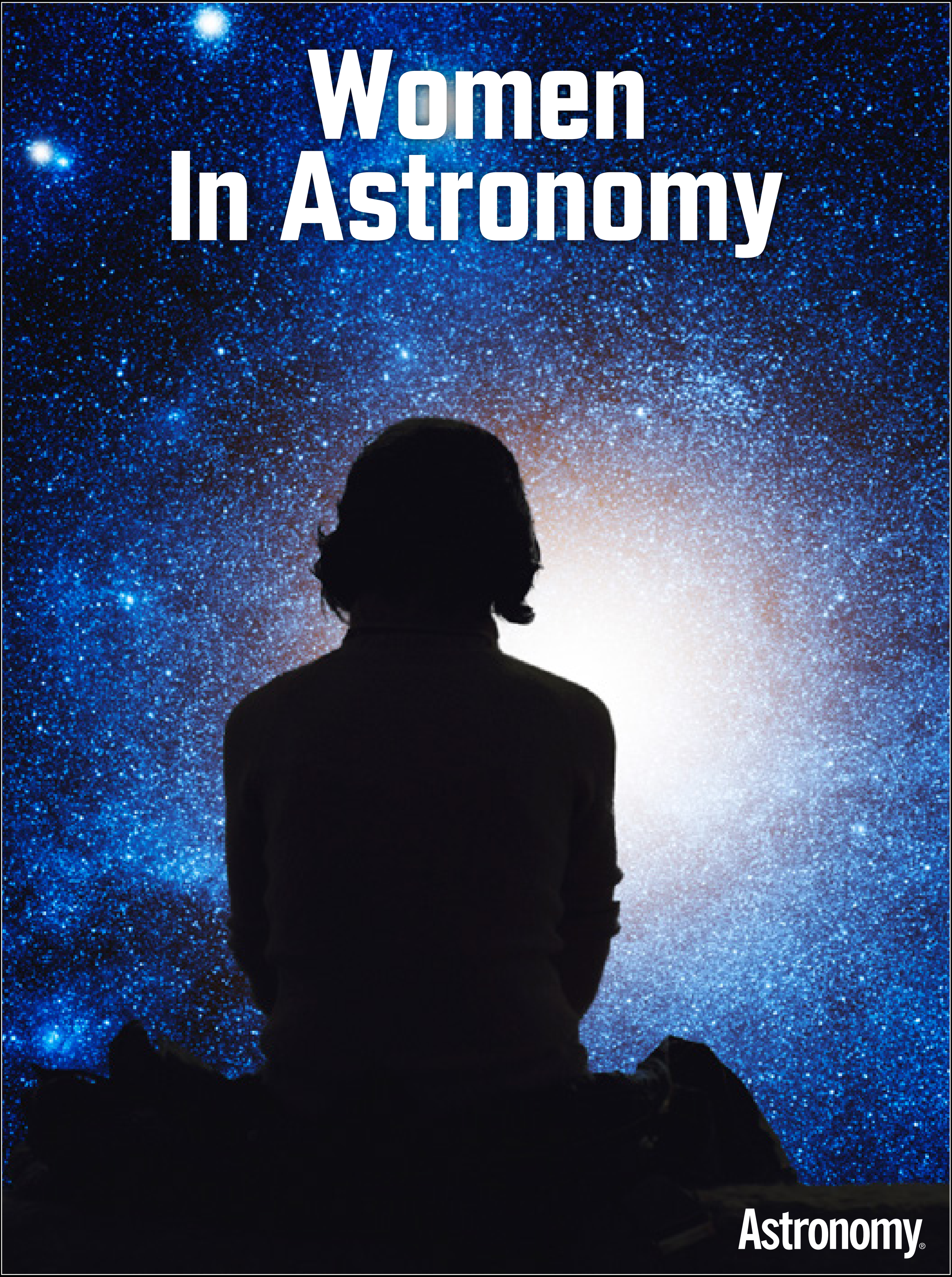
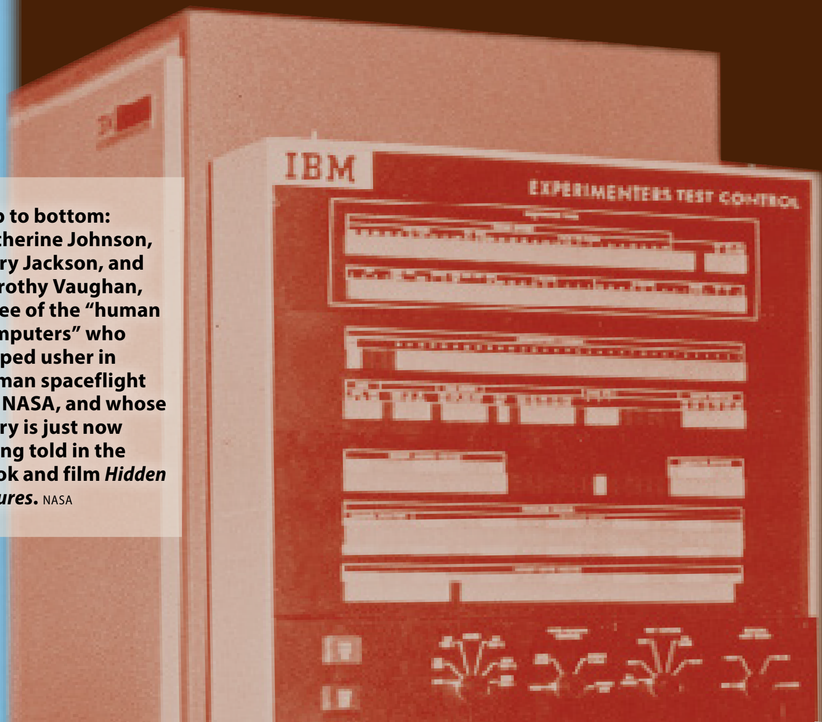


ASTROSTAR/SHUTTERSTOCK

Fighting FOR Visibility

From pre-NASA days to Apollo, the struggles of black women in the early space program rarely came to light. Until now.

by Korey Haynes



Top to bottom: Katherine Johnson, Mary Jackson, and Dorothy Vaughan, three of the "human computers" who helped usher in human spaceflight for NASA, and whose story is just now being told in the book and film *Hidden Figures*. NASA

In the heady days of the space race, the Mercury Seven astronauts were celebrities, and the Moon's silver face seemed, for the first time in human existence, close enough to touch. For many, space was a tantalizing promise of a wonderful future, beyond the strife of an increasingly divided Earth. For others, supremacy in space was the answer to the Cold War. And for yet others, space was a sign of profligate spending of time and energy on dreams, when reality desperately needed America's attention.

NASA achieved its most spectacular first steps in those days, making heroes out of men and women who dared to push harder, dream bigger, and be smarter than anyone before them. Those moments created titans in American history, such as rocket pioneers Robert Goddard and Wernher Von Braun, or astronaut adventurers John Glenn and Neil Armstrong.

But many of the actors in this play remain hidden in the wings. Now, decades after the work that should have made them legendary, the black women who helped put the United States in space are finally having their stories told.

These women, though not the faces memorialized in crowded mission-control room photos or seen waving from catwalks before launching beyond Earth's grip, were nonetheless stars in their own right. And one of the brightest was Katherine Johnson.

