

History and Philosophy of Physics

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Laudation for Emmy Noether - The struggles and triumphs of a mathematical genius who helped shape modern physics

by Paul Halpern, Saint Joseph's University

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Modern physics owes an enormous debt to the work of early 20th century German-born mathematician Emmy Noether. By discovering the fundamental relationship between symmetry groups and conserved properties, she introduced the power of group theory and other aspects of abstract algebra to the field. Yet, as a woman researcher in her time, her triumph necessarily coincided with a change in attitude from oppressive to more enlightened conditions for female scientists and mathematicians in Germany and elsewhere. Alas, the progressive climate in her native land gave way, starting in 1933, to the heinous Nazi regime, forcing her to flee to America. A brief, happy period ensued at Bryn Mawr College, in tandem with an association with the Institute for Advanced Study, that ended with her untimely death after a surgical procedure. Nonetheless, her monumental contributions to the application of algebraic techniques to modern physics, including the vital relationship between symmetry and conservation, live on in the important work done by theoreticians in unraveling the fundamental properties of the natural world.

1 Conservation and symmetry

Early natural philosophers, such as many of the ancient Greek thinkers, placed symmetry at the heart of nature. Regular shapes offered a kind of beauty that seemed to reflect deeper truths. Thus, symmetry arguments applied aesthetics to a vision of how nature ought to be. The Pythagoreans, for example, viewed the equilateral triangle formed by enumerating the first four numbers to be a sacred emblem of reality. Adding up to the number ten, they believed that those digits explained all manner of phenomenon, from unity and division to the astral objects. Plato, considered the circle sheer perfection, influencing Aristotle and later Ptolemy to envision planetary orbits as constructed from circles (in Ptolemy's case, circles within circles). It took great intellectual courage for German mathematician Johannes Kepler in the 17th century to

break from that millennia-old tradition and represent those trajectories as elliptical instead. Conservation laws, in contrast, have had more mundane origins – stemming from the basic process of measurement and noting which quantities are preserved over time. With accurate scales, one might strive to weigh the products before and after some kind of chemical process or physical transformation. If one is careful enough to account for all ingredients, one would



Paul Halpern

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International Quantum Year Report

The International Quantum Year Draws to a Close

By Paul Cadden-Zimansky, Bard College

The United Nations-declared 2025 International Year of Quantum Science and Technology (IYQ), marking the centennial of the initial development of quantum mechanics, officially concluded with a closing ceremony in Accra, Ghana in February 2026. The ceremony was the final one of twenty-five sponsored IYQ events and initiatives around the world, which included the 5th International Conference on the History of Quantum Physics held in Salvador, Brazil in August 2025. In addition to sponsored events, individuals and organizations around the world voluntarily created over 1,300 contributed events, reaching in excess of one million people, to mark IYQ. One such event was the *Helgoland 2025* conference, featuring both scientific and public talks, held on the small North Sea island exactly 100 years after Werner Heisenberg began work there

on what would become matrix mechanics. Other markers of the centennial included special journal issues and books, such as the publication of *Women in the History of Quantum Physics: Beyond Knabenphysik*. An archive of event listings and reports from the year can be found at quantum2025.org. The idea for marking a century of quantum mechanics with an international celebration and UN-declared year began in 2018 at the annual meeting of the FHPP Executive Committee. Other APS Fora subsequently joined the conversation and development of the initiative leading to the APS Council and Senior Leadership endorsing the idea. APS then partnered with five other scientific organizations (DPG, SPIE, Optica, IOP, and the Chinese Optical Society) to put forth resources and a framework for getting UN recognition. With the added endorsement of over 60

international scientific organizations and UNESCO, the country of Ghana chose to be the lead sponsor of the UN resolution proclaiming the Year and recommending that it “should be observed through activities at all levels aimed at increasing public awareness of the importance of quantum science and applications.” The resolution was co-sponsored by 72 countries, representing over five billion people, and adopted by the consensus of every UN member country. More information on the activities during the International Year of Quantum and its legacy can be found in the UNESCO final report on the year, *The Quantum Moment: A Global Report*, which is available freely online [<https://unesdoc.unesco.org/ark:/48223/pf0000398055.locale=en>].

History and Philosophy of Physics

NEWSLETTER
Forum on History and Philosophy of Physics | American Physical Society,
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FHPP News

2025 History Physics Essay Contest Winners

The essay contest winner this year is India Bhalla-Ladd of UC-Irvine for “Introducing the Technical Typists of APS.” Yuxin Fang of the University of Minnesota was named a Runner-Up for “Cold War Echo: Reconstructing the Geopolitical Origins of the 19645 Discovery of Cosmic Microwave Background Radiation.”

2026 Global Physics Summit FHPP Sessions

MONDAY 3/16 8:00 AM – 11:00 AM (INVITED SPEAKERS)

80th Anniversary of Operation Crossroads and the Atomic Energy Act

Chair: Ryan Dahn, American Institute of Physics

- Sovereignty at Crossroads, Mary X Mitchell
- Beyond the Threshold: The Regulatory Origins of the Linear Non-Threshold (LNT) Model for Radiation Protection, Toshihiro Higuchi
- 80th Anniversary of the US Space Age? Upper Atmospheric Science and Rocket Soundings in the American Southwest, Andrew Ross
- The Medical Section of the Manhattan Project and Radiological Data Collection during Operation Crossroads, Joshua McGuffie
- Modeling Harm in Nuclear Environments after Operation Crossroads, Jacob D Hamblin

MONDAY 3/16 12:00 – 3:00 PM

Black Holes, Quarks, Noise Mitigation, Typists & Metaphors

Chair: Kevin Vallego, Idaho National Laboratory

- Introducing the Technical Typists of the American Physical Society, India Bhalla-Ladd
- Shielding Observatories through Legal Constructs: Noise Mitigation for Radio Astronomy, Tiffany Nichols
- The Development of Black Hole Thermodynamics: A Novel Historical Approach, Juan Diego Garcia
- Two Quark Colors of the Cold War: Schism of Narratives, Vitaly Pronskikh

- The Use of Metaphor in and outside the Laboratory: The Story of Science, Kevin Vallejo
- Thomas Henshaw, The Forgotten Alchemist Who Saved the Scientific Journal, Gracie Burrows
- The Strange History of the Doppler Effect and Binary Stars, Paul H Halpern
- The use of metaphor inside and outside the laboratory: the story of science, Kevin Daniel Vallejo

TUESDAY 3/18 10:45–12.33

Pais Prize (Invited Session)

Chair: Kathryn Olesko, Georgetown University

- Building the Cathedral of Quantum Mechanics, Michel Jannsen
- Revisiting the Origins of Schrödinger's Wave Mechanics, Alexander Blum
- Stages in the Conceptual Development of Wave Mechanics, A. Douglas Stone

WEDNESDAY 3/18 2:00 – 3:00 PM

The Crisis in American Science (Invited Session)

Chair: Kathryn Olesko, Georgetown University

- Guiding Physics: The Managerial Ecosystems Supporting US Scientific Research, Michael Riordan
- From the Cold War to the China Initiative: Crisis in American Science in Historical Perspective, Zuoyue Wang
- Peer review: The end of an American institution?, Melinda Baldwin
- A Regime Change and the Scientists' Response, Mitchell G. Ash

- Where Are the Philosophers of Science in the Debates about a Crisis in American Science?, Donald Howard

