UC **SANTA BARBARA**

Kavli Institute for Theoretical Physics

Newsletter

www.kitp.ucsb.edu
Spring 2022

CARTER HIYAMA

Lars Bildsten

KITP continues to provide scientists from around the world the opportunity to interact again here at Kohn Hall and the Munger Physics Residence. The banner above shows the excellent array of cookies that our staff provide to our visitors daily in Kohn Hall's Gurley courtyard. I'm happy to report that if you are ten minutes late for cookie-time, it's all gone! Life appears to be going back to normal, and the blackboards are full of new ideas every day.

None of this would happen without KITP's staff, who continue to impress all of us with their persistent passion to deliver on KITP's mission and keep science happening. A big change to KITP's operations has been the seamless incorporation of remote program participants via Zoom. Led by KITP staff members Alina Gutierrez and Craig Kunimoto, this has enhanced participation, increased the size of the audience for each talk, and triggered richer discussions. We are now working to ensure this new modality stays with us "forever", as the value is now evident to us and the physics community. It's a positive development that arose during the pandemic.

In addition to our in-person scientific activities, we have also resumed in-person activities for the Santa Barbara public. From a talk about pandemics by former KITP postdoc Richard Neher at the downtown New Vic Theatre to a celebration in Kohn Hall of the life of Jean-Pierre Hébert (KITP's longtime inaugural Artist-in-Residence who passed away in 2021), we continue to welcome back good friends to Kohn Hall who we've not seen for quite a while. We also continue to host our virtual public events, and just this spring had an online Book Talk by Nicole Yunger Halpern entitled: "Quantum Steampunk: The Physics of Yesterday's Tomorrow". Nicole also wrote a nice piece about her recent visit to KITP, which you can read on page 7.

On March 11, 2022, we were delighted to host a visit to KITP of Jim and Marilyn Simons to celebrate the renaming of one our most favored convening spaces to the Simons Amphitheater. The plaque in that room clearly states their impact: "Named in honor of Jim and Marilyn Simons and the Simons Foundation for their decades of generous support of the international physics community and their sustained investment in the KITP". As you can see on pages 4 and 5, we had a wonderful time celebrating together that day!

Our KITP postdocs continue to be very productive and impactful in their research. They are also now returning to in-person work at Kohn Hall. I will update you on their departures and arrivals in the Fall 2022 Newsletter, but in the meanwhile please enjoy the article starting on Page 2 about Grant Remmen's work connecting scattering amplitudes to Riemann's zeta function. It's really wonderful to behold. Deep work in relations arising from particle scattering has a long tradition at KITP, and on page 5 you can read an article about the rise and impact of these connections that sprouted during a program in 2004. As noted in that article, these connections continue to grow and we just completed a program exploring the connections between scattering amplitudes and gravitational wave emission.

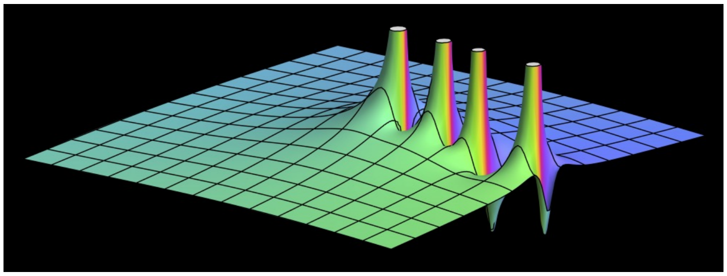
The pandemic also gave us time to tackle long overdue projects. One that I am quite proud of is the completion of the Art Catalog for the Munger Residence. I had collected all of the information early on about the art on display, but never found the time or had the team to make it happen. Well, due to the remarkable effort of Megan Turley (then KITP's Development Coordinator), we were able to pull this together with the excellent design assistance of Megan Shoemaker (UCSB Graphic Designer). This book allows our visitors to fully appreciate and understand the art that graces the Residence and is a lasting legacy of Megan Turley's time with us at KITP. Starting a few months back, Megan was promoted to Associate Director of Development at the Gevirtz Graduate School of Education (GGSE), allowing her to continue to support the intellectual life at UCSB through fundraising for GGSE. All of us wish Megan the best in her career and look forward to introducing you to Demi Cain, our new KITP Development Coordinator, when we see you here again this summer!