A HUMAN COMPUTER

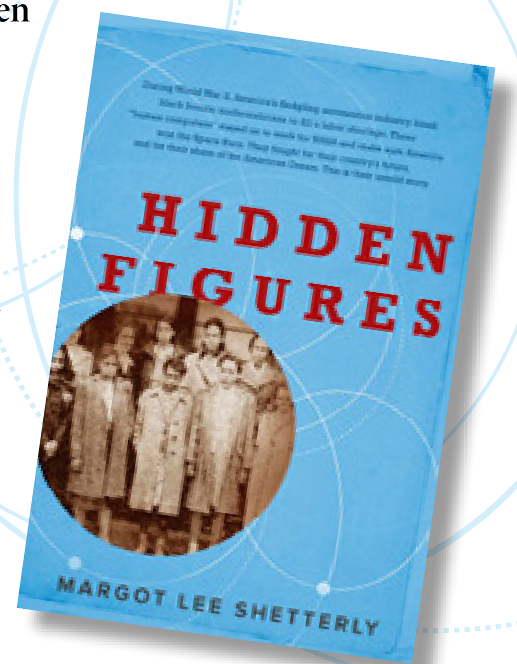
Born in 1918 in White Sulphur Springs, Virginia, Johnson loved numbers as a child. She started college at West Virginia State University at age 15 and blew through the school catalog's listed courses; her professor created new ones just for her. By 18, she had graduated summa cum laude with degrees in math and French. But career paths for black women were stark in the 1940s, even with a mind as sharp as Johnson's. She taught school for more than a decade before joining the space race as one of the women, black and white, whom NASA (and its predecessor, the National Advisory Committee for Aeronautics, or NACA) hired as "computers"— people to do the math that kept NASA running.

Korey Haynes *is a contributing editor to* Astronomy.

When engineers needed to calculate the trajectory for Alan Shepard's historic suborbital flight, Johnson volunteered. She told the men she worked with exactly where and how to shoot Shepard into the sky so he would splash down safely in range of watchful Navy ships. By the time Glenn orbited Earth, mechanical computers were beginning to replace humans. But Glenn, fearless as he was, wanted his path checked and his life in the hands of someone he could look in the eye, not an unfeeling machine. Johnson was that person, matching the computer decimal for decimal. And when Armstrong, Buzz Aldrin, and Michael Collins left Earth for the Moon, Johnson used the powerful new computers to calculate their trajectory as well. By the time she retired in 1986, she had left her fingerprints on NASA missions from the agency's first forays beyond Earth into the space shuttle era.

Johnson and her colleagues, Dorothy Vaughan and Mary Jackson, feature prominently in the new book *Hidden Figures*, by Margot Shetterly. The book, which came out in September 2016, is about to hit the big screen as a major motion picture. Johnson is the lead character, played by Taraji P. Henson of the Fox television show *Empire*; Octavia Spencer and Janelle Monáe round out the cast as Vaughan and Jackson, respectively.

Johnson is arguably the most famous of a group of black women Langley Research Center hired to perform calculations during World War II. They were known as the West Computers because they worked in the segregated West Area of Langley. Toiling as brainy beasts of burden, these women — and their white counterparts in the East wing — took math problems parceled out by engineers and solved them with lightning speed and meticulous accuracy.

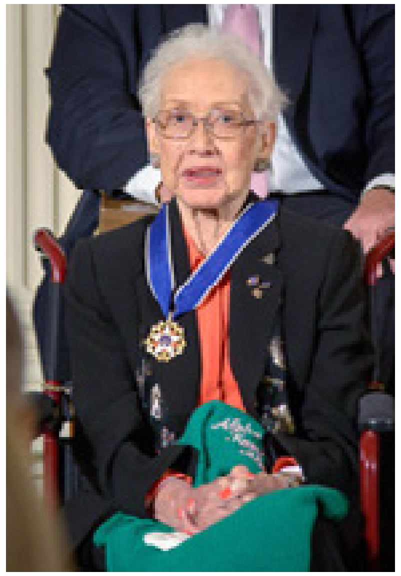


Women who showed particular skill and interest moved out of the computing pool to work directly with specific engineering groups. This allowed Johnson and others to break free of the physical walls segregating them by race and gender from the rest of the NASA team. Her work earned her NASA achievement awards and landed her in lists of both women's and African-Americans' success stories. But her work also landed men on the Moon, and she deserves — and is finally getting — recognition beyond these lesser-known lists. So why are we only hearing her story now?

"She's almost 98, and she's still alive and able to tell her own story," Shetterly says. "A lot of people have passed away, and so she's around in a moment when we're looking for people like her. You open the news, and there are a lot of really depressing stories out there. And this is a positive African-American story, it's a positive female story, it's a positive American story, it's a great space story."

Johnson's story, in fact, seems

Katherine Johnson sits at her desk, performing the sorts of calculations that eventually led to the Moon landing. NASA



Katherine Johnson receives the Presidential Medal of Freedom for her work ushering in the age of human spaceflight. NASA / BILL INGALLS

almost tailor-made for the big screen. The roots of her computing legacy reach from World War II through the looming threat of the Cold War and the strife and successes of the civil rights movement, hurtling through all of it in the pursuit of space dreams. She was a natural fit in an agency that broke scientific barriers and never stopped asking questions — except that Johnson and her fellow computers were breaking racial as well as scientific ground.

In 2015, President Barack Obama awarded the real Katherine Johnson the Presidential Medal of Freedom. And in May 2016, Langley, where Johnson spent her NASA career, dedicated a building in her name. NASA dedicated the new research facility on the 55th anniversary of Glenn's victorious return to Earth, but that milestone is only one small piece of the puzzle of "why now?"

"There's some kind of magic other thing," Shetterly admits. "I have no idea, but it just is happening of its own accord."

THE SILVER SCREEN TOUCH

Shetterly is one of the people who has long known not only Johnson's name, but many women like her. Shetterly grew up in Hampton, Virginia, in Langley's backyard. Her father worked at Langley as a research scientist. If anything, it took her this long to tell the women's story because for many years, their work didn't seem like much of a feat.

"I feel like it was probably one of the greatest gifts in my life just growing up thinking this was normal," she says. "There was nothing to me that was out of the ordinary about either living in a community with a lot of scientists or living in a community with a lot of African-American scientists or living in a community with a lot of female scientists and engineers and such. It seemed totally normal."

It wasn't until Shetterly explained the West Computers to her husband — and witnessed his wonder at their role in history — that a switch flipped in her mind. She began asking around for the women's stories and realized there were easily enough to fill a book.

> While the film was never meant to be a documentary, Barry is satisfied that the film will bring the key players and events to life.

She hadn't even finished writing that book when film producer Donna Gigliotti optioned the rights for a movie, based on only Shetterly's 50-page book proposal. Screenwriter Allison Schroeder took the proposal and many of Shetterly's primary source materials and got to work. She focused on three of the women who shine particularly brightly in Shetterly's research: Johnson, who was central to the leading missions of NASA's heyday of space flight; Jackson, an energetic young woman who smashed barriers in her advance from computer to engineer; and Vaughan, one of NASA's first black managers, who ran the segregated West Area Computing Division.

Schroeder was excited to tell the story of these women against the backdrop of the most exciting science program in U.S. history. With grandparents who worked for NASA, and a love of numbers and strong women all her own, Schroeder promises, "I was born to write this."

But she had her work cut out for her. Unlike the popular *Apollo 13* film — which relied on hours of recorded conversations and minute-by-minute accounts of the event for screenwriters to insert directly into the movie about a single, compact event — scant evidence existed from which *Hidden Figures* could draw.

While Johnson's work is well preserved in history, she recalls her day-to-day interactions only by memory. And in a story that spans decades — Shetterly's book opens in the height of World War II and follows Johnson until her retirement — the movie is obliged to condense multiple historical people into a few characters, the better for the audience to track and connect with. For instance, Kevin Costner plays a character stitched together out of real-life details from multiple flight directors and administrators in NASA's history.

"There's always a balancing act," says Bill Barry, a NASA historian who worked as a consultant for the film. His team delighted in replicating the halls of Virginia's Langley Research Laboratory in a disused hospital in Atlanta, right down to the art on the walls. But they were also patient with certain necessary adjustments made in order for the film to tell a cohesive story out of the jumble of real people's lives.

