY YVE-ALAIN BOIS



ELLSWORTH KELLY/EDITIONS CAHIERS D'ART

Spectrum I *(1953)*

Ellsworth Kelly likes to recall the incident in which a child, pointing at the five panels of *Painting for a White Wall*, enumerated their colors from left to right and back. It was at this moment that the artist realized that what he had wanted to do in this painting was to "name" colors.

The idea that a juxtaposition of color rectangles was the visual equivalent of a suite of color names had two components, both related to an essential property of language, namely its infinite permutational capability. When the child enumerated the colors of *Painting for a White Wall* in both directions, he produced a permutation on what linguists call the syntagmatic level (in an enumeration, to take the example of the child's utterance, the sequencing of the terms is of no grammatical consequence: "black, rose, orange, white, blue" is as correct grammatically as "blue, white, rose, orange, black"—or, for that matter, "blue, rose, black, orange, white," or whatever word order). Investigating this aspect of the comparison between colors and linguistic units is what the artist set out to do in *Red Yellow Blue White and Black*, *Red Yellow Blue White and Black II*, and *Red Yellow Blue White and Black with White Border*.

The second aspect of the comparison concerns permutation on what linguists call the paradigmatic level: on this level, it is not a matter of changing the *position* of a given term within a set sequence but it involves the potential for replacing

(Continued on page 18)

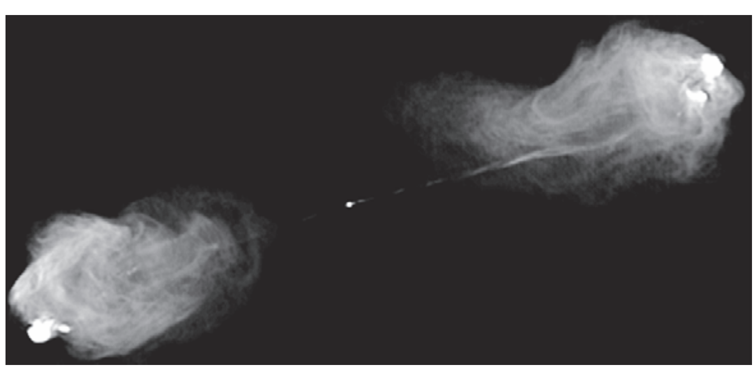
The Odd Couple: Quasars and Black Holes

A cosmic detective story

BY SCOTT TREMAINE

Black holes are among the strangest predictions of Einstein's general theory of relativity: regions of spacetime in which gravity is so strong that nothing—not even light—can escape. More precisely, a black hole is a singularity in spacetime surrounded by an event horizon, a surface that acts as a perfect one-way membrane: matter and radiation can enter the event horizon, but, once inside, can never escape. Remarkably, an isolated, uncharged black hole is completely characterized by only two parameters: its mass, and its spin or angular momentum.

Laboratory study of a macroscopic black hole is impossible with current or foreseeable technology, so the only way to test these



NATIONAL RADIO ASTRONOMY OBSERVATORY/R. PERLEY

Figure 1: A radio image of jets from the quasar Cygnus A. The bright spot at the center of the image is the quasar, which is located in a galaxy 240 megaparsecs away. The long, thin jets emanating from the quasar terminate in bright "hotspots" when they impact the intergalactic gas that surrounds the galaxy. The hotspots are roughly 70 kiloparsecs (or 228,000 light years) from the quasar.

predictions of Einstein's theory is to find black holes in the heavens. Not surprisingly, isolated black holes are difficult to see. Not only are they black, they are also very small: a black hole with the mass of the Sun is only a few kilometers in diameter (this statement is deliberately vague: because black holes bend space, notions of "distance" close to a black hole are not unique). However, the prospects for detecting black holes in gas-rich environments are much better. The gas close to the black hole normally takes the form of a rotating disk, called an accretion disk: rather than falling directly into the black hole, the orbiting gas gradually spirals in toward the event horizon as its orbital energy is transformed into heat, which warms the gas until it glows. By the

(Continued on page 14)

News of the Institute Community

Yve-Alain Bois, Professor in the School of Historical Studies, has received François Pinault's Pierre Daix Prize for *Ellsworth Kelly: Catalogue Raisonné of Paintings, Reliefs, and Sculpture, Volume One, 1940–1953* (Editions Cahiers d'Art, 2015), which contains exhaustive documentation and high-quality images of works and preparatory drawings.

Didier Fassin, James D. Wolfensohn Professor in the School of Social Science, et al., has authored *At the Heart of the State: The Moral World of Institutions* (Pluto Press, 2015), the result of a five-year investigation of the police, court system, prison apparatus, social services, and mental health facilities of France.

Jonathan Haslam, George F. Kennan Professor in the School of Historical Studies, has authored *Near and Distant Neighbors: A New History of Soviet Intelligence* (Farrar, Straus and Giroux, 2015), a comprehensive account of Soviet intelligence from the October Revolution to the end of the Cold War.

Brill Academic Publishers has published *Accusations of Unbelief in Islam: A Diachronic Perspective on Takfīr* (2015), edited by Sabine Schmidtke, Professor in the School of Historical Studies, et al. The book presents nineteen case studies of individuals or groups who used *takfīr* to brand their opponents as unbelievers.

Thomas Spencer, Professor in the School of Mathematics, and two Members in the School, Alexei Borodin (2001–02) and Herbert Spohn (1990, 2013–14), have received 2015 Henri Poincaré Prizes from the International Association of Mathematical Physics.

Edward Witten, Charles Simonyi Professor in the School of Natural Sciences, has received the American Physical Society's Medal for Exceptional Achievement in Research for discoveries in the mathematical structure of quantum field theory.

CONTENTS

Questions and comments regarding the *Institute Letter* should be directed to Kelly Devine Thomas, Editorial Director, via email at kdthomas@ias.edu or by telephone at (609) 734-8091.

Issues of the *Institute Letter* and other Institute publications are available online at www.ias.edu/about/publications/.

Articles from the *Institute Letter* are available online at www.ias.edu/about/publications/ias-letter/articles/.

To receive monthly updates on Institute events, videos, and other news by email, subscribe to *IAS eNews* at www.ias.edu/news/enews-subscription/.

The Lod Mosaic: A Spectacular Roman Mosaic Floor (Scala Arts Publishers, Inc., 2015), edited by Glen W. Bowersock, Professor Emeritus in the School of Historical Studies, et al., has been published to celebrate the opening of The Shelby White and Leon Levy Lod Mosaic Archaeological Center, created by Shelby White, Institute Trustee, to house the archaeological find.

The Holland Society of New York has awarded the Gold Medal for Outstanding Achievement in Science to Robbert Dijkgraaf, Director of the Institute and Leon Levy Professor.

Ian Agol, Distinguished Visiting Professor in the School of Mathematics, has received the 2016 Breakthrough Prize in Mathematics.

Behold the Black Caiman: A Chronicle of Ayoreo Life (University of Chicago Press, 2014), written by LUCAS BESSIRE while a Member (2012–13) in the School of Social Science, has received the Society for Cultural Anthropology's Gregory Bateson Prize, the Society for Latin American and Caribbean Anthropology Book Prize, and second place for the Victor Turner Award for Ethnographic Writing. LAURENCE A. RALPH, Member (2012–13) in the School, was honored as runner-up for the Gregory Bateson Prize for his work *Renegade Dreams: Living Through Injury in Gangland Chicago* (University of Chicago Press, 2014).

Patricia Meria Clavin, Visitor (2009) in the School of Historical Studies, has received the 2015 British Academy Medal for *Securing The World Economy: The Reinvention of the League of Nations, 1920–1946* (Oxford University Press, 2013).

The Association of Members of the Institute for Advanced Study has elected William E. Connolly, Member (1986–87) in the School of Social Science, and Robert B. Kusner, Member (1992–93, 1997) and Visitor (1996) in the School of Mathematics, to its Board of Trustees.

The 2015 Shaw Prize in Mathematical Sciences was awarded to two Members in the School of Mathematics, Gerd Faltings (1988, 1992–93) and Henryk Iwaniec (1983–84, 1984–86).

Three Members in the School of Natural Sciences, Raphael Flauger (2011–14), Leonardo Senatore (2008–10), and Yuji Tachikawa (2006–11, 2014), are among the recipients of the 2016 New Horizons in Physics Prize.

Kristen Rogheh Ghodsee, AMIAS Board President and Member (2006–07) in the School of Social Science, has received a Heldt Prize honorable mention for best book in Slavic and East European Women's Studies for *The Left Side of History: World War II and the Unfulfilled Promise of Communism in Eastern Europe* (Duke University Press, 2015).

Larry Guth, Member (2010–11) in the School of Mathematics, is among the recipients of the 2016 New Horizons in Mathematics Prize.

Joel Kaye, Member (2004–05) and Visitor (2010) in the School of Historical Studies, has received the American Philosophical Society's 2015 Jacques Barzun Prize in Cultural History for *A History of Balance, 1250–1375* (Cambridge University Press, 2014).

The American Physical Society has honored three Members in the School of Natural Sciences: G. Peter Lepage (1982) with the J. J. Sakurai Prize for Theoretical Particle Physics, David Pines (1958–59) with the Julius Edgar Lilienfeld Prize, and Henriette Elvang (2008–09, 2010) with the Maria Goeppert Mayer Award.

Gregory Moore, Member (1986–89, 1999, 2002, 2012) and Visitor (2006) in the School of Natural Sciences, is among the recipients of the 2015 Dirac Medal and Prize from the International Center for Theoretical Physics in Trieste.

Susan Pedersen, Member (2011) in the School of Historical Studies, has received the 2015 Cundill Prize in Historical Literature from McGill University for *The Guardians* (Oxford University Press, 2015).

Mitra June Sharafi, Member (2011–12) in the School of Historical Studies, has received the Law and Society Association's 2015 J. Willard Hurst Prize for *Law and Identity in Colonial South Asia: Parsi Legal Culture, 1772–1947* (Cambridge University Press, 2014).

Members in the School of Natural Sciences Andrew Strominger (1982–87) and Cumrun Vafa (1994) have received the 2016 Dannie Heineman Prize for Mathematical Physics from the American Physical Society.

John Overdeck Appointed to Board of Trustees

DAN KOMODA

John Overdeck (right) at the Institute

The Institute has appointed John Overdeck to its Board of Trustees, effective October 30, 2015. Overdeck is Co-Chairman of Two Sigma Investments, LLC, a systematic investment manager founded with the goal of applying cutting-edge technology to the data-rich world of finance, based in New York.

Prior to founding Two Sigma Investments, LLC, in 2001, Overdeck was Managing Director at D. E. Shaw, where he directed the firm's Japanese equity and equity-linked investments and supervised the firm's London investment management affiliate. Overdeck also spent two years at Amazon, first serving as Vice President and technical assistant to Jeff Bezos, former Institute Trustee (2004–11). He went on to lead customer relationship management at Amazon, directing its personalization, community, and targeted-marketing features, and leading critical efforts to make its customer technology more scalable.

A lifelong math enthusiast, Overdeck won a silver medal for the United States in the 27th International Mathematics Olympiad. He serves on the Boards of the Hamilton Insurance Group, the National Museum of Mathematics, and the Robin Hood Foundation. Overdeck earned a Bachelor of Science in Mathematics, with distinction, and a Master of Science in Statistics, both from Stanford University.

A Celebration of Freedom, Vision, Talent, and Support

Going against the grain and swimming as far upstream as we can

The Institute celebrated the successful completion of the Campaign for the Institute on October 29 with an event hosted at Bloomberg Philanthropies by Michael Bloomberg, former Mayor of New York City and former Institute Trustee (1995–2001). The event was attended by major donors to the Campaign, including Trustee leaders James and Marilyn Simons and Charles and Lisa Simonyi, who provided an extraordinary $100 million challenge grant, and Trustee David Rubenstein, who donated $20 million to build the new Rubenstein Commons. A total $212 million was raised from more than 1,600 former Members, Friends of the Institute, foundations, Faculty, and Staff. Robbert Dijkgraaf, Director and Leon Levy Professor, gave the following remarks.

Eighty-five years ago the founders of the Institute had a very clear vision: to create a place unique in the world that would attract scholars of the highest quality from all over the world and provide them with the best environment to pursue their studies. The idea was to set those scholars free and imagine that with the right support they would do great things. With the Campaign for the Institute that we are now finishing, that mission has been reinforced in a powerful way. The fact that our message is resonating with all of you, and that you are willing to support it, is to me the strongest evidence that we are still doing the right thing.

Since the Institute's establishment, its independence and excellence have been almost fully reliant on philanthropy. Unlike universities, IAS has neither tuition nor intellectual property income. The $212 million that we have raised in this Campaign strengthens our financial core and ensures the development of new lines of inquiry and vital fields of thought. It is important to emphasize that the essential role of the Institute, which is providing freedom for scholars, can only be achieved because of our independence.

> *Their truly groundbreaking and inspiring work is only possible because of generous, private donors like you who enable the Institute's independence. They know like I do that many of the most profound discoveries in human history take place through collaboration that can only happen in places like the Institute.*
> —Michael Bloomberg

ALL IMAGES COURTESY OF BLOOMBERG PHILANTHROPIES

Clockwise from top: Robbert Dijkgraaf (left), Director and Leon Levy Professor, Trustee Nancy Peretsman (center background), and Michael Bloomberg (right), former Trustee (1995–2001); Charles Simonyi (left), Chairman of the Board, Michael Bloomberg (center), and James Wolfensohn (right), Chairman Emeritus of the Board; Daniel Goroff (left), Vice President and Program Director at the Alfred P. Sloan Foundation, and James Simons (right), Vice Chairman of the Board

I often say the Institute is totally unique in its kind. But I think it was Jim Simons who told me, "You have to be careful with that word, because these days everything is declared to be unique. Unique means there is only one." And that's absolutely true for the Institute. As somebody said when I tried to explain how we function, "Well you can stop there, because the number of institutions like this is either zero or one." I feel it is our mission to keep it one. I am very happy that you all joined this effort.

What is the magic of the Institute? A hundred years ago, Einstein thought of his general theory of relativity—a new way to think about space and time and gravity. I think actually gravity is also the mysterious ingredient of the Institute: it is the attraction of talent, the pull of great ideas. I know of no place that is more intense, and yet has fewer rules and fewer excuses to not do great work. I know of no place that listens more carefully to the voice of scholarship and the needs of the individual.

> *What I like about the Institute is that it allows people to come together and take this great device, the human brain, and think about things without other considerations that they might have at universities and so forth.*
> —David Rubenstein

Indeed, the Institute operates on a human scale. So I would like to say it is all about people, but it's not. I want to recognize that it is about something bigger that you are all part of: an institution that transcends generations, a belief in the capacity of individuals to change the world, to probe deeper than anybody else, to veer off the beaten path, to exemplify what scholarship stands for, and do so in a real community of scholars.

Now, these days it is difficult to be optimistic about the world of scholarship. We see a lot of perverse effects: short-term thinking, regression to the mean, the tyranny of metrics and goal-oriented research. But it is very easy to be optimistic about the Institute, because all of that means that our role—going against the grain, swimming as far upstream as we can, and being a forceful advocate for basic research—is more important than ever. Never before has there been such a wealth of talents, of ideas, of unsolved questions, and goodwill to support institutions of excellence. We hope you will continue to support us in this most rewarding adventure.

—Robbert Dijkgraaf, Director and Leon Levy Professor

A $20 Million Rubenstein Commons

An environment for scholars to collaborate, socialize, and work

A $20 million gift to the Institute from Trustee David M. Rubenstein, Co-Founder and Co-CEO of The Carlyle Group, will support the creation of a new building on the Institute campus to be known as Rubenstein Commons. Conceived as a welcoming and flexible environment for interaction among the permanent Faculty and visiting scholars, the Commons will greatly enhance the Institute's role as a convener of academic thought and activities across the sciences, humanities, and social sciences.

DAN KOMODA

David Rubenstein at the Institute's October Board of Trustees meeting

The Rubenstein Commons will be located to the east of Fuld Hall to provide convenient access for resident scholars and short-term visitors, and will feature a conference space, meeting rooms, and a lounge with a cafe. The Commons will also house office space and will be a venue for displaying images and materials that illustrate the Institute's extraordinary history and its current significance as a national and international center for curiosity-driven research.

"The Institute for Advanced Study not only has a fascinating and rich history, but it is a beacon for pure, unrestricted research," noted David Rubenstein. "This new building is essential for the Institute to continue to provide a complete and rewarding experience for scholars from around the world who are investigating some of the most intriguing questions across the sciences and humanities. I am confident that this addition to the campus will be beneficial and energizing, and will result in highly productive visits for future Institute scholars."

"This incredible donation to create the Rubenstein Commons is important and inspirational in so many ways," stated Robbert Dijkgraaf, Director of the Institute and Leon Levy Professor. "David's visionary philanthropy will enable the Institute to beautifully enhance its unique and optimal environment for scholars to collaborate, socialize, and work. There is a crucial need for such a resource here at the Institute, and we are grateful for David's commitment to our mission and his belief in the benefits that this new building will yield for years to come."

General Relativity at 100: Celebrating Its History, Influence, and Enduring Mysteries

An exploration of its continuing impact across physics, cosmology, and mathematics

Albert Einstein finished his general theory of relativity in November 1915, and in the hundred years since, its influence has been profound, dramatically influencing the direction of physics, cosmology, and mathematics. The theory upended Isaac Newton's model of gravitation as a force of attraction between two masses and instead proposed that gravity is felt as a result of the warping by matter of the universe's four-dimensional spacetime. His field equations of gravitation explained how matter curves spacetime, how this curvature tells matter how to move, and it gave scientists the mathematical tools to understand how space would evolve in time, leading to a deeper understanding of the universe's early conditions and development.

INSTITUTE FOR ADVANCED STUDY

This image taken of the total solar eclipse of May 29, 1919, was among Albert Einstein's possessions when he died in 1955, then Professor Emeritus in the School of Mathematics. The image, taken by astronomer Arthur Eddington and now in the collection of the Institute's Shelby White and Leon Levy Archives Center, provided striking evidence of Einstein's general theory of relativity because of the way starlight was shown to curve around the mass of the Sun.

Einstein was first informed of the success of the experiment in a telegram from Dutch physicist Hendrik Lorentz, whose transformation equations were used by Einstein to describe space and time and who later called the experiment's outcome one of the "most beautiful results that science has produced." When Eddington's experiment was publicized four years after Einstein first published the theory, The Times of London *called it "one of the most momentous, if not the most momentous, pronouncements of human thought."*

"The general theory of relativity is based on profound and elegant principles that connect the physics of motion and mass to the geometry of space and time," said Robbert Dijkgraaf, Director of the Institute and Leon Levy Professor, who gave a lecture "100 Years of Relativity" in October, sponsored by the Friends of the Institute. "With Einstein's equations, even the universe itself became an object of study. Only now, after a century of calculations and observations, the full power of this theory has become visible, from black holes and gravitational lenses to the practical use of GPS devices."

To celebrate the centennial of Einstein's general theory of relativity, the Institute held a special two-day conference November 5–6, cohosted with Princeton University and made possible with major support from IAS Trustee Eric Schmidt, Executive Chairman of Alphabet Inc., and his wife Wendy. The conference, General Relativity at 100, examined the history and influence of relativity and its continuing impact on cutting-edge research, from cosmology and quantum gravity, to black holes and mathematical relativity.

The celebratory activities began on Wednesday, November 4, with *Light Falls*, a theatrical production by Brian Greene, Member (1992–93) in the School of Natural Sciences, and closed with a special performance by Joshua Bell and a screening of *Einstein's Light*, a documentary film by Nickolas Barris, Director's Visitor (2013).

It also highlighted the role of Princeton physicists, particularly IAS Member John Archibald Wheeler and Robert Henry Dicke and their students, in pushing forward an examination of general relativity, its reach, power, and enduring mysteries. "The first fifty years were very much an effort of Einstein and a handful of people," said Dijkgraaf. "For the last fifty years, general relativity has blossomed, and physicists and mathematicians both from the Institute and Princeton University have played a crucial role in bringing this theory to full bloom."

With his general theory, Einstein used mathematics to discover and calculate nature's laws. To do this, he introduced little-known mathematics, which caught the attention of Princeton University mathematician Oswald Veblen when the theory was published in 1916. Veblen would serve with Einstein as one of the Institute's first Professors in 1933.