- Lars Bildsten, KITP Director

Quantum Zeta Epiphany

KITP Postdoc finds a new approach to a mathematical enigma

GRANT REMMEN



Remmen's scattering amplitude (pictured) translates the Riemann zeta function into the language of quantum field theory.

Numbers like π, e and φ often turn up in unexpected places in science and mathematics. Pascal's triangle and the Fibonacci sequence also seem inexplicably widespread in nature. Then there's the Riemann zeta function, a deceptively straightforward function that has perplexed mathematicians since the 19th century. The most famous quandary, the Riemann hypothesis, is perhaps the greatest unsolved question in mathematics, with the Clay Mathematics Institute offering a $1 million prize for a correct proof.

KITP Postdoctoral Scholar and UCSB Fundamental Physics Fellow Grant Remmen believes he has a new approach for exploring the quirks of the zeta function. He has found an analogue that translates many of the function's important properties into quantum field theory. This means that researchers can now leverage the tools from this field of physics to investigate the enigmatic and oddly ubiquitous zeta function. His work could even lead to a proof of the Riemann hypothesis. Remmen lays out his approach in Physical Review Letters.

COURTESY IMAGE

Grant Remmen, KITP Postdoctoral Scholar and UCSB Fundamental Physics Fellow

"The Riemann zeta function is this famous and mysterious mathematical function that comes up in number theory all over the place," said Remmen, "It's been studied for over 150 years."

An outside perspective

Remmen generally doesn't work on cracking the biggest questions in mathematics. He's usually preoccupied chipping away at the biggest questions in physics. Supported by the Simons Foundation, he normally devotes his attention to topics like particle physics, quantum gravity, string theory and black holes. "In modern high-energy theory, the physics of the largest scales and smallest scales both hold the deepest mysteries," he remarked.

One of his specialties is quantum field theory, which he describes as a "triumph of 20th century physics." Most people have heard of quantum mechanics (subatomic particles, uncertainty, etc.) and special relativity (time dilation, $E=mc^2$, and so forth). "But with quantum field theory, physicists figured out how to combine special relativity and quantum mechanics into a description of how particles moving at or near the speed of light behave," he explained.

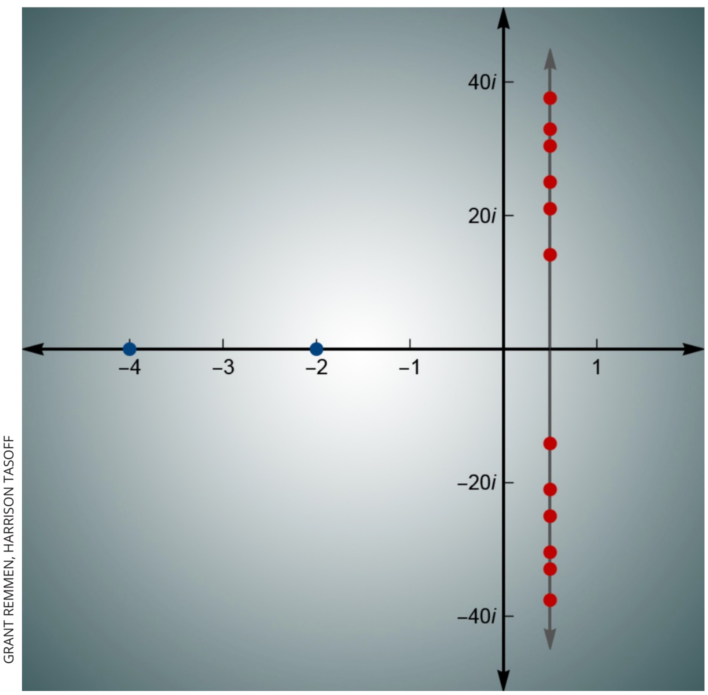
Quantum field theory is not exactly a single theory. It's more like a collection of tools that scientists can use to describe any set of particle interactions.