While the film was never meant to be a documentary, Barry is satisfied that the film will bring the key players and events to life.

A QUESTION OF HISTORY

Another part of the balancing act, not so dissimilar from the question the women themselves contemplated, is how much to talk about the challenges facing three black women in the '60s, racing for the Moon when so much stood in their way down on Earth.

"We really don't even deal with race," observes Henson, who plays Johnson in the movie. "Because you know what was going on in the '60s. … We deal with how to rise above it. At the end of the day, how do we get this man on the Moon?"

Barry agrees. "They were focused on the mission," he says. "So if you had the skill set to do the mission, they put you to work, and who cares about the rules." But Barry also admits there were rules even NASA wouldn't break, such as segregated restrooms and a designated cafeteria area.

Left to right: Janelle Monáe as Mary Jackson, Taraji P. Henson as Katherine Johnson, and Octavia Spencer as Dorothy Vaughan in the film *Hidden Figures*, based on the works of the women and their colleagues in the early space program. 20TH CENTURY FOX

Duchess Harris, a professor of American studies at Macalester College, argues, "That's not meritocracy." Harris has written her own book about the West Area computers, *Hidden Human Computers*. Like Shetterly, she has a personal connection to these women: Miriam Daniel Mann, one of the Langley computers, was her grandmother. She points out that the land Langley stands on was, until 1950, a plantation. While NASA extended science jobs to black employees, the segregation of the times meant race was still a constant presence in their lives.

Many NASA employees took classes to extend their already advanced technical knowledge, but African-Americans were forbidden from many of the local colleges because of segregation laws. The nearby Hampden Institute, a well-respected black university, supplied much of the desired coursework. Compounding the problem, NASA's standard position for hiring women was as a computer — a subprofessional position that paid half an engineer's salary, even for men and women with identical degrees. While NASA gave a few black women an important foothold, the deck was very much stacked against them.

But Henson is convinced that the film doesn't need to discuss race — or gender — to make powerful statements about representation. "As I'm doing my research," she recalls, "I see all of this NASA footage, and I don't see any women, not even white women. There was a west wing of computing and an east wing of computing, and they're just erased from history. … It blows my mind that little girls don't know that they can do this."

In another still from the film *Hidden Figures*, the human computers gather around a screen during an important space launch. 20TH CENTURY FOX

THE SPACE WOMEN OF TOMORROW

Spreading the women's message is both an important first step, and an incredibly rewarding one. Many hope that seeing Johnson on the big screen will trumpet her name far beyond NASA write-ups and awards.

But the Hollywood story, and even

OTHER IMPORTANT FIGURES EMERGING FROM HISTORY'S SHADOW

Miriam Daniels Mann was hired at the same time as Dorothy Vaughan, in 1943. Refusing the indignity of segregation in her supposedly enlightened workplace, Mann stole the signs marking the "colored" section of the cafeteria for years. Her granddaughter, Duchess Harris, is now researching the stories of all the West Computers. DEWITT WALLACE LIBRARY AT MACCALASTER COLLEGE

One of the younger computers, Christine Darden began working at NASA in 1967. She rose to the title of engineer in 1973, one of the few women of any color at the time to hold that position. Since then, she has published more than 50 papers and is recognized as a world expert in sonic booms. NASA

Dorothy Vaughan sits with Leslie Hunter and Vivian Adair (left to right); all three women worked as human computers. NASA

Melba Roy Mouton, pictured next to an electronic computer, was the leader of a group of human computers who helped track Echo satellites in the early 1960s. NASA

Shetterly's more in-depth book, are only narrow peeks into the rich history of the women who provided the bedrock of NASA's endeavors. Last year, Nathalia Holt released *Rise of the Rocket Girls*, about the women of the Jet Propulsion Laboratory, whose calculations guaranteed the success of rocket flights and planetary missions. Holt credits their legacy to JPL's retaining more women-powered space teams than elsewhere in the NASA family, where female team leads are hard to come by. But her book tells the story of only one center and its largely white team. Elsewhere, black women struggled up a steeper hill.

Harris continues her own study of the women of Langley, her research finding a home in museums and classrooms instead of in popular media. She hopes targeting children with these women's stories will provide role models for kids who often don't see scientists who look like them.

Speaking for NASA, Barry agrees. "We hope [the *Hidden Figures* film] encourages more young people to go into the field. From our perspective, there's lots of fallout benefits from telling this kind of story."

Those benefits are desperately needed. The space science fields, engineering in particular, suffer acutely from a lack of women and minorities. While the earliest computer programmers were exactly these human computers of NASA — adapting their math from pencil and paper and bulky calculator to computer punch cards — women's participation in computing fields flagged as the field advanced. And less than a hundred African-American women have earned Ph.D.s in physics.

Ever.

The reasons for this are manifold and complex, but it is a self-perpetuating problem. With so few black women in these fields, even those who complete advanced degrees can feel unwelcome at their work and find themselves treading ground not so dissimilar from Johnson's days, the social barriers less visible but still extant. And seeing few black women in those workspaces can discourage young potential scientists, who see no one like themselves to whom they can aspire.

Chanda Prescod-Weinstein, a professor of physics at the University of Washington, counts herself among the few black women with physics Ph.D.s. "Our institutional bias against black women scientists is so strong that it is literally hard for people to imagine I exist," she says. "I overcame it. The people who hired me overcame it."

She points to the "nonlinearity" of progress in STEM diversity. (STEM refers to the disciplines in science, technology, engineering, and math.) While Johnson and the other *Hidden Figures* characters worked in a team with other black women, Prescod-Weinstein says that she was 13 years into her research before she found the chance to work with another woman on a project.

"This film offers us an opportunity to really reflect on how science was done then, and why community took the structure it did, including the fact that because of segregation, sometimes it was easier for people to create community because they were forced into it," she says. "Now the segregation is less visible or less present, but I think a lot of times just less visible, and it can be harder for people to find community."

Studies show that as early as middle school, girls and minorities are opting out of science not because they enjoy it less or even see themselves as less capable, but because they don't see science as something that is for them.

> **"Our institutional bias against black women scientists is so strong that it is literally hard for people to imagine I exist."**

Understanding that not only can black women excel in space science, but they have been doing so all along, could make a huge impact on the next generation of scientists. "It really highlights the importance of not separating the science from the history of how it was produced," Prescod-Weinstein says.

FOR THE GREATER GOOD

It's also noteworthy that the human computers' stories center not on one lone genius, but on brilliant women who were part of a team. Science is often seen as a lone wolf endeavor, idealizing individuals like Albert Einstein or Stephen Hawking. But NASA has always been about team efforts.

Studies show that women are drawn to jobs that foster cooperation and have a clear impact, and that physics' reputation for cold calculation turns many of them off at young ages.

It is not just the faces of Langley's human computers that are important, but the ways in which they did their jobs.

"Somebody wants to know something," said the 98-year-old Johnson, explaining her math skills in a speech at her own Langley dedication ceremony. "Help them. Help anybody you can help." She saw her love of math as a way to further America's dreams. After her retirement, she spent decades traveling to classrooms and meeting school groups, encouraging more women to follow in her footsteps.

"She would always include other people," says Henson, who has come not only to admire, but to adore the woman she portrays. "Because she knows it's teamwork. But it was her calculations."

"If you've done an answer to a problem … yours is the answer," Johnson said in her dedication ceremony. And she is proud of her years of service: "When they pulled out a few notes to write down what I had worked on, the guy had 20 pages."

Johnson said she was pleased to see the emerging pattern of recognizing women's work, something she says men have long gotten credit for.

