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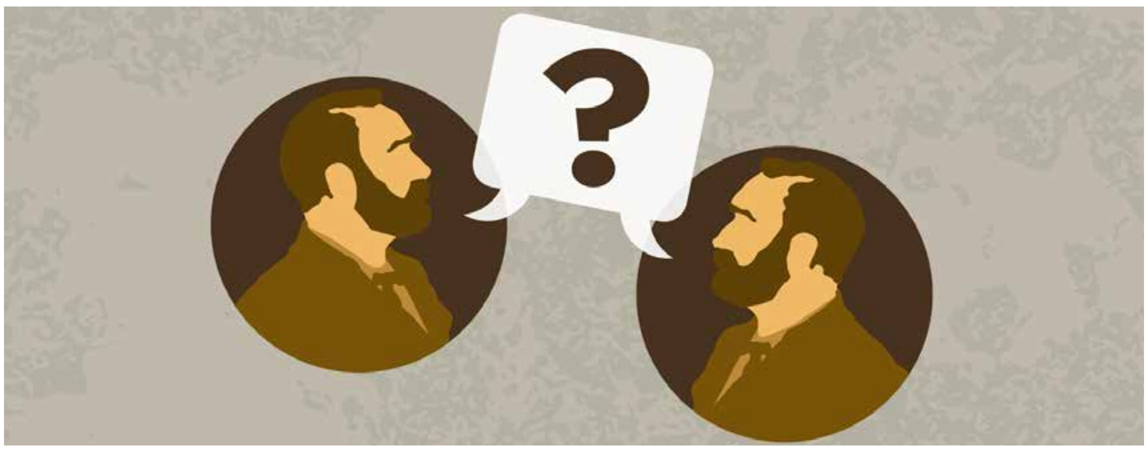
What Does the Nobel Prize's Fame Mean for Science?

Physicists weigh in on physics' most famous award.

BY ERIKA K. CARLSON



Credit: Elia King / APS

Each October, scientists around the world turn their attention to a series of press conferences in Sweden to see who will receive the most famous scientific honor of the year — the Nobel Prize. And though the Nobel Prize is ostensibly a celebration of scientific accomplishments, its influence extends far beyond the scientific community.

"The main benefit of Nobel Prizes is that there is a week every year when science is in the news for sure," says Gabriela González, an experimental physicist at Louisiana State University, "with radio and TV programs explaining important results of modern science and its implications."

But this fame can contribute to inaccuracies in the general public's perception of science, including physics.

Part of the problem is built into the rules of the Nobel Prize: The prize is only awarded once a year, to a maximum of three people per field for the science prizes. "You miss a lot of people who did excellent work that you cannot reward, so there's some arbitrariness in the whole thing," says Baha Balantekin, theo-

Nobel Prize continued on page 4

Astroparticle Physicist Wins 2023 Valley Prize for Work on Dark Matter

As a child in Tunisia, Lina Necib watched the 1997 film "Contact" and decided to become an astrophysicist. Now at MIT, she studies dark matter's shadowy clues.

BY LIZ BOATMAN

Lina Necib is on the hunt for something invisible.

"It's a little bit like detective work," she says. "We have a lot of observational types of evidence, and we're trying to put all of it together into one picture."

Necib, an assistant professor of physics at the Massachusetts Institute of Technology, studies dark matter, the elusive stuff that makes up most of the universe's mass but doesn't reflect, emit, or absorb light. For her work, Necib has won the 2023 APS Valley Prize, which recognizes early-career physicists for research expected to have a dramatic impact in the field.

In 2020, Necib and her colleagues reported their discovery of a massive stellar stream, a ribbon of stars left over when a galaxy is torn and stretched, orbiting on the outskirts of the Milky Way. Dark matter tugs at these streams, leaving behind fingerprints — evidence of its ex-

Necib continued on page 7

Lina Necib Credit: David Sella

From Banking to Quantum Physics

At age 30, Michelle Lollie, APS Bridge Program graduate, abandoned her career in finance and leapt into physics.

BY SOPHIA CHEN

Michelle Lollie worked in banking for years before going back to school for physics. She received her doctorate from Louisiana State University in March 2022. Credit: LSU

In 2010, Michelle Lollie — then a disillusioned 28-year-old banker in Michigan — read a paper on quantum teleportation and decided to become a physicist.

"To this day, I cannot remember why that paper crossed my field of view," says Lollie.

But starting over, as a non-traditional student, would be an uphill journey. Lollie enrolled at Indiana's Rose-Hulman Institute of Technology for her second bachelor's degree, this time in physics instead of finance. She had to fill in the gaps — computer programming, linear algebra, vector calculus — sometimes retaking classes multiple times. "I had a ton of insecurities," she says.

But bruised ego or not, Lollie had tenacity. After earning her degree from Rose-Hulman, she set her sights on graduate school. She got accepted to Indiana University through APS's Bridge Program, which helps underrepresented students of color pursue PhDs, and later transferred to Louisiana State University. "The Bridge program provided that foundation to help me get my footing, whether it was additional academic help or research," says Lollie.

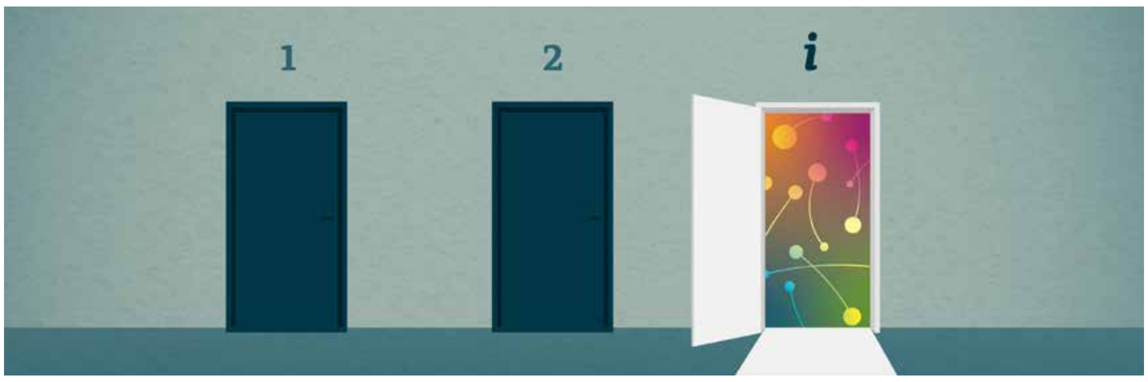
This March, Lollie became the first Black woman to receive her Ph.D. from LSU's physics and as-

Lollie continued on page 7

New Experiment Suggests Imaginary Numbers Must Be Part of Real Quantum Physics

A new experiment closes theoretical loopholes, strengthening the evidence that imaginary numbers play an irreplaceable role in quantum theory.

BY BAILEY BEDFORD



New research tightens the argument that imaginary numbers — denoted as i — are vital to quantum theory. Credit: Elia King/APS

Since quantum mechanics' inception nearly a century ago, there has been controversy about the math at the heart of the field: Does quantum theory require the use of imaginary numbers?

Imaginary numbers — numbers given in terms of the square root of negative one and that produce real numbers when multiplied together — are an important part of mathematics, but in physics, no observation has demanded their use. Until recently, it seemed like imaginary numbers in quantum physics calculations might make things easier, but be unnecessary.

A paper published September 26 in *Physical Review Letters* details an experiment that demonstrates that quantum mechanics formulations that utilize complex numbers — numbers with both real and imaginary pieces — can outperform formulations that exclusively use real numbers. The research closes some loopholes that might undermine the refutation of real-valued quantum mechanics, boosting the argument that imaginary numbers are vital to the field.

"I think it's a fundamental question to ask — the question whether a complex number is really necessary for quantum mechanics," says Chao-Yang Lu, a physics professor at the University of Science and Technology of China and a co-author of the paper.

According to Lu, that question has remained mostly philosophical throughout quantum mechanics history. Then, in a 2021 paper in *Nature*, researchers "proposed an experiment that can actually put the philosophical argument into [a] test," he explains. "You can see the test as a game between three players, Alice, Bob and Charlie."

In that game, the three players receive quantum particles from two independent sources. Through a carefully orchestrated trick that hinges on the quantum property of entanglement, two players can find that their particles influence each other, despite never having directly interacted.

While playing the game can be complicated, the essence of the test is simpler: Complex and real num-

Quantum physics continued on page 6

APS Has a New Look and Logo. With these changes, we strengthen our commitment to our members and welcome a new generation of physicists. And with hope and enthusiasm for our mission and future, APS continues to advance physics, as it has sought to do since its founding in 1899.

Albert-László Barabási, Network Scientist, Wants Physicists to Connect with Wider Audiences

An interview with the recipient of the 2023 Lilienfeld Prize.

BY RACHEL CROWELL

Albert-László Barabási, winner of the 2022 Lilienfeld Prize for his work in — and communication of — network science. *Credit: Hamu és Gyémánt / Lábady István*

What do the internet, neurons in the brain, and cellular metabolism have in common?

According to Albert-László Barabási, all are complex networks with hidden patterns. Barabási, a physicist at Northeastern University and leader in network science, is the recipient of the 2023 Julius Edgar Lilienfeld Prize, which awards physicists who've made "outstanding contributions" to the field and communicate with diverse audiences.

> "When we started studying networks, we were not entering with a solution to a random problem. We were defining a new problem." — Barabási

"Network science has [come] of age," says Barabási.