THURSDAY 3/19 10:30 AM – 12:18 PM

History, Philosophy, Education, & International Engagement

- Empowering Students Through Interactive Physics Simulations: Integrating Replit for Hands-On Computational Learning, Rahmat Rahmat
- A review of Mixed Reality Technologies to Increase Physics Comprehension, Lori A Rebenitsch
- Why are we, the physicists of the modern world, not able to find the theory of everything, Scott S Gordon
- Two Core Organizing Principles Lost in the History of Physics: How it happened and why it matters, Peter Cameron
- Small-scale optical particle counters for actionable air quality data in resource-limited settings, Tchanche F Bertrand
- Astronomy for a Better World: How IAU Office of Astronomy for Development Uses Astronomy to Drive Global Development, Joyful E Mdhuli
- Graduate Teaching Assistant Experiences in Remote Asynchronous and In-Person Introductory Physics Laboratories, Angela Kelly
- Introducing physics students to biophysical reactions, Samuel Safran
- Logic, Human Perception, and Cognition Are at the Heart of the Principle of Relativity, Douglas M Snyder

March 2026 FHPP Pais Prize

2026 Pais Prize Awarded to Michel Janssen and Anthony Duncan – Session Report

By Donald Salisbury, Department of Physics, Austin College, Sherman, Texas



Michel Janssen



Alex Blum



Douglas Stone

This year's Pais prize session constituted a kind of memorable closing session of the world-wide one hundred year celebration of quantum mechanics, launched initially by our active Forum on the History and Philosophy of physics member Paul Cadden-Zimansky. This year's recipients and session speakers all played a significant role in analyzing its fascinating historical development. Michel Janssen and Anthony Duncan received the prize this year, and Michel presented an overview in which he further elucidated a reformed historical analysis that he and Anthony have over several years promoted. His talk was entitled Building the Cathedral of Quantum Mechanics. He argues that there remain some underlying structures in scientific progress, and a convenient theme is the creation of temporary scaffolds followed by solid arches. Indeed, these notions appear in the titles of the recent quantum history books authored by Duncan and Janssen¹ and I would also recommend one of their brief overviews.² Among the many builders they discuss the work of the American physicist, John Hasrouck Van Vleck, who is now recognized as a central player in the growth of quantum theory following the initial quantization scheme of Niels Bohr in 1913. Readers would benefit much from their published analysis of his work.³ Alex Blum gave the second talk, entitled From Dispersion to Matrix Mechanics. He focused on Heisenberg's path to the first formulation of modern quantum mechanics. I note here a deeply instructive analysis of this route that Alex co-authored.⁴ Then the outgoing chair of our Forum, Douglas Stone, addressed mainly the earlier chapter in this history, with the title Stages in the Conceptual Development of Wave Mechanics. A notably related article was published in 2005,⁵ and his book would attract a wide readership.⁶

Michel initially undertook a brief but extensive overview of the birth of quantum mechanics, noting first Max Planck's 1900 macroscopic thermodynamic state counting procedure. Already in his 1879 thesis Planck had focused on entropy, and in the

late 1890's he began to seek its interpretation in the frequency distribution of black body radiation. This led, beginning in 1899, to his interpretation in terms of electrically charged oscillators. His famous 1901 statistical black body radiation law, involving the Planck constant h , was the remarkable outcome.⁷ Michel noted that even though he had written that the electromagnetic energy was proportional to the frequency, this was just a means of "binning energy", and not a quantization. Rather, it was Einstein in 1905 and 1906 who introduced the notion of quantization of Planck's resonators.⁸ And perhaps less appreciated is Paul Ehrenfest's 1906 independent grasp of this concept.⁹ Michel indeed stressed Ehrenfest's role as one of the early architects of quantum theory. These were themes addressed in the first Solvay conference in Brussels in 1911 where Einstein and Planck were present. See Straumann's fascinating account.¹⁰ The next step in the brief history is of course the initial atomic approach of Niels Bohr in 1913, laid out in a three paper series.¹¹ There followed the work of Arnold Sommerfeld. He gave talks in 1915 and 1916 in which he addressed Bohr's ideas in terms of phase space quantization, followed by two papers.¹² Planck also addressed the phase space transition approach. Soon afterward Karl Schwarzschild applied atomic phase space techniques of the type that had been developed in the context of celestial mechanics.¹³

The major challenge that ensued was the task of incorporating a microscopic atomic model to explicate macroscopic light dispersion. I do think it is appropriate here to track some of the earlier historical chapters in this challenge. This history was actually the focus of another Max Planck Institute for the History of Science (MPIWG) researcher in Berlin, Marta Jordi Taltavull. Her doctoral thesis¹⁴ was overseen by Jürgen Renn. I cite two relevant recent papers. The first focuses in part on the eighteenth century effort to explain the splitting of incident light into rainbow colors.¹⁵ The second focuses on the work of the experimentalist Rudolf Ladenburg who began even before 1913 to work with

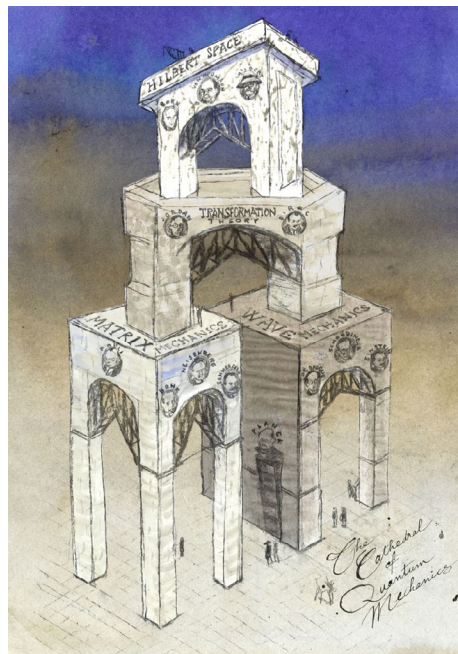
optical dispersion. She expresses gratitude to Michel for his support of this project, and both he and Anthony had addressed Ladenburg's role. Marta points out that already in 1921 Ladenburg was led to an alternative theoretical approach in terms of Bohr's atomic model.¹⁶ He skillfully combined his experimental skills with the theoretical implementation of Einstein's 1916 introduction of atomic emission and absorption of electromagnetic radiation, using his A and B coefficients.¹⁷ Marta points out that this played a crucial role in the ultimate 1925 quantum dispersion theory of Hendrik Anthony Kramers and Werner Heisenberg.

But of course, as mentioned earlier, another not sufficiently recognized leader in this direction was van Vleck who made a use of the classical correspondence principle that served as a step toward Heisenberg's ultimate 1925 theory. Michel did not, in his talk, give himself and collaborator Anthony the sufficient merit that they deserve in elucidating van Vleck's role. But first a significant step was undertaken by Kramers in incorporating also radiative emission in broadening Ladenburg's results for induced macroscopic polarization.¹⁸ As noted by Michel, van Vleck was one of the first two to give a full derivation of this result.¹⁹ He used Hamiltonian perturbation procedures from celestial mechanics. The other was Max Born.²⁰ Anthony and Michel published a detailed analysis of van Vleck's polarization procedure and it is clear that van Vleck opened a window that could have led himself to Heisenberg's ultimate 2025 result.²¹

Michel did of course continue with an analysis of this development, citing both the improvements of Heisenberg's results achieved by himself, Born and Jordan²², and Schrödinger's quantum wave mechanics.²³

Readers will surely agree that the evolving temporary scaffolding and the resulting permanent (at least in the eyes of some participants) arche conveys a useful model of the development of quantum mechanical theory!