Prescod-Weinstein anticipates the film as "an opportunity to write history correctly, finally, about what has been the nature of black contributions to American intellectual history."

For many reasons, the West Computers' names are never likely to rise to the level of Neil Armstrong's or Jim Webb's renown. But the solutions were theirs.

Women like Katherine Johnson have always been part of the story. It's high time we told it.

How VERA RUBIN discovered dark matter

This famous astronomer carved herself a well-deserved place in history, so why doesn't the Nobel committee see it that way? by Sarah Scoles

In the late 1970s, Vera Rubin and Kent Ford of the Carnegie Institution of Washington stared, confused, at the punch-card readouts from their observations of the Andromeda Galaxy. The vast spiral seemed to be rotating all wrong. The stuff at the edges was moving just as fast as the stuff near the center, apparently violating Newton's Laws of Motion (which also govern how the planets move around our Sun). While the explanation for that strange behavior didn't become clear to Rubin until two years later, these printouts represented the first direct evidence of dark matter.

Scientists now know that dark matter comprises some 84 percent of the universe's material. Its invisible particles swarm and stream and slam through the whole cosmos. It affects how stars move within galaxies, how galaxies tug on each other, and how all that matter clumped together in the first place. It is to the cosmos like air is to humans: ubiquitous, necessary, unseen but felt. The discovery of this strange substance deserves a Nobel Prize. But, for Rubin, none has come, although she has long been a "people's choice" and predicted winner.

In the past few years, scientists have gotten that free trip to Sweden for demonstrating that neutrinos have mass, for inventing blue LEDs, for isolating graphene's single carbon layer, and for discovering dark energy. All of these experiments and ideas are worthy of praise, and some, like dark energy, even tilted the axis of our understanding of the universe. But the graphene work began in 2004; dark energy observations happened in the late '90s; scientists weighed neutrinos around the same time; and blue LEDs burst onto the scene a few years before that. Rubin's work on dark matter, on the other hand, took place in the 1970s. It's like the committee cannot see her, although nearly all of astrophysics feels her influence.

Rubin is now 87. She is too infirm for interviews. And because the Nobel can only be awarded to the living, time is running out for her.

► **Vera Rubin, with collaborator Kent Ford, is responsible for finding dark matter, one of the most fundamental discoveries of the past century in astrophysics. Yet a Nobel Prize still eludes her.** PETER GINTER, GETTY IMAGES

▲ **Our near neighbor, the spiral Andromeda Galaxy (M31), was Rubin's first target in her study of galaxy rotation. While telescopes reveal glittering stars and glowing clouds of dust and gas, Rubin's studies implied an additional invisible halo of dark matter.** NASA/JPL-CALTECH

► **A young Vera Rubin was already observing the stars when she was an undergraduate at Vassar College, where she earned her bachelor's degree in astronomy in 1948.** ARCHIVES & SPECIAL COLLECTIONS, VASSAR COLLEGE LIBRARY

Emily Levesque, an astronomer at the University of Washington in Seattle who has spoken out about Rubin's notable lack of a Nobel, says, "The existence of dark matter has utterly revolutionized our concept of the universe and our entire field; the ongoing effort to understand the role of dark matter has basically spawned entire subfields within astrophysics and particle physics at this point. Alfred Nobel's will describes the physics prize as recognizing 'the most important discovery' within the field of physics. If dark matter doesn't fit that description, I don't know what does."

There's no way to prove why Rubin remains prize-less. But a webpage showing images of past winners looks like a 50th-reunion publication from a boys' prep school. No woman has received the Nobel Prize in physics since 1963, when Maria Goeppert Mayer shared it with Eugene Wigner and J. Hans Jensen for their work on atomic structure and theory. And the only woman other than Mayer ever to win was Marie Curie. With statistics like that, it's hard to believe gender has nothing to do with the decision.

Some, like Chanda Prescod-Weinstein of the Massachusetts Institute of Technology, have called for no men to accept the prize until Rubin receives it. But given the human ego and nearly million-dollar prize amount, that's likely to remain an Internet-only call to action.

No room for women

Rubin isn't unfamiliar with discrimination more outright than the Nobel committee's. Former colleague Neta Bahcall of Princeton University tells a story about a trip Rubin took to Palomar Observatory outside of San Diego early in her career. For many years, the observatory was a researcher's man cave. Rubin was one of the first women to gain access to its gilt-edged, carved-pillar grandeur. But while she was allowed to be present, the building had no women's restroom, just urinal-studded water closets.

"She went to her room, she cut up paper into a skirt image, and she stuck it on the little person image on the door of the bathroom," says Bahcall. "She said, 'There you go; now you have a ladies' room.' That's the type of person Vera is."

Rubin has continued to champion women's rights to — and rights within — astronomy. "She frequently would see the list of speakers [at a conference]," says Bahcall, "and if there were very few or no women speakers, she would contact [the organizers] and tell them they have a problem and need to fix it."

But, as Rubin told science writer Ann Finkbeiner for *Astronomy* in 2000, she is "getting fed up. … What's wrong with this story is that nothing's changing, or it's changing so slowly."

An early start

Rubin, born in 1928, first found her interest in astronomy when her family moved to Washington, D.C. Windows lined the wall next to her bed. She watched the stars move, distant and unreachable. "What fascinated me was that if I opened my eyes during the night, they had all rotated around the pole," she told David DeVorkin in 1995 as part of the American Institute of Physics oral history interview series. "And I found that inconceivable. I just was captured."

She started watching meteor showers and drew maps of the streaks, which striped the sky for a second and then were gone. She built a telescope and chose astronomical topics for English papers, using every subject as an opportunity to peer deeper into the universe. "How could you possibly live on this Earth and not want to study these things?" she wondered, retelling the story to DeVorkin.

While her parents supported her, it was a different story at school. When she told her physics teacher, for instance, that she had received a scholarship to Vassar College, he said, "As long as you stay away from science, you should do OK."

She didn't.

"The existence of DARK MATTER has utterly revolutionized our concept of the universe and our entire field."
— Emily Levesque

Rotation of the universe

After receiving her bachelor's degree from Vassar, Rubin enrolled in graduate school in astronomy at Cornell University in Ithaca, New York. Ensconced in Ithaca's gorges and working with astronomer Martha Stahr Carpenter, Rubin began to hunt around for a master's thesis idea. Carpenter was obsessed with galaxies and how their innards moved. "Her course in galaxy dynamics really set me off on a direction that I followed almost my entire career," said Rubin.

One day, her new husband, Robert Rubin, brought her a journal article by astronomer George Gamow. In it, Gamow wondered, "What if we took the way solar systems rotate and applied it to how galaxies move in the universe?"

Rubin wondered, "What if, indeed?" and took that wonder a step further. She began to measure how galaxies moved. Did some cluster together in their travel through space — perhaps rotating around a pole, like the planets rotate around the common Sun? Was it random?

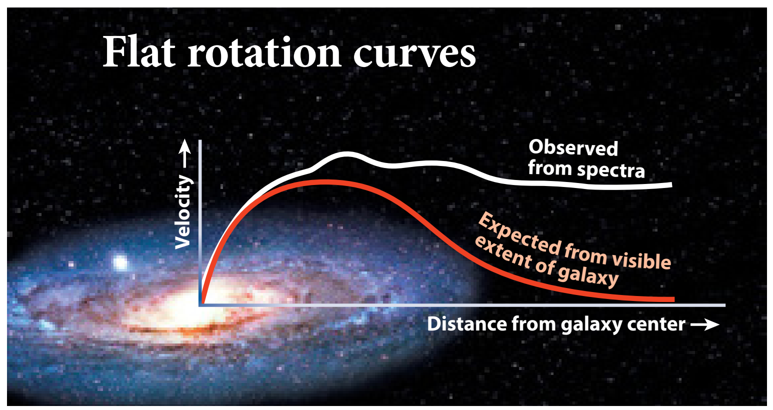
While gathering data, she found a plane that was denser with galaxies than other regions. She didn't know it at the time, and no one else would discover it for years, but she had identified the "supergalactic plane," the equator of our home supercluster of galaxies.