After Barabási earned his doctorate in statistical physics in 1994 from Boston University, he took a postdoctoral role in New York City. It was there, over the winter holidays, that he picked up a book on problems in computer science and first learned about graphs and networks. "How many networks must be supporting this interesting, fabulous, complex city?" he thought. Those networks, he realized, lacked "a theory of their own."

A few years later, Barabási was running a materials science laboratory at the University of Notre Dame and had just received a federal grant to study quantum dots. Then, in 1999, he and co-author Réka Albert published a paper in the journal *Science* asserting that an enormous range of networks were "scale-free," meaning they followed mathematical rules called power laws.

The paper changed everything. Barabási told his lab members, "I have zero interest from now on in materials science. I want to use all my resources and energy to focus on networks." He sought to redirect his federal grant toward network research, to no avail; the funding was revoked. Still, he dove into networks and never looked back.

Barabási's work helped fuel modern network science. It has also spurred debate, as some scientists dispute the ubiquity of scale-free networks in the real world.

Today, Barabási directs Northeastern University's Center for Complex Network Research and is a lecturer in Harvard Medical School's Department of Medicine. He also co-leads a European Research Council project on network science. He's authored three popular science books, and, most recently, co-authored, with Dashun Wang, "The Science of Science," a book examining patterns of career success in science.

Barabási spoke with *APS News* about the changing landscape of network science and his views on why physicists must communicate their research widely.

This interview has been edited for length and clarity.

How has the field of network science changed over your career?

In 1994, I wrote a paper [on networks] that I could not publish anywhere. The feeling from the referees was, "Why do we care?" In 1999, when our first real network paper started to emerge, people started to become interested in networks. There was lots of puzzlement among even my physics colleagues: "What are we really trying to study? Neural networks or spin classes?"

I kept saying, "It's about any kind of network out there. We're trying to find, like physicists do, universal organizing principles. What are the laws common across different networks?"

When we started studying networks, we were not entering with a solution to a random problem. We

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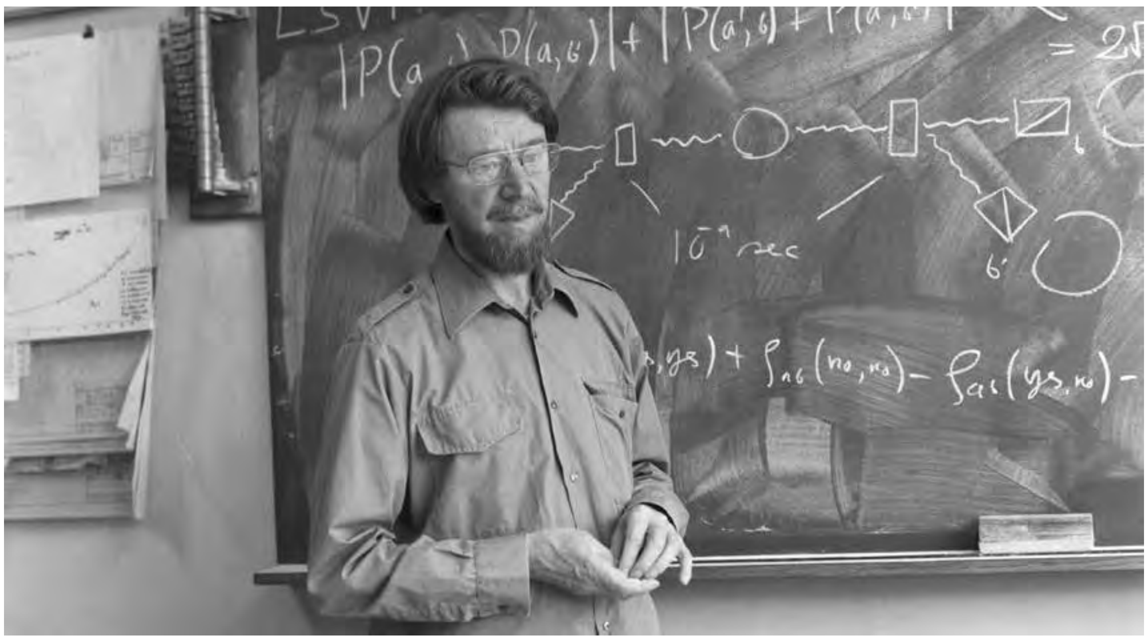
THIS MONTH IN PHYSICS HISTORY

November 1964: John Stewart Bell Quietly Rings in New Era of Quantum Theory

BY DANIEL GARISTO



John Bell lectures on his theorem in 1982. *Credit: CERN*

When the most important quantum theory paper in 30 years was published November 4, 1964, virtually no one noticed. "On the Einstein Podolsky Rosen Paradox" accumulated fewer than a dozen citations in its first six years, and when it garnered wider attention, many physicists dismissed its implications. Even now, with the 2022 Nobel Prize in Physics awarded to experimenters performing eponymous Bell tests, its singular role wresting concrete answers from nature about reality remains underappreciated.

Its author, John Stewart Bell, was born July 28, 1928, in Belfast. His mother Annie was a dressmaker and his father Jackie sold horses. The family was not wealthy; in Bell's biography, Andrew Whitaker notes that Annie sewed John's academic gown from blackout curtains.

Bell entered Queen's University as World War II ended. There, he was academically excellent but already unsatisfied with physics orthodoxy. The ruling Copenhagen Interpretation proposed a distinction between classical observer and quantum observable — a belief Bell would later deride as a "shifty split." Seen through the Copenhagen Interpretation, the location of an electron, for example, exists as a nebulous cloud of probabilities described by the wave function until it collapses into a fixed value. Because of this "shifty split," proponents often caution against philosophizing about the quantum world, and making assumptions beyond what can be experimentally proven.

An older paper, published in 1935 by Einstein, Boris Podolsky, and Nathan Rosen (EPR), would capture Bell's imagination. EPR argued, using a thought experiment, that quantum mechanics was correct, but incomplete. As Einstein later quipped: "Do you really believe the Moon exists only when observed?" One possible solution for the ills of quantum mechanics was "hidden variables," undetectable traits baked into particles all along. If these traits were secretly present, they would return existence to things, giving even the Moon properties regardless of whether it was measured.

Concerned with what is measurable, not what *is*, the Copenhagen Interpretation and its high priest, Niels Bohr, rejected hidden-variable theories. The indeterminacy of particles was fine, and in any case, the theorist John von Neumann had proven hidden-variable theories impossible in 1932. For Copenhagen Interpretation adherents, there was no reason to discuss hidden variables that had been ruled out.

> [Bell] took inspiration from Bohm's orthodoxy-defying work to not just "shut up and calculate."

Bell saw things differently. EPR pointed out a central problem, a deep philosophical question about reality — and there was no way of telling who was correct.

In 1952, Bell received a jolt of inspiration when David Bohm published his interpretation of quantum mechanics, a hidden-variable theory that could go toe-to-toe with the Copenhagen Interpretation. Bohr's acolytes were unimpressed. They attacked Bohm's theory as superfluous — ironically, for making the same predictions as existing quantum theory. (This was, in fact, the point — to show that a hidden-variable theory could also account for observations.) Albert Einstein, meanwhile, rejected Bohm's ideas because they didn't preserve locality, the commonsense principle that objects are affected only by their immediate surroundings.

But for Bell, it was critical, and he would later recall that he "saw the impossible done" by Bohm, though Bell never became a Bohmian. "This was not the one horse he lashed his wagon to," says David Kaiser, a physicist and historian at the Massachusetts Institute of Technology. Rather, he took inspiration from Bohm's orthodoxy-defying work to not just "shut up and calculate."

Over the next twelve years, Bell kept the ideas in the back of his head, working through them in his free time. Occasionally, he ran into workplace colleagues he could debate, such as Franz Mandl at Harwell, the newly formed UK atomic research center where Bell worked in the late 1950s, and Josef-Maria Jauch at CERN, where he took a job in 1960. In 1963, Bell and his wife,

History continued on page 6

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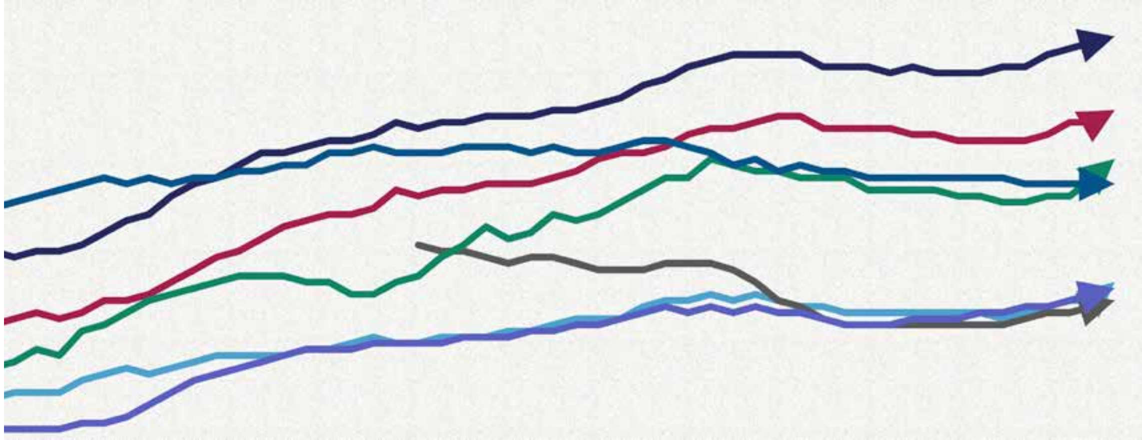
Newest Data Shows Mixed Progress for Women and Marginalized Groups in Physics Higher Education

BY LIZ BOATMAN



Credit: APS

For more than two decades, APS has published data on physics degrees in the U.S., including degree-earning by women, racial and ethnic minorities, and international students. To update this data, APS typically recruits the help of a Society of Physics Students summer intern. This year's intern, Lucy Corthell, is a junior at Juniata College in Pennsylvania studying engineering physics.

