Text of the Bridge Forum Dialogue conference

Scientific Advances by Women Researchers and Challenges They Faced

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Good evening! I am very pleased to have this opportunity to tell you about important scientific advances made by eminent women researchers, and the challenges that they have faced. I am greatly honored by the invitation to speak in the Bridge Forum Dialogue. Thank you!

I would like to begin by speaking about the work of Marie Skłowdowska Curie, a truly remarkable woman who used her discoveries in the service of humanity. She is the only woman to have won the Nobel Prize twice, one in physics in 1903 and a second in Chemistry in 1911.

Marie and her husband Pierre carried out their initial research on radioactive materials in a converted shed that was poorly ventilated and not waterproof. Marie suspected that pitchblende, a uranium ore, might contain a substance more radioactive than uranium itself. They started to work with 100 grams of pitchblende, and eventually had to process several tons of pitchblende, because the elements they sought were present in such small quantities. In 1898, they isolated first polonium and then radium.

Marie had triumphed over very considerable challenges to carry out her important research. She was born in Warsaw. In her era, Polish universities were closed to women. So, she and her sister Bronisława took classes at the “Flying University,” an underground organization that moved from place to place to evade the czarist police. In 1891, Marie came to Paris, to enroll at the University of Paris. She found lodging in a rented garret in the Latin Quarter. In the winter, she kept herself warm by wearing all of her clothing. Sometimes she forgot to eat!

Marie received her doctorate from the University of Paris in June 1903, and then won the Nobel Prize together with her husband Pierre in December 1903. This is almost certainly the shortest interval ever between the completion of a doctorate and the award of the Nobel Prize!

Marie's older daughter Irène collaborated with her on radioactive materials. Irène Joliot-Curie won the Nobel Prize with her husband in 1935, another of the five Nobel Prizes won by the Curie family.

I would especially like to honor the important service of Her Royal Highness, the Grand Duchess as the Patron of the Luxembourg Red Cross, among her humanitarian services, by focusing next on Marie Curie's service during the First World War.

Marie realized that X-rays could show the precise location of bullets and shrapnel in wounded soldiers, often making radical surgery unneeded. As the Director of the Red Cross Radiology Service in World War I, she had the idea of taking mobile X-ray units near the front lines, to aid battlefield surgeons.

Marie first traveled to the battlefront in October 1914. She deployed twenty mobile X-ray units, along with another two hundred X-ray instruments in field hospitals.

As her first assistant in the field, Marie selected her daughter Irène who was seventeen years old at the time. Irène was able to take the X-rays and then calculate the locations of bullets and shrapnel, sometimes working against the skepticism of physicians. Marie Curie provided the

"transformative moral courage of an example." Irène also had this quality, as did the other women Marie trained as aides.

To carry the X-ray units to the battlefront, Marie had to learn how to drive, learn auto mechanics, procure auxiliary generators, and arrange for the retrofitting of vehicles. The mobile X-ray units came to be called "les petites Curies." It is estimated that over one million soldiers were treated with her X-ray units.

Now I will shift from Marie Curie to another remarkable woman, one I would characterize as a "woman who knew how to enter a room." Hedwig Kiesler, Frau Fritz Mandl.

If you did not recognize her by those names, you may know her better as the actress Hedy Lamarr.

You may wonder, why is Hedy Lamarr mentioned in this talk about eminent women scientists? Hedy and George Antheil invented a radio guidance system for torpedoes so that they could be controlled without wires. Standard radio control did not work, because the guidance system could be jammed.

Hedy and George Antheil received a patent for their invention in August 1942. It is safe to say that George Antheil was equally unconventional. At the Paris debut of his works in 1926, *Airplane Sonata*, *Sonata Sauvage*, and *Mechanism*, a riot broke out. Man Ray, Pablo Picasso, and Jean

Cocteau were in the audience. The riot may have been orchestrated. Antheil's first "big work," was *Ballet Mechanique*, which was originally scored for sixteen synchronized player pianos, two grand pianos, electronic bells, xylophones, bass drums, a siren, and three airplane propellers. A riot also broke out at the first performance of this work in Paris.