I do want to add a few words about the fascinating talks of Alex and Douglas. Both do support Michel's thesis. Yet Alex did stress another connection that does merit further attention. He focused on the time in 1925 between the collaborative work of Kramers and Heisenberg and the latter's turn to matrix mechanics. He pointed



The ultimate quantum mechanical arch structure by Laurent Taudin. Many thanks to Michel for permitting its publication!

out that at least initially, a primary focus of Heisenberg was not dispersion, but an attempt to find rules for multiplet intensities resulting from an applied magnetic field. This is analyzed in detail in his joint publication.⁴ Also, Douglas did present several details of the earlier history of the development of quantum mechanics, focusing in large part on the associated work of Einstein. I would strongly recommend his 2013 book.⁶ He did refer to an additional fascinating issue²⁴, namely the subject of Einstein's 1917 article.²⁵ Only forty-one years later was the problem of quantizing chaos recognized as an ongoing problem!²⁶

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The Search for William Francis Bouchet

By Ronald E. Mickens, Department of Physics (Emeritus), Clark Atlanta University, rldmickens@gmail.com

Edward Alexander Bouchet (EAB) is recognized as the first African American to earn the PhD at a North American University [1, 3, 16, 23] and this academic degree was from Yale University, in physics, in 1876. While we are aware of the genealogy of his mother, Susan Cooley [15, 16], we have essentially no substantial information on his father's (William Francis Bouchet) heritage. What is known and repeatedly stated is that the father was born ca 1817 in Charleston, South Carolina, and taken north to New Haven, Connecticut, in 1824 by the son of a southern planter, John Brownlee Robertson [6]. William was to serve as Robertson's manservant during Robertson's matriculation at Yale University. Other than this "fact," nothing is definitively known about WFB prior to 1824, except for the (approximate?) date of his birth.

Given this situation, the following questions and issues arise:

1. Who were William Francis Bouchet's parents? And what were their origins?
2. The fact that WFB had a "full name" strongly implied that his parents were involved in some type of "marriage arrangement." So, what exactly was their involvement with each other? And how did WFB acquire his name?
3. WFB was seven years old when he was "selected" by Robertson to be his manservant. Just what were the abilities and skills possessed by WFB that made this selection possible?
4. From 3), questions arise as to just who was John Brownlee Robertson. The nature of his interactions with WFB after JBR's graduation from Yale? And what were the accomplishments of JBR?

As for WFB, a rather full accounting of his life, career, and family situation exists and is generally publicly known and documented [1, 4].

The main goal of this short essay is to provide some tentative answers to the above questions. However, the conclusions reached and understandings and interpretations are based on my own analyses of the many resources that were available to me. These items included various books and scholarly articles on the Caribbean

and North American slave trades in the 18th and 19th centuries, the various racial definitions used in these locations, and the social, economic, and political interactions and practices between Europeans and people of color. The following short listing of references to such materials illustrates the nature of such resources: references [5, 7, 8, 9, 10, 11, 20].

I also involved myself in discussions with several friends and colleagues who are knowledgeable about slavery in the Caribbean islands and North America. These persons were faculty members in the Atlanta University Center, Fisk University, and Howard University. Some of these individuals may not agree with all of the conclusions presented in this essay.

It should be indicated that I have also consulted, when needed, various Wikipedia websites to obtain general overviews of several topics and to provide the names and locations of first level scholarly, research sources. An example is the meaning, interpretation, and the practice of the "placage system of marriage."

To repeat and summarize, all of the main conclusions given here are solely of my own creation, i.e., "my-story." Others should not be asked or required to validate their validity or accuracy. Reconstructing the details of a long ago event and turning it into history is a daunting task [17], and generally does not lead to a unique outcome or interpretation. This is especially the case for biographical efforts [17, 18].

Abbreviations and Explanations

In the remainder of this essay, it will be useful to use, when needed, some abbreviations and concepts to better understand what is being discussed. The following is a brief presentation of these items.

Abbreviations

- **EAB:** Edward Alexander Bouchet (1852-1918) son of William Francis Bouchet [1, 16]
- **WFB:** William Francis Bouchet (1817-1885) [1, 4, 16]
- **UFWFB:** unknown father of William Francis Bouchet
- **UMWFB:** unknown mother of William Francis Bouchet

- **JBB:** John Brownlee Robertson (1809-1892) son of a "planter" from South Carolina [6]
- **FW:** Francis Williams (19690 -1770) a Black Jamaican polymath [21, 22]

Brief explanations

- a) **European** – "white" member of one of the European colonial powers. In our discussions, England and France.
- b) **Enslaved person** – Someone forcibly held in a state of servitude, derived of all personal freedoms, subjected to the control of others, and generally considered property of their "owners."
- c) **Person of color** – A person who is not white/European.
- d) **Mulatto** – A person of mixed white and black ancestry.
- e) **Racial classifications** – Ranked in the order: European/white, mulatto, people of color, Black.
- f) **Economic, political, and social rankings** – European/white; free people of color having special privileges granted by the government or some other administrative unit; free people of color not having special privileges; enslaved people [20, 24].
- g) **Placage** – This was a recognized extra-legal system [5, 20] in the French slave colonies of both North America and the Caribbean where male Frenchmen entered into civil unions with non-European women. While these relationships were not legally recognized, they generally provided the women and children with property and other financial resources, and in many cases gave both their freedom if they were enslaved.
- h) **Caribbean states** – There are currently over a dozen such sovereign nations. However, for this essay, the principle states in the 18th and 19th centuries were Hati (Saint-Domingue was the colonial name before the revolution) and Jamacia [8, 9, 10].
- i) **Planter class** – This was a racial and economic class that arose in North America and the Caribbean during the 18th and 19th centuries, the majority from Europe. Their plantations were generally operated and run using both

enslaved persons and indentured servants [7, 23, 24].

- j) **Robertson family** – A “distinguished” South Carolina plantation family who also had properties in Jamaica. The original family members came from Scotland [25, 26].
- k) **Manservant** – This person is a male servant or enslaved person with the responsibility for taking care of the personal needs of their employer/master. Such duties may include meal preparation; pressing, cleaning, and selection of clothing; providing social company and advice; the running of errands; household tasks such as gathering firewood, lighting the heaters, disposing of fireplace ashes; making the bed, and general cleaning. In other words, the manservant “tries” to carry out the general wishes of his employer or master (owner).

The Frenchman’s son – “Mystery”

At the beginning of the 19th century, UFWB, like many men of his generation, saw few opportunities in France for an individual of his social and economic status. He therefore did what many others had done to enhance their fortunes, namely, go to one of the Caribbean islands and test his chances for enhancing his economic future. Hayti [9] was his initial choice, but the recent revolution and continuing unrest made this a dangerous and uncertain selection. So he went to Jamaica [8], which was mainly under the control of Great Britain. Always in need of Europeans to manage the large plantations, he easily found a position on one of the Robertson family’s many plantations [18, 24, 25, 26]. Their agriculture empire included large holdings not only in Jamaica, but also in the states of Carolina in America [26]. One consequence of this geographic spread was that it permitted UFWB to make frequent trips between Jamaica and various locations in North America, particularly, Charleston, South Carolina. Thus, he quickly became socially acquainted with members of the extended Robertson clan and their families, and friends.

In general, the colonial islands had economies based on slave labor [8, 9, 11]. Furthermore, there were very few European women who lived at these locations [7, 10, 20, 24]. Consequently, a system of “placage” type of arrangements arose, generally, between European men and

“mulatto” women [5, 7, 20]. UFWB became involved in such a union with one of the mulatto women who worked in the “Big House” of one of the Robertson plantations. Soon they had a son and named him William Francis Bouchet. (It should be noted that WFB’s given name, “Francis Bouchet,” was given to honor Francis William, a Black, Jamaican polymath, who was well known internationally for his accomplishments in science, poetry, and the arts [13, 14]. His distinctions related to astronomy have been recently honored by the naming of an asteroid after him [19].