Veblen's and his Princeton University colleague Luther Eisenhart's interest in the geometry associated with general relativity—based on the work of two Italian mathematicians, Tullio Levi-Civita and Gregorio Ricci–Curbastro—was one of the reasons that Einstein chose to immigrate from Germany to the Institute rather than another institution, according to IAS Member Albert Tucker, the late former chair of Princeton University's mathematics department, in an oral history interview about the Princeton mathematics community in the 1930s. "It was an area of research that was scarcely known anywhere. Einstein's general relativity turned the spotlight on it. Veblen and Eisenhart took it up. With Veblen's experience with a variety of geometries and Eisenhart's previous work in differential geometry, they were ideally qualified to lead research in the geometry associated with general relativity . . . I think that it was this kindred feeling that Einstein had for Veblen and Eisenhart that made him willing, in 1933, to come to Princeton to stay. "

Until the Institute's first building, Fuld Hall, opened in 1939, Einstein's office and those of his IAS colleagues were located in Fine Hall on Princeton University's campus. There were two problems that concerned Einstein at the time, according to the late IAS Member Valentine Bargmann, one of Einstein's assistants.

"One was the problem of motion, the other was unified field theory. The first had been started with Leopold Infeld and Banesh Hoffmann, and it was a question in general relativity," said Bargmann in his oral history interview about Princeton in the 1930s. "The second was the construction of a unified field theory. It was a major interest, which would occupy Einstein to the end of his life. But the problem of motion had also occupied him for many years and had, in Einstein's view, not been adequately resolved."

IAS Member James Wallace Givens described working with Veblen on an elusive goal that they were too modest to speak aloud. "The thing we were trying to do, though we never talked about it in this language—Veblen would have dismissed it as being too majestic—was to get a mathematical foundation for relativity, which would unite it with quantum theory," said the late Givens in his oral history interview. "We never spoke of unified field theory. We did not want to be guilty of *Iese majesty*!"

During his time at the Institute, where he worked until his death in 1955, Einstein was consumed with constructing a unified field theory that would present a single framework for all the known forces of physics—believing that all of nature must be described by a single theory. Having introduced what is now known as quantum physics in 1905—his theory of special relativity brought forth the odd idea that light could behave both as a particle and a wave—Einstein was resistant to accept that general relativity describes gravity and the world at large, and quantum mechanics, which does not account for gravity, describes atoms and particle physics. He worked on a unified field theory until his last days, even though the goal of unifying the four fundamental forces of nature—gravity, electromagnetism, the strong nuclear force, and the weak nuclear force—had been set aside by the majority of working physicists.

In the 1930s and 1940s, only a handful of mathematicians and physicists in Princeton were working on general relativity. "By '58 when I arrived here as a graduate student, the general feeling was that general relativity was an elegant theory but of very limited interest. The big actors then were particle physics and quantum physics. Condensed matter was starting to heat up, but general relativity? Eh, a dead end," said IAS Member Jim Peebles, Princeton University's Albert Einstein Professor of Science, Emeritus. As part of General Relativity at 100, Peebles organized a dinner program with Dieter Brill, Jim Faller, Bill Hoffmann, Sidney Liebes, Charles Misner, and Rai Weiss, who were among Wheeler's and Dicke's students.

By 1960, Wheeler (on the theoretical side) and Dicke (on the experimental side) had moved into gravity physics and become dominant leaders in testing and furthering the field. "It became clear that there was a lot to be done, both theory and observation. There were lots of people working on both sides. It was an exciting time," said Peebles. "Back when I was a graduate student, general relativity was a theory without support. Now, it is more than a little startling to consider how well tested the theory is. Einstein's vision of 100 years ago has survived. The theory has been tested and it passes. This is the glory of physical science."

(Continued on page 5)

IMAGE CREDITS, L TO R: WILLIAM WICKES, DAN KOMODA, DAN KOMODA, DAN KOMODA

A TOAST TO EINSTEIN

Christmas Day, 1942, was the three hundredth birthday of Isaac Newton. I was then an undergraduate at Trinity College, Cambridge. Since Newton was our most famous fellow, the college organized a meeting to celebrate his birthday. Since it was war-time and very few fellows and students were in residence, the meeting was modest and the audience was small. We heard John Maynard Keynes, the famous economist who was then successfully keeping the British economy from collapse, give a talk with the title, "Newton, the Man." Amid the intense pressures of his public duties, Keynes had found time to pursue his hobby of collecting and studying unpublished Newton manuscripts. I have a vivid memory of the frail and white-faced Keynes, lying exhausted under a reading-lamp in the darkened college hall. He pulled out of the darkness his image of the genius of Newton. Keynes told us that the essence of Newton's greatness was his ability to hold an intellectual problem in his mind with total concentration for months and years on end until he had solved it. Newton, he said, was gifted with muscles of intellectual concentration stronger than the muscles of anyone else.

Three years later, in 1946, the war was over, and the Royal Society organized a much bigger celebration in London. Scientists came from all over the world to honor Newton. By that time Keynes had died, worn out by too many crossings of the Atlantic to negotiate with the United States the conditions for keeping the United Kingdom afloat. The talk that we heard in Cambridge was read in London by his brother Geoffrey Keynes, and published by the Royal Society in the proceedings of the London celebration. It became a classic portrait of Newton, written by a man who had studied Newton intensively and penetrated deep into his mind.

We now know that Keynes was wrong. Newton did not have the strongest muscles of intellectual concentration. Einstein's muscles were stronger. Einstein held the problem of understanding gravitation in his mind for ten years, from the discovery of special relativity in 1905 to the birth of general relativity in 1915. He held onto the problem with all his strength until it was solved. After it was solved, the new science of cosmology was born, allowing us to explore the size and shape of the universe, holding the universe in our minds as a dynamical system which we can grasp with real understanding. Einstein enlarged our vision of nature even more than Newton. Newton saw nature as dynamical. Einstein saw nature as geometrical.

We are here tonight to celebrate the hundredth birthday of general relativity. Einstein, our most famous colleague, also made a massive contribution to the birth of quantum mechanics, but that is a subject for another occasion. I will add only a few remarks about quantum mechanics that are relevant to the understanding of general relativity. It is now fashionable for physicists to search for a unified theory in which the universe is basically quantum mechanical, with the classical world of general relativity emerging as a limiting case when masses are large and quantum fluctuations are small. According to this fashionable view, quantum mechanics is exact and general relativity is approximate. I reject this fashionable view. In my view, which was also the view of Niels Bohr, the quantum world and the classical world are equally real. They both give valid descriptions of the universe, but they cannot both be seen in the same observation. This situation is a fine example of Bohr's principle of complementarity. Roughly speaking, quantum mechanics describes the universe when you look forward into the future and the theory gives you probabilities. General relativity describes the universe when you look backward into the past and the theory gives you facts. Probabilities describe the future. Facts describe the past. Quantum mechanics and general relativity together give us a coherent view of nature with all its magical beauty and diversity. General relativity is half of the picture, and to my taste the more beautiful half.

Let us now drink to the hundredth birthday of general relativity.

—Freeman Dyson, Professor Emeritus in the School of Natural Sciences, who first joined the Institute as a Member in 1948 when Einstein was an IAS Professor

GENERAL RELATIVITY *(Continued from page 4)*

Since then, the theory has been used to discern the composition and evolution of the universe. As Dijkgraaf writes in "Without Albert Einstein, We'd All Be Lost" in the *Wall Street Journal*,

> The past decade has brought a new cascade of discoveries. The most important is that we now know precisely what we don't know. Einstein's theory allows us to measure the weight of the universe and thereby its energy content. This has been a shocker. All known forms of matter and energy—that is, all the particles and radiation that make up us, the Earth, the sun, all planets, stars, and intergalactic clouds—comprise just 4 percent of the grand total. The remaining 96 percent is made of unknown forms of "dark matter" and an even more mysterious "dark energy," which permeates all of space and drives the universe to expand faster and faster. These days there is a lot of talk about the 1 percent of society, but from a cosmic point of view, we are all part of just 4 percent of the cosmos.

Today, a unified field theory is a central goal of physicists, and string theory has become the favored candidate to provide a framework for a unified understanding of the basic laws of the physical universe. At the Institute, some of the world's foremost string theorists and cosmologists continue to interpret and test Einstein's theory of general relativity, about which questions persist: What is the physics of black holes? Do space and time emerge from a more fundamental description? Why is the universe accelerating? How can general relativity be reconciled with quantum mechanics? What are the origins and the long-term fate of the universe? General relativity set us on a course of understanding that we are still trying to fully grasp. *—Kelly Devine Thomas, Editorial Director, kdthomas@ias.edu*

Recommended viewing and reading:

Videos of talks from the General Relativity at 100 conference: www.ias.edu/relativity-100

"Without Albert Einstein, We'd All Be Lost" by Robbert Dijkgraaf, *Wall Street Journal,* November 5, 2015: ow.ly/UjiYu

"100 Years of General Relativity," a lecture by Robbert Dijkgraaf, October 14, 2015: www.ias.edu/2015/dijkgraaf-relativity

"Mathphilic" by Rebecca Mead, *New Yorker*, November 30, 2015: www.newyorker.com/magazine/2015/11/30/mathphilic

"A Century Ago, Einstein's Theory of Relativity Changed Everything" by Dennis Overbye, *New York Times*, November 24, 2015: nyti.ms/1XoaMLq

The Princeton Mathematics Community in the 1930s: An Oral History Project: www.princeton.edu/mudd/finding_aids/mathoral/pm03.htm

ALL IMAGES DAN KOMODA

Einstein's Pacifism: A Conversation with Wolfram Wette

A lifelong struggle for peace amid militarism, Nazi mobilization, and the threat of nuclear war

BY KRISTEN ROGHEH GHODSEE

Wolfram Wette is one of Germany's foremost military historians and Professor at the Albert-Ludwigs-Universität in Freiburg. He is the author or editor of over forty books, including The Wehrmacht: History, Myth, Reality *(Harvard University Press, 2007), which was translated into five languages and radically reshaped the way historians think about the role of the German army in World War II. In 2015, the German government awarded Wette the Order of Merit of the Federal Republic of Germany, the only federal honor bestowed upon German citizens for their exceptional accomplishments. In July, Wette sat down with me to talk about Albert Einstein's little-known activism in the German peace movement.*

Most people know about Einstein as a scientist, but few outside of Germany know about his commitment to pacifism. Yes, most people know Albert Einstein for his theory of relativity of 1905, but they don't know about his lifelong struggle for peace. But when you speak with some of the people who knew him, they will tell you that half of his life's energy was dedicated to the struggle for peace and the other half to his atomic research. In 2005, there was an international congress in Berlin celebrating the centenary of the theory of relativity: "Thinking Beyond Einstein." A good portion of the papers presented there focused on his role as a peace activist during the time of the Weimar Republic between 1918 and 1933.

HERBERT MCCORY/NY DAILY NEWS ARCHIVE/GETTY IMAGES

Albert Einstein, Rabbi Stephen Wise, and novelist Thomas Mann at the preview of the anti-war film The Fight for Peace *in 1938*

So he became active in peace politics after World War I? No, he was involved in the peace movement before the First World War. Before 1914, Einstein was openly opposed to German militarism, racism, nationalism, and the use of violence in foreign policy. But he was in a minority. When the war started, about one hundred members of the German cultural elite made a public manifesto in support of German nationalism and patriotism. They defended the military's actions. Only a very few scientists didn't follow this line. Einstein, together with two other prominent scientists, tried to publish a counter-manifesto, denouncing the war. But none of the German newspapers would publish "unpatriotic" texts. So Einstein knew that he had a position that was not very popular with his colleagues.

Did his position become more popular after 1918? Yes, Germany after the war was a very divided society. Questions of war and peace were very much in the public debates. It cannot be compared to any other country. Hundreds of thousands of peace activists marched in the streets of Berlin to protest militarism and war, and Einstein rode in a car at the front of the demonstrations. He was the most famous activist in the country, especially after he won the Nobel Prize in 1921.

I know the communists and the social democrats were also opposed to war at this time. Was Einstein affiliated with any political party? Not only the communists and social democrats, but the left liberals and other parties as well. It was a mass movement in favor of diplomacy with the victorious powers of the First World War. They were in favor of non-violent conflict mediation. Their movement was called *Nie wieder Krieg!* (Never again war!). There were many parties involved, but Einstein himself was not a member of any political party. Peace was more important than party politics to Einstein.

WHEN HITLER CAME TO POWER, EINSTEIN SAW THE DANGER. HE SAID, "I AM A PACIFIST IN PRINCIPLE, BUT I AM NOT AN ABSOLUTE PACIFIST."

But he abandoned his position after 1933? Yes, when Hitler came to power, Einstein saw the danger. He said, "I am a pacifist in principle, but I am not an absolute pacifist." Many of his friends and colleagues in the peace movement were irritated with him for changing his position. But Einstein said that he hated the military and militarism as much as before, but that he could not close his eyes to the coming danger of Hitler.

Why did Einstein change his position so quickly? I think it is because he was reading the writings of a very prominent academic and peace activist named Friedrich Wilhelm Foerster. Foerster understood the German military mentality, the power of the *kriegmenschen* (war people) to set the political agenda in his country. He called their kind of thinking the *schwertglauben*.

Sword believers? Those who believe in the sword? Yes. And Foerster wrote in 1932 that there will be war guilt for the peace activists who close their eyes before reality. I think Einstein read this and understood that he had to act.

What did he do? Many things, but one interesting thing is that Einstein told the leaders of the victorious powers of World War I to occupy Germany in 1933. At that time, this would have been a legal action, and they could have stopped Hitler. Later in the war, Joseph Goebbels said that if he had been prime minister of France, he would have occupied Germany in 1933–34. Goebbels admitted that a French occupation could have prevented the Nazi mobilization. "But because they didn't," Goebbels said, "we were able to prepare for war." Albert Einstein made this proposal very early, but the Western leaders ignored him.

Then there was the letter to Franklin Delano Roosevelt. Einstein wrote to the American president and told him to start working on the atomic bomb. Einstein feared that the Germans would get this technology first, and he wanted the Americans to have the bomb to use against the Germans. He never expected that this bomb would be used against Japan or any other country. In 1945, after the destruction of Hiroshima and Nagasaki, Einstein believed that his letter to Roosevelt had been a mistake.

Then he went on to oppose the threat of nuclear war. Toward the end of his life when he was living in the United States, he dedicated many efforts to preventing the possibility of a third world war. He wanted a world government that would eliminate nationalism and the need for military aggression. He was absolutely opposed to nuclear weapons of any kind, and one of the final acts of his life was to sign what became known as the Einstein-Russell manifesto, calling for human beings to set aside their political differences in order to ensure world peace. Eleven prominent scientists signed this manifesto, and they told world leaders to: "Remember your humanity, and forget the rest."

How did you become interested in Einstein's work as a pacifist? I'm one of the founders of the field of historical peace research in Germany, a community of about two hundred historians working on issues of peace. We have two book series in this field, and it is an area of active scholarly interest here. This started in the 1970s, when Germany had a new president, Gustav Heinemann, who wanted to develop more research on peace movements in Germany. This was at the time of Willy Brandt's *Ostpolitik*, when Germans were more interested in non-military diplomacy and normalization with Eastern Germany. So my interest in Albert Einstein's pacifism is part of my broader interest in the peace movements in Germany and in Europe in the nineteenth and twentieth centuries.

Before our interview, I asked several of my colleagues at the university if they knew that Einstein was a pacifist, and very few had any idea about it, especially those from outside of Germany. In the United States, where I am from, even educated people know very little about his peace activism. Why do you think that is? Well, the United States since the Second World War is primarily a military country. There hasn't been a year since 1945 when your country was not embroiled in some military conflict. In the United States, it is normal to solve conflicts with military power. In Germany, this is no longer normal. ■

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Near and Distant Neighbors: A New History of Soviet Intelligence

A vantage point into the story of the present

BY JONATHAN HASLAM

Mikhail Gorbachev defied every expectation at home and abroad by permitting the Berlin Wall to be breached in November 1989. He had finally allowed the imbalance of military power in Europe, which had stood provocatively and overwhelmingly to Soviet advantage since 1945, to be broken unopposed. Behind all this lay a basic truth: Moscow had effectively already given up the ideological struggle. The Russia reborn in 1992 had to confront the unexpected need to substitute at short notice raw patriotism for a long-outmoded belief in a global ideal, all in the face of falling living standards and full consciousness—not least via MTV, now beamed freely into city apartments—of what the West could offer in return for betrayal.

The negative impact on intelligence assets and their recruitment was severe, given how heavily Moscow depended upon human resources once attracted by and tied to the Soviet model. Only with the emergence of their own man, former Lieutenant Colonel Vladimir Putin, as president in 2000 could the "organs" hope to regain lost ground. He rose to power as a result of the chaotic conditions prevailing in Yeltsin's Russia, the state in retreat, criminality rife, and widespread corruption associated with the liberation of the state's assets to the market. Putin's message in 1999 was twofold: reestablishment of order and restoration of the Soviet Union, not as a Communist entity but as an imperial stronghold. Inevitably, practices rapidly reverted to those of an era we had all thought dead and buried.

DAN KOMODA

In October, Jonathan Haslam gave an Institute lecture, which asked: "What is Putin up to and why?"

How much was all this an essentially Russian phenomenon rather than the temporary aberration produced by the Communist order? The saying goes that when the tide goes out, you can see who is swimming naked. Once the Soviet régime collapsed, we could begin to separate out what was essentially Russian (that which remained) and that which was peculiarly Communist (which is largely in the process of falling away despite the nostalgia it evokes). Ugly practices, such as assassination, reemerged within a decade after Soviet rule had ended for good. The role of the GRU special forces in the takeover of the Crimea in the spring of 2014 and in the undeclared war to take over the Eastern Ukraine is an ugly reminder of times past, the *aktivka* against Poland in the 1920s.

Such phenomena cannot be viewed as accidental. Their occurrence suggests that rather than being a complete displacement of and substitution for traditional ways and means, the Soviet model was in some fundamental way their continuation, albeit in revised form. Is one to forget that assassination was an instrument much favored by the Narodniki, the forerunners of the left Socialist Revolutionaries and the Bolsheviks? Were they so different from the Rote Armee Fraktion and the Brigate Rosse, who found favor in Moscow? As distance grew from the time of the old autocracy, it became easier to imagine that the horrors that emerged under Stalin were unprecedented rather than a reversion to earlier times, the ruthless systematization and application of older practices under new guises.

After the final collapse of Soviet power, a golden opportunity arose to break completely with the past. To reduce the disproportionate reach of the security services within Russian politics, President Boris Yeltsin splintered the KGB into three: the FSB (domestic intelligence), the SVR (foreign service), and the FAPSI (communications intelligence). Necessary cuts in government expenditures in order to substitute a welfare state for the warfare state and a market for the Five-Year Plan reduced the relentless growth of the fighting services. These changes in priorities failed, however, to make a lasting impact on attitudes. Although redundancies followed, and the private sector soon absorbed many of the more entrepreneurial and technologically sophisticated, by the mid-1990s cutbacks were being reversed.

Moreover, although the goal of communism disappeared, methods tried and tested from the more distant past reasserted themselves with the wars against Islamic-led separatism to the south and the postimperial resentment at U.S. supremacy. It is no coincidence that Putin's emergence and speedy ascendance, culminating in his electoral victory in March 2000, coincide with both. By 2003, the *siloviki* ("men of power"), who were figures from the security services, held all the reins. They had come from out of the shadows for everyone to see, a caste that owed its very existence and identity to the history of the Cheka. It is striking, however, that the dominant element has been counterintelligence, represented in the FSB, rather than foreign intelligence represented in the SVR. Counterintelligence was, after all, where Putin served. The FSB, some claim, has become a law unto itself.

One symptom of this reversion to the past was the reappearance of the expression *Eto ne telefonnyi razgovor* ("This is not a telephone conversation"), meaning

Recommended viewing: In Jonathan Haslam's first public lecture at the Institute, he discussed post-Soviet Russia and the challenges encountered after a great power loses its empire, exploring how Putin's leadership and influence has impacted international affairs. Watch the video lecture at www.ias.edu/haslam-2015.