Hedy had taught herself a great deal of mathematics and physics, by reading in her first husband's library. He was an Austrian munitions manufacturer; he met often with scientists and weapons technologists. In these meetings, Hedy learned that radio guidance of torpedoes failed because the signals could be jammed. Hedy came up with the idea of frequency hopping, to permit radio guidance. She enlisted George Antheil's assistance because she knew of *Ballet Mechanique*, and thought that the method used to synchronize sixteen player pianos would also work to synchronize the torpedo and the system firing it.

Hedy faced serious difficulties to reach Hollywood. Initially, she attracted the attention of Fritz Mandl when she performed as Empress Elisabeth of Austria in a play at the Theater an der Wien. Mandl wanted to keep German influence out of Austria, and he had allied with Mussolini in the attempt to do that. Hedwig's parents may have thought that the alliance would help to protect Hedwig, and secondarily her parents themselves. Mandl grew jealous of Hedwig, after their marriage. He would not allow her to leave their residence at Schloss Schwarzenau without his explicit permission.

On August 25, 1937, as the story goes, Hedwig left a dinner party where she was wearing her Cartier jewelry with sapphires and rubies, disguised herself as one of the maids, took the maid's car to the Hauptbahnhof and then . . . She took the Orient Express to Paris, then a train to Calais, a boat to Dover, and a train to London.

Hedwig Kiesler Mandl became Hedy Lamarr on the *SS Normandie* in the Atlantic, traveling from London to the US in 1937.

In London, she had met Louis B. Mayer, the founder and head of MGM Studios. He offered her a contract. She turned it down. Then she arranged to travel to the US on the same ship that Mayer and his wife were taking.

I have mentioned that Hedy was a woman who knew how to enter a room. On the first evening at sea, she donned a dark green gown and headed for the ballroom. She reportedly stood at the top of the staircase, waited until all eyes were upon her, then stepped down to the dance floor. She accepted a contract for nearly four times Mayer's original offer. Mrs. Mayer suggested the name.

This is the full current periodic table, with 118 elements.

The names of many of the transuranic elements honor individual scientists. Here are a few of them. It may help with the identification to know that Cm (Element 96), has that abbreviation because Cu was already taken for copper, Cr was already taken for Chromium, and Ce was already taken for Cerium.

Here is a slide with the names of the elements identified. You may recognize Element 99 (Einsteinium), Element 100 (Fermium), Element 101 (Mendelevium), and Element 102 (Nobelium). I would also like to point out Element 111 (Roentgenium), since it was named in honor of Wilhelm Röntgen, who won the first Nobel Prize in 1901 for the production and detection of X-rays. His discovery enabled the technology that Marie Curie employed to save lives and limbs in World War I. You might be surprised by Element 112 (Copernicum), since Copernicus predated Mendeleyev; but even many scientists cannot identify the person honored by Mt (Element 109).

Element 109 is Meitnerium, named after Lise Meitner.

Lise Meitner was the co-discoverer of nuclear fission. She collaborated with nuclear chemist Otto Hahn at the Kaiser Wilhelm Institute für Chemie in Berlin. The institute was directed by Emil Fischer. Fischer reluctantly agreed to allow Meitner to work with Hahn there, provided that she did not enter a chemistry laboratory; he was concerned that Meitner's hair might catch on fire.

Lise faced challenges in gaining the education she desired. When she was young, education for girls ended at the age of 14 in Austria. Lise learned arithmetic for bookkeeping, but no higher mathematics in the Mädchen Bürgerschule. When Austrian Universities first opened to women students, Lise began to prepare for the Matura, although she had to wait for her older sister Gisela to prepare first.

Lise faced a rather daunting challenge, to compress eight years of study into two, in preparation for the Matura. Lise studied with two other young women. One of their tutors was Arthur Szarvassy, a young physicist who had just completed his doctorate in physics at the University of Vienna. Fourteen students took the Matura in July 1901 at the Akademisches Gymnasium. Four passed. Three were Lise and the two women who studied with her. The fourth was Henriette Boltzmann, daughter of the famous physicist Ludwig Boltzmann.