Remmen realized one of the concepts therein shares many characteristics with the Riemann zeta function. It's called a scattering amplitude, and it encodes the quantum mechanical probability that particles will interact with each other. He was intrigued.

Scattering amplitudes often work well with momenta that are complex numbers. These numbers consist of a real part and an imaginary part — a multiple of $\sqrt{-1}$, which mathematicians call i. Scattering amplitudes have nice properties in the complex plane. For one, they're analytic (can be expressed as a series) around every point except a select set of poles, which all lie along a line.

"That seemed similar to what's going on with the Riemann zeta function's zeros, which all seem to lie on a line," said Remmen. "And so I thought about how to determine whether this apparent similarity was something real."

GRANT REMMEN, HARRISON TASOFF



The zeta function maps all the colored points to zero. The non-trivial zeros (red) all seem to lie on a line where the real component of the number equals ½.

The scattering amplitude poles correspond to particle production, where a physical event happens that generates a particle with a momentum. The value of each pole corresponds with the mass of the particle that's created. So it was a matter of finding a function that behaves like a scattering amplitude and whose poles correspond to the non-trivial zeros of the zeta function.

With pen, paper and a computer to check his results, Remmen set to work devising a function that had all the relevant properties. "I had had the idea of connecting the Riemann zeta function to amplitudes in the back of my mind for a couple years," he said. "Once I set out to find such a function, it took me about a week to construct it, and fully exploring its properties and writing the paper took a couple months."

Deceptively simple

At its core, the zeta function generalizes the harmonic series:

$$\frac{1}{1^x}+\frac{1}{2^x}+\frac{1}{3^x}+\cdots$$

This series blows up to infinity when $x \leq 1$, but it converges to an actual number for every $x > 1$.

In 1859 Bernhard Riemann decided to consider what would happen when x is a complex number. The function, now bearing the name Riemann zeta, takes in one complex number and spits out another.

Riemann also decided to extend the zeta function to numbers where the real component was not greater than 1 by defining it in two parts: the familiar definition holds in places where the function behaves, and another, implicit definition covers the places where it would normally blow up to infinity.

Thanks to a theorem in complex analysis, mathematicians know there is only one formulation for this new area that smoothly preserves the properties of the original function. Unfortunately, no one has been able to represent it in a form with finitely many terms, which is part of the mystery surrounding this function.

Given the function's simplicity, it should have some nice features. "And yet, those properties end up being fiendishly complicated to understand," Remmen said. For example, take the inputs where the function equals zero. All the negative even numbers are mapped to zero, though this is apparent — or "trivial" as mathematicians say — when the zeta function is written in certain forms. What has perplexed mathematicians is that all of the other, non-trivial zeros appear to lie along a line: Each of them has a real component of ½.

Riemann hypothesized that this pattern holds for all of these non-trivial zeros, and the trend has been confirmed for the first few trillion of them. That said, there are conjectures that work for trillions of examples and then fail at extremely large numbers. So mathematicians can't be certain the hypothesis is true until it's proven.