When she presented her thesis, William Shaw, one of her advisers, told her just two things: One, the word *data* is plural. Two, her work was sloppy. But, he continued, she should consider presenting it at the American Astronomical Society (AAS) meeting. Or, rather, she should consider having it presented for her. Because she was pregnant with her first child — due just a month before the meeting — and not a member of the society, he graciously volunteered to give a talk on her results. "In his name," she clarified to DeVorkin. "Not in my name. I said to him, 'Oh, I can go.'"

She called her talk "Rotation of the Universe," ascribing the ambitious title to "the enthusiasm of youth," as she recalled. At the AAS meeting, she didn't know anyone, and she thought of herself as a different category of human. "I put these people in a very special class. They were professional astronomers, and I was not," she said, showcasing a classic case of impostor syndrome, a psychological phenomenon in which people don't feel they deserve their accomplishments and status and will inevitably be exposed as frauds. "One of the biggest problems in my life [during] those years was really attempting to answer the question to myself, 'Will I ever really be an astronomer?'"

The "real astronomers" pounced on her result (except, notably, Martin Schwarzschild, who defined how big black holes are). "My paper was followed by a rather acrimonious discussion," she told DeVorkin. "I didn't know anyone, so I didn't know who these people were that were getting up and saying the things they said. As I recall, all the comments were negative."

Her paper was never published.



If galaxies were only the stars, dust, and gas that astronomers can see, then you would expect the red line: Gravity pulls most strongly and objects therefore rotate more quickly where most of the matter resides. But Rubin's and hundreds of later observations revealed that the speed of the galaxy's outer material is the same as the speed of matter closer in, indicating some enormous invisible mass hurrying things along. *ASTRONOMY*: ROEN KELLY

Rubin and Kent Ford (white hat) check on their equipment at Lowell Observatory in 1965 during one of their first observing runs together. CARNEGIE INSTITUTION, DEPARTMENT OF TERRESTRIAL MAGNETISM

Back into the field

For six months after her first child was born, Rubin stayed home. But while she loved having a child, staying at home emptied her. She cried every time *The Astrophysical Journal* arrived at the house. "I realized that as much as we both adored this child, there was nothing in my background that had led me to expect that [my husband] would go off to work each day doing what he loved to do, and I would stay home with this lovely child," she said to DeVorkin. "I really found it very, very hard. And it was he who insisted that I go back to school."

She was accepted into a Ph.D. program at Georgetown University in Washington, D.C., and she discovered that galaxies did clump together, like iron filings, and weren't randomly strewn. The work, though now part of mainstream astronomy, was largely ignored for decades; that lack of reinforcement perhaps contributed to her lingering, false feeling that she wasn't a *real* astronomer. As she described it, "My husband heard my question often, 'Will I ever really be an astronomer?' First I thought when I'd have a Ph.D., I would. Then even after I had my Ph.D., I wondered if I would."

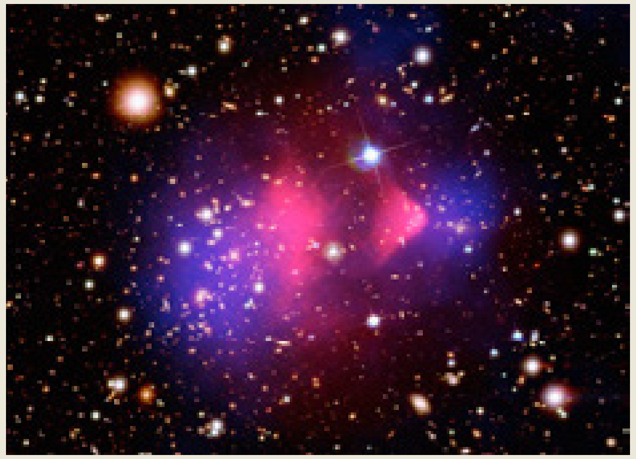
Mysteriously flat

In 1965, after a stint as a professor at Georgetown, Rubin began her work at the Carnegie Institution's Department of Terrestrial Magnetism in Washington, D.C., where she met astronomer Kent Ford and his spectacular spectrometer, which was more sensitive than any other at the time.

A spectrometer takes light and splits it up into its constituent wavelengths. Instead of just showing that a fluorescent bulb

Former Astronomy *Associate Editor* **Sarah Scoles** *is a freelance writer living in the San Francisco area. She is writing a book on astronomer and SETI pioneer Jill Tarter.*

THE BULLET THAT KILLED MOND



The Bullet Cluster is often claimed as a smoking gun for dark matter.

Dark matter is hard to believe. We can't see it, and it barely interacts with normal matter. Vera Rubin and others inferred its presence from Isaac Newton's laws about gravity. But what if Newton was wrong?

In 1983, Mordehai Milgrom suggested Modified Newtonian Dynamics (MOND) as a more palatable explanation. He proposed that gravity behaves differently in low-acceleration regions such as the outskirts of galaxies. It neatly explained most of the galaxies Rubin had observed without invoking a mysterious new form of matter.

But MOND can't explain objects such as the Bullet Cluster, the result of two colliding galaxy clusters. Gravitational lensing (shown in blue) maps most of the mass to the bright stellar material. But galaxies carry most of their normal mass in hot gas (shown in pink from X-ray emission) and waylaid in the middle of the collision thanks to drag forces.

Just as Rubin showed with her rotation curves, the Bullet Cluster proves that galaxies hold far more mass than our telescopes can see. And neither Newton nor MOND can explain that without the mysterious power of dark matter. **— Korey Haynes**

Rubin operates the 2.1-meter telescope at Kitt Peak National Observatory. Kent Ford's spectrograph is attached so they can measure the speed of matter at different distances from galaxies' centers. NOAO/AURA/NSF

glows white, for instance, it would show how much of that light is blue and how much yellow, and which specific wavelengths of blue and yellow. Ford's spectrometer stood out from others at the time because it employed state-of-the-art photomultipliers that let researchers study small regions of galaxies, and not simply the entire objects.

With this device, Ford and Rubin decided to look at quasars — distant galaxies with dynamic, supermassive black holes at their centers. But this was competitive work: Quasars had just been discovered in 1963, and their identity was in those days a mystery that everyone wanted to solve. Rubin and Ford didn't have their own telescope and had to request time on the world-class instruments that astronomers who worked directly for the observatories could access all the time. Rubin didn't like the competition.

"After about a year or two, it was very, very clear to me that that was not the way I wanted to work," she told Alan Lightman in another American Institute of Physics oral history interview. "I decided to pick a problem that I could go observing and make headway on, hopefully a problem that people would be interested in, but not so interested [in] that anyone would bother me before I was done."

Rubin and Ford chose to focus on the nearby Andromeda Galaxy (M31). It represented a return to Rubin's interest in galaxy dynamics. "People had inferred what galaxy rotations must be like," said Rubin, "but no one had really made a detailed study to show that that was so." Now, because of Ford's out-of-this-world spectrograph, they could turn the inferences into observations.

When they pointed the telescope at M31, they expected to see it rotate like the solar system does: Objects closer to the center move faster than ones toward the edge. Mass causes gravity, which determines the speed of rotation. Since most of the stars, dust, and gas — and therefore gravity — is clustered in the middle of galaxies, the stuff on the periphery shouldn't feel much pull. They concentrated their observations on Hydrogen-II (HII) regions — areas of ionized hydrogen gas where stars have recently formed — at different distances from the galaxy's center. But no matter how far out they looked, the HII regions seemed to be moving at the same speed. They weren't slowing down.