When Meitner started to collaborate with Otto Hahn at Friedrich Wilhelm University in Berlin, she had to enter through the back door. After Hahn and Meitner moved to the Kaiser Wilhelm Institute for Chemistry, her career advanced. She and Hahn discovered ^{231}Pa, protactinium. She became the first female professor of physics in Germany in 1926. But in 1938, she had to flee to Sweden. So, she was not in Berlin in December 1938 when Hahn and Fritz Straßmann triggered nuclear fission for the first time. However, in February 1939, Meitner and her nephew Otto Frisch published the first theoretical explanation of nuclear fission, a calculation of the energy that was released.

Certain numbers of electrons confer an unusual stability on an element, causing the atomic form to be unreactive. This occurs when a p shell is filled, in the leading electronic configuration. These are the noble gases, helium, neon, argon, krypton, xenon, and oganesson, 2, 10, 28, 36, 54, 86, and 118.

There are also magic numbers of protons or neutrons that confer special stability on a nucleus. These are 2, 8, 20, 28, 50, and 82. They are different from the magic numbers of electrons.

Maria Goeppert Mayer was the first to explain the magic numbers of nucleons. The photo shows her at the Argonne National Laboratory, where she worked from 1946 to 1960. The caption on the Argonne web site reads,

"Maria Goeppert Mayer (fourth from right) poses with her colleagues . . . ." It was hardly necessary to identify her as fourth from right.

At the University of Chicago, Maria had a conversation about nuclear stability with Enrico Fermi. Fermi asked about spin-orbit coupling, but then he had to leave immediately to take a telephone call. He came back 10 minutes later, and by that time Maria had the full answer! The stability resulted from completed shells in the nuclear shell model. The magic numbers for nucleons are different from those for electrons due to differences in the shell structures and the magnitude of spin-orbit coupling.

Maria Goeppert Mayer used an analogy to a room full of waltzers, to explain the special numbers of nucleons that conferred stability.

"Think of a room full of waltzers. Suppose they go round the room in circles, each circle enclosed within another. Then imagine that in each circle, you can fit twice as many dancers by having one pair go clockwise and another pair go counterclockwise. Then add one more variation; all the dancers are spinning twirling round and round like tops as they circle the room, each pair both twirling and circling.

But only some of those that go counterclockwise are twirling counterclockwise. The others are twirling clockwise while circling counterclockwise. The same is true of those that are dancing around clockwise: some twirl clockwise, others twirl counterclockwise."

Maria worked out the theory of two-photon absorption in her 1930 Ph.D. thesis. This could not be tested until lasers had been developed, but in 1961 it was verified. All three of Maria's thesis examiners were or became Nobel Laureates: Max Born, James Franck, and A. O. R. Windaus.

Maria Goeppert Mayer faced challenges in her career as well, some due to nepotism rules that prohibited her from being hired by a university that had hired her husband, Joseph. At Johns Hopkins, she had a position working with German correspondence; at Columbia, she had an office, but no salary. She obtained a part-time lectureship at Sarah Lawrence College only after she was elected as a Fellow of the American Physical Society. After working on the Manhattan Project, she served as a "voluntary Associate Professor" at the University of Chicago, without pay. Only in 1960 was she finally appointed as a Full Professor of Physics in her own right, at the University of California, San Diego. She won the Nobel Prize three years later, in 1963. The local newspaper carried the headline, "S. D. Mother Wins Nobel Physics Prize."

As Carl Sagan said in his 1980 series Cosmos, "The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars." He added, "We are made of starstuff," and "The cosmos is within us."

How did the heavier elements form? Current thinking is that elements heavier than gold were formed preponderantly when neutron stars collided. These elements have a significant excess of neutrons over protons. The bright yellow color indicates elements formed in neutron star collisions, with the fraction of the square colored bright yellow showing the fraction of the element formed in that way. In the fall of 2017, the LIGO-Virgo detector picked up a neutron star collision for the first time; LIGO is the Laser Interferometer Gravitational-wave Observatory, and Virgo is its companion observatory interferometer. The gravitational wave signal was accompanied by a short gamma-ray burst and an apparent kilonova. Heavier elements were being forged!

This is our Sun viewed from the Land of the Midnight Sun. The time lapse photo shows that the sun does not set. The photo is posted by Hurtigruten, a company that offers excursions in Norway and the Norwegian archipelago Svalbard.