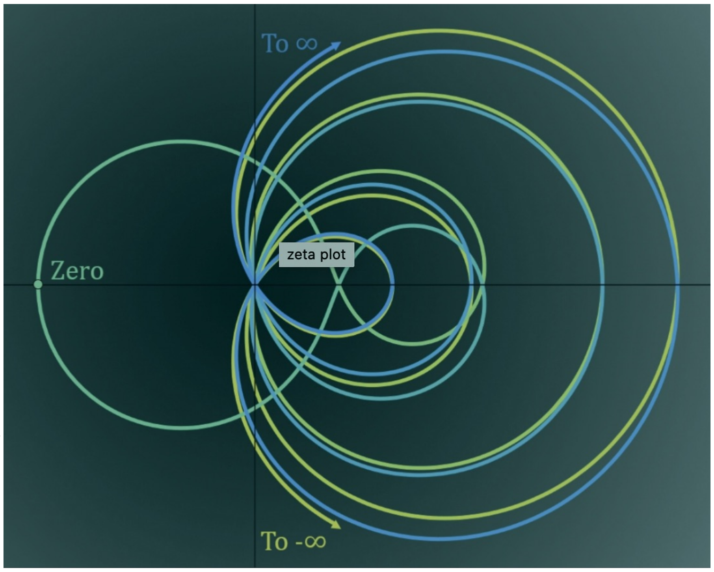
But if it is true, the Riemann hypothesis has far-reaching implications. "For various reasons it crops up all over the place in fundamental questions in mathematics," Remmen said. Postulates in fields as distinct as computation theory, abstract algebra and number theory hinge on the hypothesis holding true. For instance, proving it would provide an accurate account of the distribution of prime numbers.

A physical analogue

The scattering amplitude that Remmen found describes two massless particles interacting by exchanging an infinite set of massive particles, one at a time. The function has a pole — a point where it cannot be expressed as a series — corresponding to the mass of each intermediate particle. Together, the infinite poles line up with the non-trivial zeros of the Riemann zeta function.

What Remmen constructed is the leading component of the interaction. There are infinitely more that each account for smaller and smaller aspects of the interaction, describing processes involving the exchange of multiple massive particles at once. These "loop-level amplitudes" would be the subject of future work.

The Riemann hypothesis posits that the zeta function's non-trivial zeros all have a real component of ½. Translating this into Remmen's model: All of the amplitude's poles are real numbers. This means that if someone can prove that his function describes a consistent quantum field theory — namely, one where masses are real numbers, not imaginary — then the Riemann hypothesis will be proven.



GRANT REMMEN, HARRISON TASOFF

The zeta function transforms the grey line from the previous image into this curve. Each of the red points is a spot where this curve passes through the origin (0,0).

This formulation brings the Riemann hypothesis into yet another field of science and mathematics, one with powerful tools to offer mathematicians. "Not only is there this relation to the Riemann hypothesis, but there's a whole list of other attributes of the Riemann zeta function that correspond to something physical in the scattering amplitude," Remmen said. For instance, he has already discovered unintuitive mathematical identities related to the zeta function using methods from physics.

Remmen's work follows a tradition of researchers looking to physics to shed light on mathematical quandaries. For instance, physicist Gabriele Veneziano asked a similar question in 1968: whether the Euler beta function could be interpreted as a scattering amplitude. "Indeed it can," Remmen remarked, "and the amplitude that Veneziano constructed was one of the first string theory amplitudes."

Remmen hopes to leverage this amplitude to learn more about the zeta function. "The fact that there are all these analogues means that there's something going on here," he said.

And the approach sets up a path to possibly proving the centuries-old hypothesis. "The innovations necessary to prove that this amplitude does come from a legitimate quantum field theory would, automatically, give you the tools that you need to fully understand the zeta function," Remmen said. "And it would probably give you more as well."

By Harrison Tasoff

Celebrating the Dedication of the Simons Amphitheater at Kohn Hall

March 11, 2022

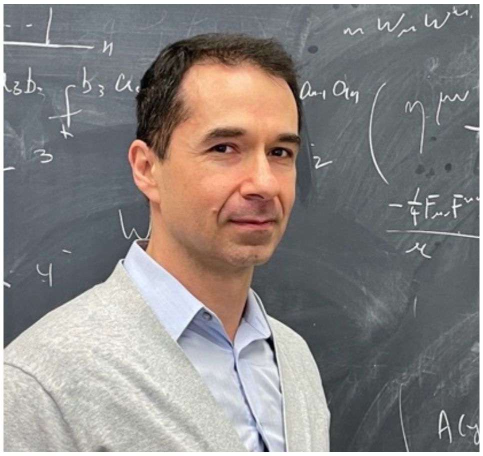
Named in honor of Jim and Marilyn Simons and the Simons Foundation with gratitude for their generous, steadfast support of KITP.