"We can speak openly." Those in the business of intercepting communications and who were destined to become unemployed in the early 1990s soon found themselves back at work. And instead of interception being run as a monopoly by the twelfth department of the KGB, any number of agencies have been conducting their own operations. The official number of intercepts, for example, doubled between 2007 and 2011. But it is doubtful whether this tells the whole story. Another symptom, of a more sinister nature, was the shattering news of the ex-FSB officer Alexander Litvinenko's assassination.

Instead of the Soviet Union's collapse leading directly to the dismantling of the security organs, a decade later they had taken over the Russian Federation. It did not take long after Putin's electoral triumph for the Jewish oligarchs (who had acquired much of the Soviet Union's capital portfolio and were now seeking leverage for political purposes) to be driven out of Russia. The sole dogged figure of resistance, the ruthless Mikhail Khodorkovsky, was brutally given to understand that he was digging himself ever deeper into a hole of his own making by continuing to oppose the inevitable. Simultaneously, every vital post in the public and private sectors of the economy was appropriated by either a former *gebist,* a close relative of the same, or an asset of the security organs.

The Russian sociologist Ol'ga Kryshtanovskaya, director of the study of the elite at the Institute of Sociology (Russian Academy of Sciences), in her earlier guise as critic, pointed to the formation of a new elite and the incorporation of the state by the security services. Nikolai Patrushev, who succeeded Putin as director of the FSB, described them as Russia's "new nobility." Former general of the KGB Alexei Kondaurov boasted, "There is nobody today who can say no to the FSB." He added: "Communist ideology has gone, but the methods and psychology of its secret police have remained."

For a while it looked as though the GRU was heading for dismemberment under Putin as a force that no longer served a useful purpose. Yet the operations launched against the Crimea, with "little green men," and against the rest of the Eastern Ukraine propelled the GRU back into life. Until 2014, its role as policeman of the "near abroad" (former Soviet republics) looked redundant. All of a sudden the GRU has found a new role in what might be described as "implausibly deniable" *aktivka*, operations not unlike those conducted against Poland by the Fourth in the 1920s: sufficient to keep the wound bleeding but insufficient, thus far, to warrant massive retaliation.

These forms of covert operations were heralded by the new chief of the General Staff, Valery Gerasimov, in January 2013. The business-speak within the army today is "outsourcing," which has been coined as a new Russian word. Now it has acquired a new meaning altogether. Moscow "outsources" its war fighting. Considered "an intellectual," in the words of the editor of *Natsional'naya oborona*, Gerasimov assured those assembled at the Academy of Military Sciences that force continued to play an important role in resolving disputes between countries and that "hot points" existed close to Russian frontiers. Referring to the spring revolutions in various states, he went on to point out that even a country in good condition could fall victim to foreign intervention and descend into chaos. A broad range of nonmilitary measures could be used in support of popular protest, plus the use of "covert military means."

We began with the emergence of the Cheka out of the dust of Russia's ancient régime. We end with Russia incorporated by the diehards of the Cheka. Even the GRU has rediscovered a role hitherto lost in the mists of the past. The history of the Soviet intelligence services thus becomes not just an end in itself but also a vantage point into the story of the present, a state within a state retreating into the past with the destruction of pluralism and the recentralization of power then exerting itself to determine the future through a process of stealthy expansion into the former territories of the Soviet Union. ■

This article is an excerpt of Near and Distant Neighbors: A New History of Soviet Intelligence *(Farrar, Straus and Giroux, 2015) by Jonathan Haslam, George F. Kennan Professor in the School of Historical Studies. Haslam is a leading scholar on the history of thought in international relations and the Soviet Union whose work builds a bridge between historical studies and the understanding of contemporary phenomena through critical examinations of the role of ideology.*

Behold the Black Caiman: A Chronicle of Ayoreo Life

An ethnographic account of the seeming destruction of a small group of South American Indians

BY LUCAS BESSIRE

This ethnographic project and I have grown up together. It evolved through repeated returns over the course of forty-two months of fieldwork carried out in Bolivia and Paraguay between 2001 and 2013. Its focus has sharply changed since I began traveling to the Chaco as a twenty-one-year-old. From the outset, I was an active participant in representing Ayoreo humanity to fellow outsiders, most notably in two documentary films. Yet I soon came to feel that there was something profane about anthropology as commonly practiced in the Chaco. And Ayoreo-speaking people wouldn't let me forget it. Unsettled by the process of making my second video during the aftermath of a 2004 "contact," I resolved that a collaborative project was the only option for the immersive research that I began in 2006 among Totobiegosode—Ayoreo in northern Paraguay.

This elementary recognition turned out to be quite difficult to realize. Eventually I was permitted to stay with them under certain conditions, not least because I gladly offered myself as an immediate source of food, medicine, money, and most importantly, transport. At the time, the relatively remote communities with which I worked did not have access to a vehicle. The children named my old army ambulance *Jochekai*, the Giant Armadillo, and quickly bedecked its rearview mirror with gifts. My presence in the Chaco was as much political and economic as personal and intellectual. Invited to work as an "advisor" to a recently formed tribal organization, I also became a wedge between the Totobiegosode communities and an NGO that controlled the material sources of their daily existence. Early on, it was apparent that there were stark differences of opinion all around. Taking an active role in these daily negotiations gave me standing in the communities; it also made my relations with contracted experts strained and often conflictive. Totobiegosode leaders enlisted me alternately as ally, agitator, and foil to leverage slight openings in a constrained social space. Over the years, these relations thinned and thickened, dried out and grew up. In the process we all assumed forms impossible to foresee. This book, then, is equally a chronicle of lives shared and a genealogy of why this was only partially so.

FIELDWORK MEANT CONFRONTING SITUATIONS I WAS NOT EQUIPPED TO DEAL WITH IN RATIONAL WAYS, FROM BLUNT-FORCE BRUTALITY TO INCREDIBLE GRACE. THERE WAS NO COHERENT WHOLE TO MASTER OR BECOME FLUENT IN.

I'd like to think that the woman I will call Tié is my friend, even though there is no word in her language for the absent kind of friendship I can offer.

She was one of a small band of Ayoreo-speaking people who emerged from the dwindling forests of northern Paraguay in March 2004, fleeing ranchers' bulldozers and fearing for their lives. These seventeen people called themselves Areguede'urasade ("band of Areguede") and formed part of the Totobiegosode ("People of the Place where the Collared Peccaries Ate Their Gardens"), the southernmost village confederation of the Ayoreode ("Human Beings"). Along with two other small bands that still roam the dense thickets of the Bolivia/Paraguay borderlands, they were the last of the forest-dwelling Ayoreo.

Startling photographs of these brown-skinned people made headlines around the world that spring. Experts jockeyed to declare this one of the final first contacts with isolated Indians. At first everyone wanted in, including me. When the first tremors of the event reached me, I was a second-year anthropology graduate student at New York University. I thought I understood something of Ayoreo people and the Chaco, as I'd already spent fourteen months living among and collaborating with northern Ayoreo-speaking people as a Fulbright scholar in Bolivia three years before. When I heard they'd come out, I couldn't sleep. I rushed through coursework and film training, and by July I was headed south—as if to bear witness.

What does it mean to write or read yet another ethnographic account of the seeming destruction of yet another small group of South American Indians? What kind of humanity is possible for anyone once the spectacular upheavals of a twenty-first-century "first contact" supposedly subside?

For many earlier anthropologists, like Claude Lévi-Strauss and Pierre Clastres, the answer was clear. So-called primitive society was imagined to be intrinsically opposed to Western civilization. It was, in Clastres's famous writings, a "society against the state." Clastres argued that "primitive man" refused the political and economic forms required for modern statecraft. For Clastres, the modern state was defined by its centralizing drive to erase and homogenize difference while primitive society was outward-facing and deeply antiauthoritarian. Where the modern state was "the One," primitive society was the unassumable "Multiple" that existed beyond it. This primitive multiplicity, for Clastres, was "the conceptual embodiment of the thesis that another world was possible." Yet Clastres and many of his contemporaries imagined this possibility as an ever retreating horizon. Primitive societies, he was convinced, were doomed to disappear before the violent onslaught of capitalist modernity.

Contact was supposed to initiate such disappearances. Because it meant the inevitable loss of this multiplicity, contact made the South American tropics tristes, a zone of mourning and what Renato Rosaldo calls "imperialist nostalgia." In the words of Alfred Métraux, the great ethnographer of the Chaco, "For us to be able to study a primitive society, it must already be starting to disintegrate." Such sentiments oriented ethnography. Clastres argued that what was needed was an anthropology capable of interrupting the surrender to singularity by taking seriously the radical otherness of primitive society and experience. It was a political anthropology based on a search for the primitive.

If this binary schema was correct, then the events of 2004 were devastatingly clear. They followed a well-worn script of social disintegration and the loss of future possibility. To be sure, many ethnographers have made exactly this argument. As Ticio Escobar put it long before he became Paraguay's minister of culture, the Totobiegosode Ayoreo are victims of "ethnocide" or "the violent extermination of culture." This process of contact "converts their members into caricatures of Westerners and sends them to a marginal underworld where they end as beings that have no place in their culture nor the culture of others." Escobar argued that this process transformed contemporary Ayoreo-speaking people into a peculiar form of nonhumanity, a population whose "men wander as shadows of themselves through work camps or colonies … and their women, defeated, arrive at the towns to give themselves up as semi-slaves or prostitutes." For Escobar, Clastres, and others, the supposed death of culture also meant a wider social death. It was believed to manifest in affective or psycho-pathologies, including "all of the side effects of losing one's cultural identity: alcoholism, social disorganization, apathy, violence, suicide, prostitution, and marginalization." In this reckoning, the values of culture and life were conflated. We do not need to read or write about the contact with the Areguede'urasade; we only need to properly mourn their passing.

At first, it was tempting to see traces of decay everywhere I turned. No matter where I went in the Chaco, I found that Ayoreo were disenfranchised as subhuman matter out of place: cursed, subordinated, neither this nor that. On both sides of the Bolivia/Paraguay border, Ayoreo-speaking people were the poorest and most marginalized of any Indigenous people in a region where camps of dispossessed Natives lined the roads and Indians were still held in conditions described as slavery. They confronted a mosaic of violence: enslavement, massacres, murder, and rape were venerable traditions. Many of the girls exchanged sex for money on the peripheries of cities or towns. The pet parrots in one settlement imitated tubercular coughing. People seemed to alternate between nervous motion and opaque waiting. Many sought escape by whatever means were near at hand: prayers, disco music, shoe glue. The violence was unavoidable. Everyone got tangled up in it; we all mouthed its lines.

Fieldwork meant confronting situations I was not equipped to deal with in rational ways, from blunt-force brutality to incredible grace. There was no coherent whole to master or become fluent in. The closest things I found to Ayoreo cultural institutions were those described so confidently in books or pieced together from elders' memories and sold to visiting anthropologists. Sociality swung wildly between extremes of collective affiliation and agonistic striving for dominance. Merely surviving required a thick skin; I never quite got used to the fact that conflict and brinksmanship were defining parts of everyday personhood.

Yet the more time I spent in the Chaco, the more clear it became that death was only part of the story. What appeared initially as losses were, on more thorough acquaintance, zones of intense translation, rational calculus, and partial potentials for Ayoreo-speaking people. If such sensibilities reflected a failure, it was the failure of the New World to deliver on its promise and the failure of others to take seriously the kinds of possibility these emergent attitudes contained. By the time I left the Areguede'urasade in 2004, I was increasingly convinced that primitivist narratives of culture death were not any kind of answer at all. Rather, they were part of the problem. I wondered: How did the New People come to inhabit a world in which their disintegration was foretold? How were classic accounts of contact revised and refracted in twenty-first-century contexts? At which points did the kinds of self-fashioning by Ayoreo and by ethnographers fall apart, and at which did they unexpectedly merge? ■

This article is excerpted from Behold the Black Caiman: A Chronicle of Ayoreo Life *(University of Chicago Press, 2014). Written by Lucas Bessire while a Member (2012–13) in the School of Social Science, the book draws on Bessire's ten years of fieldwork with the Ayoreo. It received the Society for Cultural Anthropology's 2015 Gregory Bateson Prize, and the 2015 Society for Latin American and Carribean Anthropology Book Prize. Bessire is currently Assistant Professor at the University of Oklahoma.*

Aramaic and Endangered Languages

Recording the last cadences of an ancient language

BY GEOFFREY ALLAN KHAN

THE TIMES OF ISRAEL/MIRIAM SHAVIV

A Christian Aramaic speaker in Georgia talks with Geoffrey Khan.

I had the privilege of being a Member at the Institute for Advanced Study from January to April 2015, during which my main research project concerned a corpus of Arabic documents from medieval Nubia. I had the opportunity to make a presentation at the Institute's informal "After Hours" gatherings about another field of research I have been working on for the last twenty years or so, namely endangered Aramaic dialects.

For my academic degrees at the University of London (School of Oriental and African Studies), I studied the classical Semitic languages, in particular the classical written forms of Arabic, Hebrew, and Aramaic, and went on to take up a postdoctoral position on a project on medieval Arabic and Hebrew manuscripts at the University of Cambridge. Some years later, I spent a year off from my postdoctoral job in Jerusalem, where I planned to spend most of my time reading microfilms of medieval manuscripts. While buying vegetables in the market one day, I heard the owner of the stall speaking a language that turned out to be a dialect of Aramaic. This whetted my appetite and I subsequently arranged to meet an elderly man who spoke Aramaic in his small apartment in the area of Jerusalem known as Qatamon. This meeting turned out to be a life-changing experience for me. I realized on that day that I was sitting in front of one of the last surviving speakers of a dialect of Aramaic. Aramaic was one of the major languages of the ancient Near East. Since the Middle Ages it has largely been replaced by Arabic, but it survived as a spoken language in a number of Jewish communities in the mountainous regions of northern Iraq, southeastern Turkey, and western Iran down to modern times. Spoken Aramaic also survived to modern times among Christian communities in the same regions and also in a few villages in Syria. Over one hundred dialects of Aramaic were spoken in the Middle East in the first half of the twentieth century. The Jews adopted Aramaic when they were exiled to Mesopotamia in antiquity by the Babylonians, and some remained there. What I was hearing that day were the surviving cadences of the language of the ancient Jewish exile.

SOME ESTIMATE THAT AS MANY AS NINETY PERCENT OF THE LANGUAGES CURRENTLY SPOKEN WILL BE EXTINCT BY THE END OF THIS CENTURY. THIS IS VASTLY GREATER THAN THE EXTINCTION RATES OF BIOLOGICAL SPECIES.

In the second half of the twentieth century, virtually all the Aramaic-speaking Jews settled in the State of Israel, and their children and grandchildren adopted modern Hebrew as their spoken language. As a result, Aramaic is now spoken by only a very few elderly people. Some dialects have now been reduced to a single final speaker or have already become extinct. The same fate has befallen a large proportion of the Christian dialects, as a result of the fact that many of the Aramaic-speaking Christians have left the Middle East, mainly during periods of political and social upheaval. The major upheaval for the Christian communities was World War I, during which thousands of Aramaic speakers were displaced or lost their lives. This displacement from their native villages is still taking place as I write, due to the atrocities that are unfolding in northern Iraq and Syria. All of this means that Aramaic is now an endangered language.

Sadly, many languages in the world are currently experiencing the same fate as Aramaic and are now endangered. The statistics are frightening. Some estimate that as much as 90 percent of the languages that are currently spoken will be extinct by the end of this century. This is vastly greater than extinction rates of biological species (currently 7 percent of mammals and 3 percent of birds in the worst-case scenario). A language becomes endangered when it has only a few elderly surviving speakers and is not spoken by younger generations. Since the majority of the world's languages have no written tradition, most such endangered languages are doomed to extinction and oblivion. The threat of extinction even extends to many of the major languages of the modern world, since these languages have many spoken dialectal varieties, and some of these varieties are now endangered, such as Central Asian and Judeo–Arabic dialects, Cappadocian Greek, Guernsey Norman French, and many dialects of English.

Why are so many languages endangered? Four main causes can be identified: (i) the displacement of communities, due to violent upheavals in war or economic migration to towns, (ii) the dominance of national standard languages in modern nation states, (iii) the impact of education and media in standard languages, and (iv) a negative attitude to ancestral languages. All of these factors have affected the fate of Aramaic.

What needs to be done about it? In some cases there is still a possibility that an endangered language can be saved by a concerted program of revitalization through education involving teachers from within the language communities. Such revitalization is, however, very difficult and the eventual extinction of the majority of the world's endangered languages is inevitable. The most important task for a linguist, therefore, is to carry out a systematic documentation of endangered languages through fieldwork in the communities. This is what I have been attempting to do for Aramaic over the last twenty years. Most of my fieldwork has been among the diaspora Jewish and Christian communities of Aramaic speakers around the world. In some cases, I have interviewed the final speaker of a dialect.

Unfortunately, final speakers are often physically frail and decrepit, and this can complicate fieldwork. It is common for elderly speakers to be lacking in teeth, which wipes out all their dental and interdental consonants. One final speaker I met in New Zealand turned out to have a lisp, which complicated the reconstruction of the original phonology of the dialect. Some years ago, I tried to work with the last speaker of a Jewish dialect in Israel, an elderly woman in her 90s, who could only breathe with a ventilator and could only give me single words as answers to my questions—sentences required too much breath. The speakers I have worked with have generally been very hospitable. Too much hospitality, however, can lead to complications. Some years ago I tried to work with a community of Aramaic speakers in Armenia, but every time I visited them they insisted on honoring me with a series of toasts of vodka before they answered my questions. It is not clear, therefore, whether the various losses of consonants and contractions in my recordings of their dialect are due to diachronic linguistic development or the influence of their hospitality. Occasionally I have had the opposite experience and been treated with fear and suspicion. One elderly lady in Tbilisi set her Rottweilers on me when I tried to interview her in her home.

Why should we care about the extinction of languages? There are numerous reasons why we should be concerned about the loss of languages. Some of these are as follows.

- Language diversity is a reflection of human diversity and this can be regarded as important as ecological diversity.
- Every language and every dialect within a language is unique and reflects distinct aspects of human language in general. So loss of language diversity is an impoverishment of human language and diminishes opportunities for us to study the full potential of human language, arguably the most important manifestation of humanity.
- When a language of a community dies, many aspects of culture are lost, in particular traditions of oral literature that have been passed down for generations.
- A language contains history. This is found in oral traditions of a community's history and also in its oral literature. Some of the stories of the Greek myths, for example, have survived in the Aramaic-speaking communities (with all the names of characters changed). A language also contains history within its own linguistic structure. The study of the oral literature and the language structure can tell us a lot about the historical background of the community, which may not have any written historical records. ■

Geoffrey Allan Khan, Member (2015) in the School of Historical Studies, worked at the Institute on a corpus of medieval Arabic legal documents and correspondence from Nubia that cast new light on medieval trade networks in the region. Khan is the Regius Professor of Hebrew at the University of Cambridge.

Designing the Digital Ottoman Project

Six hundred years, twenty-five languages, and eight alphabets

BY AMY SINGER

What makes a digital *Ottoman* project different from other digital projects and why isn't it a straightforward endeavor but rather one that will probably take several years to develop successfully? And why isn't there one already? Why would twenty-four people need one week together even to figure out where to begin? The Digital Ottoman Platform (DOP) workshop convened at the Institute June 8–12, 2015, to establish a transnational digital space in which to create, collect, and manage source materials, datasets, and scholarly work related to the Ottoman world. The goal is that these resources will be transparently and reliably authored, referenced, and reviewed to ensure that scholarly standards of research and publication are maintained for materials created and made available. The site, its materials, and its datasets will be sustainably managed to serve the global community of scholars, many of whom will also have contributed to the platform from their own research. At the same time, the space will be accessible to students, researchers, and readers worldwide.

Our vision is that the DOP will make it possible to locate and share resources and results in original, intermediate, and published formats and to create new collaborations for research and learning. It also aims to identify and document best practices among the dynamically developing digital technologies that now enrich the tools and methodologies of the humanities. Although these efforts focus specifically on Ottoman history, they may well create models for other fields of study or enterprises facing similar challenges.

ANDREA KANE

With a vision to enrich and advance the field of Islamic and Near Eastern studies, Sabine Schmidtke (far left) and Amy Singer (right) are among the DOP participants compiling the pages of Ottoman history.

A brief perspective on Ottoman studies and the ex-Ottoman lands makes clear the scope of the challenge and also emphasizes why the DOP could play a leading role in expanding the digital capacities not only of Ottoman studies but of Islamic and Near Eastern studies generally.