"What really caught my eye was the science and equity parts coming together" in one experience, says Corthell.

Over the coming months, APS will add data from the 2019-2020 school year, pulled from the Integrated Postsecondary Education Data System (IPEDS), to the APS education statistics. IPEDS data is also used to populate the Society's interactive resource "How Does Your Institution Compare?"

So, what does the newest data say about trends in physics higher education?

Women earned 1 in 4 physics bachelor's degrees in 2020

In 2020, 25% of physics bachelor's degrees in the US went to women — the highest percentage ever recorded (Fig. 1). This might sound like progress, but the story is complicated: This number also peaked two decades ago, at 23%, before declining to just 19% in 2015. That means twenty years elapsed with only a few percentage points gained for undergraduate women in physics.

"It's concerning to see," says Corthell, but "being informed can also be helpful, because then we can learn about how to improve."

The trend isn't just seen in physics. Although the percentage of women earning degrees in STEM (science, technology, engineering, and math) grew steadily between 1970 and 2000, it dipped abruptly in the early 2000s. Since then, progress has been mixed. In computer science, math, and statistics, the percentage of bachelor's degrees earned by women decreased over the past two decades and hasn't recovered; in the earth sciences, numbers have finally crept back to 2002 levels.

This is hardly a triumph, but there's reason to be hopeful: In terms of the percentage of bachelor's degrees awarded to women, every STEM field except math and statistics now shows an upward trend.

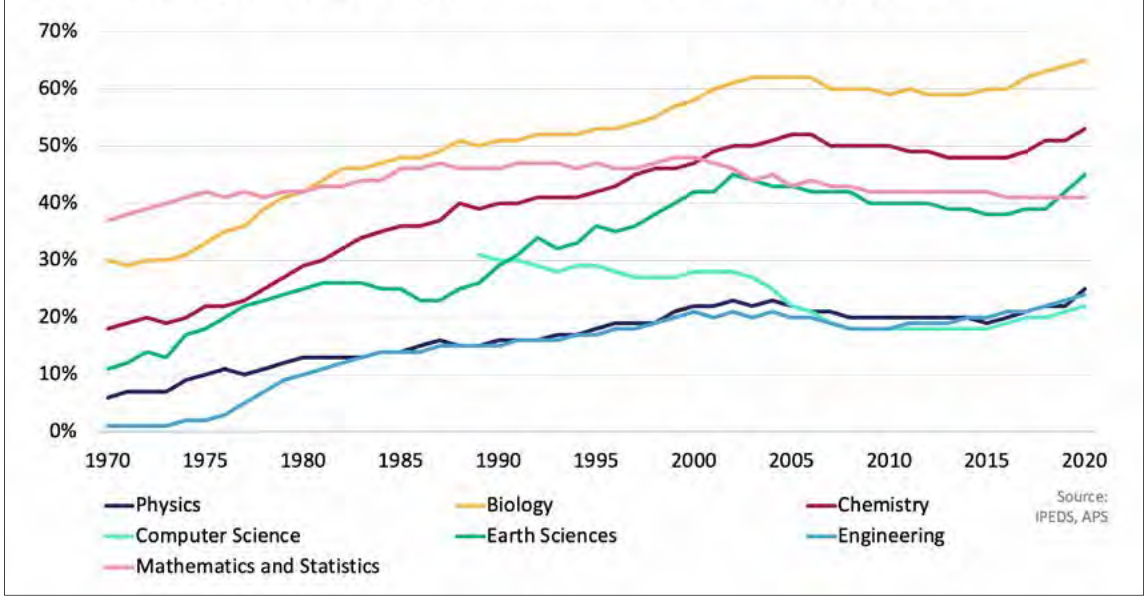
Echoing challenges at the undergraduate level, gains in graduate physics have stagnated in recent years. From 1966 to 2010, the percentage of physics doctorates awarded to women increased from 2% to 20% and then mostly stopped growing. Since 2010, the number has hovered around 20%, dipping periodically. As of 2020, this figure sits at 21%.

As a percentage, students of color aren't gaining traction at the doctorate level

The 2020 data shows another trend: Collectively, Black or African

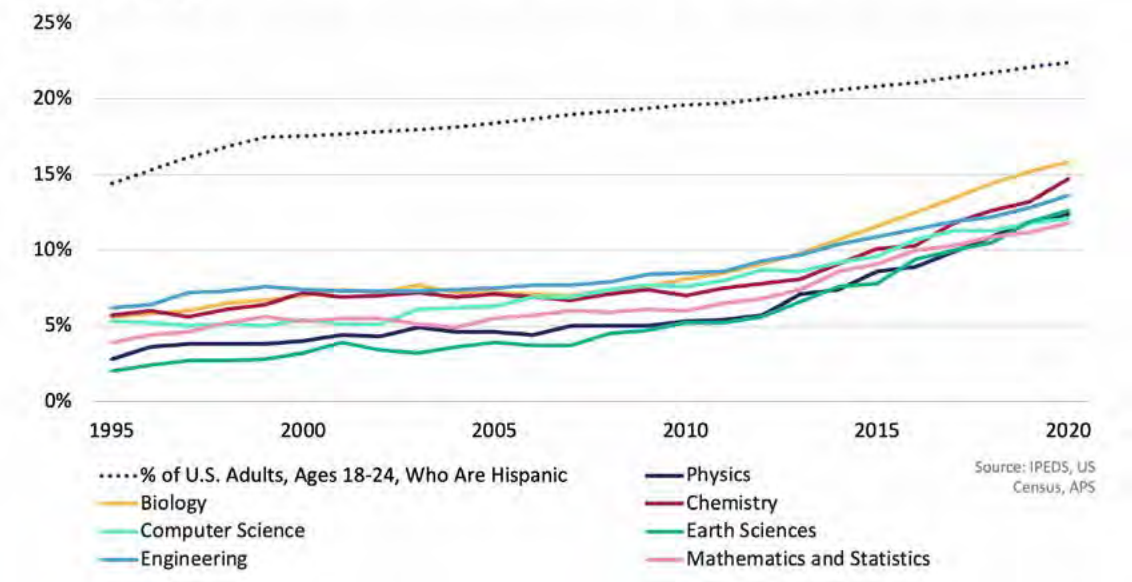
Data continued on page 6

Fig. 1: Percentage of Bachelor's Degrees Awarded to Women Each Year, by STEM Field



Source: IPEDS, APS

Fig. 2: Percentage of Bachelor's Degrees Awarded to Hispanic Americans Each Year, by STEM Field



Source: IPEDS, US Census, APS

Four Mistakes Early-Career Scientists Make in Interviews and How to Correct Them

BY ALAINA G. LEVINE

Credit: Antonio Rodriguez/Adobe

I love job interviews! Why? Because an interview is your finest opportunity, as an early-career scientist, to share why and how you'll be an asset to an organization and convince an employer to hire you.

But to land that job, you'll need to avoid common mistakes physicists make before and during job interviews. Fear not, fair physicists! Here are a few fixes to ensure these errors do not become epic fails.

Mistake 1: Not understanding the dynamics of the interview

An interview is a sales pitch: You're convincing the employer to invest money in you (compensation) in exchange for a service (your work). It's not about you; it's about what you can do for the employer. When an interviewer asks about a candidate's experience in an area, some people will get stuck in the weeds, diving into a chronological history of every paper and project they've had. But the interviewer just wants to know how you'll add value. To fix this, frame your accomplishments as:

- A problem you solved
- A solution you utilized
- The result you got

For example, an interviewer might ask, "What is your experience with complex materials?" Your answer might be, "I gained expertise in complex materials through a project that explored the relationship between *x* and *y*. I was tasked with characterizing *z* system in complex materials [the problem], so I built a novel model using c and d [the solution]. I discovered a causality between *x* and *y*, which enabled us to better do *z* [the result]."

When you communicate your value this way, you make it easy for decision-makers to understand why they should invest in you. After all, they're hiring you to solve problems, and this framework forges a bridge between your past and future problem-solving experiences.

Mistake 2: Not customizing your answers

This is a big mistake, but it's also easy to fix, by tailoring your answers with information about the employer's teams, projects, and goals. When an interviewer asks about your experience with spin glasses, don't answer, "I did *x* and researched *y*." Instead, add context and connect your experiences to the employer. A better answer might be, "During *x* internship, I developed skills in *y* optimization methods, which would give me strong foundations for jumping in on a project like the one you described in *z* publication." Translate your experiences into their language, which you can gather from their website, social media, and writing (e.g., papers).

There are two important points here. First, this is an opportunity to be your own champion. When you describe how your work matches the employer's needs, explain and specify the skills you've leveraged to solve problems. This isn't bragging — it's self-advocacy. Second, show that you've done your research. By discussing the needs or goals of the employer and the individuals interviewing you, using their verbiage, you show you've prepared, and you help them envision you in the role.