WFB’s parents quickly discovered him to be a very curious, bright, perceptive, and quick learner. His father, to further enhance his son’s abilities, hired private tutors in English, French, mathematics, Greek, natural philosophy, and religion to provide a very rich educational experience. However, both parents realized that their son would have great limitations placed on his economic, social, and political abilities if he remained in Jamaica. This was due to the status of his mother as an enslaved person, and as a result, the children of an enslaved woman were also enslaved. [5, 7, 8, 20, 24].

UFWB had grown close to his son and therefore he thought about how this difficult situation could be resolved to everyone’s optimal satisfaction given the constraints of the European colonial slave systems in the Caribbean islands and North America.

UFWB’s solution was to place his son in “partial” or “limited” servitude for a fixed period of time and hope that advantages would come afterwards. To accomplish this task, he turned to his associates in the South Carolina branch of the Robertsson



Portrait of Francis Williams with Halley's Comet, by painter William Williams, ca. 1760. Williams was a well known black Jamaican polymath.

family. He was aware that one of the sons, John Brownlee Robertson, would leave for studies at Yale College and, like many southern students at that college, often took a manservant to carry out their daily household chores and other related tasks. UFWB also was aware of the Gradual Emancipation Act of 1784, which freed any enslaved person within the state of Connecticut when they reached the age of 25 years old. Given that WFB was born in 1817, he would achieve his freedom in 1842.

The family of John Brownlee Robertson agreed to have WFB be their son’s manservant during his college stay as an undergraduate student at Yale, and further, retain him as a manservant, in New Haven, up to the year 1842, at which time WFB would be released of his obligations to Robertson.

One tragic consequence of this arrangement was that neither WFB nor his mother and father, ever saw each other again! As far as I am aware, there are no existing records, public or private, which indicate that WFB ever spoke or wrote about his biological parents.

WFB at Yale

John Brownlee Robertson and William Francis Bouchet both arrived together in New Haven, CT via passenger ship ride from the port of Charleston, SC. This trip took nearly a week because of stops at the cities of Norfolk, Baltimore, and New York. Upon disembarking, they went immediately to the Yale campus and JBB checked into his dormitory. His housing consisted of a large room with ample space for a bed, study desk, fireplace, and bathing facilities. Also, attached to the room was a smaller one used to house WFB and serve as a storage room

WFB was present to take care of essentially all of the “material” needs of JBB. And they consisted of the following tasks:

- gathering wood and coal, and keeping the fireplace burning during the winter ...
- sweeping the floor, cleaning and making the bed ...
- making sure hot water was available (when needed) for body cleaning and assuring that cool water was always ready to drink ...
- carrying written messages from JBB to professors, student friends of JBB, and anyone that JBB felt a need to communicate with ...
- acquiring, preparing food and snacks when appropriate ...
- go off campus, when needed, to deliver and pick up clothing for repair and/or cleaning ...
- upon request, act as a companion to JBB ...
- in general, carry out any instructions given by JBB ...
- do all of these things while exhibiting the proper deference to all (white) Europeans.

These tasks WFB was able to do during the four years JBB was an undergraduate at Yale College.

After graduation from Yale, JBB traveled to Charleston, studied medicine with his brother-in-law and obtained the MD degree in 1832 from the Charleston Medical College. But in 1830, he married in New Haven, and as a consequence, after medical school he returned to New Haven for the remainder of his very successful life and career as both a politician and businessman.

I found no records to indicate clearly what WFB did during the period 1829 - 1842, but the following scenario is very

plausible. After graduation from Yale, JBB kept the services of WFB, to take care of his (first) wife from 1829 to her death in 1835. From after her passing to 1842, WFB remained in the services JBB (and his second wife, married in 1838) to be their “manservant.”

The year 1842 is an especially important date for WFB for the following reason: In 1784, the state of Connecticut passed the Gradual Abolition Act [27] which permitted children born into slavery after 1 March 1784 to be freed by the age of 21 for females and 25 for males. The year 1842 was the 25th birthday of WFB. Thus, during this year, WFB was released from JBB’s “family’s ownership.” He was now a free man! One of the first actions that he performed was to marry Susan Cooley, a free (mulatto) woman from Westport, Connecticut, born in the same year of his birth, 1817. It is likely that the two met while attending services at the Temple Street Church [28], one of the oldest Black congregations in New Haven.

WFB in New Haven (1842 – 1885)

William Francis Bouchet from the beginning of both his attainment of freedom and getting married, lived life to the maximum extent allowed as a free-man-of-color in Connecticut in pre-civil war America. Within ten years, his family grew to have four children, three girls and one boy: Jane (b. 1843), Frances (b. 1845), Georgiana (b. 1849) and Edward (b. 1843). His son would later attend and graduate from both Yale College (1874) and Yale University (1876). The latter degree, a PH.D in Physics, would distinguish him as the first known African American to earn the doctorate degree in any academic discipline in North America [16].

During the remainder of his life, in New Haven, WFB was employed by Yale University as a “sweep” [2]. While this provided him with limited economic resources and mobility, it did not prevent him from participating in many activities related to his church. The Temple Street Congregational Church, the oldest African American church in New Haven, which was formally recognized in 1829. WFB served as a deacon in the church and, as a consequence, became a prominent person within the African American community, engaging his time and efforts in many civic, social, political, and economic endeavors related to enhancing the lives



Portrait of William Francis Bouchet's son, Edward Alexander Bouchet, Yale college class of 1874; Yale University, PhD, Physics, 1876

and experiences of not only his own family, but also those of other Black communities in Connecticut and America.

It is interesting to note that for the 1850, 1860, 1870, and 1880 United States censuses, WFB was “marked” for racial status, respectively, as mulatto, mulatto, black, mulatto. Interesting! Were the “ghosts memories” of his mixed-race parents making an appearance? Certainly, it would be of no surprise that this was his situation since so many mulattos were produced as a legacy of slavery!

Finally, it is of value to imagine William Bouchet taking his young son to the Yale campus to show him around the “great university” and imprint in Edward the desire to be curious, to be creative, to want and attain the highest forms of learning. (It should be noted that it was not likely that Yale would permit WFB’s daughters on its campus, because they generally did not allow even European women that luxury.) I suspect that Edward would be awed by the grounds, the building, the library, and the students, even if they looked upon him with contempt.

Legacy of WFB

William Francis Bouchet’s path led from Jamaica, to Charleston, South Carolina, to New Haven, Connecticut, to becoming a manservant, to Yale as a sweep, to being a family man, to respected and prominent member of the New Haven African American community. He produced a

son, Edward, who received one of the first Ph.D.'s from an American university. His life and career illustrate both the complexities and possibilities of living in the United States during the 19th century for a person of color. And, he succeeded!

William Francis Bouchet died in 1885 in New Haven and was buried in its Evergreen Cemetery.

Final remarks

My starting issue was centered on constructing the genealogical origins of William Francis Bouchet, the father of Edward Alexander Bouchet [16]. From my perspective and satisfaction, the following conclusions and resolutions were reached:

1. WFB was probably born in Jamaica, his father, a Frenchman, and his mother an enslaved mulatto. The date of birth being 1817.
2. WFB was named after Francis Williams (1690 – 1770), a Black Jamaican polymath.
3. WFB was a very intelligent and curious child and was educated by private tutors until the age of seven.
4. WFB's father, UFWB, was employed on one of the Robertson family plantations in Jamaica and used his social connections with the Robertson family living in South Carolina to have his son become a manservant to John Brownlee Robertson, who would become an undergraduate at Yale College in 1824.
5. In 1842, JBR freed WFB based on Connecticut law pertaining to enslaved persons.

The major reason for these actions by WFB's father was to ensure that his son had some measure of safety, security and freedom, that he would not likely achieve if he remained in Jamaica.