Ottoman history is narrowly defined by the six hundred years of Ottoman dynastic rule over a single entity (that grew and shrank), yet builds more broadly on legacies inherited in the lands conquered by the Ottomans; the Empire also left legacies with direct implications for the history of the ex-Ottoman lands even today. Addressing the largest Muslim state from the sixteenth to the twentieth century, Ottoman history is also integral to the study of Islamic thought and practice. The Ottoman Empire included a geography that today encompasses some twenty-five to thirty countries, including Anatolia, large portions of the Arab world, the Balkans and eastern Europe, the Crimea, the Caucasus, and western Iran. Scholars working on Ottoman history use original written sources in at least twenty-five languages that engage at least eight separate alphabets. Added to the written literary and documentary sources is a vast array of architectural, pictorial, numismatic, textile, metal, wood, and other evidence.

Obviously, no single person has the skills to work with this diversity of sources. Thus scholars of the Ottoman empire will benefit exponentially if systems and methods can be created for sharing not only the results of their separate research but also for collaborating on projects that demand a multiplicity of sources and methods, and for making available source materials in primary or intermediate formats for comparative projects. Sharing and collaboration of this kind necessarily (but not always easily) occurs across geographic distances, political divides, and language barriers. Some of these are more daunting or intractable than in many other fields of research. If successful, this digital platform will facilitate new kinds of research and communication, while making scholars of the Ottoman empire generally more efficient and effective in their work.

The workshop was sponsored by Sabine Schmidtke, Professor in the School of Historical Studies, and convened together with me, along with Chris Gratien (Yale), Michael Polczynski (Georgetown), and Nir Shafir (UCLA), who have each worked on a digital resource for Ottoman history and were together the authors of "Digital Frontiers of Ottoman Studies," *Journal of the Ottoman and Turkish Studies Association* 1, no. 1–2 (2014): 37–51. A further nineteen participants from the United States, Canada, Britain, Germany, Greece, Bulgaria, and Turkey included scholars of pre-Ottoman and Ottoman history, librarians with digital expertise, geographers specializing in historical GIS projects, and an engineer with extensive management experience and digital skills.

Participants shared their knowledge of existing digital resources for Ottoman studies: programs, databases, published research, pedagogical materials, and research tools for scholars. These include, for example, databases on Ottoman historians and inscriptions from Ottoman buildings; books and original manuscripts from library collections worldwide; the Ottoman History Podcast (ottomanhistorypodcast.com) with some two hundred episodes; Hazine, a research guide; online catalogues to archives; costly and rare dictionaries online; and published scholarly work (out of copyright).

Individual presentations of hands-on experience with different digital methodologies and technologies fostered discussions of the advantages and challenges of digital endeavors in the humanities. Each contributed a valuable perspective on what is required to design, initiate, manage, fund, scale up, and sustain a project of the magnitude we envisage. The workshop emphasized to all of its participants that digital projects such as this can only thrive as partnerships of skills, enthusiasm, professional standards, and material support. At the same time, the discussions also considered carefully how and why digital projects falter or fail. Workshop participants shared their own experiences, frustrations, and critiques, examining carefully past projects and those currently under way. Declining or absent human or financial resources, technologies that became obsolete, and uncertain goals are only a few of the persistent problems that have undermined promising initiatives. Successful projects must address specific needs and be critically evaluated and tested on a small scale before committing extensive resources to them. As a result, the DOP is proceeding deliberately and with caution.

The collective decision to emerge from the workshop was that a gazetteer of the Ottoman lands will constitute the greatest contribution to the largest number of scholars. It will be a geo-referenced catalogue of places, each to be listed with its various names, in several languages, in their original alphabets and transliterated to Latin characters. Every entry and its variants will include dated references to its sources, and contributions will be reviewed before uploading, to make the gazetteer a reliable scholarly resource. From a practical perspective, the gazetteer can grow in a modular fashion, incorporating contributions as they are submitted. While it builds on the existing models from other fields, many Ottoman-specific challenges will need to be resolved. Of relevance far beyond the field of Ottoman studies is the larger challenge of how to ensure that the contributing authors of the gazetteer receive adequate academic credit for the critical scholarship needed to create sound data.

We envisage that the DOP will not only create datasets (gazetteer, biographies, monuments). It will also link to (and be interoperable with) robust digital projects (that pass a scientific review); provide a reference source for tested digital tools; incubate new projects; and serve as a digital publication site. The DOP will thus create basic resources for the entire field and exemplify how best to engage digital capabilities for humanistic research.

The DOP project fits as a natural complement to the ongoing projects in the IAS School of Historical Studies that engage digital capabilities in their research. In the specific context of the DOP, Schmidtke will focus on the creation of a Yemen Historical GIS as a complement to her ongoing studies of Yemeni manuscripts and scholarship. We believe that the IAS can play a unique role in this project, providing the ideal environment in which to define and nurture its successive phases. A local by-product of the seminar is the plan by the HS–SS Library to hold a series of workshops offering Members in both Schools the opportunity to explore and apply the digital tools that are expanding the parameters of scholarly inquiry. As the DOP workshop clarified, these tools work best when deployed by historian/social scientist–librarian–technologist teams, each bringing professional experience and a refined skill set to the endeavor. ■

Amy Singer, William D. Loughlin Member (2014–15) in the School of Historical Studies and Professor at Tel Aviv University, uses historical Geographical Information Systems and insights from spatial history to study the long-neglected Ottoman city of Edirne (Adrianople), the capital before the conquest of Istanbul and thereafter an enduring center of imperial and international activity.

Genius at Play: The Curious Mind of John Horton Conway

The elusive nature of biographical truth

BY SIOBHAN ROBERTS

During a visit to the Institute in the 1970s, the mathematician John Horton Conway, then of Cambridge, spent the ten most interesting minutes of his life. Invited to deliver a talk to the undergraduate math club at Princeton, Conway made his way across town and wangled himself a private audience with the God of logic, Kurt Gödel.

Conway had recently enjoyed his self-proclaimed *annus mirabilis:* In a period of twelve months in and around 1969 (which he usually rounds up to 1970), he invented the cellular automaton Game of Life, he discovered the 24-dimensional symmetrical entity named the Conway group, and while playing around with trivial children's games, he happened upon the aptly named surreal numbers. While Conway might be most popular among the masses for Life and its cult following, and while he might be most highly regarded among mathematicians for his big group, Conway himself is proudest of his surreal numbers. The surreals are a souped-up continuum of numbers including all the merely real numbers—integers, fractions, and irrationals such as π—and then going above and beyond and below and within, gathering in all the infinites and infinitesimals; the surreals are the largest possible extension of the real number line. And deferring to *Scientific American* columnist Martin Gardner's reliable assessment, the surreals are "infinite classes of weird numbers never before seen by man. They provide a secure foundation on which Conway … carefully builds a vast and fantastic edifice."

But an edifice of what? Conway wrote a paper on the surreals titled "All Numbers, Great and Small," and he concluded by asking, "Is the whole structure of any use?" The Hungarian American mathematician Paul Halmos reckoned, "It is on the boundary between funny stuff and serious mathematics. Conway realizes it won't be considered great, but he might still try to convince you that it is."

Halmos was mistaken, on one point at least, and quite possibly two. Conway believes the surreals are great. There's no "might" about it. If anything, he is keenly disappointed that the surreals haven't yet led to something greater. And he had good reason to hope. Based on his readings of Gödel's work, he thought the surreals might crack Cantor's continuum hypothesis—the hypothesis proposed by Cantor speculating on the possible sizes of infinite sets, stating that there is no infinity between the countable infinity of the integers and the uncountable infinity of the real numbers. Gödel and Paul Cohen (the latter achieving a result in 1963 that Conway called the "work of an alien being") collectively showed the hypothesis to be "probably unsolvable," at least according to the prevailing axioms of set theory, leaving the door ajar a sliver.

In this caricature sketched by his friend, John Conway's head has grown a "horned sphere," a topological entity that is counterintuitive and ill-behaved, much like the mathematician himself.

SIMON J. FRASER

To travel back in time a bit, Gödel and his wife Adele had fled Nazi Vienna and landed in Princeton in 1940. Gödel became good friends with Einstein, working on a theory of relativity that entailed a nonexpanding "rotating universe" wherein time travel was in fact a physical reality. Gödel also did his part regarding the continuum hypothesis while at the Institute. And even after having proved the impossibility of a disproof, the issue with the infinities nagged at him. In 1947, he published a paper, "What Is Cantor's Continuum Problem?" in the *American Mathematical Monthly*. He tried to provide an answer, first with some reinterpretive questions. "Cantor's continuum problem is simply the question: How many points are there on a straight line in Euclidean space?"

PERHAPS CONWAY'S SEEMING INABILITY TO DISTINGUISH FACT FROM FICTION CORRELATED TO HIS UNCANNY ABILITY TO SEE MATHEMATICS DIFFERENTLY AND TO ACHIEVE HIS IDIOSYNCRATICALLY ORIGINAL RESULTS.

Conway had read this and later papers by Gödel numerous times, before discovering the surreals and after. What struck Conway during these readings was Gödel's assertion—the Surprising Assertion, as Conway came to call it—that a solution to the continuum hypothesis might yet be possible, if *only* once the correct theory of infinitesimals had been found. Conway couldn't help but wonder: With the surreals, he believed that he had found at least *a* correct theory of the infinitesimals (and he still believes so). He wouldn't go as far as to say it was *the* correct theory, not before eliciting Gödel's opinion. During his visit to Princeton in the 1970s, Conway got the chance to ask the great man himself.

Conway would never have been so daring as to simply ring Gödel and request an appointment. The meeting came about via their mutual friend Stanley Tennenbaum, a mathematician and logician who for a time lived alone in the woods in New England, but he did the rounds through Montreal, Chicago, New York, and Princeton, the last being a regular pit stop for the purpose of talking to Gödel. "Stan was a sort of pet or protégé of Gödel's," recounted Conway. "So he had the ins to Gödel, and he said, 'If you like, I'll introduce you to God'—that's what he always called him. So anyway, Tennenbaum offered: 'Would you like to be introduced to God?' I said, 'Yes, of course.' You don't turn an invitation like that down."

Writing my biography of Conway (*Genius At Play: The Curious Mind of John Horton Conway* published last July) over several years and as many visits to the Institute from 2007–14, I found the date of Conway's meeting with Gödel impossible to pinpoint. The year had to be less than 1978, when Gödel died, and greater than 1970, the year Conway found the surreals. Probably also less than 1976, after which Gödel was in very poor health and rarely left his home, and greater than or equal to 1972, when Conway spent the spring term at Caltech. Somewhere therein, Conway had his visit with Gödel.

But never mind what year it was. I had other unanswerable questions as well. Where did the meeting transpire? In Fuld Hall at teatime, or in Gödel's office just off the mathematics library? What was Gödel like? Did he look well? I pestered Conway with these fiddly detail questions, for which he had no answers. And all my badgering made Conway, fellow of infinite jest that he is, laughingly wonder whether he'd met the great Gödel at all.

This gave me pause. Conway had already proved himself to be an unreliable narrator of his own life—and worse, an accomplished fictioneer, whenever the mood struck. I was both impressed and perplexed by his derring-do. Here I was attempting a finely drawn portrait of my subject, and against my best intentions and best efforts the biography seemed to be going a bit off the rails. Mingling with my betters at the Institute—where the world's best scholars delve deep into the past, the history of humanity, the evolution of the universe—I was ever answering the question from people as to how one writes about a living subject. And indeed, having Conway looking over my shoulder inevitably made his vital signs a liability, mostly for him. I realized this over lunch with Heinrich von Staden, an authority on ancient science, Professor Emeritus in the School of Historical Studies. He told me about the Greek and Roman tradition of vivisection, making public spectacle of strapping a live pig to a plank and cutting him open and observing the mechanics of his beating heart. A fitting metaphor, I realized, for what this experience was like for Conway.

Doing my part to contribute to the Institute community, I presented an After Hours Conversation on my predicament, on the elusive nature of biographical truth. Most talks in this neighborhood of the intellectual firmament were more rarefied. One scholar, the fabulously monikered Aristotle Socrates, an astrophysicist, spoke on "Solar Systems Unlike Our Own." Conway was, by comparison, high comedy, in an orbit all his own—prankish, belligerent, hijacking the process. As Exhibit A, I presented to my audience a caricature of Conway done by his friend Simon J. Fraser at the University of Toronto. The sketch was inscribed, "In homage to a diabolical mathematician," and as such it depicted Conway with hooves for feet and a topological entity called a "horned sphere" growing from his head—and to wit, more generally speaking a horned sphere is known as a "pathological example," an entity that is counterintuitive and ill-behaved, much like my subject himself.

Irving Lavin, an esteemed art historian and Professor Emeritus in the School

(Continued on page 12)

Patricia Crone's Enduring Legacy

New Membership in Near Eastern studies created in honor of Patricia Crone

A remembrance of Patricia Crone, Professor Emerita in the School of Historical Studies, was held at the Institute on October 24. Crone, whose pioneering and innovative approach to the history of Islam brought about lasting change in the field, died at the age of 70 on July 11 in Princeton, New Jersey, after a courageous fight against cancer. Led by a welcome from Robbert Dijkgraaf, remembrances were shared by colleagues Nicola Di Cosmo, Michael Cook, Carmela Franklin, Emma Gannagé, Judith Herrin, and Carol Bakhos, nephew Thomas Frank, and sister Diana Frank, followed by a video about Crone's life.

A new Membership has been created with Crone's generous designation of a significant portion of her estate to support a visiting scholar in Near Eastern studies, an area that she helped to build and strengthen at the Institute during her tenure. Gifts made in Crone's memory will be added to the Patricia Crone Fund, which will be used to support a Patricia Crone Member in the School.

Commenting on the establishment of the Membership, Sabine Schmidtke, Professor in the School of Historical Studies, noted, "Patricia's outstanding accomplishments as a scholar and the impact her research had on the field can hardly be estimated. What made her even more exceptional, however, was her quiet way of caring and her skills as a mentor. Her generous gift to the School of Historical Studies is a wonderful manner to keep her legacy as a *scholar-cum-mentor* alive."

"Patricia's final and touching act of generosity is an incredible gift for the Institute," added Robbert Dijkgraaf, Leon Levy Professor and Director of the Institute. "We now have a wonderful opportunity to honor Patricia's formidable legacy as a scholar by hosting some of the brightest minds in her field."

Patricia Crone served as the Andrew W. Mellon Professor in the School of Historical Studies since 1997, before retiring in 2014. Her insightful work, compellingly conveyed in her adventurous and unconventional style, shed important new light on the critical importance of the Near East in historical studies—in particular on the cultural, religious, and intellectual history of Islam.

Crone's significant scholarly impact and influence was recognized in the many appreciations that appeared after her death, including one in the *Economist*, which noted, "Islam arose with remarkable speed and mystery. Patricia Crone's well-stocked mind, clear prose, and unflinching intellectual honesty were devoted to explaining why."

Recommended viewing: Videos of the talks given in honor of Patricia Crone are available at https://video.ias.edu/crone-remembrance.

ANDREA KANE

Diana Frank shares remembrances of her sister Patricia Crone.

ROBERTS *(Continued from page 11)*

of Historical Studies, took an interest in the drawing and offered his assistance in deciphering what it said about my subject's antics. Lavin observed that Conway was in good company among artists who matched creativity with promiscuity, intellectual and/or interpersonal—Picasso, for example. Perhaps Conway's seeming inability to distinguish fact from fiction correlated to his uncanny ability to see mathematics differently and to achieve his idiosyncratically original results. Commenting on the caricature itself, Lavin rummaged around for relevant references and pointed to the seventeenth-century Italian artist Gian Lorenzo Bernini as an early ancestor of artists doing exaggerated comical drawings with massive heads to malign or poke fun at their subjects. Lavin thought the caricature vividly captured Conway as rapscallion. "Very cunning!" he said. Hear, hear—cunning: showing dexterity in artfully achieving one's ends by deceit, evasion, or trickery.

But all joking aside. Conway *had* met Gödel, really and truly. And luckily, I found some proof pointing in this direction archived among the Institute's Gödel papers. In a file labeled "discussion notes" for 1974, there was a list detailing Gödel's roving discussions with Tennenbaum, touching on everything from politics to mathematics—from Nixon, McGovern, hippies protesting the middle class, drug addicts, Vietnam, riots, and the decay of the United States, to Cohen and Dedekind, Coxeter and modern geometry, Nash and games, Chomsky and the "linguistic aspect of math ed"—I found a single word that looked like "Conway," then an eminently legible "Game of Life." This goes some distance, at least, as confirmation: Tennenbaum commended one friend to another, and they set up a date. When pressed for details of the meeting, Conway dug around in his memory bank and supposed they talked about some generally logical things while he worked up the nerve to ask Gödel about his Surprising Assertion.

"So I had, it can't have been much more than ten minutes with him," recalled Conway. "Between five minutes and half an hour, because it didn't seem to go on very long. But it might have actually just been because I wanted more. Anyway, whatever it was, I hesitantly asked him: Had he heard of the surreal numbers? And he had. And I asked him about the Surprising Assertion he'd made. I said to him that I thought I'd discovered the correct theory of infinitesimals. And he agreed. And I said, 'Well, what about your idea that we would learn more about the continuum hypothesis?' And he said, 'If I said that, I was wrong. Yes, you may very well have discovered the correct theory of infinitesimals, but it's not going to do anything for us.' I wonder what exactly his words were. The words I remember are 'I was wrong.' And I do remember the feeling of disappointment. And by the way, that seemed right to me. I never understood what he meant by the Surprising Assertion, what was in his mind. I think it was probably just a passing idea that he had without any real support for it. But I'm happy to have met the great man, even if it was only for a short interval."

Those ten minutes, give or take, count as the ten most interesting minutes of Conway's life—even if his theory of the infinites and the infinitesimals was left bereft of greater application.

A little more than twenty years later, Conway was installed as John von Neumann Distinguished Professor in Applied and Computational Mathematics at Princeton (where he's been ever since). The university communications office sent out a glossy press release, and the president, Bill Bowen, in announcing the hire, praised Conway into hyperspace. He was a "multifaceted phenomenon . . . one of the most eminent mathematicians of the century."

Conway bathed in the limelight, eager to woo the masses, the students, and his fellow colleagues. "Conway is a seducer, *the* seducer," said his Princeton colleague Peter Sarnak—speaking exclusively of Conway's skills as a teacher, of course. In time, Conway became the department's prize attraction, holding forth in the common room, usually doing nothing but piddling away his days playing more games. There he engaged Sarnak, who arrived at Princeton in 1991, in a viciously aggressive (if ostensibly playful) competition with a spinning toy called a Levitron. When Sarnak proved the superior levitator, Conway banned the Levitron from the premises. A gifted expositor, Conway taught at public lectures and private parties. And during a math department party at Sarnak's house, Conway pulled out his best parlor trick and performed it all night in the kitchen, mostly for women. The come-on, still attempted now and then, Conway always relishes recounting: "I can make U.S. pennies land the way you want for the rest of your life!" "He was the center of the party," recalled Sarnak, who in 2007 was cross-appointed Professor in the School of Mathematics at the Institute.

Conway is his own party, and he's always at the center. But Sarnak also holds Conway in high regard for his profound contributions to the mathematical oeuvre, especially the surreals. "The surreal numbers will be applied," assured Sarnak. "It's just a question of how and when." ■

This article is an adapted excerpt from Genius at Play: The Curious Mind of John Horton Conway *(Bloomsbury Publishing, 2015) by Siobhan Roberts, a journalist and biographer whose work focuses on mathematics and science. Roberts wrote the book while in residence at the Institute as a Director's Visitor (on various occasions, 2007–14).*

Dating the Earth, the Sun, and the Stars

Might stellar rotation explain the variance of ages seen in star clusters?

BY TIMOTHY BRANDT

"How big" is almost always an easier question to answer than "how old." Though we can measure the sizes of animals and plants easily enough, we can often only guess at their ages. The same was long true of the cosmos. The ancient Greeks Eratosthenes and Aristarchus measured the size of the Earth and Moon, but could not begin to understand how old they were. With space telescopes, we can now even measure the distances to stars thousands of light-years away using parallax, the same geometric technique proposed by Aristarchus, but no new technology can overcome the fundamental mismatch between the human lifespan and the timescales of the Earth, stars, and universe itself. Despite this, we now know the ages of the Earth and the universe to much better than 1 percent, and are beginning to date individual stars. Our ability to measure ages, to place ourselves in time as well as in space, stands as one of the greatest achievements of the last one hundred years.