Mistake 3: Not double-checking basic, logistical interview parameters

This is especially vital for virtual interviews. Confirm the date, time, time zone, and digital platform. Make sure you know who will join the interview, and do your research on them ahead of time, so you know their names, titles, and backgrounds. If the interview will be on Zoom, practice on the platform with a buddy in a different location, at the time of day when the interview will take place, to check the video, sound, lighting, and internet connection. If you'll be giving a job talk, confirm that you can share your screen and that your desktop and browsers are clear of distractions. To maintain eye contact on Zoom, you need to look at the camera; one of my favorite hacks is to put a sticky note with arrows pointing to the lens, to remind me where to gaze.

Mistake 4: Not showing your enthusiasm

You may be nervous, but the interviewer could be tired or frustrated from having had so many interviews. Make it easy for the decision-maker to imagine how collaborative and valuable it would be to work with you. Smile and be your authentic, enthusiastic self! An employer should get to know you for you, and learn how your best self is going to help you achieve your objectives — and theirs.

Alaina G. Levine is a professional speaker, STEM career coach, and author of the books Networking for Nerds *(Wiley) and* Create Your Unicorn Career *(forthcoming). This article builds on content that has appeared in her other works.*

Nobel Prize continued from page 1

retical physicist at the University of Wisconsin, Madison.

When the Nobel Prize was established at the turn of the 20th century, most research groups were made up of only a handful of members. "But now, some experimental groups have thousands of members," Balantekin says. "So that's a conundrum." In cases where the Nobel Prize Committee has recognized the work of large research collaborations, such as the 2017 physics prize for the LIGO project to detect gravitational waves from black holes and neutron stars, it has awarded the prize to a few key individuals.

> "You're basically choosing to honor those areas of science where you can cleanly separate a few people's work from the pack," says Karen Daniels. "And that doesn't necessarily accurately represent how science is done."

"So you're basically choosing to honor those areas of science where you can cleanly separate a few people's work from the pack," says Karen Daniels, experimental physicist at North Carolina State University. "And that doesn't necessarily accurately represent how science is done."

In contrast, some other prominent awards recognize entire collaborations rather than a few representatives. For example, the 2020 Breakthrough Prize in Fundamental Physics honored all 347 team members behind the Event Horizon Telescope project that captured the first image of a supermassive black hole.

Many scientists have also expressed concerns about the skewed demographics of Nobel laureates.

"Most of the Nobel Prize winners are recognized many years after their results were obtained, which means they are in general old and male," says González. "This generates an association for the general public of all current scientists being old and male, which is absolutely not true."

The demographics of laureates not only presents the public with a warped view of who scientists are, Daniels says, but of what scientists value.

"The Nobel Prize Committee has historically essentially ignored the contribution of both women and people of color and a lot of other underrepresented groups and folks at the intersection of those categories," says Daniels. Of the more than 200 laureates in physics so far, only four have been women, and only a handful more have been people of color. The people who have received the Nobel Prize in Physics so far have all done great work, Daniels says. "But it's a choice to say that we value decades-old work by one demographic, and I think it's tough to get behind that as the best thing to do with our attention."

Representing the diverse body of scientists is important not just for the public-facing Nobel, but for less visible prizes awarded by universities and scientific societies as well, many researchers say. These awards, arising from the research community, can bolster scientists' careers by helping them find new collaborators or more funding. And prizes awarded by representatives of one's subfield can let recipients feel recognized by their peers, which is "not a small thing," Balantekin says.

"If we're not awarding them to a diverse group of scientists, then we're not only saying that 'we didn't value your work, and we didn't value your membership in our community' — which is incredibly hurtful — we're also hurting that person's career relative to someone who did get the award, who then gets the benefits of it," Daniels says. "There's a great ability to do harm when they aren't handled in a way that is equitable."

For better or worse, the Nobel Prize offers a unique — and very public — opportunity to celebrate and communicate scientific discovery. Other big prizes in science may emulate aspects of the Nobel, but "none of them really captures the public's imagination the way the Nobel Prize does," Balantekin says.

"It reminds people that we should be excited about discovery, and that we are continuing to do exciting science," Daniels says. "I still actually look forward to finding out who's gonna get it, because it's always some cool piece of science. I just really think the process is pretty flawed."

Erika K. Carlson is a science writer at APS.

Astrophysics in Albuquerque: The APS Four Corners Section Met in October

Physics thrives in the Southwest.

BY ABIGAIL DOVE

The APS Four Corners Section met this year in Albuquerque, New Mexico. Credit: SeanPavonePhoto/Adobe

On October 14, at the annual meeting of the APS Four Corners Section, hundreds of physicists gathered in Albuquerque to discuss very small things — and, in Sarah Kendrew's case, very large ones.

Kendrew, a scientist at the European Space Agency and plenary speaker at the meeting, works on the newly launched James Webb Space Telescope (JWST), which can spy on ancient parts of the universe formed soon after the Big Bang. JWST's first images were released this July.

"Anywhere you point, there are galaxies. It's unprecedented for an infrared telescope to show us such a wealth of data, and we have barely scratched the surface," she says.

Kendrew shared the plenary roster with other leading physicists in the four corners region. Established in 1998, the Four Corners Section, or 4CS, is a hub for 1,800 APS members in Colorado, Utah, Arizona, and New Mexico. APS's geographical sections let physicists connect in their own regions and foster collaborations between nearby companies, schools, and national laboratories, like — in 4CS's case — Los Alamos, Sandia, and the National Renewable Energy Laboratories.

This year's meeting was the Section's first in-person gathering since 2019. The meeting's plenary sessions touched on everything from nanoscale protein interactions to the use of machine learning to study chemical properties.

Astrophysics was a big-ticket agenda item. Kendrew discussed not only the JWST images, but her experience watching the launch and working on the team that ensured the scientific instruments on board, a million miles away, were aligned and calibrated.

Maria Rodriguez, another plenary speaker and a theoretical physicist at Utah State University, discussed black holes, the hungry mouths at the center of many galaxies. "Black holes used to be invisible, but now something miraculous is happening in that we are able to measure what they are doing," says Rodriguez. Her talk traced the evolution of our knowledge of black holes, from the detection of gravitational waves to the shadows of black holes glimpsed by the Event Horizon Telescope and the JWST, which could help us understand black holes' behavior.

Diana Dragomir, an exoplanetologist at the University of New Mexico, presented on NASA's TESS telescope. Launched in 2018, TESS was designed primarily to find exoplanets, but it has been vital for research on supernovae, black holes, and asteroids. In its first year online, TESS fueled as many research publications as the much larger, more expensive Hubble Space Telescope, earning TESS a reputation as "the little telescope that could."

> "Anywhere you point, there are galaxies," Kendrew says [of JWST]. "It's unprecedented for an infrared telescope to show us such a wealth of data, and we have barely scratched the surface."

"When we put even small tele-

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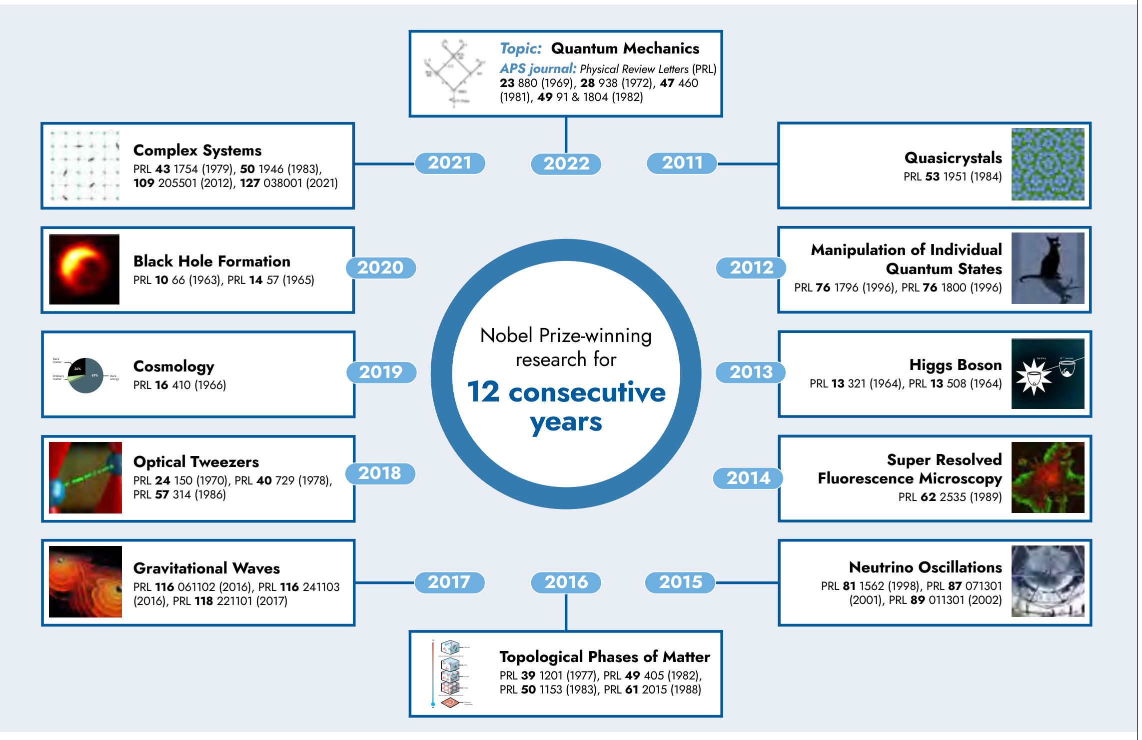
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APS

Taking on Climate Change and Cryptomining Carbon Emissions

Stephanie Mack, the 2021 APS Congressional Science Fellow, wraps up her year in Congress.