As previously stated, this narrative and explanatory story, i.e., “my-story,” is consistent with the historical evidence that I have considered. It is also consistent with the realization that the recalling and writing of history is never fully accurate or true, but carrying out associated tasks, can still be justified [29] and worth all the efforts placed into the completion of a document for others to read, examine, analyze, and interpret [18].

Finale

We end this short essay with interesting and curious facts. John Brownlee Robertson finished Yale College in 1829, and

his son, Abram Heaton Robertson, graduated from Yale College in 1872. Edward Alexander Bouchet, the son of William Francis Bouchet graduated from Yale College in 1874 and completed his doctorate degree in 1876. This data allows us to conclude that the two sons overlapped on the Yale campus for (at least) two years, 1870 - 1872. So, the following questions naturally arise:

1. Were the two sons aware of their fathers' connections?
2. What, if anything, was the nature of Abram's and Edward's interactions both on and away from campus?
3. Since both fathers remained in New Haven after William gained his freedom, how did the two fathers view and interact with each other?

Unfortunately, no records were available to me to provide answers/responses to these questions and related issues. Hopefully, some future scholar will come to our rescue and through their research efforts resolve these matters.

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Comment

During the formulation and writing of this essay, while carrying out searches on my personal computer, its AI software constantly sought to provide additional assistance on a broad range of issues related to this essay. Almost all of this unwanted commentary contained serious errors of fact and/or interpretation, or agreed with my own previous conclusions. Consequently, this essay was composed and written by an actual “human,” Ronald

E. Mickens.

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Laudation for Emmy Noether - The struggles and triumphs of a mathematical genius who helped shape modern physics

Continued from page 1

likely conclude that mass is at least approximately conserved. Conservation of mechanical energy – which can nicely be derived from Newton's second law and knowledge of calculus – represents the basic fact that it takes the same amount of energy to lift or stretch an object as it releases when it is let go. However, that is, of course, an ideal situation. Noting friction, air resistance, and other damping forces, and recording what happens to objects exposed to such factors, one might infer that the heat produced represents energy lost during the process. Calorimetry might then show that indeed many processes turn work and other forms of usable energy into energy released through heat exchange. The laws of thermodynamics, so brilliantly represented by Rudolf Clausius, encapsulate such conclusions. Energy is conserved, while entropy – as a measure of what portion of energy is unusable – tends to increase in irreversible processes such as heat engines.

Momentum conservation similarly derives from Newton's principles of motion. It offers an encapsulation of the second and third laws, particularly applied to collisions, explosions, and other interactions between bodies taking place at a particular point in time. It also expresses the state of equilibrium, when all external forces on a body or set of bodies are balanced.

In the late 18th and early 19th centuries Italian-born French mathematician Joseph-Louis Lagrange and Irish mathematician William Rowan Hamilton lent more mathematical power to classical

mechanics through the development of Lagrangian and Hamiltonian methods, framed in terms of the differences and sums, respectively, of the kinetic and potential energy functions that apply to physical situations. In such frameworks, generalized coordinates describe the positions of bodies or sets of bodies. From these coordinates and the Lagrangian, generalized momenta emerge correspondingly.

Hamilton showed beautifully how the Principle of Least Action, the counterpart to Fermat's Principle of Least Time in Optics, naturally leads from Lagrangians and Hamiltonians to the Euler-Lagrange relationships and Hamilton's equations, which, in turn, produce the equations of motion. By defining the action as the time integral of the Lagrangian from starting time to end time in a physical situation, and then optimizing its value, he found a natural route to explaining the workings of mechanics. Consequently, Newton's laws of motion, rather than seemingly handed down from on high like sacred scrolls or mathematical postulates, instead emerged from a kind of balancing of potential and kinetic energy over time, conveyed by minimizing the action.

One remarkable fact about Lagrangian mechanics is the relationship between the concept of ignorable coordinates (also known as cyclic coordinates) and conserved quantities. Ignorable coordinates are generalized coordinates that do not explicitly appear in the Lagrangian. For example, a particle moving in such a way that its potential energy is constant, and thereby independent of position, would

ordinarily have a Lagrangian that does not explicitly include position coordinates. In such cases of ignorable coordinates, the canonical momentum components that are the counterparts to those coordinates would be conserved. In the case of time not being explicitly included, mechanical energy would be conserved. Thus, Lagrangian mechanics offers a natural way of expressing conservation laws.

Problems involving Newtonian gravitation, such as solving for the motions of planets around the Sun, lend themselves well to such treatment. The inverse-squared dependency of gravitational strength on the mutual distance between masses implies a gravitational potential that is inversely proportional to radial distance. In other words, it is a central potential with no angular component. Consequently, modeling the behavior of a massive object in a gravitational potential might best be analysed using polar coordinates, radial and angular. In such a formulation, clearly the angular coordinate is absent from the potential energy part of the Lagrangian and thereby from the Lagrangian itself. In other words, polar angle is an ignorable coordinate. Therefore, its canonical momentum counterpart – namely angular momentum – is conserved. With the orbits of planets conserving angular momentum, the Euler-Lagrangian equations become simplified and lead to a ready solution. The result is an elegant proof of Kepler's laws of planetary motion, including his conclusion that planets travel in elliptical orbits with the Sun as one of the two foci.

In 1915, however, Albert Einstein shook up the world of physics with his novel formulation of gravitation, the general theory of relativity. Although for weak gravity it reproduced Newton's findings, such as orbital predictions, it veered sharply from Newtonian models in all other cases. Notably, it predicted the precession of Mercury's orbit in an accurate way. It also predicted the bending of starlight by the Sun, and a red-shift of light in a gravitational well – two prognostications that would similarly later prove successful.

General relativity, in Einstein's formulation, does very well in plotting the geodesics – the paths that light would take. It shows how massive objects and energetic fields produce spacetime curvature, described by the Ricci, Riemann, and Einstein tensors. Those are three alternative tensor formulations of curvature. Tensors are mathematical entities that transform in predictable ways, rendering general relativity a covariant theory – essentially meaning independent of coordinate system. That is, in Cartesian, spherical, or any other coordinate system, the relationships of general relativity must similarly hold true. However, Einstein's 1915 paper was incomplete as a replacement for classical mechanics as applied to gravitation. It faltered in failing to develop a full description of particle motion, a way of analysing energy flow, and other aspects of the equivalent of classical mechanics.

To remedy that situation required the work of brilliant thinkers. One was German mathematician David Hilbert, based at the University of Göttingen, who proposed a Lagrangian formulation of general relativity. It appeared shortly after Einstein's publication, and bolstered its mathematical framework. Einstein's field equations emerged as consequences of that choice of Lagrangian. However Hilbert's work was far from enough. To establish conservation principles in general relativity required the unique insight of Emmy Noether. By connecting conservation laws with symmetry groups she achieved the breakthrough needed to move modern physics forward.

2 Rescuing Einstein's theory

Amalie "Emmy" Noether came upon her discovery after years of struggle. Born in Erlangen, Germany on March 23, 1882, her father Max Noether was a distinguished mathematician specializing in

algebraic geometry. As a child, she was shy and focused on learning, finding pleasure in studying foreign languages as well as mathematics. She went to a high school for girls, that, because of the sexism of the time, was not designed to prepare pupils for university. Only boys, attending their own schools, could aspire to that goal. Girls could become schoolteachers, but not academics. Nevertheless, with the help of her father, who was a professor and Dean at the University of Erlangen, along with a certificate qualifying her to teach French and English to schoolchildren, she obtained permission to audit university classes [1]. There at Erlangen she proved a gifted student. While initially she pursued French and English, she soon decided to follow in her father's footsteps and study mathematics – even choosing a similar specialty. Her younger brother Fritz would study mathematics as well, without the same obstacles, and go onto a distinguished career. She completed her PhD under the supervision of eminent algebraic geometry expert Paul Gordan in 1907. Gordan is famous for his contribution to the Clebsch-Gordan coefficients of spherical harmonics used in solving the hydrogen atom problem in quantum mechanics. In line with Gordan's main focus, her doctoral research concerned the notion of invariants – quantities that retained the same value during certain transformations of polynomials. She soon established a reputation as being one of the world's foremost experts in that subject. At the same time, she assisted her father at the university, without any official role there.