What is the composition of our own Sun? Until the mid-1920s, it was usually thought that the elements in the Sun had essentially the same distribution as on Earth. In fact, the relative proportions of silicon, carbon, and common metals are quite Earthlike. However, hydrogen is more abundant in the Sun than on Earth by a factor of approximately one million!

In her Harvard doctoral thesis, Cecilia Payne-Gaposchkin proposed that the Sun was composed primarily of hydrogen and helium, based on her spectroscopic observations. Her idea was initially rejected. She was forced to characterize her results as “spurious.” Once it was accepted, the idea was generally credited to Henry Norris Russell. Payne-Gaposchkin’s priority was eventually recognized, and Otto Struve called her thesis “the most brilliant Ph.D. thesis ever written in astronomy.” Women could not become professors at Harvard when Payne-Gaposchkin finished her thesis in 1925. In 1958, she became the Phillips Professor of Astronomy at Harvard.

Emmy Noether was a mathematician who established an extremely important theorem in physics. She connected conservation laws to symmetries, or more exactingly, to invariances. A quantity is invariant if it does not depend on the coordinate system. Einstein characterized Noether as “the most significant creative mathematical genius thus far produced since the higher education of women began.” Noether developed her theorem while she was teaching at the University of Göttingen. However, she could not offer classes under her own name; her lectures were listed under the name of the great mathematician David Hilbert.

The statements of the theorems are rather technical, but Noether showed that symmetry with respect to motion in space implies conservation of momentum; symmetry with respect to rotation implies conservation of angular momentum; and symmetry with respect to translation in time implies conservation of energy. Noether’s theorem resolved a scientific conundrum that had puzzled Einstein and Hilbert. In general relativity, an object that is emitting gravitational waves can speed up. This appears to contradict energy conservation. Noether realized that matter and gravity need to be regarded as a single, unified quantity. Noether also found that charge is conserved as a consequence of the global gauge invariance of the electromagnetic field.

Phillippa Fawcett is a personal inspiration to me. She took the Tripos, the final examinations in mathematics at Cambridge University at the end of three years of study. There are typically four exams, lasting three hours each. The results of the degree candidates are announced in order of the scores, from first to last. Women could not receive degrees from Cambridge at the time, so their scores were not included in the list, but were read separately, in the form “between A. B. Smith and C. D. Jones.” The announcement of Phillippa’s score simply started “Above,” and the crowd began to shout. Her placement was “Above the Senior Wrangler.”

One of her students at Newnham College commented, “My deepest debt to her is a sense of the unity of all truth, from the smallest detail to the highest that we know.” Phillippa died at age 80, just one month after royal assent was received to allow women to take degrees from Cambridge.

Baroness Ingrid Daubechies was awarded the Wolf Prize in 2023 for her “creation and development of wavelet and harmonic analysis.” Wavelets are oscillatory waves of limited extent. Wavelets offer a great advantage for digital processing because their use limits the amount of data that is required for digital storage of images. They are used in the jpeg 2000 standard. Baroness Daubechies and her team also applied their techniques to art restoration, most famously the restoration of the Ghent altarpiece from the fifteenth century, the work of Hubert and Jan Van Eyck.

The Ghent Altarpiece shown on this slide reflects the genius of Hubert and Jan Van Eyck. It is also indicative of the intricacy and complexity of the restoration project. The team also restored the text of the polyptych, attributed to Saint Thomas Aquinas. Additionally, Baroness Daubechies used image processing techniques to help establish the authenticity of works by Van Gogh and Rembrandt.

Donna Strickland received the Nobel Prize in Physics in 2018 for the use of chirping to allow for laser pulse amplification. A chirped laser pulse has components of various frequencies that are spread in time, so that red light might precede blue light in a single pulse, or vice versa. She was still an Associate Professor when she won the Prize. She said that it wasn’t the fault of the University of Waterloo; she “simply never applied” for promotion.

Anne L′Huillier received the Nobel Prize in Physics in 2023 for her production of laser pulses on the attosecond time scale, ten-to-the-minus-eighteenth seconds. Pulses this short make it possible to follow the motion of electrons during chemical reactions, in real time.

This slide shows a schematic diagram of the production of attosecond pulses. You can see chirped pulses in the middle of the slide. Anne L′Huillier’s work built upon Donna Strickland’s work.