In the Western world, the key to the age of the Earth was long assumed to be the Bible and its account of creation. Creation dating required careful accounting of the chronology given in Genesis and then matching it to historical events recorded elsewhere. Though James Ussher's date of 4004 B.C.E. is the most famous result (and is still accepted by many Biblical literalists), scientists and theologians including Maimonides, Isaac Newton, and Johannes Kepler also worked out dates around 4000 B.C.E. These estimates were not seriously challenged until the emergence of modern geology in the eighteenth century.

In the mid-1700s, the Scottish geologist James Hutton proposed that the processes of erosion, sedimentation, and volcanism that we observe today happened much the same way in the past. Acting over many millions of years, they could explain the geological record without recourse to the great flood of Noah. Charles Lyell popularized the concept of uniformitarianism in the mid-1800s and argued that the Earth had to be very old indeed. More generally, uniformitarianism holds that the physical laws and processes we see today are the key to understanding the past. This is the idea that, today, enables scientists (including many past and present Members of the Institute) to understand the afterglow of the Big Bang and to see the universe as it was 380,000 years after it formed.

Timothy Brandt is a NASA Sagan Fellow and a Member in the School of Natural Sciences. He studies how rotation changes our age estimates for stars and star clusters, and how rotation can resolve the puzzle of apparent age spreads seen in some clusters.


ANTHONY AYIOMAMITIS

Star clusters have a range not of ages, but of aging rates. Above: NGC 6811

Astrophysics first had something to add to the question of ages with the discovery of thermodynamics in the late 1800s. The gradual contraction of the Sun due to gravity could be a source of energy, replenishing the energy radiated away by sunshine. The Sun must be shrinking for this explanation to work. Turn the clock backwards, and at some point, the Sun must have extended past Earth's orbit. Lord Kelvin calculated that the Sun could only have sustained its current luminosity for about 20–40 million years. This was much too short for the geologists. It remained a puzzle until the discovery of nuclear fusion, the Sun's actual energy source, in the 1930s.

It was also astrophysics that finally provided a method for dating the Earth itself. In the early twentieth century, it was discovered that some chemical elements decay into others at highly stable rates. By measuring these rates, and the relative amounts of parent and daughter atoms in a rock, scientists could measure how long it had been since the rock solidified. The problem was that even the oldest rocks were not as old as the Earth itself. The young Earth was a hot and violent place, and even now, the Earth's surface is constantly changing as rocks are deposited, eroded away, and subducted into the mantle. The solution lay in space, where asteroids have remained essentially unchanged since the formation of the solar system. In 1953, Clair Cameron Patterson measured the abundances of three isotopes of lead in meteorites and calculated that the Earth must be about 4.6 billion years old. Small uncertainties in this number exist not because of any shortcomings of radioactive dating, but because we do not know the exact order in which the solar system formed. We can measure the ages of tiny grains in meteorites, called chondrules, to just 100,000 years out of 4.6 billion.

The measurement of the age of the universe is a similar triumph. It began with Edwin Hubble's discovery that galaxies are all flying away from one another. If galaxies are flying apart now, they must have been closer together in the past, and we can keep turning the clock back until all galaxies lay on top of one another. The universe at this time would have been incredibly hot and dense, bathed in radiation that could still be seen today. The discovery of this background radiation in the 1960s was strong evidence for a beginning (a Big Bang). Its detailed study in the last two decades, with major contributions from past and present Members of the Institute, has enabled us to determine the age of the universe to incredible precision: 13.8 billion years, give or take 40 million, an error of just 0.3 percent.

While we know the age of the Sun to about 0.1 percent, this is not true of any other star. It would not even be true of our Sun without meteoritic dating. Stars change little over billions of years: the Sun would have looked much the same to the dinosaurs as it does to us. However slowly though, stars do evolve. As the Sun's core converts hydrogen into the heavier element helium, its temperature increases to maintain the pressure needed to balance the crushing force of gravity. The same physics applies to balloons: filling a balloon with helium will keep it aloft, but switch out the helium for the same mass of heavier air molecules and

(Continued on page 14)

HAS THE MYSTERY OF THE GAMMA RAYS FROM THE GALACTIC CENTER BEEN SOLVED?

FIVE YEARS AGO, NASA's Fermi Gamma-ray Space Telescope saw more gamma rays than expected from the area around the center of our galaxy. Many scientists suggest that the extra gamma rays could be from the annihilation of dark matter particles. This exotic interpretation, however, requires ruling out all other possible sources of the gamma rays. While working at IAS as Members in the School of Natural Sciences, Bence Kocsis and I have discovered an ideal candidate source.

Rapidly spinning neutron stars, called millisecond pulsars, emit gamma rays just like those seen by Fermi. They are known to be created in globular clusters, the dense stellar islands in the galactic halo beloved by astrophotographers. While the region around the galactic center has few globular clusters today, recent research suggests that it once had many. Nearly all of these clusters would have migrated inwards and dissolved, releasing their millisecond pulsars into space. The extra Fermi gamma rays may be the first direct evidence of our galaxy's once-abundant globular cluster population.

Globular clusters are extraordinary environments. A star in the core of a globular cluster core could have hundreds of thousands of neighbors within a couple of light years; the Sun's nearest neighbor is four light years away. The stars deflect one another gravitationally, driving some closer together and ejecting others out of the cluster entirely. Given enough time, the stars of a globular cluster will evaporate into space like molecules from a droplet of water.

Because their interactions can drive pairs of stars close together, globular clusters can make exotic stellar systems. Neutron stars have the masses of stars, but have collapsed down to the sizes of cities, making them trillions of times denser than lead. Millisecond pulsars are neutron stars that have further grown by consuming matter from a companion star. The pulsars spin up until they rotate hundreds of times per second and have more energy in their rotation than the Sun will emit over its ten billion year lifespan. They slowly radiate this enormous reservoir of energy in gamma rays, shining for many billions of years. Millisecond pulsars are also the best clocks known: their radio pulses keep time better than the best atomic clocks on Earth.

Millisecond pulsars are much more common in globular clusters than in our galaxy's field of stars. They can also be longer-lived than the clusters themselves. While globular clusters evaporate and can be torn apart by the galaxy's gravitational tides, their millisecond pulsars will continue to shine for many billions of years. Using recent calculations of our galaxy's initial population of globular clusters, Kocsis and I have predicted the current gamma-ray signal. It is almost identical to what is seen by Fermi. The star clusters themselves have dissolved, leaving their millisecond pulsars to testify to their former existence. —*Timothy Brandt*

BRANDT *(Continued from page 13)*

you need a heater to keep it in the air (a hot-air balloon). The rate of nuclear reactions goes up as the core temperature rises, and the Sun shines more brightly. It is about 30 percent brighter today than when the Earth was young. This slow change in a star's temperature and brightness provides a clue, for many stars the only clue, to its age.

We estimate the ages of stars by simulating them on a computer and trying to match their properties to those of the stars we see. We take a star's worth of gas held together by gravity, calculate its structure, and then follow its evolution over millions or billions of years. The process relies on a lot of measurements and simplifying assumptions—from the temperature-dependent rates of many different nuclear reactions, to the absorbing and emitting properties of atoms under temperatures and pressures inaccessible on Earth, to the treatment of convection and rotation in the stellar interior. A full three-dimensional simulation of a star over its entire lifetime is well beyond the reach of any supercomputer. Perhaps surprisingly, the physics of the early universe is much simpler than the physics of a stellar interior, which is one reason why we can know the universe's basic properties to such precision.

The basic picture of stellar evolution was worked out decades ago: stars use up their hydrogen fuel, their cores contract and heat up, and sufficiently massive stars can fuse the helium into heavier and heavier elements. Eventually, either a star cannot attain the temperatures and pressures needed to fuse the next element, or it has fused all the way to iron (the most stable element) and cannot extract any more nuclear energy. The stellar core becomes a compact remnant (a white dwarf, neutron star, or black hole), and its outer layers either drift off into space or are thrown off violently in a supernova. The lifetime and fate of a star depend mostly on its mass, with massive stars living short lives, shining brightly, and dying in supernovae.

While the outline of stellar evolution is clear, it is the details that matter for stellar ages. Advances are made with careful improvements to stellar modeling, and typically make small differences in the results. Occasionally, though, it becomes possible to model an important physical effect that was previously neglected. This is now the case with stellar rotation. Rotation breaks a star's spherical symmetry (making the problem much more computationally challenging), but it also helps to support the stars against gravity, and can mix huge amounts of extra fuel into the core. Rotating stars burn more hydrogen over their lives; they live longer and shine brighter than their nonrotating counterparts. Rotating stellar models are forcing us to reconsider the ages of nearby star clusters, making them as much as 25 percent older than had been thought. These cluster ages are often used to anchor other dating techniques. Revising them could lead to a sort of domino effect, where many physical processes happen a bit more slowly than we had thought.

More intriguingly, stellar rotation may also explain a recent puzzle. Some star clusters seem to show a range of several hundred million years in age, much longer than standard star formation theory predicts. Just a few million years after forming, the most massive stars in a cluster end their lives as powerful supernova explosions, blowing away the remaining interstellar gas and cutting off star formation. Stellar rotation provides a simple solution: rotating stars can mix more fuel into their cores, increasing their supply of available energy and slowing the stellar aging process. These clusters have a range not of *ages*, but of *aging rates*. The effect is even stronger when considering that rapid rotation flattens a star. The poles of a rotating star are hotter than the equator; someone viewing the star pole-on will see a higher temperature and a larger area. Vega, one of the brightest stars in the night sky, is a very rapid rotator seen nearly pole-on. Viewed edge-on, Vega would only appear to be half as bright. A population of Vega clones oriented in all directions would show a wide range of apparent temperatures and luminosities, exactly the properties that we use to infer ages.

As stellar models continue to improve, a new tool has begun to offer a window into stellar interiors. Our best data on the interior of the Earth comes from measuring vibrations, from earthquakes to waves crashing on a shore, as they travel through rock, mantle, and core. These waves propagate differently depending on the material and allow us to peer inside the Earth. The same thing happens in stars, where convection and mixing stir up the stellar interior, which vibrates in response. We can detect these vibrations as tiny fluctuations in brightness produced by waves on the stellar surface. By measuring their frequencies, we learn about the conditions deep in the stellar interior.

The Kepler satellite is famous for detecting thousands of exoplanets by their transits across the faces of their host stars. Arguably just as important, however, are Kepler's measurements of starquakes on thousands of stars. These have allowed us to probe far below the stellar surface, into the cores where hydrogen fuses into helium over billions of years. The composition of the core tells us how much hydrogen has been burned, while the amount of starlight tells us how fast the core must be using up its nuclear fuel. Kepler has now brought the former measurement within reach. We build space telescopes like Kepler and its successor TESS mostly to find planets. But thanks to these missions, it may soon be possible to know the age of almost any bright star in the sky. ■

TREMAINE *(Continued from page 1)*

time the inward-spiraling gas disappears behind the event horizon a vast amount of radiation has been emitted from every kilogram of accreted gas.

In this process, the black hole can be thought of as a furnace: when provided with fuel (the gas) it produces energy (the outgoing radiation). Einstein's iconic formula $E=Mc^2$ relates mass M and the speed of light c to an energy E called the rest-mass energy. Using this relation, there is a natural dimensionless measure of the efficiency of this or any other furnace: the ratio of the energy it produces to the rest-mass energy of the fuel that it consumes. For furnaces that burn fossil fuels the efficiency is extraordinarily small, about 5×10^{-10}. For nuclear reactors using uranium fuel, the efficiency is much better, around 0.1 percent; and for the fusion reactions that power the Sun and stars, the efficiency can reach 0.3 percent.

> ARE BLACK HOLES AND QUASARS AN INTERESTING BY-PRODUCT OF GALAXY FORMATION THAT HAS NO INFLUENCE ON THE FORMATION PROCESS, OR DO THEY PLAY A CENTRAL ROLE IN REGULATING IT?

Black-hole furnaces can have even higher efficiency than any of these: between 10 and 40 percent. In the unlikely event that we could domesticate black holes, the entire electrical energy consumption in the United States could be provided by a black-hole furnace consuming only a few kilograms of fuel per year (an additional benefit of black holes is that they can consume radioactive waste, rather than generating it!).

Despite the relatively low efficiency of fusion reactions, most of the light in the universe comes from stars. Most of these stars are organized in galaxies. Our own galaxy contains a few tens of billions of stars arranged in a disk; the nearest of these is about 1 parsec (3.26 light years) from us, and the distance to the center of our galaxy is about 8 kiloparsecs (about 26,000 light years). The diffuse light from distant stars in the galactic disk is what we observe as the Milky Way.

A small fraction of galaxies contain mysterious compact light sources near their centers, called active galactic nuclei. The brightest of these are the quasars; remarkably, quasars can emit up to 10^{13} times more light than the Sun, thereby outshining the entire galaxy that hosts them. Even though quasars are much more rare than galaxies, they are so bright that they contribute almost 10 percent of the light emitted in the universe.

Ironically, the extraordinary luminosity of quasars is what made them hard to discover. Except in a few cases, they are so bright that the host galaxy cannot be seen in the glare from the quasar, and so small that they look like stars (in fact, "quasar" is a contraction of "quasi-stellar object"). Thus, even the brightest quasars are usually indistinguishable from millions of stars of similar brightness. Fortunately, some quasars are also strong sources of radio emission, and in 1963 this clue enabled astronomers to identify a radio source called 3C 273 with a faint optical source that looked like an undistinguished star. With this identification in hand, Maarten Schmidt at Caltech was able to show that 3C 273's spectral lines were redshifted—Doppler shifted by the cosmological expansion of the universe—to wavelengths 16 percent longer than laboratory spectra, and thus that 3C 273 was at a distance of eight hundred megaparsecs, ten million times further away than it would have been if it were a normal star.

By now we have discovered almost one hundred thousand quasars. Most were formed when the universe was 20–30 percent of its current age, and by now the population has declined from its peak by almost two orders of magnitude, presumably because the fuel supply for quasars is drying up as the universe expands at an accelerating rate.

How can quasars emit so much energy? The suggestion that they are black-hole furnaces was made soon after they were first discovered. But in the 1960s the black hole was a novel and exotic concept, and staggeringly massive black holes (roughly one hundred million solar masses) were required to explain quasar properties. Thus, most astronomers quite properly focused on more conservative models, such as supermassive stars, dense clusters of ordinary stars or neutron stars, and collapsing gas clouds. Over the next two decades, however, all of these models proved unable to explain the growing body of observations of quasars. Furthermore, other studies showed that the formation of massive black holes in the centers of galaxies is natural and perhaps even inevitable.

A number of indirect but compelling arguments also support the black-hole furnace hypothesis. For example, the luminous output of a bright quasar over its lifetime corresponds to a rest-mass energy of about one hundred million times the mass of the Sun. If this were produced by the fusion reactions that power stars with the efficiency of 0.3 percent given earlier, the required mass of fuel would be almost the total of all the stars in our galaxy. There is no plausible way to funnel this much mass into the tiny region close to the black hole. On the other hand, for a black-

(Continued on page 15)

hole furnace the efficiency is 10 percent or more, so the required mass is less than 10^9 solar masses, and this much gas is not hard to find close to the center of many galaxies. Thus, the black-hole furnace is the only model that does not exhaust the host galaxy's fuel budget.

A second argument concerns the size of quasars. Quasars vary irregularly in brightness on timescales as short as weeks. It proves quite difficult to construct any plausible model of a luminous astrophysical object that varies strongly on a timescale smaller than the light-travel time across the object: different parts of the object are not causally connected on this timescale, so they vary independently and their contributions tend to average out. Thus the size of the most rapidly varying quasars must be less than the distance light travels in a few weeks, around a few hundredths of a parsec or a few thousand times the Earth-Sun distance. Such distances are large by our standards but extremely small on galactic scales, a millionth of the size of the galaxy as a whole. A black hole of one hundred million solar masses and its surrounding accretion disk would fit comfortably inside this volume—its event horizon has a radius of about the Earth-Sun distance—but almost all of the alternative models for quasars fail to do so.

A third argument emerges because some quasars emit powerful jets of plasma that extend for up to a megaparsec (see Figure 1), probably collimated and accelerated by magnetic fields near the black hole. The production of these jets is not so remarkable: for example, various kinds of star also produce jets on a much smaller scale. However, quasar jets typically travel at close to the speed of light, and there is no plausible way to produce such high velocities except close to the event horizon of a black hole. Moreover, the jets are accurately straight, even though the innermost parts of the jet were emitted a million years after the material at the far end. Thus, whatever structure collimated the jet must maintain its alignment over several million years; this is easy if the jets are squirted out along the axis of a spinning black hole, but difficult or impossible in other quasar models.

IMAGE COURTESY OF R. GENZEL AND S. GILLESSEN

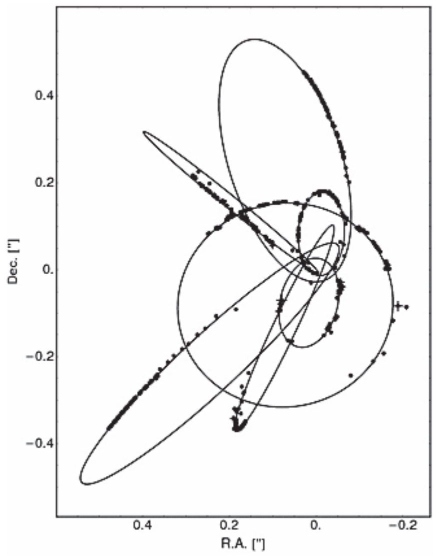

Figure 2: Orbit of stars near the center of our galaxy. The radio source Sagittarius A, believed to coincide with the black hole at the galaxy center, is at the zero point of the coordinates. The width of the frame is 0.03 parsecs or 6700 times the Earth-Sun distance. The smallest orbit, called S2, has a period of 15.8 years, and its point of closest approach to Sagittarius A* is 120 times the Earth-Sun distance. Fitting the orbits requires that Sagittarius A* is associated with a mass of 4.3 million solar masses contained within about 100 times the Earth-Sun distance.*

Based on these and other arguments, there is near-complete agreement that the power source for quasars is accretion of gas onto black holes of a hundred million solar masses or more. Accepting this model leads to a simple syllogism: if the number of quasars shining now is far smaller than when the universe was young, and quasars are black-hole furnaces, then many "normal" galaxies should still contain the black holes that used to power quasars at their centers, but are now dark. Can we find these "dead quasars" in nearby galaxies?

An important guidepost in this search came from the Polish astronomer Andrzej Sołtan. The universe is homogeneous, so on average the energy density in quasar light must be the same everywhere in the universe (here *average* means averaged over scales greater than about ten megaparsecs, which is still small compared to the overall "size" of the universe, a few thousand megaparsecs). We can measure this energy density by adding up the contributions from all the quasars found in surveys. If this energy were produced by black-hole furnaces with an efficiency of 10 percent, for example, then a mass M of material accreted by black holes would produce $0.1Mc^2$ in quasar light. Similarly, if the average mass density of dead quasars is ρ, then the energy density of quasar light must be $0.1\rho c^2$.

CAN WE UNDERSTAND THESE PROCESSES WELL ENOUGH TO TEST THE PREDICTIONS OF GENERAL RELATIVITY IN STRONG GRAVITATIONAL FIELDS, AND WILL EINSTEIN TURN OUT TO BE RIGHT?

Since we know the latter figure, we can invert the calculation to determine the mass density of dead quasars. The power of this argument is that it requires no assumptions about the masses or numbers of black holes; no knowledge of when, where, or how quasars formed; and no understanding of the physics of the quasar furnace except its efficiency. Sołtan's argument tells us that the mass density of dead quasars should be a few hundred thousand solar masses per cubic megaparsec, compared to a density of large galaxies of about one per hundred cubic megaparsecs. What it does not tell us is how common or how massive individual dead quasars are: on average there could be, for example, one dead quasar of ten million solar masses in every galaxy, or one of one billion solar masses in 1 percent of galaxies.