BY TAWANDA W. JOHNSON


Credit: Jason Yoder/Adobe

From wildfires to floods, the effects of climate change wreak havoc across the country — a reality that has shaped the work of physicist Stephanie Mack, the 2021-22 APS Congressional Science Fellow. Since last fall, she has worked on energy and environmental policy for Democratic Sen. Sheldon Whitehouse of Rhode Island.

“Being trained as a scientist, you bring a certain perspective when crafting policy and identifying outstanding questions,” she said.

Because environmental and energy policies often rely on complex scientific issues, having a scientist on a policymaking team has big benefits. APS’s year-long fellowship program makes a scientist available to members of Congress, who rarely have scientific backgrounds, and lets scientists be directly involved in policymaking. The fellow completes a two-week orientation in Washington, D.C., and then is matched with a congressional office or committee.

During Mack’s fellowship, Whitehouse partnered with Democratic Sen. Chris Coons of Delaware to introduce the Federal Carbon Dioxide Removal Leadership Act. The bill, intended to promote U.S. innovation that combats climate change, is a companion to one in the House of Representatives. Mack helped the team introduce the bill earlier this year.

“The bill would enable the government to create a market for nascent carbon dioxide removal technologies,” Mack said — technologies that could help the U.S. meet its target for reducing carbon emissions. The bill also “involved a lot of stakeholder engagement,” she added, “so it was satisfying to introduce the bill with broad support.”

Mack’s interest in science policy was piqued at the University of California, Berkeley, where she earned her PhD in physics. There, she also co-founded Berkeley’s Science Policy Group, which hosts speakers and discussions and plans events related to science policy.

After receiving her doctorate, Mack sought to tackle science policy as a Congressional Science Fellow. “I wanted to better understand the legislative process,” she said, “and explore a broad swath of environmental and energy policy areas.”

As a member of Whitehouse’s “Green Team,” Mack — in addition to her work on carbon dioxide removal — advocated for greater deployment of advanced nuclear reactors. She also helped research and draft a letter to the White House’s Office of Science and Technology Policy about the environmental toll of cryptocurrency mining, which emits an enormous amount of greenhouse gases, and the need for more transparency around its energy consumption.

“She is now regarded as one of the Senate’s foremost experts on the subject,” said Whitehouse, who recently hired Mack as a member of his legislative team because of her outstanding work as a fellow.

But Mack won’t be with his team much longer: She recently accepted a fellowship in the State Department with the Bureau of International Security and Nonproliferation. There, she’ll work to support nuclear power, “part of the solution to help meet the nation’s climate goals,” she said.

Tawanda W. Johnson is the Senior Public Relations Manager at APS.


2021-22 AAAS Congressional Science and Technology Policy Fellows. Stephanie Mack is wearing sunglasses and a black jacket in the upper right. Credit: Ryan Dudek

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Barábasi continued from page 2

were defining a new problem. And we were building the community, one paper at a time.

In a talk you gave, you said that our society is becoming a “laboratory” because of a “huge amount of data” available to study. Does this reality make it increasingly urgent that physicists communicate about their research to wider audiences?

Absolutely. I would even go further. COVID showed us how important this whole line of data-based thinking — and the role of physicists — is. Before COVID, epidemic prediction was based on traditional statistical methods. After our paper in ‘99 came out, another physicist, Alessandro Vespignani, defined network epidemiology. Network epidemiology allowed Vespignani’s team and others to start predicting, even before COVID, that something bad [would] happen. That’s one reason why Vespignani's work shaped the White House's response to COVID.

This was possible because physicists realized that epidemic processes are fundamentally network-based processes. They’re [also] stochastic processes, so you need statistical mechanics to properly describe them. Physics has been able to make a big impact in the community.

The circumstances [have] forced us to communicate what we do, because many of these models have really impacted people's lives. They were governing vaccine distribution, shutdown, all those things. Many physicists were the driving force behind that.

What open research questions fascinate you?

[Some] of the most exciting work we're doing now is to focus on physical networks—networks like in the brain, like neurons. The links are physical objects; there are cables there that cannot cross each other. We realized a few years ago that much of network science has sidelined the question of the physicality of the links in systems, like [the] vascular system or the brain or metamaterials. Now, a big effort in my lab is to develop the mathematical foundations and the physics of how we describe physical networks.

How can physicists better communicate about their research to diverse audiences?

First thing, do it. I think that 50% of success is your willingness to step out from your own narrow community and talk to a wider audience. That doesn't need to be a book. It can be an article in a newspaper. It can be a talk to undergrads.

We as physicists [tend] to be driven by intellectual curiosity and the coolness of the results that we get. There's an inherent beauty in some of the results, and we're happy if a few people understand that. When you step out of that community, that transition is not easy. It is, even today, painful for me, when I talk about a new subject, to formulate the message of “Why does this matter?” But I spend time to answer that in a way that is accessible to non-physicists, as well.

In a talk about your book “The Formula: The Universal Laws of Success,” you described performance as focused on the person who’s performing, but success as focused on how others perceive a person’s performance. How could this distinction impact research and recognition in the scientific community?

It's very important for a scientist to understand the patterns that govern their performance, the reception of their performance, or their scientific impact.

Thanks to the fact that research papers published since 1900 have been digitized and processed in a way that is analyzable, we have started massive research projects to understand the quantitative patterns that describe how a successful scientific career emerges.

Those patterns are very robust, and ignoring those is like trying to build an airplane without knowing Newton's Laws. The way scientific success emerges is not a random process. It has reproducible features, and understanding those could help young researchers have their work accepted much more widely and much faster.

For that reason, we wrote “The Science of Science.” The goal was to make [these lessons] accessible to any scientist. What are the quantitative laws that govern scientific careers? How do we not overestimate some of the measurable things, like citations, when it comes time to reflect on somebody's career?

Rachel Crowell is a math and science journalist based in Iowa.

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APS

Data continued from page 3

American, Indigenous, and Hispanic or Latino American students earn more physics doctorates today than a decade ago — but as a percentage of total doctorates awarded, their representation remains the same: about 6% of doctoral degrees. However, the percentage of *bachelor's* degrees awarded to students in these groups nearly doubled over that same period, from about 9% to 16%.

Corthell is concerned about the doctorate-level trend, which has persisted despite an uptick in programs intended to support students of color pursuing doctorate programs. "It's a shame right now that there continue to be a lot of roadblocks and obstacles for so many people," she says.

In terms of the percentage of bachelor's degrees awarded to women, every STEM field except math and statistics now shows an upward trend.

Hispanic and Latino Americans now earn nearly 1 in 8 physics bachelor's degrees

Despite limited doctorate-level progress, Hispanic and Latino American students in physics have made major gains at the undergraduate level in the last two decades, now earning over 12% of physics bachelor's degrees (Fig. 2).

A closer look at the data reveals another interesting trend. Since 1995, the percentage of bachelor's degrees in physics awarded to Hispanic and Latino American students has inched up each year. But in 2011, that rate of increase more than tripled, outpacing growth in the college-age Hispanic and Latino population in the U.S.

If this trend continues, physics bachelor's degrees awarded to Hispanic and Latino American students could be proportional to the college-age Hispanic population in a little more than a decade.

In contrast, although about 100 more Black or African American students earn bachelor's degrees in physics annually today than in 1998, the percentage of bachelor's awarded to students in this group has declined, from about 5% to just over 3% today. This is due in part to a drop in the number of physics bachelor's degrees awarded from historically black colleges and universities, or HBCUs.

Meanwhile, over the past five years, an annual average of 24 physics bachelor's degrees has been awarded to Native American and Alaska Native students, about 673 to Asian American students, and about 9 to students who are Native Hawaiian or Pacific Islander. Relative to their college-age populations, Black and African American, Indigenous, and Hispanic and Latino American students remain underrepresented, while white and Asian American students are overrepresented (the number of bachelor's degrees awarded to Asian American students has grown steadily for years) (Fig. 3).

For Corthell, diversity makes physics better for everyone. "It feels like you're more included," she says. "In a group that is aware of our differences and committed to working together, it is, I've found, very successful — we can bounce ideas off each other."

Where do we go from here?

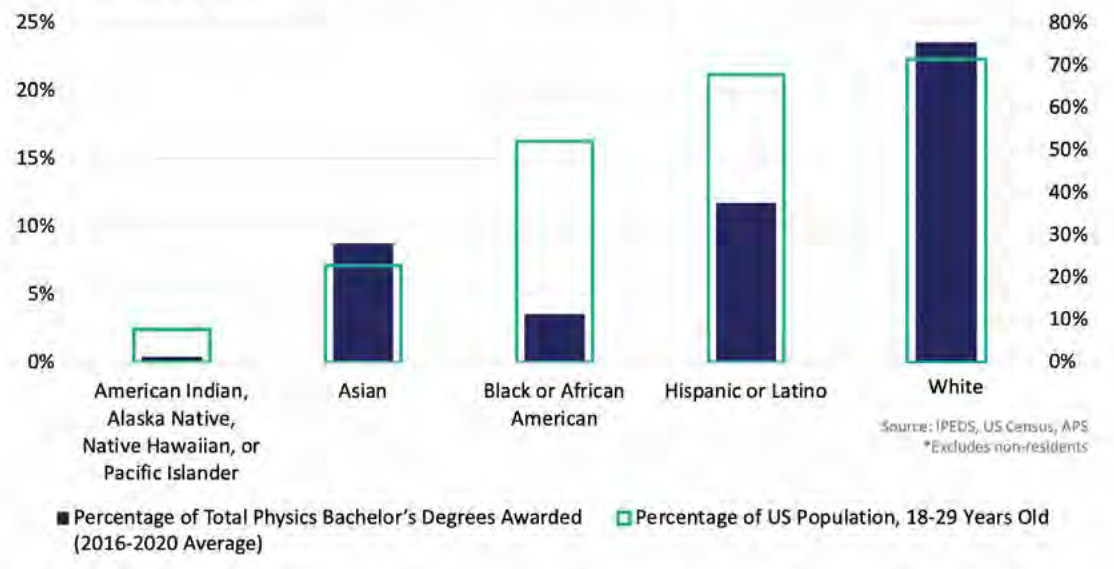
Enormous questions remain. How did the pandemic affect enrollment? Which students did the crisis impact most? It will be years before we have a complete picture, in large part because of the lag in IPEDS data collection.