EATER

Colliding in Harmony

KITP Postdoctoral Scholars Helped Create a New Field in Physics

Anastasia Volovich, Brown University Professor and former KITP postdoctoral scholar



Radu Roiban, Penn State Professor and former UCSB postdoctoral scholar

At KITP, postdoctoral scholars (i.e., postdocs) enjoy exceptional intellectual freedom, and every year they have access to over 1,000 leading scientists who convene for the institute's programs and conferences. Not only does this benefit the postdocs, but integrating these early-career scientists into programs catalyzes scientific breakthroughs like one that took place at the 2004 "Collider Physics" program.

Focused on particle physics and collider phenomenology, "Collider Physics" was to be well outside of Anastasia Volovich's field of interest. Volovich, now a professor at Brown, was a second-year string theory postdoc. "The program was supposed to be on Collider Phenomenology, completely outside my field. . . If somebody told me about this program when I just arrived at KITP I would have thought okay, this is not my field, but maybe I will go to a couple of talks," she admits.

Then, a month before the program, something happened that changed the course of her career, as well as an entire sub-field of science. In December 2003, particle physics collided with string theory when Professor Ed Witten (Institute for Advanced Study) published a groundbreaking paper called "Perturbative Gauge Theory as a String Theory in Twistor Space." The work applied ideas from string theory to the mathematical structure of scattering amplitudes, predictions that calculate the likelihood that when two particles collide, other particles form.

With the release of Witten's paper, the physics community was crackling with creative energy, and in Santa Barbara, three early-career scientists—KITP postdocs Anastasia Volovich and Marcus Spradlin, and UCSB physics postdoc Radu Roiban—were particularly inspired.

Roiban, who was in his last year of his postdoc and interviewing for his next position, scrambled to attend. KITP and the program coordinators responded quickly, as well—the focus shifted largely toward ideas related to the December 2003 paper, which Roiban says "shook the field." Witten accepted a last-minute invitation to visit, string theorists and particle physicists descended on Santa Barbara, and the connection began to gel. Volovich recounts: "That paper happened in December, and in January he actually came to KITP for a few days to give a talk, and that's where the whole interaction started happening between these two communities [string theorists and collider phenomenologists], and a lot of new insights came out of it. "

Volovich, Roiban, and Spradlin made rapid strides. "[Witten] proposed the framework and described some examples," Radu explains, "We showed that the framework described in his paper applies to essentially all scattering amplitudes." Their work provided a key element to the conversation.

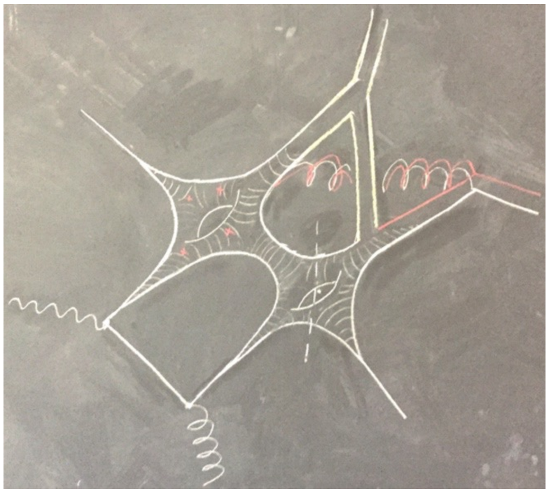
"For the longest time there were two distinct fields, scattering amplitudes and integrability," Roiban recalls. "A lot of people were talking about more or less the same few theories, but there were no direct relations between the methods and the questions that were asked." At first, the fields seemed disconnected from each other, but ties quickly emerged, which over time were developed and clarified into a larger framework.