Stars that come under the influence of the black hole's gravitational field—typically those within a distance of a parsec or so—are accelerated to higher velocities. This acceleration leads to increased Doppler shifts, which broaden the spectral lines from the collective stellar population. The search for this effect in the centers of nearby galaxies began around 1980 and yielded evidence for black holes—or, at least, for massive dark objects—in a handful of cases. These results were tantalizing, but incomplete: the problem was that the angular resolution of ground-based telescopes is limited by blurring caused by the atmosphere, so the effects of a black hole could be detected only in the closest galaxies. This problem was one of the motivations for constructing the Hubble Space Telescope, which at the time of its launch in 1990 had roughly ten times the angular resolution of the best ground-based telescopes. Since then the Hubble Telescope has devoted thousands of hours to the hunt for black holes at the centers of galaxies, and this search has confirmed the early ground-based detections in nearby galaxies and produced firm evidence for massive dark objects in several dozen more distant ones. We believe that the massive dark objects observed by Hubble are black holes because the alternatives (for example, a dense cluster of low-luminosity stars) are far less plausible. In recent years the search for dead quasars has been resumed by ground-based telescopes, now using adaptive optics that corrects for atmospheric blurring in real time, providing angular resolutions that equal or exceed Hubble's.

Our own galaxy also contains a black hole. Very close to the center of the Milky Way is a compact source of strong radio emission known as Sagittarius A*. High-resolution infrared observations reveal a handful of bright stars within a few hundredths of a parsec from Sagittarius A*. The positions and velocities of these stars have been tracked, some for as long as two decades; in particular, the star S2 has an orbital period of only 15.8 years and now has been tracked through more than one complete orbit (Figure 2). Using first-year mechanics, we can deduce from this orbit that the star is orbiting a body that is located at Sagittarius A*, that this body has a mass of 4.3 million solar masses, and that the size of this body is less than only one hundred times the Earth-Sun distance. This extreme concentration of mass is incompatible with any known long-lived astrophysical system other than a black hole.

What have we learned more broadly about the relation between black holes and galaxies? First, black holes seem to be present in most galaxies. Second, in most cases the black-hole mass is about 0.2 percent of the mass of the stars in the galaxy. But are the black holes that we are finding really dead quasars? From galaxy surveys we can determine the average mass density in stars in the local universe, and since black-hole masses are typically 0.2 percent of the stellar mass in a galaxy, we can estimate the average mass density of black holes. Sołtan's argument, described earlier, gives the average mass density of dead quasars from completely different data. The two estimates agree to within a factor of about two—well within the uncertainties—so there is little doubt that the black holes we have found are indeed the ash from quasars. Thus quasars—one of the most remarkable components of the extragalactic universe—turn out to be black holes—one of the most exotic predictions of twentieth-century theoretical physics.

One of the most profound unanswered questions about these objects is the relation between black holes and galaxy formation. Although black holes make up only a fraction of a percent of the mass of the stars in galaxies, the energy released in forming them is hundreds of times larger than the energy released in forming the rest of the galaxy. If even a small fraction of this energy were fed back to the surrounding gas and stars, it would have a dramatic influence on the galaxy formation process, perhaps blowing the gas out of the galaxy and thereby quenching the formation of new stars. Are black holes and quasars an interesting by-product of galaxy formation that has no influence on the formation process, or do they play a central role in regulating it? More succinctly, do galaxies determine the properties of quasars or vice versa?

A second profound question is whether these black holes can serve as physics laboratories. All of the tests of Einstein's theory so far—which it has passed with flying colors—have been conducted in weak gravitational fields, such as those on Earth or in the solar system. Thus we have no direct evidence that the theory works in strong gravitational fields. Many naturally occurring processes near black holes in galaxy centers, such as swallowing of stars and black-hole mergers, may potentially be measured with the next generation of astronomical observatories. Can we understand these processes well enough to test the predictions of general relativity in strong gravitational fields, and will Einstein turn out to be right? ■

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From Quantum Field Theory Esoterica to Wide and Continuing Implications

Exploring the connection between anomalies and counting quark degrees of freedom

BY STEPHEN ADLER

The article by Wally Greenberg in the spring 2015 *Institute Letter* mentions the anomalous axial current triangle diagram and describes its connection with counting quark degrees of freedom. This derives from a calculation I did when a long-term Member at the Institute in 1968, so I thought it would be useful to describe in detail the work done by me and by Bill Bardeen at the Institute on axial-vector or chiral anomalies. At first, this work was considered to be quantum field theory esoterica, but it has turned out to have wide and continuing implications.

But first, what is an axial-vector? A vector is a directed arrow. If you hold your right hand up to a mirror with the thumb pointing towards the mirror, you will see as the image a left hand with the thumb pointing towards you. This reversal of direction is characteristic of a *vector* under inversion of the coordinate axes (in this case, inversion of the axis perpendicular to the mirror). But another behavior is possible: a directed arrow that remains the same under inversion of the coordinate axes. Such a quantity is called an *axial-vector* or *pseudovector*. In the Maxwell equations for electromagnetism, electric fields behave as vectors and magnetic fields behave as axial-vectors under coordinate inversion, so this distinction has been around for many years.

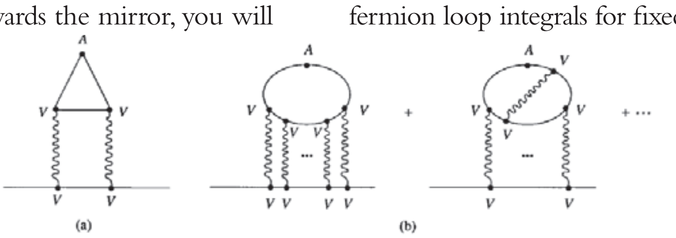


Fig. 1. Fermion loop diagram contributions to the axial-vector vertex part. Solid lines are fermions and dashed lines are photons. (a) The smallest loop, the AVV triangle diagram. (b) Larger loops with four or more vector vertices, which (when summed over vertex orderings) obey normal Ward identities.

Now let us fast forward to 1956, when Tsung Dao Lee (then at Columbia, later an IAS Faculty member) and Chen Ning Yang (at that time an IAS Faculty member) proposed a then-radical solution to a puzzle that had appeared in the decay of what are now called K mesons. At that time, these particles were called theta or tau mesons, depending on the decay mode, because it was assumed that inversion-symmetry or *parity* had to be conserved in all particle interactions. Lee and Yang studied the literature on weak interactions, and showed that there was no evidence supporting the idea of parity conservation in the weak interactions. If parity were violated (as noted at the Rochester Conference by Martin Block of Northwestern, via his roommate Richard Feynman), then a single type of meson could be decaying to final decay states with different parities. Lee and Yang proposed specific experimental tests of their suggestion, one of which was carried out by Madam Chien-Shiung Wu of Columbia and collaborators at the National Bureau of Standards, confirming in 1957 that parity is violated in weak decays. The experimental discovery of parity violation was front-page news in the *New York Times*. This was the year I graduated from high school, and it helped motivate my interest in particle physics. Lee and Yang received the 1957 Nobel Prize in physics for their joint work. (Much has been written about the omission of Madam Wu from Nobel recognition, which could be an essay in itself.) In the standard model of particle physics, parity violation in the weak interactions takes the form that the force carriers of the weak interactions couple to a left-handed (or *left chiral*) mixture of vector and axial-vector currents, in symbolic terms $A-V$. Under axis inversion, A does not change in sign, but V does. Under axis inversion, the coupling becomes $A+V$, a right handed (or *right-chiral* mixture) of vector and axial-vector currents.

CHIRAL ANOMALIES AND $\pi^0 \to \gamma\gamma$ DECAY

Let us now fast forward again to 1968, when I was a long-term Member at the Institute, having been recruited in 1966 together with Roger Dashen to restart particle theory, after IAS particle theorists Abraham Pais, Lee, and Yang left for positions elsewhere. I got into the subject of anomalies in an indirect way, through exploration during 1967–68 of the speculative idea that the muon-electron mass difference could be accounted for by giving the muon an additional electromagnetic coupling through an axial-vector current, which somehow was nonperturbatively renormalized to zero. After much fruitless study of the integral equations for the axial-vector vertex part, I decided in the spring of 1968 to first try to answer a well-defined question, which was whether the axial-vector vertex in quantum electrodynamics is renormalized by the same factor as the vector vertex, as I had been implicitly assuming. When I turned to this question, I had just started a six-week visit to the Cavendish Laboratory in Cambridge, England, after flying to London with my family in April 1968. In the laboratory, I shared an office with my former adviser Sam Treiman and was enjoying the opportunity to try a new project not requiring extensive computer analysis, unlike my thesis work on weak pion production.

Working in the old Cavendish, I rather rapidly found an inductive multiplicative renormalizability proof, paralleling the one in the text of James Bjorken and Sidney Drell for the vector vertex. I prepared a detailed outline for a paper describing the proof, but before writing things up, I decided as a check to test whether the formal argument for the closed loop part of the Ward identity, meaning the current conservation identity, worked in the case of the smallest loop diagram. This is a triangle diagram with one axial and two vector vertices (the AVV triangle; see Fig. 1(a)), which has no analogue in the vector vertex or VVV case. I knew from a student seminar that I had attended during my graduate study at Princeton that this diagram had been explicitly calculated by Leonard Rosenberg, who was interested in the astrophysical process $\gamma_V + \nu \to \gamma + \nu$, with γ_V a virtual photon emitted by a nucleus. I got Rosenberg's paper, tested the Ward identity, and to my astonishment (and Treiman's when I told him the result) found that it failed! I soon found that the problem was that my formal proof used a shift of integration variables inside a linearly divergent integral, which (as I again recalled from student reading) had been analyzed in an appendix to the classic text of Josef Jauch and Fritz Rohrlich, with a calculable constant remainder. For all closed loop contributions to the axial vertex in electrodynamics with larger numbers of vector vertices (the $AVVVV$, $AVVVVVV$,... loops; see Fig. 1(b)), the fermion loop integrals for fixed photon momenta are highly convergent and the shift of integration variables needed in the Ward identity *is* valid, so proceeding in this fermion loop-wise fashion, there were apparently no further additional or "anomalous" contributions to the axial-vector Ward identity. With this fact in the back of my mind, I was convinced from the outset that the anomalous contribution to the axial Ward identity would come just from the triangle diagram, with no renormalizations of the anomaly coefficient arising from higher order AVV diagrams with virtual photon insertions.

In early June, at the end of my six weeks in Cambridge, I returned to the United States and then went to Aspen, where I spent the summer working out a manuscript on the properties of the axial anomaly, which became the body of the final published version. Several of the things done there deserve mention, since they were important in later applications. The first was a calculation of the field theoretic form of the anomaly, giving the now well-known result

$$\partial^\mu j^5_\mu(x) = 2im_0 j^5(x) + \frac{\alpha_0}{4\pi} F^{\xi\sigma}(x) F^{\tau\rho}(x) \epsilon_{\xi\sigma\tau\rho} ,$$

with $j^5_\mu = \bar{\psi}\gamma_\mu\gamma_5\psi$ the axial-vector current (referred to above as A), F the electromagnetic field strength tensor, $j^5 = \bar{\psi}\gamma_5\psi$ the pseudoscalar current, with ϵ a totally antisymmetric tensor, and with m_0 and α_0 the (unrenormalized) fermion mass and coupling constant. In this formula, the first term on the right is the "normal" conservation result, and the second term on the right is the "anomaly," a term I coined in my paper that has stuck. The second was a demonstration that because of the anomaly, the renormalization factor for the axial-vector vertex is not the same as that for the vector vertex (called Z_2), as a result of the diagram drawn in Fig. 1(a) in which the AVV triangle is joined to an electron line with two virtual photons. Instead, the axial-vector vertex is made finite by multiplication by the renormalization constant

$$Z_A = Z_2[1 + \frac{3}{4}(\alpha_0/\pi)^2 \log(\Lambda^2/m^2) + ...] ,$$

thus giving an answer to the question with which I started my investigation. As an application of this result, I showed that the anomaly leads, in fourth order of perturbation theory, to infinite radiative corrections to the current-current theory of $\nu_\mu\mu$ and $\nu_e e$ scattering, but that this infinity can be canceled between different fermion species by adding appropriate $\nu_\mu e$ and $\nu_e\mu$ scattering terms to the Lagrangian. This result is a forerunner of anomaly cancelation mechanisms in modern gauge theories.

No sooner was this part of my paper completed than Sidney Coleman arrived in Aspen from Europe, and told me that John Bell and Roman Jackiw had independently discovered the anomalous behavior of the AVV triangle graph, in the context of a sigma model investigation of the Veltman–Sutherland theorem stating that $\pi^0 \to \gamma\gamma$ decay is forbidden in a calculation assuming non-anomalous behavior of the axial-vector current. Bell and Jackiw analyzed this theorem by a perturbative calculation in the sigma-model, in which the connection between normal axial-vector current conservation and pion properties is built-in from the outset, and found a non-vanishing result for the $\pi^0 \to \gamma\gamma$ amplitude, which they traced back to the fact that the regularized AVV triangle diagram cannot be defined to satisfy the requirements of both normal axial-vector and vector current conservation. This constituted the "puzzle" referred to in the title of their paper. They then proposed to modify the original sigma-model by adding further regulator fields with mass-dependent coupling constants in such a manner as to simultaneously enforce normal axial-vector and vector current conservation, thus enforcing the Sutherland–Veltman prediction of a vanishing $\pi^0 \to \gamma\gamma$ decay amplitude.

It was immediately clear to me, in the course of the conversation with Sidney Coleman, that introducing additional regulators to eliminate the anomaly would entail other problems, and was not the correct way to proceed. However, it was also clear that Bell and Jackiw had made an important observation in tying the anomaly to the Sutherland–Veltman theorem for $\pi^0 \to \gamma\gamma$ decay, and that I could use the sigma-model version of the anomaly equation to get a nonzero prediction for the $\pi^0 \to \gamma\gamma$ amplitude, with the whole decay amplitude arising from the anomaly term!

(Continued on page 17)

I then wrote an appendix to my paper, clearly delineated from the manuscript that I had finished before Sidney's arrival, in which I gave a detailed rebuttal of the regulator construction, by showing that the anomaly could not be eliminated without spoiling either vector current conservation or renormalizability. (In later discussions I added unitarity to this list, to exclude the possibility of canceling the anomaly by adding a singular term to the axial current.) In this appendix, I also used an anomaly modified axial-vector current conservation equation

$$\partial^\mu j_\mu^5(x) = (f_\pi M_\pi^2/\sqrt{2})\varphi_\pi(x)+S\frac{\alpha_0}{4\pi}F^{\xi\sigma}(x)F^{\tau\rho}(x)\epsilon_{\xi\sigma\tau\rho}\,,$$

with M_π the pion mass, φ_π the pion field, and f_π the charged pion decay constant, and with S a constant determined by the neutral pion's constituent fermion charges and axial-vector couplings, to obtain a formula for the $\pi^0 \to \gamma\gamma$ amplitude F^π

$$F^\pi = -(\alpha/\pi)2S\sqrt{2}/f_\pi \quad .$$

My paper was typed on my return to Princeton and was submitted to *Physical Review.* It was accepted along with a signed referee's report from James Bjorken stating, "This paper opens a topic similar to the old controversies on photon mass and nature of vacuum polarization. The lesson there, as I (no doubt foolishly) predict will happen here, is that infinities in diagrams are really troublesome, and that if the cutoff that is used violates a cherished symmetry of the theory, the results do not respect the symmetry. I will also predict a long chain of papers devoted to the question the author has raised, culminating in a clever renormalizable cutoff which respects chiral symmetry and which, therefore, removes Adler's extra term." Thus, acceptance of the point of view that I had advocated was not immediate, but only followed over time. In 1999, Bjorken was a speaker at my sixtieth birthday conference at the Institute for Advanced Study, and he amused the audience by reading from his report, and then very graciously gave me his file copy, with an appreciative inscription, as a souvenir.

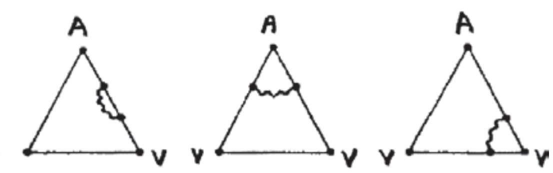


Fig. 2: Typical second-order radiative corrections to the triangle diagram in spinor electrodynamics.

The viewpoint that the anomaly determines the $\pi^0 \to \gamma\gamma$ decay amplitude had significant physical consequences. In the appendix to my paper, I showed that the value $S = \frac{1}{6}$ implied by the fractionally charged quark model gave a decay amplitude that was roughly a factor of 3 too small. More generally, I showed that a triplet constituent model with charges $(Q, Q-1, Q-1)$ gave $S = Q - \frac{1}{2}$, and so with integrally charged constituents ($Q = 0$ or $Q = 1$), one gets an amplitude that agrees in absolute value, to within the expected accuracy, with experiment. This gave the first indications that neutral pion decay provides empirical evidence that can discriminate between different models for hadronic constituents. The correct interpretation of the fact that $S \simeq \frac{1}{2}$ came only later, when what we now call the "color" degree of freedom was introduced in the seminal papers of Bill Bardeen, Harald Fritzsch, and Murray Gell-Mann and Fritzsch and Gell-Mann. These papers used my calculation of $\pi^0 \to \gamma\gamma$ decay as supporting justification for the tripling of the number of fractionally charged quark degrees of freedom, thus increasing the theoretical value of S for fractionally charged quarks from $\frac{1}{6}$ to $\frac{1}{2}$. The paper of Bardeen, Fritzsch, and Gell-Mann also pointed out that this tripling would show up in a measurement of R, the ratio of hadronic to muon pair production in electron positron collisions, while noting that "experiments at present are too low in energy and not accurate enough to test this prediction, but in the next year or two the situation should change," as indeed it did.

ANOMALY NONRENORMALIZATION

Before the neutral pion low-energy theorem could be used as evidence for the charge structure of quarks, one needed to be sure that there were no corrections to the anomaly and the low-energy theorem following from higher orders in perturbation theory. The fermion loop-wise argument that I used in my original treatment left me convinced that only the lowest order AVV diagram would contribute to the anomaly, but this was not a proof and was controversial. This was the motivation for a more thorough analysis of the nonrenormalization issue that I undertook with Bill Bardeen (an IAS Member at the time) in the fall and winter of 1968–69.

We approached the problem of nonrenormalization by two different methods. We first gave a general constructive argument for nonrenormalization of the anomaly to all orders, in both quantum electrodynamics and in the sigma model, and we then backed this argument up with an explicit calculation of the leading-order radiative corrections to the anomaly, showing that they canceled among the various contributing Feynman diagrams. The strategy of the general argument was to note that since the anomaly equations written above involve unrenormalized fields, masses, and coupling constants, these equations are well defined only in a cutoff field theory. Thus, for both electrodynamics and the sigma model, we constructed cutoff versions by introducing regulator fields. In the cutoff theories, the fermion loop-wise argument I used in my original anomaly paper is still valid, because regulating boson propagators does not alter the chiral symmetry properties of the theory, and thus it is straightforward to prove the validity of the anomaly equations involving unrenormalized quantities to all orders of perturbation theory.

In our explicit second-order calculation, we calculated the leading-order radiative corrections to this low-energy theorem, arising from addition of a single virtual photon or virtual σ-meson to the lowest order diagram (see Fig. 2). We did this two ways, which both gave the same answer: the sum of all the radiative corrections is zero, as expected from our general nonrenormalization argument. This paper with Bardeen should have ended the controversy over whether the anomaly was renormalized, but it continued for several more years. Suffice it to say here that no objections raised have withstood careful analysis, and there is now a detailed understanding of anomaly nonrenormalization both by perturbative methods, and by nonperturbative methods proceeding from the Callan–Symanzik equations. There is also a detailed understanding of anomaly nonrenormalization in the context of supersymmetric theories, where initial apparent puzzles are now resolved.