For Corthell, data-sharing is the first step. She also wants the community to do what's needed to make physics an inclusive, welcoming environment. She encourages physics educators to use resources published by the Effective Practices for Physics Programs initiative, or EP3, and the initiatives of the APS Inclusion, Diversity, and Equity Alliance program.

"I just want everyone to have the opportunity to find their enjoyment in physics," says Corthell.

Liz Boatman is a staff writer for APS News.

Fig. 3: Percentage of Physics Bachelor's Degrees Awarded by Race/Ethnicity (Five-Year Average, 2016 to 2020)*



Source: IPEDS, US Census, APS
*Excludes non-residents

History continued from page 2

Mary, also a physicist, took a sort of sabbatical in America, freeing him up to work on quantum foundations. The resulting two papers would, eventually, revolutionize the field.

Bell's first paper, "On the Problem of Hidden Variables in Quantum Mechanics," as part of a muck-up involving a misfiled manuscript and unreturned mail, was not published until 1966 — two years after his more famous "second" paper. In this first paper, which was published in *Reviews of Modern Physics*, even though it was anything but a review, Bell targeted proofs by von Neumann and others that claimed to rule out hidden variables. While von Neumann's math was sound, Bell acknowledged, the proof was fatally flawed because it rested on a false assumption that the rules for quantum mechanics applied to hidden variables.

Toward the end of the paper, Bell discussed Bohm's theorem and non-locality. Foreshadowing, he noted that "there is no proof that any hidden variable account of quantum mechanics must have this extraordinary character" but that it would be "interesting, perhaps" to find such a proof.

In his second paper, Bell took what was a philosophical debate and turned it into an experimental question. The correlations between a pair of entangled particles — how often both were polarized vertically, for example — could be used to differentiate local hidden-variable theories from quantum mechanics. The key was to "ask different questions of the two particles," Kaiser says. "You start getting a very clear quantitative distinction."

Bell's inequality puts a limit on local hidden-variable theories; with correlations above that limit, the universe must be quantum. Finally, there was a way to tell which theory was correct, and whether the universe obeyed the "local realism" EPR longed for. But Bell did not trumpet the finding; it was published in a prestigious but new journal, *Physics Physique Физика*, which would shutter just four years later. The foundations of quantum mechanics were still mostly off-limits, seen as philosophy for cranks.

Experiments would eventually vindicate Bell, though not as he'd hoped: They ruled out local hidden variables, and locality as well. What they did, however, was prove that the foundations of quantum mechanics were interesting and valuable. "Philosophically-inclined physicists have a seat at the table now, in a way that they didn't in Bohm's day, they didn't in Bell's day," Kaiser says.

Broader recognition outside of the physics community has come slowly, too. In Belfast, it is illegal to name roads after people. So in 2015, when a semicircular road at the waterfront was renamed, it was dubbed Bell's Theorem Crescent.

Daniel Garisto is a writer based in New York.

Quantum physics continued from page 1

ber formulations bet on the outcome of several game rounds. Each formulation predicts a highest possible number for the correlation between the particles' measured properties. The paper in Nature proved that for this quantum game, complex formulations, with the extra flexibility of imaginary numbers, will always predict a higher value than any real-valued formulation (as long as the formulations abide by certain rules that define foundational features of quantum mechanics).

The new experiment used photons, produced as entangled pairs, as the quantum particles. The resulting observations exceeded the constraint predicted by the real-valued formulation by 5.30 standard deviations, supporting the assertion that complex numbers are needed to make the best possible quantum predictions. This builds on similar conclusions reached by two experiments earlier this year, one of which involved Lu and other authors of the new paper. But all these tests had loopholes. In both previous tests, parts of the experiments were located close enough together that information might have passed between the players, which could alter what predictions are possible using only real numbers.

"The goal of this kind of experiment is to rule out a class of theory, and you haven't really done it if there are these loopholes remaining," says William Wooters.

To close this loophole, called a locality loophole, the team spread the new experiment over five locations, each at least 89 meters apart, ensuring that information would need to travel from one part of the experiment to another faster than the speed of light to interfere with the results. This precaution, Lu says, was intended to help rule out the possibility that unknown mechanisms — at least, those allowed by the current laws of physics — would influence the experiment.

"The goal of this kind of experiment is to rule out a class of theory, and you haven't really done it if there are these loopholes remaining," says William Wooters, an emeritus professor of physics at Williams College who was not involved in the paper. "It is good to close the loopholes."

By ensuring events in the experiment happened quickly and far enough apart, the researchers say in the paper that, given reasonable assumptions, they have closed three loopholes: locality, independent source, and measurement independence.

Marc-Olivier Renou, a researcher at the Institute of Photonic Sciences in Spain, who was not involved in this research and was a co-lead author of the *Nature* paper, says that the important loophole of independent source can never be absolutely closed, but that, in the future, researchers might be able to quantify how much the loophole is closed.

"In this paper, they really formally and very clearly close the locality loophole," says Renou. "But now you have a second loophole, which is always a matter of belief — you believe that in your experiment your two sources are independent, but there is no very absolute way to close it. ... Someone could always say, 'Oh, no, but actually the state is not created at this moment; it was created before that.' And there is absolutely no way to rule out these kinds of explanations."

In the new paper, the researchers acknowledge that, without making an assumption, "it is impossible to rule out all loopholes" because the particles' correlations could result from "hidden variables" — some strange, unobserved hypothetical entities — that have existed since the birth of the universe.

The new experiment left open the detection loophole, which was closed in Lu and his colleague's previous experiment. Lu says the team hopes to develop new techniques to enable an experiment that simultaneously closes the loopholes.

Bailey Bedford is a science journalist based in the Washington, D.C. area.

Astrophysics continued from page 4

scopes in space and start looking, we often end up finding a lot more than we thought we would," says Dragomir.

To encourage participation, 4CS's meeting locations rotate between the four states from year to year. "Even the next state over can be 300 or 500 miles away," says David Dunlap, a physics professor at the University of New Mexico who led planning for the meeting. "Some people fly, others caravan in cars, others send groups of students in buses. One way or another, people get here." To increase access, the Section waives fees for students with limited funding and offers travel grants. This year, the plenary talks were broadcast on Zoom.

Over the past 25 years, the meeting's goals have evolved. When it was founded, "the main purpose of the meeting was to meet colleagues," Dunlap says. "In the ensuing years, more of an effort was made to have the meeting be an opportunity for graduate students. Then, over the past decade, with undergraduate research ramping up, we've seen the makeup of students at the meeting shift to 50% graduate students and 50% undergraduate students."

This shift to students has shaped the meeting's activities, including a crowd favorite: a session for the Harry Lustig Award, which offers a $1,000 prize for graduate research. Three finalists deliver back-to-back, 30-minute talks, and the winner is decided on the spot afterward.

The Section enables collaboration and even resource-sharing for students and senior scientists alike. For example, its instrument exchange program lets researchers sell lab instruments to other local scientists for far cheaper than new equipment. And one initiative funds projects that bring physics to primary and secondary school students, particularly from groups underrepresented in the field. Increasing representation is a 4CS priority, said Pearl Sandick, a physics professor at the University of Utah, and Section chair.

"I would love to see membership grow and reflect the diversity of the region," Sandick says.

To learn more about the Four Corners Section, visit engage.aps.org/4cs.

Abigail Dove is a writer based in Stockholm, Sweden.

Lollie continued from page 1

tronomy department, although one more has graduated since, with three more in the pipeline, she says. This August, Lollie began work at Quantinuum, Honeywell's quantum computing spinoff. Outside of physics, she recently picked up the violin and has a burgeoning whiskey collection. She spoke with *APS News* about her nontraditional path into physics.

This interview has been edited for length and clarity.

You're from Southfield, Michigan. What was it like growing up there?

I grew up in this white picket fence neighborhood, one mile outside of Detroit, so it was a pseudo-suburb with a city feel. Most of my family members went to the same public schools. I ended up going to a private all-girls' Catholic high school, where they bused in students from Detroit, and it was pretty diverse.

You studied finance as an undergrad and had a career in banking before returning to school to pursue physics at age 30. How did that play out?

A lot of my family has degrees in finance — my older brother, and many of my cousins. In high school, I envisioned myself on Wall Street in one of those $50,000 suits. But in college, I heard stories from friends after internships about how cutthroat it was, where they'd get pitted against other interns to produce results. I didn't want to be the type of person I needed to become to succeed in that environment.