One of the most important inspirations to Noether was German mathematician Felix Klein. In the 1872 "Erlangen program" Klein had applied the notion of invariants to geometry, showing how many geometric figures could be defined on the basis of their invariant properties. For example, planes possessed translational (x , y , and z movement) symmetry with the axis perpendicular to them maintaining an invariant, and spheres harbor rotational symmetry with the radial coordinate being an invariant. Those are simple cases; Klein enlarged those characterizations by invariants to more complex situations, including higher dimensions. Noether would carry studies of invariants and geometry along a similar vein, making even greater progress.

In April 1915, David Hilbert invited Noether to the University of Göttingen. He

felt that her mastery of invariants would provide a valuable addition to his group. Klein had long before also relocated there, making Göttingen the leading mathematical research center in Germany and arguably the world.

Several weeks after Noether arrived, Einstein gave a talk at Göttingen about his mission to finish building the edifice of general relativity in a satisfactory way using what we now call differential geometry (the area of mathematics that includes tensor calculus). Hilbert was skeptical about the depth of Einstein's knowledge of higher mathematics. He once quipped: "Every boy in the streets of our mathematical Göttingen understands more about four-dimensional geometry than Einstein..." [2].

After Einstein's visit, Hilbert started independently trying to complete the mathematical structure behind general relativity. While Hilbert worked on his own, his zeal helped inspire Noether to apply her extensive knowledge to the question of invariants and conservation laws in that domain. Ultimately Einstein published the field equations for general relativity first, while Hilbert supplied the proper Lagrangian, and Noether made use of that innovation to pursue a more refined examination of the mathematical properties pertaining to group theory and invariants.

Despite her vital knowledge and enthusiasm for conveying it through pedagogy, Noether could not at first be provided at the University of Göttingen with a regular teaching appointment. For that, she would need to undergo the process of habilitation, which was not available to her. A habilitation is something like a second doctorate, with the explicit purpose of allowing university teaching and, in some cases, a professorship. Back in 1908 the government of Prussia had decreed that women were forbidden to habilitate. By the mid-to-late 1910s it was still the firm law – in Berlin, Göttingen, and elsewhere in Germany [3]. Hilbert thought the law was preposterous, and tried to see if an exception could be made for someone as talented as Noether to habilitate and serve as professor. Some of Hilbert's colleagues in other fields rebutted him with silly arguments, such one worrying that the all-male faculty dining room would no longer have the same ambience if women were allowed. The idea that gender would affect

academic appointment in any way baffled Hilbert. Rather, the most qualified candidates of either sex, he thought, should achieve status as a lecturer or professor. Noether clearly was a giant in her field, and deserved a teaching appointment. As Hilbert sardonically remarked to an administrator: “I do not see that the sex of the candidate is an argument against her admission as Privatdozent. After all, we are a university and not a bathing establishment” [4].

In the meanwhile, Hilbert would sign off on the lectures that Noether taught. In effect, he needed to act as her surrogate for her to be able to teach. Only in 1919, after World War I ended, the German Empire fell, and Germany became a republic would the habilitation law be repealed. Finally Noether could habilitate. Nevertheless, even then, the faculty at Göttingen remained disinclined to grant her a fully paid professorship on the same level as Hilbert. Ultimately she would be appointed to a special professorship that did not offer the same salary as normal academic professorships.

The specific issue Noether successfully addressed was defining conservation of energy in general relativity. Einstein’s theory made that tricky because, while it assigned the so-called stress-energy tensor as a means of including energy (along with mass), that tensor accounted for all types except for gravitational energy. For example, the energy of electromagnetic fields was included in the stress-energy tensor, but that of gravitational fields was not. His goal was a clean relationship between the non-gravitational content of the universe, including matter and electromagnetic fields, and the curvature tensors representing the warping of spacetime in the vicinity of such substances.

In the special theory of relativity, Einstein expressed conservation of energy and momentum by setting the divergence of the stress-energy tensor (without gravitation) to zero. Naturally, that meant that the time derivative of energy was zero, resulting in its constancy. However, in exporting that expression to general relativity standard partial derivatives needed to be replaced with covariant derivatives sensitive to the ever-shifting coordinate systems characterizing the rest frames of each spacetime point – something like the mesh of patches that are stitched together to fabricate certain types of quilts.

However in that generally-covariant generalization of the stress-energy tensor divergence, no physically accurate conservation law emerged. Even if that generalization had worked, it still excluded gravitational energy, which was a big problem.

As a stop-gap measure, Einstein defined an additional energy-momentum pseudotensor to embody the energy and momentum of gravitation on a point-to-point basis. That is, it was a local measure, akin to the positional dependence of gravitational potential energy in classical mechanics. A pseudotensor has the indices of a tensor but does not transform in the same way. The result is an unfortunate dependence on the use of particular coordinate systems. While the Einstein energy-momentum complex is well defined in close approximations to the flat Minkowski metric (also known as quasi-Cartesian coordinates), it is ill-defined in many other coordinate systems. It even vanishes – when transformed into certain coordinate systems – in cases where mass and energy are clearly present. Nonetheless, Einstein apparently found no better alternative. By adding that entity to the stress-energy tensor, and restricting the coordinate systems used, he found that he could express conservation of energy and momentum locally.

Among the many quirks of the Einstein energy-momentum pseudotensor is ambiguity about whether or not gravitational waves carry energy. While Einstein’s 1937 paper with Nathan Rosen on the topic described gravitational wave solutions in terms of cylindrical coordinates [5] and Rosen would later calculate a value of zero for the energy of such solutions [6], that sparked debates over the nature of gravitational radiation. However, in 1993, Rosen and K. S. Virbhadra would recalculate the energy-momentum pseudotensor for the same solution, but expressed in Cartesian coordinates, and obtain a finite, non-zero result [7]. We now know, thanks to the excellent findings over the past decade of LIGO, Virgo, and other gravitational wave observatories, that such signals do indeed carry energy – despite the ambiguity of local energy-momentum pseudotensors in characterizing them.

For the mathematically-minded, such as Noether, Hilbert, and Klein, such vagueness and inelegance – seen in Einstein’s 1915 definition of local energy using a pseudotensor – simply meant that a deeper

truth about gravitational energy needed to be unearthed. Crafting a more comprehensive approach required looking at the global picture. That daunting task – which even defied great minds such as Einstein, Hilbert, and Klein – tapped into Noether’s extraordinary skills and confidence in abstract algebra and algebraic geometry. She mastered the mission and thus revolutionized theoretical physics. When she sent an early copy of her paper to Einstein in May 1918, he informed Hilbert that he was most impressed by her findings [8].

Noether’s highly influential paper, “Invariante Variationsprobleme” (Invariant Variation Problems) was presented at the July 16, 1918 meeting of the *Königliche Gesellschaft der Wissenschaften zu Göttingen* (Royal Society of Sciences in Göttingen). Because Noether, as a woman, was forbidden from belonging to that society and participating in its meetings, Klein read the paper to the group. He extolled the basic truth that the work revealed – that continuous symmetry groups involving the generalized coordinates of any physical situation, including general relativity, naturally determine that system’s invariant properties including conservation laws. Such continuous symmetry groups include translations, rotations, and also a host of other smooth transformations from one coordinate representation to another. She distinguished between global and local symmetries in classifying her results as the “first theorem” and “second theorem.”