THE NON-ABELIAN ANOMALY, ITS NONRENORMALIZATION AND GEOMETRIC INTERPRETATION

Since in the zero fermion mass limit the AVV triangle is identical to an AAA triangle, I knew already in unpublished notes dating from the late summer of 1968 that the AAA triangle would also have an anomaly. From fragmentary calculations begun in Aspen I suspected that higher loop diagrams might have anomalies as well, so after the nonrenormalization work was finished I suggested to Bardeen that he work out the general anomaly for larger diagrams. I showed Bill my notes, which contained a pertinent remark by Roger Dashen that including charge structure (which I had not) would allow a larger class of potentially anomalous diagrams. Within a few weeks, Bill carried out an impressive calculation of the general anomaly in both the Abelian (i.e., electromagnetic) and the non-Abelian cases. Expressed in terms of vector and axial-vector Yang-Mills field strengths

$$F_V^{\mu\nu}(x) = \partial^\mu V^\nu(x) - \partial^\nu V^\mu(x) - i[V^\mu(x), V^\nu(x)] - i[A^\mu(x), A^\nu(x)]\,,$$

$$F_A^{\mu\nu}(x) = \partial^\mu A^\nu(x) - \partial^\nu A^\mu(x) - i[V^\mu(x), A^\nu(x)] - i[A^\mu(x), V^\nu(x)]\,,$$

his result takes the form

$$\begin{aligned}\partial^\mu j_\mu^{5a}(x) &= \text{normal divergence term}\\ &+ (1/4\pi^2)\epsilon_{\mu\nu\sigma\tau}\mathrm{tr}_I[\lambda_A^a[(1/4)F_V^{\mu\nu}(x)F_V^{\sigma\tau}(x)+(1/12)F_A^{\mu\nu}(x)F_A^{\sigma\tau}(x)\\ &+ (2/3)iA^\mu(x)A^\nu(x)F_V^{\sigma\tau}(x)+(2/3)iF_V^{\mu\nu}(x)A^\sigma(x)A^\tau(x)\\ &+ (2/3)iA^\mu(x)F_V^{\nu\sigma}(x)A^\tau(x) - (8/3)A^\mu(x)A^\nu(x)A^\sigma(x)A^\tau(x)]\,,\end{aligned}$$

with tr_I denoting a trace over internal degrees of freedom, and λ_A^a the internal symmetry matrix associated with the axial-vector external field. In the Abelian case, with trivial internal symmetry structure, the terms involving two or three factors of $A^{\mu,\nu,\dots}$ vanish by antisymmetry of $\epsilon_{\mu\nu\sigma\tau}$, and there are only AVV and AAA triangle anomalies. When there is nontrivial internal symmetry or charge structure, there are anomalies associated with the box and pentagon diagrams as well, confirming Dashen's intuition mentioned earlier.

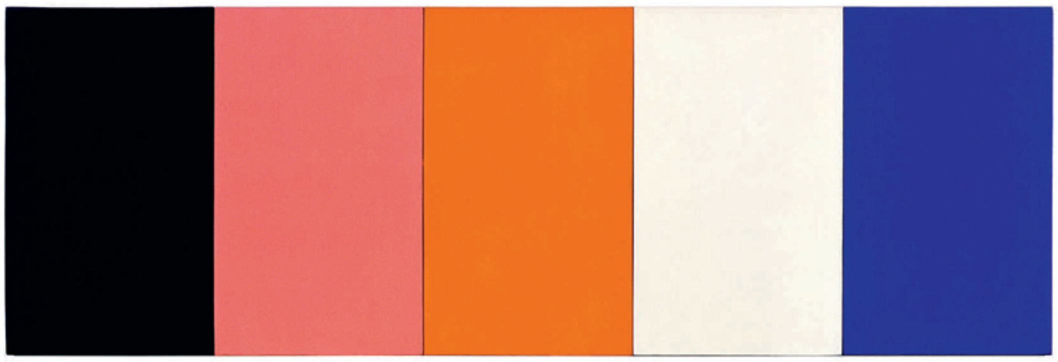
There are several lines of argument leading to the conclusion that the non-Abelian chiral anomaly also has a nonrenormalization theorem, and is given exactly by the leading-order calculation. Heuristically, what is happening is that except for a few small one-fermion loop diagrams, non-Abelian theories, just like Abelian ones, are made finite by regularization of the gluon propagators. But this regularization has no effect on the chiral properties of the theory, and therefore does not change its anomaly structure, which can thus be deduced from the structure of the few small fermion loop diagrams for which naive classical manipulations break down.

The fact that non-Abelian anomalies are given by the leading-order calculation has important implications for quantum field theory. For example, the presence of anomalies spoils the renormalizability of non-Abelian gauge theories and requires the cancelation of gauged anomalies between different fermion species through imposition of the condition $\mathrm{tr}\{T_\alpha, T_\beta\}T_\gamma = 0$ for all α, β, γ, with T_α the coupling matrices of gauge bosons to left-handed fermions. The fact that anomalies have a rigid structure then implies that once these anomaly cancelation conditions are imposed for the lowest-order anomalous triangle diagrams, no further conditions arise from anomalous square or pentagon diagrams, or from radiative corrections to these leading fermion loop diagrams. Anomaly cancelation is an amazing feature of the coupling structure of each family of quarks in the Standard Model, and is an important requirement in unifying extensions of the current theories. ■

Stephen Adler, Professor Emeritus in the School of Natural Sciences, joined the Faculty of the Institute in 1969. Apart from the first section, this article is a shortened version of Adler's Chapter 3 Commentaries *in S. L. Adler,* Adventures in Theoretical Physics: Selected Papers with Commentaries, *in volume 37 of the World Scientific Series in Twentieth-Century Physics (World Scientific, 2006). See also his article "Anomalies to All Orders" in Gerard 't Hooft, ed.,* 50 Years of Yang-Mills Theory *(World Scientific, 2005).*

BOIS *(Continued from page 1)*

any term in the set sequence with another *absent* term that fits the same grammatical criteria. In "black, rose, orange, white, blue," to take the example of the child's utterance again, the word "black" could be replaced by the word "gray," the word "rose" by the word "purple," orange by red, white by yellow, blue by green—but any other set of color names would do just as well. Just as well, that is, in grammatical terms, although not semantically, each name having its own connotations. And when we switch from the names of colors to colors per se, to Kelly's monochrome panels, this semantic uniqueness is even more acutely felt: each color, each nuance or gradation of each color, has its own character. True, colors never cease to interact, and as Josef Albers was fond of demonstrating, a particular color can be made to look, through interaction with other neighboring colors, like two utterly different ones, or two different colors can be made to look like one, but such tricks, which nature plays on us from time to time, can only be intentionally performed in full knowledge of the specific, differential character of the individual colors at play. That each color is absolutely singular, as singular a proper name, is the intuition that had guided Kelly as he was working on *Painting for a White Wall*, and it was paradoxically confirmed by the child's mistake in naming that painting's leftmost panel (which is dark blue, not black). This intuition emanates from a nominalist conception of art that pervades Kelly's whole oeuvre, from his first transfers onward (he effectively declares that there are no universals when he excerpts a flat pattern from the world at large and transcribes it as such in a painting or relief: what captured his fancy is the shape and proportions of *that* particular seaweed, of *that* window, of *that* flagstone arrangement, and it is this that he wanted to record as precisely as possible). It is this same intuition as well that he decided to explore in greater detail when he undertook *Spectrum I*.



ELLSWORTH KELLY/EDITIONS CAHIERS D'ART

Painting for a White Wall *(1952), the first manifestation of the artist's impulse to name colors*

But if one wants to investigate the infinite realm of colors, where should one begin? Just as a child had helped him pinpoint the underlying impulse behind *Painting for a White Wall* (that of naming colors), a detour via the enchanted world of childhood provided Kelly with his point of entry. One starts indeed with naming, and more exactly with the naming of the colors of the rainbow (from which pink is absent)—that is, with Roy G. Biv. Or rather, with its modern revision, which got rid of the indigo that Isaac Newton had included in his chromatic circle in order to obtain (for totally unscientific reasons) a total of seven colors. (Unlike scientists who felt they needed to stick by Newton, especially after Goethe had lambasted his *Optics*, painters were quick to object.) Among artists at least, the twelve-color chromatic circle most frequently in use today was already well established in Europe and particularly in France by the end of the nineteenth century—favored in fact by all painters, from academic followers of Ingres to the most radical members of the avant-garde. The elegant simplicity of the duodecachromatic circle, with its facing off of primaries and secondaries, is what made it so successful. It is no surprise that Kelly, then based in France, would have reached for this standard color wheel as a prop for his attempt at mapping the spectrum.

It should be noted, however, that in doing so he was departing from the color theory he had been fed as a student, which was based on the elaborate system conceived in Boston at the beginning of the twentieth century by Albert Munsell. Taught in American art schools and still in use today in many sectors of American industry, this system is based on a chromatic circle that comprises *ten* instead of twelve hues and in which green and purple are added to red/yellow/blue as principal hues. Kelly vividly remembers the color exercises he was assigned in his classes at the Pratt Institute, in 1941–42, which required him to fill up ten "Munsell student charts," one per hue, by pasting on them small cutouts of colored paper in sequential progressions of value (from light to dark) and saturation (from minimum to maximum chroma). He still possesses these charts, which have lost some of their original pasted cutouts. Leafing through them recently, he observed: "It is the first time that I realized that I preferred all the spectrum colors in their strongest chroma position, and the strongest chroma color has guided my color selections for all my works ever since." Given Munsell's goal of codifying every possible gradation of any hue, of identifying in excruciating detail every minute difference in value and saturation, which involved the manipulation of many toned-down shades, these exercises would not have been of much value in helping Kelly elaborate his spectrum sequence. Full saturation was the least of Munsell's concerns, and he certainly did not want to name colors (his whole system of notation was in fact conceived as a possible substitute to color nomination)—which is to say, at this particular juncture of Kelly's pursuit, Munsell could hardly have been the best guide. Only one extra chart, had the artist only had his Munsell kit with him in Paris, could have been helpful (and it is possible that, at lease unconsciously, he remembered it). Concerning the concepts of value, chroma, and hue in general, this eleventh chart sports both a chromatic circle and, at the top, a horizontal spectrum in "ten hues at maximum chroma," which begins at left with yellow, like *Spectrum I* (but, unlike Kelly's painting, ends at right with orange).

The only preparatory work for *Spectrum I* is a collage (there is no other sketch of any sort). It is made with the same *papier gommette* that Kelly had used for most of his collages since falling in love with this semigloss material more than two years earlier. Out of the twenty or so colors in which it was available, he chose the twelve that came closest to the hues of the color wheel. From them he cut thirteen long strips: two identical yellow ones, as this color appears at each end of his rendition of the spectrum (cartographers use the same looping device when they draw a planisphere), and one for each of the other eleven colors. Needless to say, Kelly knew full well, when he glued these strips of colored paper together, that the result would only be an approximation of the spectrum, for it was obvious that quite a few of the colors offered by the manufacturer of the gummed paper were not fully saturated (to use the artist's expression, they were "out of chroma"). But this offered enough encouragement to pursue the experiment, even if it meant breaking a rule he had followed in his previous works based on *papier gommette* collages, which was to match the hues of the material when translating them into paint. Paint can be mixed, so the matter of adjusting the color of each band in such a way that the intervals of hue and value between each strip would be equal did not seem so elusive a task (progressing symmetrically from the brightest color on both sides, yellow, to the darkest one in the center, purple or violet).

To Kelly's astonishment, he hit a snag, with the central color in particular. The purple was coming out too dark, so in order to brighten it he mixed in some white, but this "grayed" it, as he says. Intervals gave him all kinds of problems. He had thought that adding a supplementary shade of yellow would help (the canvas has one more stripe than the collage, with two different yellows on the right side), but it did nothing of the sort. The fact is that he was after the grail, trying to keep intact the identity of each color (naming it) while stringing them all together. Even an Albers, who has spent his life experimenting with color interaction, will admit that if obtaining regular intervals of value on a single field is complicated but not out of reach, it is much more difficult to achieve the same goal with regard to saturation and downright impossible with regard to hue, which is why not a single exercise of his celebrated color course dealt directly with this last conundrum. The reason for this impossibility is precisely that the regularity of intervals is constantly skewed by color interaction, and monitoring all the effects of this interaction (which, on top of everything, is subject to the slightest modification of lighting conditions) is above human capacity when many hues are simultaneously employed in a field-particularly when, as in the case of the duodecachromatic circle, they are at maximum saturation. Two other optical effects, unplanned by Kelly, are also caused by color interaction: the fluting effect that makes each band look concave, like the grooves of a Doric column, and the ghostly X that spans the whole surface of the painting, starting from each corner and crossing in the middle.

Anyone leafing through the pages of this volume cannot but be struck not only by the pace at which the artist's production evolved during this early period of his career but also by its diversity—with the exception perhaps of the paintings he produced as a student during his brief attendance at the Boston Museum School, prior to his departure for France. This diversity is the main reason many of the works examined in this volume are discussed at such length and in such detail: in almost every case, the particular question the artist was addressing, and the formal solution he devised for it, was entirely novel to him. Furthermore, no sooner had he resolved a problem than unexpected avenues of inquiry emerged from that very success and new questions appeared. The letters he writes to friends during this period are replete with complaints about not having enough time to realize in painting all his final studies, many of them neat collages that would linger in drawers awaiting a quieter time. That lull never came while he was overseas. The sketchbooks Kelly filled during his sojourn in France are a mine of brilliant ideas in draft form (especially for reliefs), so numerous that several lifetimes would not suffice to bring them to fruition.

—*Yve-Alain Bois in* Ellsworth Kelly: Catalogue Raisonné of Paintings, Reliefs, and Sculpture: Volume I, 1940–1953

(Continued on page 19)

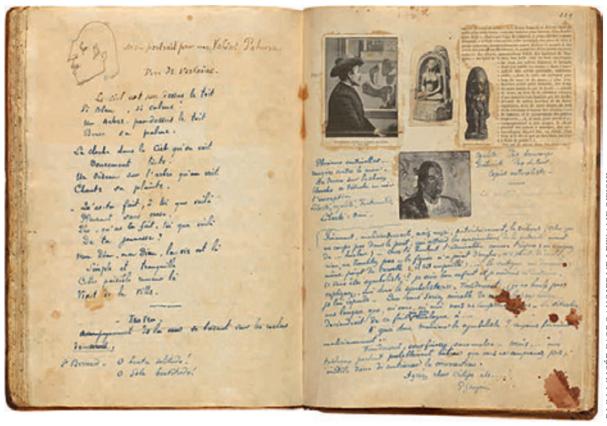
To "Write as I Paint My Pictures": Paul Gauguin as Artist-Writer

Self-portraiture on the margins of colonial power and local resistance

BY LINDA GODDARD

"When Paul Cézanne wants to speak ... he says with his picture what words could only falsify." In *The Voices of Silence* (1951), French author and statesman André Malraux expressed his view that the Post-Impressionist painter could only "speak" with paint, not with words (his letters, according to Malraux, amounted to no more than a catalogue of petty-bourgeois concerns). This gives a fair idea of the reaction that a painter who tried their hand at writing could expect in the nineteenth and early twentieth centuries. But what did this mean for artists who wished to respond, verbally, to their critics, or for whom writing and painting were equal components of an interdisciplinary practice?

My research at IAS investigated Paul Gauguin's (1848–1903) solution to this problem. Although skeptical of critics (he claimed that art needed no verbal commentary), the French Symbolist painter, best known for his vibrant paintings of Tahiti, nonetheless wrote a good deal. His literary output included art criticism, satirical journalism, travel writing, and theoretical treatises, most of it unpublished in his own lifetime. He was adamant, however, that none of this writing amounted to "art theory" as practiced by literary critics. Instead, his aim was to "write as I paint my pictures"—that is (he would have us believe) spontaneously, without regard to academic convention, and in a manner suited to the "savage" he hoped to become as a result of his relocation to French Polynesia in the 1890s. Conscious of the contradiction inherent in using words to defend the visual, he insisted: "I am going to try to talk about painting, not as a man of letters, but as a painter."



Gauguin's collaged images and text, seemingly artless (like a scrapbook), carefully project a particular self-image.

A hybrid figure, at odds with the colonial government yet necessarily an outsider to the indigenous community in Tahiti, Gauguin used his status as an artist (that is, as we have seen, one who is typically denied access to linguistic expression) to enhance his "primitive" credentials. For instance, he described his manuscript *Diverses choses* (Various Things, 1896–98) as consisting of "childish things": "Scattered notes, without sequence like dreams, like life made up of fragments: and because others collaborate in it". These qualities of fragmentation, collaboration, and childlike spontaneity can be seen in one of several double-page spreads of collaged images and text, which appear artless (like a scrapbook) but are in fact very carefully put together to project a particular self-image.

In an imaginary "letter to the editor" (signed Paul Gauguin, at bottom right), he attacked art critics who seek to categorize and label artistic styles and movements. Yet on the same page, he pasted several newspaper cuttings (which include a review of his work, and photographs of himself and his artistic creations)—undercutting his claim that artists have no need for the support of critics.

He minimized this contradiction, though, by using a careful arrangement of text and image to shift the focus away from European art criticism, and towards his affiliations with poetry and the "primitive." At the top of the left-hand page, he has drawn a simplified, stylized self-portrait, which he falsely attributed to "my vahine [mistress] Pahura," as if to confirm his savage credentials. He placed it above a transcription of the Symbolist poet Paul Verlaine's confessional poem ("The sky is, above the roof, so blue, so calm")—a poem celebrating freedom and the beauty of nature, written while Verlaine was in prison for shooting his lover and fellow poet Arthur Rimbaud. The poem is followed by a reference to the twelfth-century Cistercian monk Saint Bernard of Clairvaux, quoting his praise of solitude ("blessed solitude, only blessing"). By placing his self-portrait at the head of the page, above these borrowed texts, Gauguin links his own exile from "civilization" to the virtuous isolation of the pious monk or the incarcerated poet.

On the right-hand page, the newspaper article at top right juxtaposes one of Gauguin's sculptures, intended to evoke Tahitian idols, with a passage from Baudelaire's prose poem *Plans*, evoking a tropical landscape, and directly compares painter and poet in terms of their rejection of materialism and experience of exotic travel. In the cluster of photographs, Gauguin placed, at left, a studio portrait of himself in profile—which closely mirrors the profile of his "savage" likeness on the opposite page—alongside his representations of Tahitian women. In this photograph, he stands in front of the seated figure from his painting *Te Faaturuma* (The Brooding Woman), whose pose reflects that of the female Buddha in the reproduction of his *Idol with a Pearl* carving immediately to the right; directly below, a cropped photograph of *Vahine no te tiare* (Woman with a Flower) focuses attention on the androgynous face of the woman, whose contemplative demeanor echoes Gauguin's own static pose.

Again, this visually cements his identification with the Tahitian figures. Avoiding the dull linearity of the critic, who relies on logical explanations, Gauguin's various textual and visual allusions build up a multifaceted portrait of himself as both poet and savage—using a variety of media, authorial voices, and literary registers (aphorism, criticism, poetry, polemic). This is what he meant by writing "as a painter."

As in his self-portraiture, in his writing, too, Gauguin experimented with adopting different identities, sometimes writing under the guise of a fictional "ancient barbarian painter," whom he named Mani Vehbi Zunbul Zadi. In *Le Sourire*, the newspaper that he wrote, printed, and distributed in Tahiti, he assumed, in the opening issue, the identity of a female theatre critic (just as he drew, in Pahura's self-portrait sketch from *Diverses choses*, as if through the eyes of a young girl). In a review of a one-act play by a Tahitian woman, he wrote: "I must confess that I am a woman, and that I am always prepared to applaud one who is more daring than I in fighting for equivalent moral freedoms to men." In the voice of the female reviewer, he goes on to describe how Anna, the play's protagonist, believes in friendship and sexual freedom, but mocks romantic love and marriage.

In a contradictory blend of sexism and feminism, combined with self-interest, that is typical of Gauguin, the review ends with a call to arms, entreating men to help liberate women, body and soul, from the enslavement and prostitution of marriage, since "we women don't have the strength to free ourselves." It is signed Paretenia—Tahitian for "virgin." At the base of the page, next to the byline Paretenia, is a sketch of a puppet theater, and, alongside, one of customers rushing to buy Gauguin's newspaper, with the caption "Hurry, hurry, let's go and find *Le Sourire*." Via the guignol, an emblem for his own satirical broadsheet, Gauguin affiliates his publication with the subversive morality of the (probably fictional) Polynesian theater.

Gauguin aligned the visual artist with the "primitive" and the writer with the "civilized" but was ambivalently suspended between the two. He lamented the impact of European civilization on Polynesian society, yet remained implicated in the imperialist culture that he denounced. What I am arguing is that, similarly, he wanted to assert his autonomy as a visual artist (his freedom from literary critics, "corrupt judges" tarred with the same brush as colonial officials) but, paradoxically, he could only do so by adopting the privileged voice of the writer. His position on the margins of colonial power and local resistance—a position whose instability itself complicates those binaries—helps us to understand the situation of many others who, throughout history, have inhabited the as-yet understudied role of the artist-writer. ■

Linda Goddard, Lecturer in Art History at the University of St Andrews, Scotland, began writing a book about Paul Gauguin's writings while a Louise and John Steffens Founders' Circle Member (2014–15) in the School of Historical Studies.