But it was too late to change my major. So after graduation, I went into retail banking in Atlanta, where I went to college. After a few years of that, I found myself complacent in my job, so I went home to Michigan to regroup in 2009.

During that time, I saw this physics paper. To this day, I have no idea how I came across it. It was a seminal paper in quantum information theory by Bennett and Brassard on quantum teleportation. I didn't know what it was, but I wanted to study it. The paper mentioned entanglement, and I figured out that meant I should study physics. The rest is history.

You attended Rose-Hulman Institute of Technology in Indiana to get your second bachelor's. Were you ever intimidated to start over?

Rose kicked my butt. I don't want people to think this was an easy route. I had taken calculus in community college to prepare, but I hadn't ever done computer programming, and I didn't know about combinatorics, linear algebra, or all sorts of math until I got there.

But whether you want to be spiritual or practical about it, some things are just meant to be. I knew this is what I wanted to study. There was no quitting. If I failed a class, I would say to myself, "Okay, I'll take it again next quarter." It was like a train coming down the tracks, and it wasn't going to stop — I had to get those next tracks laid down.

> "During that time, I saw this physics paper. To this day, I have no idea how I came across it. … The paper mentioned entanglement, and I figured out that meant I should study physics. The rest is history." — Lollie

What kept you motivated?

The haters. It's cliché, but it's true. At Rose, I remember I was frustrated because I was working hard and was like, "Why can't I get this stuff?" One professor said, "Maybe you have a learning disability." His first thought when he had a struggling student was that something must be wrong with me, rather than his teaching.

Michelle Lollie as a graduate student at Indiana University, beforel transferring to LSU. *Credit: Eric Rudd, Indiana University*

I would fail these classes, and I remember thinking, "I'm stupid." But I realized a lot of the students at Rose had seen and studied this math in high school. A lot of their parents were educators, engineers, or scientists. I did not have the preparation that they had. Once I recognized that I just wasn't dealt a fair hand, that kept me motivated. And I had teachers who really personally invested in me.

In graduate school at Indiana University, one of my mentors was Garfield Warren, and you would see him literally on the floor with students going over problems. He would give students the confidence that they could learn.

You've mentioned your grandmother's influence on your life in other interviews. Can you tell me more about her?

My grandmother is sharp as a tack. She was born in 1928, and she grew up picking cotton in Mississippi. That was the only job she could find, pricking her hands on the plants in the heat of the day for little payment. I tell this to show that this is a modern story, not ancient history. My grandfather had an industrial job in Mississippi, and the two of them had to save up together to move to Detroit in the 1940s.

As I get older, I appreciate more what my grandmother had to go through. My grandmother didn't get a college education, while my mother has two degrees. If I couldn't find myself doing my degree for myself, I would think about my mother and my grandmother.

My grandmother attended my Ph.D. graduation this year. After I got my diploma, I just handed it to her. It was an honor to be able to show her that her life means more than perhaps she had thought.

What was your Ph.D. research?

My research was mainly experiments in quantum communication with photons. I was studying a particular intrinsic property of light called orbital angular momentum. This property imparts a twist to the light that we studied via the light beam's spatial profile.

You can store information in this twisting of the light. We wanted to use orbital angular momentum to build an encryption protocol to send a secret message between two parties, Alice and Bob, through a special fiber. But as light travels through this fiber, its spatial profile gets distorted, and it appears to lose information. My goal was to see if we could use machine learning to match a distorted beam with a clean, original version, and in that way, retrieve the lost message. Through our experiments, we found that the protocol could determine the original message from the distorted beams with 99% accuracy.

While in grad school, you also served as an advocate for students. What kind of work did you do?

I took the qualifying exam five times. I had to study, stress, and fail four times, and on the fifth time, I passed it, and way above the threshold required for the Ph.D. During this, I was also advocating against the qualifying exam along with several other students and faculty. A 2019 study showed that graduate entrance exams like the GRE don't correlate strongly with Ph.D. completion and limit access to underrepresented groups, and researchers are currently studying how qualifying exams might affect disparities among students. We got the faculty to vote on getting rid of it. It didn't pass, but we heard that it was a close vote.

We had several town halls where we, the students, worked together with the faculty. Now, at LSU, you still have to take the qualifying exam, but they are considering alternatives that emphasize research accomplishments for students who take it and don't pass.

Looking back, what's a piece of advice you would give your younger self?

People, no matter where they are in their careers, need to advocate for themselves. If you're afraid, advocate anyway, because otherwise no one else will. Some people say, wait until you graduate and get a professorship or a job, and then your voice will have weight. But I always say, I want my equity now.

Sophia Chen is a writer based in Columbus, Ohio.

Necib continued from page 1

istence.

Necib believes the stream, dubbed "Nyx" after the Greek goddess of night, might be the remnant of a dwarf galaxy that collided with the much larger Milky Way billions of years ago. To study the stream, her team merged particle physics with cosmological simulations, data from star catalogs, and machine learning — a groundbreaking combination of tools. They published their results in *Nature Astronomy*.

Necib credits a few other physicists for her successes — "in particular, several women," including Anna Frebel and Tracy Slatyer at MIT and Mariangela Lisanti at Princeton University. Mentors as much as colleagues, these women helped Necib adjust to her new faculty role at MIT, which she started during the pandemic and with a newborn baby, she says.

Necib grew up in Tunisia, a small country on Africa's northern coast, where she says she regularly faced sexist expectations for girls' behavior and ambitions. One night, when Necib was 8 years old, her family settled in for a movie. The selection? "Contact," starring Jodie Foster, who plays a scientist searching for aliens. The film opened Necib's eyes not only to the field of astrophysics, but to a world in which a woman could do astrophysics.

By the end of the movie, Necib had made up her mind: "I'm going to do *that*!"

> "It's a little bit like detective work," Necib says. "We have a lot of observational types of evidence, and we're trying to put all of it together into one picture."

She set her sights on college in the U.S. As an undergraduate at Boston University, she leapt into diverse research opportunities, conducting resonance testing of graphene and even joining the search for the Higgs boson at CERN. Her interest in dark matter grew.

During her senior year, at an open house hosted by MIT's physics doctoral program, Necib struck up a conversation with Jesse Thaler, a theoretical particle physicist. By the end of the chat, Necib knew she wanted to be at MIT.

Necib ultimately asked Thaler to be her dissertation advisor. "He was so enthusiastic about the work that he did. He loved it so much — it was kind of contagious," she says. "Having an advisor who really put in the time and effort to help me become the physicist that I am changed my life." Necib earned her doctorate in 2017.

Now in her second year as an assistant professor at MIT, Necib hopes to change cultural attitudes about science careers in Tunisia, where certain professions are given more weight. She wryly summarizes this ranking, starting with the best: "Doctor, engineer, lawyer, failure."

To topple these perceptions, Necib recently teamed up with Rostom Mbarek, another Tunisian physicist and the Neil Gehrels Prize Postdoctoral Fellow at the Joint Space-Science Institute. The duo just launched an astrophysics podcast entirely in Tunisian Arabic.

In her MIT classroom, Necib strives to debunk outdated perspectives on who does physics.

"I did this experiment last year in one of my first-year physics classes where I asked my students to name physicists," she recalls. "And all the names they came up with were Nobel Prize winners, but they were also all the same old, Albert Einstein-like examples."

After that session, Necib had her class learn about more recent work, including the contributions of women and scientists of color to the field.

One of Necib's "students" is particularly young. Her 17-month-old son can't yet say "dark matter," but he has the children's book "Astrophysics for Babies," and they go on excursions to Boston's Museum of Science. He's a bit young for the exhibits — "he's just impressed with the escalator," she says — but she hopes that early exposure will instill in him a love for science.

Meanwhile, her search for dark matter continues. She says that, if someone else solves the mystery of dark matter before she does, it won't phase her. For her, being a physicist is "really about the people," like her colleagues, mentors, and students.

"I know amazing people that are doing incredible work," she says. "Feeling that my work is recognized fills me with so much joy. I hope to pay it forward."

Liz Boatman is a staff writer for APS News.

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How Newton Derived the Shape of Earth

To argue for universal gravitation, Newton had to become a "geodesist."

BY MIGUEL OHNESORGE

Credit: Taryn MacKinney / APS

Isaac Newton's landmark 1687 work, "Philosophiæ Naturalis Principia Mathematica," laid the groundwork for classical mechanics, describing the laws of gravitation and predicting astronomical phenomena, like the movement of planets. The work changed physics.

But buried in the Principia is an often-overlooked triumph: Newton's derivation of Earth's figure — that is, the calculation of its shape, size, and surface gravity variation, part of a field later known as geodesy — which was crucial to his argument for universal gravitation. Here, I reconstruct Newton's derivation and its significance.

Newton's Derivation

Newton began his quantitative derivation of Earth's figure in 1686, after learning about work by the French physicist Jean Richer. In 1671, Richer had traveled to Cayenne, the capital of French Guiana in South America, and experimented with a pendulum clock. Richer found that the clock, calibrated to Parisian astronomical time (48°40' latitude), lost an average of 2.5 minutes per day in Cayenne (5° latitude). This was surprising, but it could be explained by the theory of centrifugal motion, recently developed by Christian Huygens: The theory suggested that the centrifugal effect is strongest at the equator, so the net effective surface gravity would decrease as you moved from Paris to Cayenne.