Although it would have been far more appropriate for Noether to present the paper herself, Klein was a reasonable choice in her absence. His own contributions to invariance theory in some ways foreshadowed hers. In her written presentation, she singled out a remark about relativity he once made, and showed how she fulfilled its promise in her work:

“This again confirms the correctness of a comment of Klein’s that the term ‘relativity’ current in physics is replaceable by ‘invariance relative to a group’” [9].

Klein indeed saw the economy of her work. In his representation of Noether’s (First and Second) Theorem and its application to conservation laws, he noted:

“As one will see [...] I really do not longer need to calculate but only to make use of the most elementary formulae of the calculus of variation” [10].

The gist of Noether’s breakthrough is that she extended the simple idea that

ignorable coordinates in a Lagrangian result in conserved quantities to the much deeper notion that any continuous symmetries involving generalized coordinates that leave the Lagrangian intact, coupled with constraints of the Least Action Principle, automatically produce invariant measures. Those invariants, in turn, correspond to conserved properties, such as conserved energy and momenta. In the simplest cases, that matches the earlier result. For instance, a Lagrangian corresponding to a central potential possesses a continuous rotational symmetry in its angular coordinate. The resulting invariant is the angular momentum. However, one can contrive more intricate situations – involving tensor quantities and richer symmetry groups, for example – and develop unexpected invariants and not-so-obvious conserved quantities.

As applied to general relativity, Noether's results show that trying to construct local measures of conserved energy that display coordinate system independence are bound to fail. On the other hand, continuous symmetry groups that encapsulate the entire universe guarantee that the stress-energy tensor represents a conserved entity on a global scale. The boundaries, in other words, of the domain in which conserved energy is examined need to be set to infinity.

As physicist Dwight E. Neuen-schwander in his exposition of Noether's first and second theorems eloquently expresses this:

"Conservation laws in general relativity are necessarily improper; matter and gravitation are inherently coupled. One can only speak of proper conservation for the entire system by enclosing, with a surface at infinity, all the matter (including radiation) and gravitational fields. Out there, away from all matter and fields, spacetime asymptotically becomes Minkowskian and the covariant divergence goes over to a proper divergence. Only in that sense does general relativity contain a proper energy conservation law" [11].

Thanks in part to Hermann Weyl, Noether's esteemed colleague at Göttingen, and his coining of the term "gauge theory," Noether's association of continuous symmetry groups – both local and global – with conserved currents would become a key element of quantum mechanics and quantum field theory. The

Standard Model of particle physics relies on several symmetry groups and their various commutation properties (Abelian versus non-Abelian) for example. Supergravity and superstring theories have similarly been based on Noether's brilliant work.

3 Dark days at Göttingen

The early 1930s were times of great foreboding in Germany. Colossal unemployment and rampant inflation disrupted ordinary life. Amidst the challenged fledgling democracy in the Weimar Republic, the rise of the Nazi Party frightened progressive-minded people throughout the nation and indeed the world. Yet Einstein and others expressed vain hope that its anti-semitic tide would ebb once the economy improved and dissipate in the face of common sense, reason, and concern for human rights and dignity.

Yet for Noether the days were filled with joyous pursuits of teaching, research, and supervising dissertations. Given that most of her bright young mathematics students were male, and they looked to her with admiration and respect, they were nicknamed the "Noether boys". She took great care that they were happy and active, sometimes taking walks with them and meeting up with them in casual settings such as coffee shops.

She moved, along with her colleagues, to a wonderful new building at the University, called the Mathematical Institute. Funded by the Rockefeller Foundation, the building's design was planned by another remarkable Göttingen mathematician, Richard Courant. Courant became the Institute's director. The new academic home offered space for her to conduct her scholarly pursuits.

Meanwhile, Noether finally received invitations to speak at research conferences, rather than being represented by others. In September 1932, she delivered a noteworthy address to the International Congress of Mathematicians in Zürich, Switzerland. The topic was "Hypercomplex systems in their relationships to commutative algebra and number theory". Many of the top mathematicians and physicists in the world had the opportunity to hear her speak. At last she was recognized as a brilliant, groundbreaking thinker.

However those halcyon days for Noether at Göttingen soon came to an end. On January 30, 1933, after a strong showing (but not a majority) by the Nazi Party in

the German parliamentary elections, the worst fears came to pass: Adolf Hitler was appointed Chancellor and the Nazis took power in Germany. Several weeks later, a fire in the Reichstag (German Parliament) that the Nazis falsely blamed on the left-wing opposition led to the Enabling Act and the consolidation of absolute power by Hitler. Soon Jews also became a target, along with the left, leading to mass dismissals of civil servants, teachers, and professors with Jewish heritage. The only exceptions, at first, were Jewish veterans of the First World War, some of whom were provisionally allowed to keep their positions. German academics was decimated by the loss of many prominent individuals. Göttingen, with many Jewish faculty such as Courant, Edmund Landau, Max Born in physics, and many others, was hit particularly hard.

Sometime later Hilbert, who remained at Göttingen but retired, would participate in a dinner program that included the infamous Nazi education minister Bernhard Rust. When Rust asked Hilbert if the dismissal of Göttingen's Jews affected the mathematics program at Göttingen, he bitterly responded, "There is no mathematics left at Göttingen" [12].

Noether was politically on the left and ethnically Jewish (though secular). Due to her politics and ethnicity she became an early target of such firings. She was put on leave. A campaign led by mathematician Helmut Hasse was organized to keep her at the University of Göttingen. He gathered numerous reference letters in support of her continuing, including Weyl, Harald Bohr (Niels Bohr's brother, a mathematician), and many others. Hasse prefaced the package of documents with the plea:

"The enclosed expert opinions on Miss Emmy Noether's scientific significance are intended to serve the purpose of preserving, if possible, her continued existence at the Göttingen Mathematical Institute in some form or other. It would be a significant loss not only for Göttingen, but for German mathematics as a whole, if Miss Noether were unable to continue her career as a teaching mathematician in Germany" [13].

Weyl wrote an enthusiastic letter of support, beginning with:

"Emmy Noether occupies an outstanding position in contemporary mathematical research due to her unusually natural, productive power, as well as the central

importance and broad interrelationship of the problems she addressed. Through her research and the persuasiveness of her teaching, she was able to gather the largest circle of students around her in Göttingen" [14].

Despite the entreaties of some of the most prominent mathematicians in Germany (and throughout Europe), Noether was not reinstated. Rather, she remained on leave, unable to teach or work with students. Given her facility with languages and growing international reputation, relocation abroad became an increasingly attractive option.

4 A delightful new beginning at Bryn Mawr College

Auspiciously, in August 1933, President Marion Park of Bryn Mawr College in the United States reached out to Noether with a welcome invitation to a two-year faculty position, partly funded by the Institute of International Education and the Rockefeller Foundation. After musing over a possible postponement of the appointment for a year to work possibly at Oxford, Noether gratefully accepted the offer, and eagerly headed overseas in October 1933. The importance of the appointment was recognized by an article that month in the New York Times.

Noether settled in to a humble guest house on Elliott Avenue near campus. (Sadly, that house has since been demolished and replaced with an office building.) Walking to the campus with its gothic architecture and ample greenery must have been a true delight. There, rather than being surrounded by "Noether boys," she instructed mainly bright young women, as the institution was (and is) mostly a women's undergraduate college with some graduate offerings (that are now open to both sexes).