BOIS *(Continued from page 18)*

Kelly was never satisfied with *Spectrum I* and always considered the work unfinished. Part of its "failure," he thought at the time, had to do with the fact that he had not conceived it as a multipanel painting (thus disobeying the rule of "one color per panel" that he had formulated in *Colors for a Large Wall* and had adhered to almost exclusively since). When he tackled the spectrum puzzle again in the late 1960s (making five more Spectrum paintings between 1966 and 1969), he did so in the multipanel format and at a mural scale so that at least some of the effects of color interaction would be easier to control and adjust, even almost entirely suppressed in the two cases where the panels are separated on the wall rather than juxtaposed (*Spectrum V* and *Spectrum VI*, both of 1969). As usual with Kelly, however, disappointment yielded further investigation: realizing during the process of working on *Spectrum I* that he had a lot to learn about color behavior, he decided to forgo the rainbow and learn empirically by trial and error. His first move would be, in *Tiger*, to revisit the strange orange/pink that had been so essential to his understanding of what he had achieved in *Painting for a White Wall*. After that, revisiting an even (much) earlier work, he would endeavor to test a multitude of color interactions by realizing in paint a collage of his *Spectrum Colors Arranged by Chance*, which he had made in 1951 but left unattended since then. ■

Yve-Alain Bois, Professor in the School of Historical Studies since 2005, is a specialist in twentieth-century European and American art and is considered an expert on a variety of artists, including Ellsworth Kelly. This article is excerpted from Ellsworth Kelly: Catalogue Raisonné of Paintings, Reliefs, and Sculpture, Volume One, 1940–1953 *(Editions Cahiers d'Art, 2015), which was awarded an inaugural Pierre Daix Prize from François Pinault in Paris.*

Works of Art in Number, Outline, and Position

Mathematicians and physicists transcribe their most beautiful mathematical expressions

Concinnitas *is a collection of ten aquatints produced from the contributions of ten mathematicians and physicists, nearly all affiliated with the Institute, in response to the prompt to transcribe their most beautiful mathematical expression. In October, Robbert Dijkgraaf, Director of the Institute and Leon Levy Professor, moderated a discussion with the portfolio's curator, Daniel Rockmore, former Member (1995–96, 2002) in the School of Mathematics and Professor of Mathematics at Dartmouth College, and contributors Enrico Bombieri, Professor Emeritus in the School of Mathematics, and Freeman Dyson, Professor Emeritus in the School of Natural Sciences.*

The following texts by Rockmore, Bombieri, and Dyson are part of the portfolio and describe the inspiration behind their contributions, which have been exhibited at galleries in Portland, Seattle, and Zurich. The prints were produced by Harlan & Weaver, Inc., of New York and published as a series of 100 by Parasol Press, LTD, and the Yale Art Gallery. Bombieri has generously donated to the Institute a portfolio of the prints, which includes contributions from Michael Atiyah, Simon Donaldson, Murray Gell-Mann, and Steven Weinberg. The prints are on exhibit at the Institute and are also in the collection of the Metropolitan Museum of Art.

Beautiful Mathematics

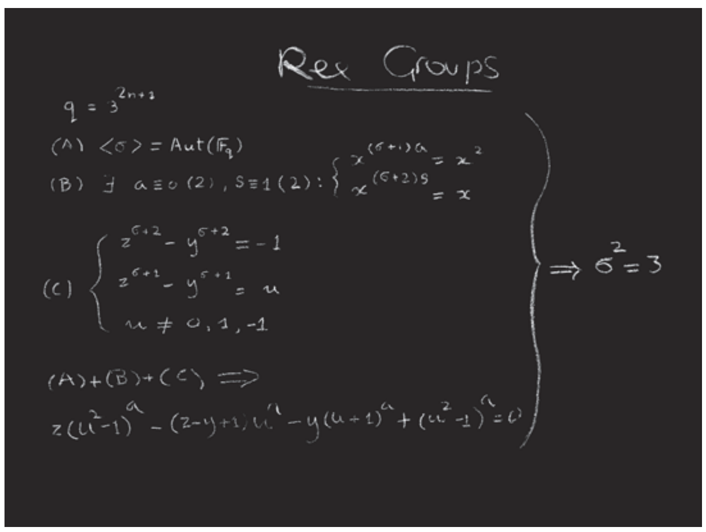
BY DANIEL ROCKMORE

MY EARLIEST MATHEMATICAL MEMORIES involve my father. One is of a walk from home to the edge of downtown Metuchen (the tiny central Jersey town where I grew up), to a little luncheonette called The Corner Confectionary. This wasn't a frequent or regular event, but from time to time on a weekend morning we'd make our way there. It was about a mile as we first walked to the corner of Rose Street and Spring Street and then strolled up Spring—a beautiful leafy street with huge oak trees on which our friends the Kahns lived—to finally reach Main Street where we made a quick left, crossed the bridge over the railroad tracks to arrive at the store. I can still see its layout, even in the cluttered neural attic that holds my childhood memories: cash register by the door, rack filled with newspapers, magazines, and comic books, ice cream treats in the back corner, and of course, the long counter, lined with stools on which we would sit and spin—until told to stop.

The walk I remember—or to be completely honest, seem to remember—involved fractions, or rather dividing up pieces of pie. That's how my Dad framed it. We were puzzling over how to divide fairly a pie among friends. I could see it was easy to make two or four even pieces of pie or eight, but three or five or six would have some challenges. We took our time getting to The Corner Confectionary, and we also took our time thinking about and talking about the basic properties of numbers and division; it was a leisurely walk through the neighborhood, accompanied by a leisurely walk through ideas, that soon led me to the exciting idea that twelve was a great number. Twelve could be divided by two, three, four, and six—that's a lot of numbers! If I had a pie in twelve pieces, it would be pretty easy to accommodate lots of different groups of friends for dessert. It seemed to me that twelve was a much better number to base things on than the number ten, which could only be divided into two things or five things. I do recall being very happy with the discovery that some numbers held more possibilities than others, a notion of possibility as expressed through division and multiplication and pie. I also recall how happy I was to have shared this little discovery with my father, the physicist, on a bright fall morning in my little town as we walked to get a morning treat.

My other early memory of mathematics is not one memory, but a whole collection of memories, accumulated over many visits to my father's office in the physics department at Rutgers University where he taught. A visit to that office was a treat, especially for access to the blackboard, always full of equations when I arrived, incomprehensible, but to me, beautiful, elegant, and full of mystery. The pads of paper and notebooks on his desk were full of similar beautiful mysteries. Nothing was more fun than trying to replicate these hieroglyphics on my own—the big looping integral signs (as I would discover later) or the snakey squiggles of a xi, psi, or any Greek letter. I didn't know what any of it meant, and the truth is, I didn't really care—I just liked the way it looked and the fact that these symbols meant something to someone, made me feel like I was writing away in a beautiful calligraphic code. I was proud that my father could make such beautiful looking things and they were meaningful to him and to others. I thought that one day, I might like to do that myself.

These are my stories about beauty in mathematics. I think they share much with the stories accompanying the work created for this collection, each of which is a response to the question "what is your most beautiful mathematical expression?" These elegant streams of symbols and diagrams serve as mathematical madeleines for moments of discovery and connection, be they between ideas, or people, or both. In those connections our artists (and all mathematicians, computer scientists, and physicists are artists!) find beauty. The *Concinnitas* project was itself born of a surprising connection between ideas and between people, the result of a chance encounter on an airplane between a mathematician who likes to think about art and an art dealer who likes to think about mathematics. I'm grateful to the many people who helped bring it to fruition—especially to the artists whose work is represented here.



The Ree Group Formula

The Ree Group Formula

BY ENRICO BOMBIERI

DOES BEAUTY EXIST IN MATHEMATICS? The question concerns mathematical objects and their relations, the real subject of verifiable proofs. Mathematicians generally agree that beauty does exist in the structural beauty of theorems and proofs, even if most of the time it is largely visible only to mathematicians themselves.

The concept of group beautifully expresses symmetry in mathematics. What is a group? Consider any object, concrete or abstract. A symmetry of the object—mathematically, an automorphism—is a mapping of the object onto itself that preserves all of its properties. The product of two symmetries, one followed by the other, also is a symmetry, and every symmetry has an inverse that undoes it. Mathematicians consider continuous Lie groups, such as the rotations of a circle or of a sphere, to be a beautiful foundation for a great portion of mathematics, and for physics as well. Besides continuous Lie groups there are noncontinuous finite and discrete groups; some are obtainable from Lie groups by reduction to a finite or discrete setting.

Groups can be extremely complicated. Given a group, it may happen that there is a mapping of it to another group, preserving the product structure. A group is simple if the image of such a mapping is always either a copy of the first group or just one element, the identity. Simple groups are the basic building blocks of all groups, so knowing all simple groups is essential in the study of arbitrary groups. General finite groups of symmetries appeared for the first time in the work of Évariste Galois on the subject of algebraic equations. Galois, at the age of only eighteen, was able to prove that the general equation of degree *5* is insoluble by means of algebraic operations by showing that the group A_5 of even permutations (that is, permutations consisting of an even number of pair exchanges) on the five letters *a,b,c,d,e* is a simple group. This group is the smallest non-commutative simple group and also turns out to be the group of symmetries of the icosahedron, a very nice geometry! It was conceivable that simple groups could be described as symmetries of special geometric objects, but the difficulty of studying an abstract, hypothetical, simple group consisted precisely in building a rich geometry out of its internal properties. As of today, the complete proof of the classification theorem that lists all finite simple groups runs over three thousand pages and took over forty years of the collective efforts of more than one hundred mathematicians.

The families of simple finite groups arising from Lie groups were found early, with three exceptions. These families arise by working not over the real or complex numbers, but instead over finite fields of characteristic p, where p is a prime number. There, one can still do the ordinary operations of arithmetic, but multiplication by p always yields *0*. Everything went smoothly, if not easily, except for the discovery by the mathematician Ree that the Lie groups B_2 and F_4 in characteristic *2*, and G_2 in characteristic *3*, also admitted an extra symmetry which could be used to obtain new families of simple groups, nowadays called the twisted Ree groups; the twisted B_2 groups and their uniqueness had been obtained earlier by Suzuki using entirely different methods. Uniqueness in the F_4 case was also found, but in the G_2 case it turned out to be elusive.

After a great effort by Thompson, the uniqueness problem for G_2 was reduced to proving that a certain transformation of a finite field of characteristic *3*, satisfying a very complicated set of equations in many variables, had the property that its square σ^2 on x was the same as the cube x^3, in other words $\sigma^2=3$. Unfortunately, ordinary algebra for eliminating variables quickly led to equations with a number of terms so big that all computers in the world could not store the formulas in their memory banks. What to do? Already in 1973, Thompson got me interested in the problem, but I got nowhere in the maze of formulas. In 1979, when the work on classification was in full swing, I looked again at Thompson's equations. I asked myself whether was it necessary to write down these "impossible" formulas, perhaps there was a way around. By a strange trick, it turned out that one small but useful addi-

(Continued on page 21)

WORKS OF ART *(Continued from page 20)*

Recommended viewing: Robbert Dijkgraaf's conversation with Daniel Rockmore, Enrico Bombieri, and Freeman Dyson may be viewed at https://video.ias.edu/concinnitas. More information about the *Concinnitas* portfolio is available at www.concinnitasproject.org, where mathematicians are invited to submit their most beautiful mathematical expressions.

tional piece of information could be extracted from the elimination. By redoing the elimination together with the trick and the new piece of information, the additional information was refined. By repeating three times this refinement process, the sought-for equation $\sigma^2=3$ was obtained, except possibly for a few cases checkable by computer. Thus the uniqueness problem was solved and another brick was added to the proof of the classification of finite simple groups.

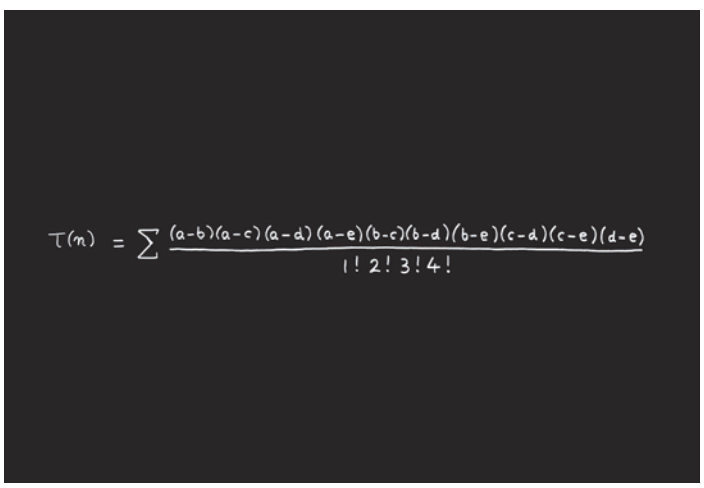
The print is done as a writing in white chalk on a dark slate-blue blackboard, starting at the left with the Thompson equations and with the double arrow pointing to $\sigma^2=3$, indicating that indeed the equations on the left imply the uniqueness of the twisted Ree groups. The problem was beautiful, the expected answer was also simple, hence beautiful, and the Thompson equations had an inner secret beauty because they reflected the properties of a group. To the expert, the solution obtained by avoiding brute force also had its own beauty. Indeed, mathematicians, sometimes involuntarily, in their search for truth also look for beauty as a guide. As the poet Keats wrote, beauty is truth, truth beauty.

* *Thanks to Sarah Jones Nelson*

The MacDonald Equation

BY FREEMAN DYSON

THE MACDONALD EQUATION is the most beautiful thing that I ever discovered. It belongs to the theory of numbers, the most useless and ancient branch of mathematics. My friend Ian MacDonald had the joy of discovering it first, and I had the almost equal joy of discovering it second. Neither of us knew that the other was working on it. We had daughters in the same class at school, so we talked about our daughters and not about mathematics. We discovered an equation for the "Tau-function" (written $\tau(n)$), an object explored by the Indian genius Srinivasa Ramanujan four years before he died at age thirty-two. Here I wrote down MacDonald's equation for the Tau-function. The MacDonald equation has an amazing five-fold symmetry that Ramanujan missed. You can see the five-fold symmetry in the ten differences multiplied together on the right-hand side of the equation. We are grateful to Ramanujan, not only for the many beautiful things that he discovered, but also for the beautiful things that he left for other people to discover.



FREEMAN DYSON/PARASOL PRESS, LTD/YALE ART GALLERY/HARLAN & WEAVER, INC

The MacDonald Equation

To explain how the MacDonald equation works, let us look at the first three cases, $n=1, 2, 3$. The sum is over sets of five integers a, b, c, d, e with sum zero and with the sum of their squares equal to $10n$. The "*(mod 5)*" statement means that a is of the form $5j+1$, b is of the form $5k+2$, and so on up to e of the form $5p+5$, where j, k, and p are positive or negative integers. The exclamation marks in the equation mean $1!=1$, $2!=1\times2=2$, $3!=1\times2\times3=6$, $4!=1\times2\times3\times4=24$. So when $n=1$, the only choice for a, b, c, d, e is $1, 2, -2, -1, 0$, and we find $tau(1)=1$. When $n=2$, the only choice is $1, -3, 3, -1, 0$, and we find $tau(2)=-24$. When $n=3$, there are two choices, $1, -3, -2, 4, 0$ and $-4, 2, 3, -1, 0$, which give equal contributions, and we find $tau(3)=252$. It is easy to check that these three values of $tau(n)$ agree with the values given by Ramanujan's equation.

The MacDonald equation is a special case of a much deeper connection that Ian MacDonald discovered between two kinds of symmetry which we call modular and affine. The two kinds of symmetry were originally found in separate parts of science, modular in pure mathematics and affine in physics. Modular symmetry is displayed for everyone to see in the drawings of flying angels and devils by the artist Maurits Escher. Escher understood the mathematics and got the details right. Affine symmetry is displayed in the peculiar groupings of particles created by physicists with high-energy accelerators. The mathematician Robert Langlands was the first to conjecture a connection between these and other kinds of symmetry. Ian MacDonald took a big step toward making Langlands's dream come true. The equation that I wrote down here is a small piece of MacDonald's big step.

SUMMER PROGRAM *(Continued from page 1)*

The Summer Program convened nineteen scholars from fourteen countries in Latin America, the Middle East, and Africa.

Science. These regions were in particular Latin America, the Middle East, and Africa. Despite specific efforts to reach out for scholars from these parts of the world, which resulted in a modest increase in applications and memberships (the 2015–16 regular program includes social scientists from the six continents), the imbalance remained, probably due to both a lack of information and a difficulty to obtain sabbatical leaves. As an alternative, a shorter program was proposed. It condensed within a few weeks what is usually undertaken during a whole academic year, the originality of this program being its extension over three years. Indeed, after the first session in Princeton, the other two will be organized in 2016 at the École des Hautes Études en Sciences Sociales in Paris, and in 2017 at the Swedish Collegium for Advanced Study in Uppsala. This continuity over time will allow for the building of a scientific network and the realization of collective projects.

The program focuses on outstanding young scholars selected in the same way as Members are in a regular year. For the first cycle, the nineteen fellows come from fourteen countries, nine in Latin America, five in the Middle East, and five in Africa. The disciplines represented are sociology, anthropology, history, geography, economics, law, political science, and literary studies. Almost half the scholars had obtained their Ph.D.s from their national universities. All of them teach and do research in local institutions of higher education or scientific research of their country.

The conversation developed during the two weeks spent at the Institute was rich and intense across disciplines, across themes, and across continents. But apart from the geographical diversity, it was not so different from the conversations that take place among Members of the regular program. What was distinct, however, is the project that emerged from the discussions: that of a meta-analysis to explore and confront the various epistemologies at work. Rather than simply presenting one's research, it consists in using this research to apprehend the global politics of knowledge that is at stake in it. Concretely, it means to inquire the circulation, appropriation, and contestation of ideas, methods, and analyses, as well as the interactions with publics and the translation of the outcome into action.

At this meta-level, the problems posed by the dominance of models elaborated can be similar for an anthropologist from the Middle East and a political scientist from Latin America, and the challenges to transform scientific results into policies can be equivalent for a Mexican sociologist and an African economist. The experience acquired in one field can thus enrich the practices in another. Interestingly, in discussing this politics of knowledge, the scholars involved in the program wanted to go beyond the simple opposition between the global North and the global South, while not ignoring the asymmetry underlying their relationships. Similarly, they considered that, to understand the difficulties faced by scholars in their countries, the intellectual aspect was as important as the material dimension, particularly in terms of access to resources or working conditions.

This project, provisionally titled "Writing the Social Science Across Different Worlds," has generated a considerable interest within the group and will be developed during the coming two years in Paris and Uppsala. It is emblematic of the general purpose of the Summer Program in Social Science, which is twofold. On the one hand, it is designed to offer scholars a stimulating scientific environment for their research. On the other hand, it is conceived to enrich the realm of the social sciences through the confrontation of different scholarly traditions. ■

Chaired by Didier Fassin, James D. Wolfensohn Professor in the School of Social Science, the Scientific Council of the program is composed of Ash Amin, University of Cambridge; Denis Cogneau, Institut de Recherche pour le Développement; Nancy Green, École des Hautes Études en Sciences Sociales; Kim Lane Scheppele, Princeton University; and Björn Wittrock, Swedish Collegium for Advanced Study. The program is supported by the Riksbankens Jubileumsfond, the Wolfensohn Family Foundation, and the three participating institutions. Besides the members of the Scientific Council, lecturers for the first session were Joan Scott and Michael Walzer from the Institute, João Biehl from Princeton University, and Adriana Petryna from the University of Pennsylvania. Marcia Tucker, from the Library, and Jonathan Peele, from the Information Technology Group, were also involved, as well as the staff of the School of Social Science.

Fall 2015

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KRISTEN ROGHEH GHODSEE
Einstein's Pacifism

YVE-ALAIN BOIS
Ellsworth Kelly: Volume I

SCOTT TREMAINE
The Odd Couple: Quasars and Black Holes

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