"We kept going farther and farther out and had some disappointment that we never saw anything," says Ford.

"I do remember my puzzling at the end of the first couple of nights that the spectra were all so straight," said Rubin, referring to the unchanging speed of the various HII regions.

They didn't know what, if anything, it meant yet.

The project took years and involved treks westward to telescopes. Ford recalls flying to Flagstaff, Arizona, dragging the spectrograph from the closet, working for a few nights at Lowell, and then throwing the instrument into a Suburban so they could drive it to Kitt Peak. "We both thought we were better at guiding the telescope," he says. They raced each other to be first to the eyepiece.

The data came out on punch cards, which Rubin spent hours analyzing in a cubbyhole beneath a set of stairs. They all showed the same thing.

Rubin and Ford moved on from M31 to test other galaxies and their rotation curves. Like an obsessive artist, each painted the same picture. Although the result contradicted theory, and although they didn't understand what it meant, no one doubted their data. "All you had to do was show them a picture of the spectrum," Rubin told Lightman. "It just piled up too fast. Soon there were 20, then 40, then 60 rotation curves, and they were all flat."

> "My entire education highlighted how fundamental DARK MATTER is to our current understanding of astrophysics."
> — Emily Levesque

(BULLET CLUSTER) X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.; OPTICAL: NASA/STSCI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.; LENSING MAP: NASA/STSCI; ESO WFI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.

A dark answer

Dark matter existed as a concept, first proposed by astronomers like Jan Oort in 1932 and Fritz Zwicky in 1933, who also noticed discrepancies in how much mass astronomers could see and how much physics implied should be present. But few paid their work any attention, writing their research off as little more than cosmological oddities. And no one had bagged such solid evidence of it before. And because no one had predicted what dark matter's existence might mean for galaxy dynamics, Rubin and Ford initially didn't recognize the meaning of their flat rotation curves.

"Months were taken up in trying to understand what I was looking at," Rubin told journalist Maria Popova. "One day I just decided that I had to understand what this complexity was that I was looking at, and I made sketches on a piece of paper, and suddenly I understood it all."

If a halo of dark matter graced each galaxy, she realized, the mass would be spread *throughout* the galaxy, rather than concentrating in the center. The gravitational force — and the orbital speed — would be similar throughout.

Rubin and Ford had discovered the unseeable stuff that influences not only how galaxies move, but how the universe came to be and what it will become. "My entire education highlighted how fundamental dark matter is to our current understanding of astrophysics," says Levesque, "and it's hard for me to imagine the field or the universe without it."

Within a few years of the M31 observations, physicists like Jeremiah Ostriker and James Peebles provided the theoretical framework to support what Rubin and Ford had already shown, and dark matter settled firmly into its celebrated place in the universe.

In more recent years, the Planck satellite measured the dark matter content of the universe by looking at the cosmic microwave background, the radiation left over from the Big Bang. The clumps of matter in this baby picture of the universe evolved into the galaxy superclusters we see today, and it was dark matter that clumped first and drew the regular matter together.

Data from galaxy clusters now also confirms dark matter and helps scientists measure how much of it exists within a given group — a modern echo of Zwicky's almost forgotten work. When light from more distant sources passes near a cluster, the gravity — from the cluster's huge mass — bends the light like a lens. The amount of bending can reveal the amount of dark matter.

Rubin measures spectra at the Carnegie Institution's Department of Terrestrial Magnetism. It was such measurements that revealed to Rubin that the outer regions of galaxies rotated as fast as their inner regions — indicating some huge amount of missing mass that would later be realized as dark matter. AIP/EMILIO SEGRE VISUAL ARCHIVES

Rubin continued to work at the Carnegie Institution's Department of Terrestrial Magnetism until recently, still fascinated by galaxies and studying how they move in the universe. AIP/EMILIO SEGRE VISUAL ARCHIVES

No matter which way or where scientists measure Rubin's discovery, it's huge.

And while no one knows what *all* the dark matter is, scientists have discovered that some small fraction of it is made of neutrinos — tiny, fast-moving particles that don't really interact with normal matter. Measurements from the cosmic microwave background, like those being taken by experiments called POLARBEAR in Chile and BICEP2 and BICEP3 in Antarctica, will help pin down how many neutrinos are streaming through the universe and how much of the dark matter they make up.

Some setups, like the Gran Sasso National Laboratory in Italy and the Deep Underground Science and Engineering Laboratory in South Dakota, are trying to detect dark matter particles directly, when they crash into atoms in cryogenically cooled tanks filled with liquefied noble gases. So far, they haven't managed to capture a dark matter particle in action. But researchers are taking dark matter — whatever it is — into account when they think about how the universe evolves.

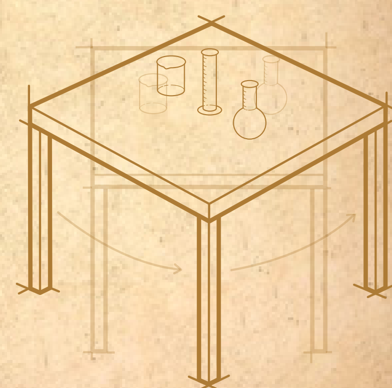
The Nobel committee may overlook Rubin, passing by her as if they can't see what all of astrophysics feels. But that won't hurt her legacy, says Levesque: It will hurt the legacy of the Nobel itself. "It would then permanently lack any recognition of such groundbreaking work," Levesque says.

Rubin herself has never spoken about how she deserves a Nobel Prize. She simply continued her scientific work until recently, all the while influencing the origins, evolutions, and fates of other scientists. "If they didn't get a job or they didn't get a paper published, she would cheer people up," says Bahcall. "She kept telling her story about how there are ups and downs and you stick with it and keep doing what you love doing."

Rubin, herself, loves trying to understand the universe, and in doing so, she has changed everyone's understanding of it. That carries more weight than some medal from Sweden. But let Sweden recognize that for what it is: worthy of a prize.

PICTORIAL PARADE/HULTON ARCHIVE/GETTY IMAGES

The Universe According to Emmy Noether



How a deceptively simple theorem from a century ago still shapes modern physics.

BY **STEVE NADIS**
ILLUSTRATIONS BY **JAY SMITH**

In her 53 years, many spent bucking a system that impeded her pursuit of mathematics, Noether had an extraordinary impact on both algebra and physics. There's no telling what else she might have accomplished if society and fate had been more kind.

In 1915, two of the world's top mathematicians, David Hilbert and Felix Klein, invited Emmy Noether to the University of Göttingen to investigate a puzzle. A problem had cropped up in Albert Einstein's new theory of gravity, general relativity, which had been unveiled earlier in the year. It seemed that the theory did not adhere to a well-established physical principle known as conservation of energy, which states that energy can change forms but can never be destroyed. Total energy is supposed to remain constant. Noether, a young mathematician with no formal academic appointment, gladly accepted the challenge.

She resolved the issue head-on, showing that energy may not be conserved "locally" — that is, in an arbitrarily small patch of space — but everything works out when the space is sufficiently large. That was one of two theorems she proved that year in Göttingen, Germany. The other theorem, which would ultimately have a far greater impact, uncovered an intimate link between conservation laws (such as the conservation of energy) and the symmetries of nature, a connection that physicists have exploited ever since. Today, our current grasp of the physical world, from subatomic particles to black holes, draws heavily upon this theorem, now known simply as Noether's theorem.

"It is hard to overstate the importance of Noether's work in modern physics," Durham University physicist Ruth Gregory said a century later. "Her basic insights on symmetry underlie our methods, our theories and our intuition. The link between symmetry and conservation is how we describe our world."