The opportunity to interact with such a brilliant thinker proved enticing to the recently-established Institute for Advanced Study in Princeton, New Jersey, which invited Noether for weekly lectures during the academic semesters. Though it was some 80 kilometers away, she relished the opportunity to share ideas with her colleagues, including Weyl, who had relocated there because of the Nazi regime in Germany. All in all, her schedule offered a delightful balance of pedagogy, research, and scholarly interactions.

By early 1935, it was clear that Noether

Emmy Noether (1882-1935)



Die Mathematikerin Emmy Noether ist vielen vor allem wegen ihrer wegweisenden Arbeit in der Algebra bekannt. Dazu zählt z.B. die Entdeckung der Ideal-Eigenschaft, die heute „noethersch“ genannt wird

$$a_1 \subseteq a_2 \subseteq a_3 \subseteq \dots \subseteq a \Rightarrow a_n = a_{n+1} = \dots$$

(aus: Math. Ann. 96, 1927, S. 26-61, 30. Abstrakter Aufbau der Idealtheorie in algebraischen Zahl- und Funktionenkörpern)

Darüber hinaus beschäftigte sie sich aber auch mit der Variationsrechnung, einem Teilgebiet der Analysis und entwickelte dabei auch die Formel zu invarianten Variationsproblemen

$$\bar{\partial}f + \text{Div}(f \cdot \Delta x) = 0$$

(aus: Nachr. v. d. Ges. d. Wiss. zu Göttingen 1918, S. 241 Formel (11))

Um die Vielfältigkeit ihrer Arbeit widerzuspiegeln, sind diese beiden Formeln auch oben auf der Tafel zu sehen.

Die Tafel wurde 2014 von der Künstlerin Stephanie Magdziak aus Princeton, New Jersey entworfen.

Display at the Göttingen Mathematical Institute

had no chance to return to her former position at Göttingen, nor would she wish to while Germany remained under the iron heel of the Nazis. Finding additional funding to renew her Bryn Mawr faculty position, or to find another academic title for her, became a priority. Bryn Mawr College itself did not have a standard faculty line to offer her; it would need to be an externally funded position. By then her reputation had soared into the stratosphere. In an attempt to help obtain funding for her, renowned mathematician Norbert Wiener, considered the father of cybernetics, praised her work with effusive comments that year:

"Miss Noether is [...] the greatest woman mathematician who has ever lived; and the greatest woman scientist of any sort now living, and a scholar at least on the plane of Madame Curie" [15].

A young mathematician from Austria, Olga Taussky (whose married name would be Olga Taussky-Todd), who had studied at the University of Vienna and worked at Göttingen, had come to Bryn Mawr in the fall of 1934 and stayed until the spring semester. Her expertise was in algebraic number theory, and also in the collected works of Hilbert for which she served as an editor. Noether enjoyed that opportunity to engage in fruitful discourse with the rising scholar who would go on to a stellar career, including a professorship at Caltech.

Meanwhile, Noether proudly supervised Ruth Stauffer (whose married name would be Ruth McKee) one of Bryn Mawr's PhD students in mathematics. She guided Stauffer in developing a thesis "The

Construction of a Normal Basis in a Separable Normal Extension Field". By spring 1935, Noether felt that Stauffer had completed enough research to obtain her PhD, and set her thesis defense to take place in June that year. Sadly, Noether would not live long enough to participate in that event.

5 A shocking death and glorious tributes

Around that time, Noether was experiencing some discomfort. She received a medical diagnosis of an ovarian cyst that was recommended for removal. Before taking care of it, she decided, as a precaution, to write a statement formally approving Stauffer's dissertation. That letter would ensure that Stauffer would receive her PhD.

Noether's surgical procedure took place at Bryn Mawr Hospital, close to campus. For three days following surgery she seemed to be making a strong recovery. However, on the fourth day, she unexpectedly became extremely ill with a high fever due to the sudden burst of a blood vessel in her brain. Her body temperature shot up to 42 °C, and she fell into a coma [16]. She died on Sunday, April 14, 1935.

A private funeral ceremony for Noether was held at President Park's house on April 17. About 60 people were present, including colleagues and students. Lovely chamber music composed by Bach and Mozart was performed on cello and piano in her honor. Weyl and others offered stirring eulogies for her [17].

After cremation, Noether's ashes were entombed under the pavement of an

enclosed courtyard of Bryn Mawr College called The Cloisters. A humble grave marker with only her initials marked the site. (In April 2025 an additional plaque with her image was placed on a wall near the gravesite to commemorate the 90th anniversary of her death.)

On April 26, 1935, a memorial service was held at Bryn Mawr's Goodhart Hall. Weyl was the principal speaker. He offered a stirring tribute to his late colleague:

"She was such a paragon of vitality, she stood on the earth so firm and healthy with a certain sturdy humor and courage for life, that nobody was prepared for this eventuality. She was at the summit of her mathematical creative power; her far-reaching imagination and her technical abilities accumulated by continued experience, had come to a perfect balance; she had eagerly set to work on new problems. And now suddenly –

the end, her voice silenced, her work abruptly broken off" [18].

Einstein wrote a moving tribute to Noether that was published in the *New York Times*:

"In the judgment of the most competent living mathematicians, Fräulein Noether was the most significant creative mathematical genius thus far produced since the higher education of women began. In the realm of algebra, in which the most gifted mathematicians have been busy for centuries, she discovered methods which have proved of enormous importance in the development of the present-day younger generation of mathematicians. Pure mathematics is, in its way, the poetry of logical ideas" [19].

6 Noether's legacy

Emmy Noether's legacy pervades the whole of modern physics. Her stunning discovery of the connection between continuous symmetry group and conservation laws has revealed novel invariants in nature, and supported the rise of gauge theory. Thanks to local symmetries, we can understand the origin of all fundamental forces of Nature, from electromagnetism to the nuclear forces, as gauge boson interactions mediated by photons, the W and Z bosons, and gluons respectively. (The existence of gravitons, the hypothesized gauge boson mediators for gravitation, is yet unproved.) Moreover, the Higgs mechanism that lends rest mass to some of those force mediators as well as matter parts

relies on a spontaneous symmetry breaking mechanism that stems from Noether's work. Numerous Nobel Prizes in fundamental physics pertaining to the Standard Model and its experimental verification have stemmed from the implications of her contributions.

More generally, discussions of symmetry groups and conservation laws have become ubiquitous in practically every subdiscipline, from analyses of crystalline structures to the search for a unified field theory. In particle physics, Murray Gell-Mann's recognition of the symmetries in the emerging particle zoo of the 1950s and 1960s led to his development of the "eightfold way" characterization of those constituents, and then to his quark model.

Recognition that certain mathematical transformations – rotations in an abstract space – might turn bosons into fermions and the converse – inspired the proposal of a higher symmetry in nature called "supersymmetry." Explicitly, that would mean, according to Noether's theorem, that there must be a hitherto unseen conserved quantity in nature that corresponds to that symmetry. Theorists have dubbed it the "supercharge". Yet, so far there has been no direct experimental evidence – in particle collider debris, for example – of supersymmetry or supercharge.

One recent avenue of exploration that does indeed have experimental evidence is the notion of "time crystals" – quantum systems that persist in periodic activity over time – proposed by Nobel laureate Frank Wilczek in 2012. For that too, Noether's results yield a useful conclusion. Because of the time symmetry, energy must be conserved, yielding a durable quantum state.

In short, it is hard to imagine contemporary physics without the vital contributions of Emmy Noether. Her life – all too brief – was full of struggle and triumph and deserves universal recognition. From Erlangen and Göttingen in Germany, to Bryn Mawr and Princeton in the United States, she left an indelible mark of brilliance everywhere she went. We salute a true pioneering thinker.

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