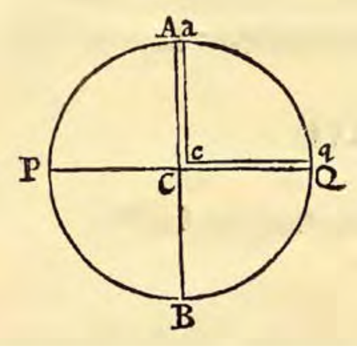

Fig. 1: Newton's illustration of hydrostatic equilibrium, a state he believed Earth to be in. *Credit: Newton's "Philosophiæ Naturalis Principia Mathematica"*

Newton accepted Huygens's theory but realized it meant something strange: If Earth is a sphere and its centrifugal effect is strongest at the equator, gravity would vary across Earth's surface, and the ocean would bulge up at the equator — a proposition that Newton considered absurd.

To resolve this, he proposed that the solid Earth had behaved like a fluid throughout its formation, gradually bulging up at the equator because of the centrifugal effect. He proposed modeling planets as rotating fluids in equilibrium, where the planet's shape is stable while the force generated by its rotational motion, and the gravitational attraction between its particles, acts on it.

To derive Earth's figure based on this theory, Newton first had to calculate the ratio between gravitational acceleration and centrifugal force at the equator (a 1-to-290.8 ratio), based on the period of Earth's diurnal rotation and estimates of Earth's equatorial diameter. Newton knew the length of two meridional arcs that he could use for this calculation, measured by surveyors in England and France. He calculated gravitational acceleration at the equator from Richer's pendulum measurements at 48°50' latitude, extrapolating the corresponding value at the equator of a homogeneous sphere.

Equipped with the ratio, Newton faced a problem: How could he express mathematically that a rotating fluid, whose constituents attract according to a certain law of gravity, is in a state of equilibrium? To answer this, Newton used an ingenious thought experiment, which he had developed in his 1685 "Liber Secundus" manuscript: A rotating body is in a state of hydrostatic equilibrium if the weight of water in two channels x and y, where x connects the equator to Earth's center and y connects Earth's center to one of the poles, is identical. Since x is affected by the centrifugal effect, equilibrium is fulfilled if the overall centrifugal "pull" on the equator is compensated by a change to the figure. In other words, the equatorial regions need to "bulge up" and the poles "flatten" to such an extent that the total weight of x and y (i.e., net gravitational attraction toward the center) is the same. This attempt to define hydrostatic equilibrium was later named the "principle of canals" (Fig. 1).

Newton then used his theory of gravitational attraction to derive the figure that a rotating body would need to have to balance the net attraction on the two columns — more precisely, the ratio between equatorial diameter and polar axis that would fulfill equilibrium. To calculate this, Newton determined the ratio between polar and equatorial surface gravity for the simpler case of a non-rotating oblate figure, with the axis-diameter ratio of 100-to-101, arriving at 501-to-500.

If this result is multiplied by the length of the two fluid columns (100-to-101), we obtain the ratio of 501-to-505 between the net gravitational forces acting on the polar and equatorial fluid columns. Therefore, the net gravitational force acting on the equatorial fluid column is greater than the corresponding net force acting on the polar fluid column by a magnitude of 4-to-505. So, if a spheroid with the dimensions of 100-to-101 is rotating and in a state of hydrostatic equilibrium, the ratio between equatorial surface gravity and centrifugal force must be 4-to-505.

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Since Newton's premise was that Earth is in a state of hydrostatic equilibrium, he extended this thought experiment to Earth. For his previously determined 1-to-290.1 ratio between equatorial surface gravity and centrifugal force, he calculated a corresponding polar axis and equatorial diameter ratio of 689-to-692. He concluded that Earth, modeled as a homogeneous spheroid that rotates with uniform angular velocity, must have polar and equatorial axes with a length ratio of 689-to-692 to be in a state of hydrostatic equilibrium.

He then calculated the effective surface gravity for this model of Earth — indicated by the length of the seconds-pendulum — to vary as the square of the sine of the latitude. By deriving a general latitudinal variation, he was no longer just concerned with the length ratio between the equatorial diameter and polar axis; instead, he was modeling Earth's overall figure — an oblate ellipsoid with an ellipticity of 3-to-692 (about 1-to-230.7). Using the pendulum length at 48°40' astronomical latitude in Paris as a reference point, he predicted that the pendulum has to be shortened by 81/1000 and 89/1000 inches in Gorée and Cayenne, respectively, to preserve its period — close but still inaccurate approximations of the measurements (100/1000 and 125/1000 inches).

Earth's Figure and Universal Gravitation

Clearly, Newton invested considerable effort in deriving Earth's figure and latitudinal variation in surface gravity. Besides presenting a novel definition for the hydrostatic equilibrium of rotating bodies, these results presumed Newton's theory of gravitational attraction. His predictions only hold if all of Earth's constituent particles mutually attract. Hence, his predictions offered a test for the most fundamental and novel assumption in Newton's theory of gravitation: that gravity acts universally between all particles of matter. In fact, as George Smith showed, these predictions are the Principia's only such test.

Newton was aware of this. His editor Roger Cotes kept pushing him to revise the geodetic results in light of new data, and in the second edition of the Principia, Newton revised Earth's ellipticity from a 689-692 ratio to a 1-to-230 ratio and added a table with detailed predictions of measurements for surface gravity and surface curvature. Newton revised these predictions again for the third edition (Fig. 2).

Were Newton's geodetic predictions accurate enough to reflect their importance in his argument for universal gravitation? On a naïve reading, the answer is no. When the third and last edition of the Principia was published, Newton had access to one arc measurement of the latitudinal variation in the length of 1° of meridian and five pendulum measurements of the variation of surface gravity with latitude. The arc measurement disagreed with Newton's predictions, seeming to indicate that Earth is an oblong, rather than oblate, spheroid. Out of existing pendulum measurements, only Jean Richer's seemed similar, but even that still disagreed with Newton's prediction. The prediction also does not match current data: Satellite measurements indicate that Earth's ellipticity has a ratio of 1-to-298.257223563.

Latitudo Loci	Longitudo Penduli	Mensura Gradus unius in Meridiano	Mensura Gradus unius in Meridiano		
	Pd. L.	Hexapod.	Hexapod.	Hexapod.	Hexapod.
0	3.7,470	56687	56677	56637	56627
5	3.7,484	56692	56682	56642	56632
10	3.7,528	56709	56699	56659	56649
15	3.7,598	56737	56727	56687	56677
20	3.7,693	56774	56764	56724	56714
25	3.7,812	56820	56810	56770	56760
30	3.7,948	56874	56864	56824	56814
35	3.8,099	56932	56922	56882	56872
40	3.8,261	56995	56985	56945	56935
41	3.8,294	57008	56998	56958	56948
42	3.8,327	57021	57011	56971	56961
43	3.8,360	57034	57024	56984	56974
44	3.8,394	57047	57037	56997	56987
45	3.8,427	57060	57050	57010	57000
46	3.8,460	57073	57063	57023	57013
47	3.8,493	57086	57076	57036	57026
48	3.8,527	57099	57089	57049	57039
49	3.8,560	57112	57102	57062	57052
50	3.8,593	57125	57115	57075	57065
55	3.8,754	57188	57178	57138	57128
60	3.8,905	57246	57236	57196	57186
65	3.9,042	57300	57290	57250	57240
70	3.9,160	57346	57336	57293	57283
75	3.9,258	57383	57373	57333	57323
80	3.9,326	57411	57401	57361	57351
85	3.9,369	57428	57418	57378	57368
90	3.9,3831	57433	57423	57383	57373

Fig. 2: Newton repeatedly revised his predictions for the measurement of the Earth's figure. *Credit: Cambridge University Library, Newton Manuscripts, MS Add 3965, 450r.*

However, such a pessimistic view of Newton's geodetic work misses important nuances of the Principia. As George Smith has argued, the Principia not only proposes theoretical predictions, but a methodology of testing through approximation. Newton accepted that his predictions would likely be inaccurate because he relied on uncertain background hypotheses when deriving them. The success of the universal theory of gravitation, then, should not be measured by the immediate agreement between initial predictions and measurements. Rather, Newton intended that his theory be tested on how well it could guide adjustments to background hypotheses, leading to converging measurements.

In other words, Newton did not aim to establish Earth's figure once and for all. Rather, he gave approximations, which would allow for adjustments to the assumptions he made in his derivation. With Newton's early derivation, for example, he assumed the rotating Earth has a homogeneous density. But when his predictions and Richer's measurements in Cayenne and Gorée disagreed, he modified this assumption in the first edition of the Principia. If Earth is denser at its center, he suggested, the ellipticity of Earth's equilibrium figure and its surface gravity variation will differ.

With this methodology, Newton passed the torch to future researchers, inviting them to develop hypotheses that would work with these initial measurements, and could then be tested with increasingly precise measurements.

In line with Newton's methodology, geodesists eventually produced convergent measurements of Earth's ellipticity based on variation in latitudinal surface gravity and curvature. For about two and a half centuries, they used the theories of gravitation and hydrostatic equilibrium to model Earth's figure, motion, and constitution, and gradually revised these parameters in light of new measurements. By 1909, all major ellipticity measurements converged within 297.6±0.9, implying that density increased inward. By 1926, Viennese astronomer Samuel Oppenheim concluded that these results offered overwhelming evidence for Newtonian gravity on Earth, vindicating both Newton's theory of gravitation and his methodology.

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For Ohnesorge's full essay, sources, and reconstruction of Newton's derivation, visit go.aps.org/geodesy. Learn more about Ohnesorge's research at mohnesorgehps.com.

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