A LIFE OF WORK

Who was this woman, called upon by two renowned mathematicians to help rescue Einstein's masterwork? On the face of it, Noether (pronounced NUR-tuh) appears to have been a curious choice. She did not have an actual job in mathematics and was barely able to get an education in the field. Yet she had published some important papers, and Hilbert felt that her expertise could help clear up the problem with general relativity.

Born in Erlangen, Germany, in 1882, Noether hoped to follow in the footsteps of her mathematician father, Max. But German universities did not admit women when she reached college age, so Noether had to audit classes instead. Eventually she did so well in the final exams that she earned an undergraduate degree.

In 1904 she was permitted to enroll in a doctoral program at the University of Erlangen. She received a Ph.D. in 1907 and spent nearly eight years working there without pay or an official position, relying on her family for financial support while occasionally filling in for her father as a substitute teacher. After her trip to Göttingen in 1915, she stayed on as a lecturer, again receiving no pay.

After years of working essentially as a volunteer, Noether finally became an untenured associate math professor in 1922 at Göttingen, where she was allotted a modest salary. But 11 years later, she lost her job when she and other Jews were cast out of academia in Nazi Germany. Soon after, she left the country and landed a job at Bryn Mawr College in Pennsylvania, with the help of Einstein. She died just 18 months later due to complications from surgery to remove an ovarian cyst.

EMILIANA AND MONICA NOETHER VIA MATHEMATICAL ASSOCIATION OF AMERICA/FLICKR

In her 53 years, many spent bucking a system that impeded her pursuit of mathematics, Noether had an extraordinary impact on both algebra (her main field) and physics. There's no telling what else she might have accomplished if society and fate had been more kind. Nevertheless, her body of work was more than enough to secure her place in the pantheon of great scientists, with her namesake theorem perhaps her most durable contribution.

THE THICK OF THE THEOREM

Noether's theorem is a simple and elegant link between seemingly unrelated concepts that is, today, almost obvious to physicists. But nonphysicists can get the gist of it, too.

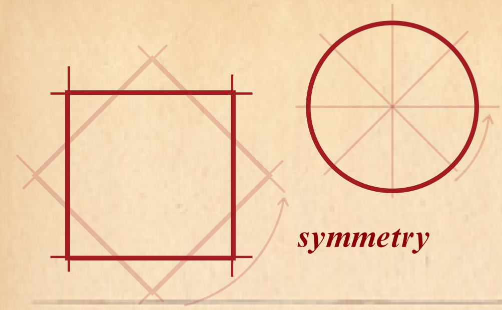
Basically, it states that every "continuous" symmetry in nature has a corresponding conservation law, and vice versa. Let's break down a few of those terms. ***Symmetry***, in this context, refers to an operation that can be done to an object or system that leaves it unchanged. Rotating a square by 90 degrees is an example of "discrete" symmetry. The square still looks the same, whereas a 45-degree rotation yields something different (commonly called a diamond). A circle, on the other hand, possesses continuous symmetry since rotating it by any degree, or a fraction thereof, doesn't alter its appearance. This is the kind of symmetry to which Noether's theorem applies. A ***conservation law***, meanwhile, refers to a physical quantity that remains fixed and hence does not fluctuate over time. Energy, for example, cannot be created or destroyed; once you've computed its value, there's no need to repeat the calculation.

Noether's theorem uncovered a hidden relationship between two basic concepts — symmetries and conserved quantities — that until then had been treated separately. The theorem provides an explicit mathematical formula for finding the symmetry that underlies a given conservation law and, conversely, finding the conservation law that corresponds to a given symmetry.

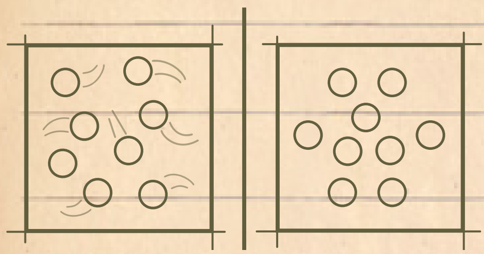
Here's a glimpse of the theorem in action: Imagine a hockey puck gliding along a perfectly smooth, endless and frictionless sheet of ice. Let's further suppose that no external forces are acting on the puck whatsoever. Under these idealized conditions, the puck will continue to glide in a straight line without ever slowing down. Its momentum, the product of its mass and velocity, will be retained, or conserved. The only thing that could cause the puck to alter its course, or to gain or lose speed, would be if space itself — the surface of the ice, in this case — were to vary. Nothing will change, however, if the ice remains smooth and space remains unchanged.

Noether's theorem shows that the puck's ***conservation of momentum*** is tied to its "symmetry of space translation," which is another way of saying that physics is not affected by linear movements (or translations) within a uniform space. The puck moves the same way on one part of the smooth ice as on another.

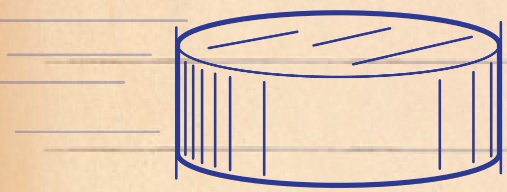
Similarly, Noether's theorem shows that symmetry under rotation, or rotational invariance, leads to the ***conservation of angular momentum***, which measures how much an object is rotating. Physics, in other words, has no preferred direction. If you do an experiment on a table and then rotate that table by 45 degrees, or indeed by any amount, the experimental results will not differ. The theorem also links the symmetry of "time translation" to the



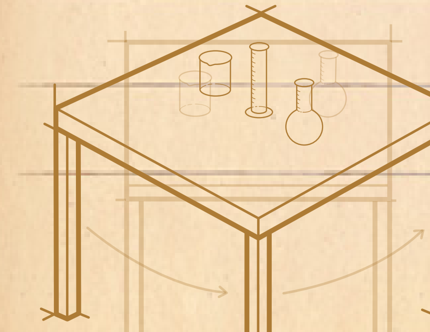
symmetry



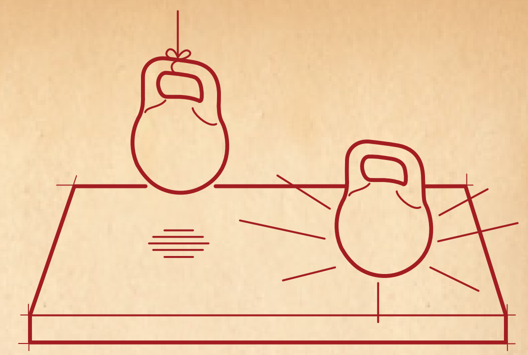
conservation law



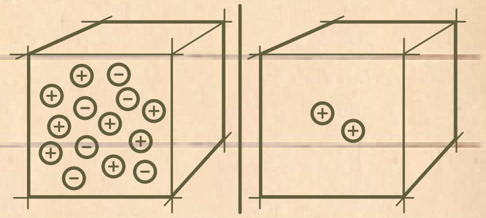
conservation of momentum



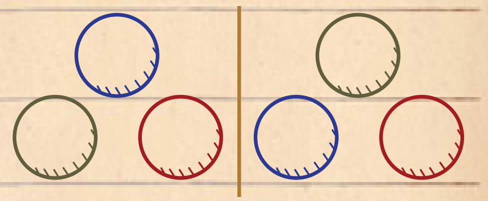
conservation of angular momentum



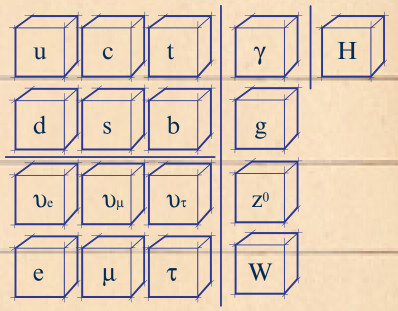
conservation of energy



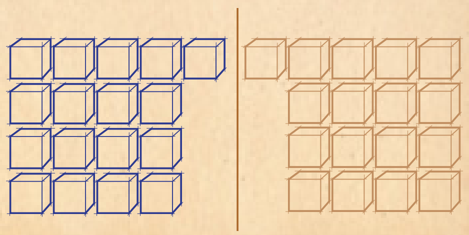
conservation of electric charge



color symmetry



Standard Model



supersymmetry

conservation of energy, so physics also doesn't care if you do an experiment today, next Tuesday or the third Sunday in October.