Volovich reflects on her KITP postdoc experience as a uniquely productive time: "It was certainly the best time in my career. On the one hand, I didn't have to teach or have committee responsibilities, because I wasn't faculty; on the other hand, I was not a graduate student, and so I could work on my own ideas, so I totally switched [fields]."

Roiban believes that the circumstances Volovich describes makes the postdoc phase an ideal time to develop big ideas. "They basically have the ability to be incredibly productive with very little restraint, which is obviously incredibly valuable to the field."

He also believes that being at KITP and UCSB positions postdocs perfectly to make huge breakthroughs: "Something extremely valuable is that UCSB and KITP . . . have great faculty, who when the postdocs get stuck on something where they need a little bit of help or just a point in the right direction, they have somebody to actually walk to their office and explain what the problem is and more often than not, they get they get the right push in the right direction."

The unique design of programs at KITP – where experts in the field can be physically present together for weeks or months at a time – was a key component in Volovich, Roiban, and Spradlin's success. "There are things that go so much faster when people are in front of a blackboard and they argue and they fight and then they eventually all agree on the right answer," Radu explains. "It leads to something, in our case, fairly interesting."



2017 Scattering Amplitudes and Beyond program logo. Radu Roiban was a coordinator and COLLIDER04 coordinator Zvi Bern was a scientific advisor. The program was one of several that have continued investigating ideas developed in 2004.

The "Collider Physics" program contributed to the emergence of a new sub-field of physics, and early-career scientists played a key role. "The most amazing thing [about this program] was that a large number of new, young people who had never really been interested in this area before moved into it, and just gave a much greater amount of ferment and vitality to the field," confirms program participant (and former KITP Advisory Board member) Lance Dixon (SLAC).

As the field has evolved, connections to still more areas of inquiry have emerged, and KITP continues to nurture them. Scientists in the fields of gravitation have joined the conversation, and the program "High-Precision Gravitational Waves," in Spring 2022, brought them together with the field theory community that the 2004 program helped to shape. "It's hard to put a number on it," Roiban says, "but I'm willing to bet that without the programs that KITP organizes, the field as a whole would be back at least 10 years."

By Maggie Sherriffs and Megan Turley

Quantum estuary

COURTESY IMAGE

Tourism websites proclaim, "There's beautiful…and then there's Santa Barbara." I can't accuse them of hyperbole, after living in Santa Barbara for several months. Santa Barbara's beauty manifests in its whitewashed buildings, capped with red tiles; in the glint of sunlight on ocean wave; and in the pockets of tranquility enfolded in meadows and copses. An example lies about an hour's walk from the Kavli Institute for Theoretical Physics (KITP), where I spent the late summer and early fall: an estuary. According to National Geographic, "[a]n estuary is an area where a freshwater river or stream meets the ocean." The meeting of freshwater and saltwater echoed the meeting of disciplines at the KITP.

The KITP fosters science as a nature reserve fosters an ecosystem. Every year, the institute hosts several programs, each centered on one scientific topic. A program lasts a few weeks or months, during which scientists visit from across the world. We present our perspectives on the program topic, identify intersections of interests, collaborate, and exclaim over the ocean views afforded by our offices.

From August to October 2021, the KITP hosted two programs about energy and information. The first program was called "Energy and Information Transport in Non-Equilibrium Quantum Systems," or "Information," for short. The second program was called "Non-Equilibrium Universality: From Classical to Quantum and Back," or "Universality." The programs' topics and participant lists overlapped, so the KITP merged "Information" and "Universality" to form "Infoversality." Don't ask me which program served as the saltwater and which as the fresh.