German Chancellor Angela Merkel conducted research in theoretical chemistry, my field, before entering politics. The photo comes from a Soviet Bloc conference for exceptionally promising graduate students in science. My colleague, now Professor Piotr Piecuch, is to Angela Merkel’s immediate left. Angela was awarded her doctorate for her thesis in 1986. Her paper “The Lowest Bound States of Triplet $(BH_2)^+$” was published in *Chemical Physics Letters* in 1989. My Ph.D. research advisor, David Buckingham, was the editor of the journal at the time.

He remarked at a conference, “Her paper was very good, so we published it.” The Berlin Wall came down in 1989, and Merkel entered politics in 1990.

Barbara McClintock won the Nobel Prize in Physiology or Medicine in 1983, for her work on the genetics of maize. Her mother was initially opposed to sending Barbara to college, for fear that it would make her unmarriageable. Barbara completed her bachelor’s degree in botany at Cornell University in 1923, her master’s degree in 1925, and her Ph.D. in 1927. Cornell would not hire a woman professor, but in 1936, she became an Assistant Professor at the University of Missouri. Excluded from faculty meetings, and seeing no possibility of advancement, she left for a visiting professorship at Columbia University, then for Cold Spring Harbor.

McClintock wanted to explain how the colored patterns developed in flint corn, on a genetic basis. She was especially interested in cases where a single kernel of corn exhibited more than one color. She explained this based on “jumping genes.” No one believed her.

Corn genetics are somewhat complicated, because corn is triploid. Its chromosomes come in sets of three. The color is controlled by a pair of genes, with alleles C′/C and Bz/bz. McClintock bred female corn stalks with C/bz alleles with male corn stalks having C′/Bz alleles. Since C′ is dominant, pale-yellow kernels were expected. But instead, the kernels had brown or reddish-brown spots. What could explain this?

The quotation from Louis Pasteur is rendered in English as “Chance favors the prepared mind.” McClintock’s earlier work had prepared her for this discovery. She and Harriet Creighton had proved that chromosomes could cross over during meiosis, shifting genes from one to the other. She had discovered that X-rays could break chromosomes, and more importantly, that the broken segments could rejoin. She realized that if the element Ds moved along the chromosome, and the chromosome broke, then C could be expressed, rather than C′ , and the kernels could gain color! Due to opposition to her ideas, McClintock stopped publishing on this topic in 1953. She won the Nobel Prize for this work in 1983.

This has been a whirlwind tour of the accomplishments of many eminent women scientists and the challenges that they faced! Still, there are many more! I want to mention just one more woman Nobel Laureate, from 2023.

Katalin Karikó won the Nobel Prize for her work on messenger RNA, used to develop vaccines against Covid. In her initial attempts to use messenger RNA, the injections always caused inflammation. She knew that transfer RNA does not cause inflammation. She and Drew Weissman discovered that replacing uridine in the genetic code of messenger RNA with pseudouridine eliminated inflammatory response.

Karikó's career trajectory was not smooth. In 1985, she left Hungary with her husband and two-year old daughter, smuggling £900 in their daughter's teddy bear. In 1989, she was hired by the University of Pennsylvania as an adjunct professor. Many of her grant proposals were declined, because RNA had fallen out of favor as a topic, in the US. In 1995, she accepted a demotion outside the faculty ranks, in order to continue her research on RNA. In 1997, the University of Pennsylvania hired Drew Weissman as a Professor of Immunology, and Karikó began to collaborate with him. In 2013, she left Penn to become a Vice President of BioNTech RNA Pharmaceuticals. As she left, she advised her boss, "In the future, this lab will be a museum." Actually, she added, "Don't touch it."

I would like to express my very deep gratitude to the organizers of the Bridge Forum Dialogue for this evening's opportunity to describe the accomplishments of a remarkable set of women. I am greatly honored by the invitation to speak!

At the University of Luxembourg, I am very grateful to the Institute for Advanced Studies for a DISTINGUISHED grant, which has made my visit possible.

I am also very grateful for the wonderful hospitality of the Department of Physics and Materials Science, and all the members of the Department. I have found a very exciting intellectual environment here, and I look forward to continuing collaborations after I have returned to my home university.