Physicists had known about the conservation of momentum, angular momentum and energy long before Noether's theorem came along. They are foundational precepts of classical mechanics. But it was not known that these hallowed laws shared a common origin, each bound to a particular symmetry. This new insight, which sprang from Noether's work, is a guiding principle that permeates physics research, while informing our views of the universe at large.

PUTTING IT ALL TOGETHER

Noether's theorem applies not only to these intuitive symmetries — rotations and shifts in time or space — but also to more abstract, "internal" symmetries that underlie the forces of nature.

For example, the ***conservation of electric charge***, a central tenet of the theory of electromagnetism, stems from a symmetry related to details of the particle's spin. Another example: A symmetry called isospin that allows electrons to be substituted for neutrinos, and neutrinos for electrons, helped physicists develop a theory in the 1960s that unified the electromagnetic force and the weak force (which explains particle decays and radioactive processes) into a single electroweak force. The conserved quantity here is "hypercharge" — a kind of charge, analogous to electric charge, that is associated with this electroweak force. A decade later, physicists devised a theory for the strong nuclear force, which binds protons and neutrons in the atomic nucleus. At the heart of this force is something called ***color symmetry***. (Color is a property of the quarks that make up protons and neutrons, which physicists view as another kind of charge.)

In the 1970s, physicists put all the known particles (including a few whose existence had not yet been confirmed, like the Higgs boson) and the forces that govern their interactions — the electromagnetic, weak and strong — into a single theoretical framework known as the ***Standard Model***.

According to Stanford University physicist Michael Peskin, Noether's theorem was a basic tool in the construction of this amazingly successful model. "In quantum mechanics, you identify two or three particles that are supposed to be tied by a symmetry and then see if the inferred conservation law is valid. That's how you learn whether it is a real symmetry of nature, and that's how the Standard Model was built" — through a cumulative, step-by-step process like this. It's also how researchers are now trying to move forward.

A SUPER LEGACY

The hunt is on to find new particles and deeper, broader symmetries from which they stem, a process in which Noether's theorem continues to play a pivotal role. Much of the current effort focuses on looking for signs of ***supersymmetry*** — a theory that postulates a symmetry between the particles that make up matter (fermions) and the particles that transmit forces, like electromagnetism (bosons). If supersymmetry is right, every known fermion has a yet-to-be-observed bosonic "superpartner," and every known boson, likewise, has an as-yet-unseen fermionic superpartner.

The hypothetical supersymmetric particles, which physicists hope to discover at giant particle accelerators like the Large Hadron Collider, would be "a reflection of all the Standard Model particles, using a mirror that is slightly distorted," explains Joseph Incandela, a physicist at the University of California, Santa Barbara. "The particles on the other side of the mirror look just like Standard Model particles, except that their spins have been slightly shifted."

One possibility that has been associated with this assumed symmetry, says Incandela, is the conservation of something called r parity, which implies that the lightest supersymmetric particle has to be stable and can never decay. If r parity is indeed conserved, every ordinary particle's unseen supersymmetric partner will eventually decay into the lightest supersymmetric particle, which sticks around forever. That particle, whatever it may be, would be available in abundant quantities and could thus be a good candidate for the mysterious dark matter believed to account for more than one-quarter of the stuff in the universe.

ILLUMINATING BLACK HOLES

Noether's theorem, however, is crucial to more than just the search for new particles; it extends to all branches of physics. Harvard physicist Andrew Strominger, for example, has identified an infinite number of symmetries related to ***soft particles***, which are particles that have no energy. These particles come in two varieties: soft photons (particles that transmit the electromagnetic force) and soft gravitons (particles that transmit the gravitational force). Recent papers by Strominger and his colleagues, Stephen Hawking and Malcolm Perry of Cambridge University, suggest that material falling into a black hole adds soft particles to the black hole's boundary, or ***event horizon***. These particles would in effect serve as recording devices that store information, providing clues about the original material that went into the black hole.

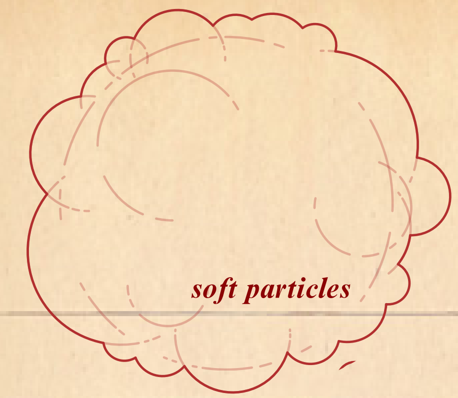
The idea proposed by the three physicists offers a new strategy for addressing a long-standing conundrum in physics known as the ***black hole information paradox***. Hawking showed in the 1970s that every black hole will eventually evaporate and disappear, potentially destroying all the information the object once contained about how it formed and evolved over time. The permanent loss of information in Hawking's scenario was troubling to theorists — including Hawking — as it would violate a cherished law of quantum physics holding that information, like energy, is always conserved.

The presence of soft particles along the event horizon, and their attendant symmetries, may point toward a way out of this dilemma. "We quickly realized through Noether's theorem that there were conservation laws corresponding to the new symmetries that place very stringent constraints on the formation and evaporation of black holes," says Strominger, although he acknowledges this work is still at an early stage.

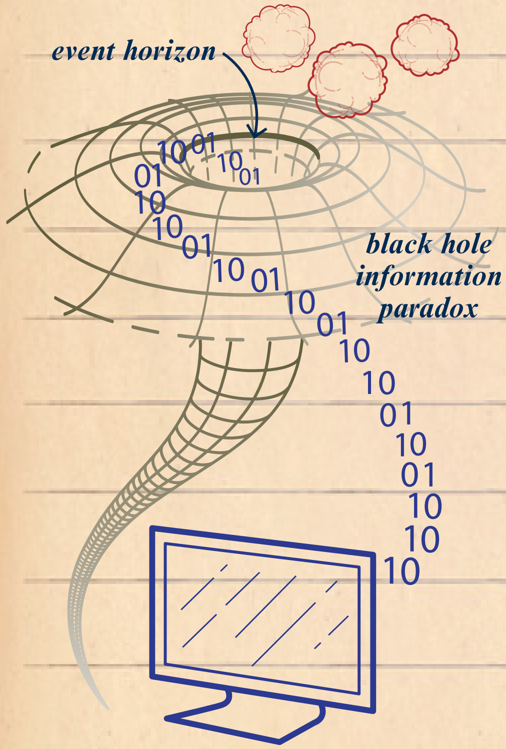
It is just one more setting in which Noether's theorem looms large, and the list of examples keeps growing. "The relationship between symmetries and conservation laws is a never-ending story," says Strominger. "One hundred years later, Noether's theorem keeps finding more and more applications."

While no one knows what will come next, the incredible power, and longevity, of Emmy Noether's theorem is undeniable. D

Steve Nadis, *a contributing editor to* Discover and Astronomy, *is co-author of* From the Great Wall to the Great Collider.



soft particles



Noether's theorem is crucial to more than just the search for new particles; it extends to all branches of physics.