But the mingling of minds ran deeper. Much of "Information" centered on quantum many-body physics, the study of behaviors emergent in collections of quantum particles. But the program introduced many-body quantum physicists to quantum thermodynamics and vice versa. (Quantum thermodynamicists re-envision thermodynamics, the Victorian science of energy, for quantum, small, information-processing, and far-from-equilibrium systems.) Furthermore, quantum thermodynamicists co-led the program and presented research at it. Months ago, someone advertised the program in the quantum-thermodynamics Facebook group as an activity geared toward group members.

The ocean of many-body physics was to meet the river of quantum thermodynamics, and I was thrilled as a trout swimming near a hiker who's discovered cracker crumbs in her pocket.

A few of us live in this estuary, marrying quantum thermodynamics and many-body physics. I waded into the waters in 2016, by codesigning an engine (the star of Victorian thermodynamics) formed from a quantum material (studied in many-body physics). We can use tools from one field to solve problems in the other, draw inspiration from one to design questions in the other, and otherwise do what the United States Food and Drug Administration recently announced that we can do with COVID19 vaccines: mix and match.

It isn't easy being interdisciplinary, so I wondered how this estuary would fare when semi-institutionalized in a program. I collected observations like seashells—some elegantly molded, some liable to cut a pedestrian's foot, and some both.

A sand dollar washed up early in the program, as I ate lunch with a handful of many-body physicists. An experimentalist had just presented a virtual talk about nanoscale clocks, which grew from studies of autonomous quantum clocks. The latter run on their own, without needing any external system to wind or otherwise control them. You'd want such clocks if building quantum engines, computers, or drones that operate remotely. Clocks measure time, time complements energy mathematically in physics, and thermodynamics is the study of energy; so autonomous quantum clocks have taken root in quantum thermodynamics. So I found myself explaining autonomous quantum clocks over sandwiches. My fellow diners expressed interest alongside confusion.

A scallop shell, sporting multiple edges, washed up later in the program: Many-body physicists requested an introduction to quantum thermodynamics. I complied one afternoon, at a chalkboard in the KITP's outdoor courtyard. The discussion lasted for an hour, whereas most such conversations lasted for two. But three participants peppered me with questions over the coming weeks.

A conch shell surfaced, whispering when held to an ear. One program participant, a member of one community, had believed the advertising that had portrayed the program as intended for his cohort. The portrayal didn't match reality, to him, and he'd have preferred to dive more deeply into his own field.

I dove into a collaboration with other KITPists—a many-body project inspired by quantum thermodynamics. Keep an eye out for a paper and a dedicated blog post.

A conference talk served as a polished shell, reflecting light almost as a mirror. The talk centered on erasure, a process that unites thermodynamics with information processing: Imagine performing computations in math class. You need blank paper (or the neurological equivalent) on which to scribble. Upon computing a great deal, you have to erase the paper—to reset it to a clean state. Erasing calls for rubbing an eraser across the paper and so for expending energy. This conclusion extends beyond math class and paper: To compute—or otherwise process information—for a long time, we have to erase information-storage systems and so to expend energy. This conclusion renders erasure sacred to us thermodynamicists who study information processing. Erasure litters our papers, conferences, and conversations.

Erasure's energy cost trades off with time: The more time you can spend on erasure, the less energy you need. The least amount of energy that erasure can cost, on average over trials, is called Landauer's bound. You'd pay this bound's worth of energy if you erased infinitely slowly. The conference talk explored this tradeoff, absorbing the quantum thermodynamicist in me. A many-body physicist asked, at the end of the talk, why we were discussing erasure. What quantum thermodynamicists took for granted, he hadn't heard of. He reflected back at our community an image of ourselves from an outsider's perspective. The truest mirror might not be the flattest and least clouded.

Plants and crustaceans, mammals and birds, grow in estuaries. Call me a bent-nosed clam, but I prefer a quantum estuary to all other environments. Congratulations to the scientists who helped create a quantum estuary this past summer and fall, and I look forward to the harvest.

by Nicole Yunger Halpern

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