Science “Fails”: A Bank of Historical Examples for Learning From Failure in Science

Christina Makkar¹, Maria Dasios²*, Nicole Laliberté³, and Fiona Rawle⁴

¹Department of Biology, University of Toronto Mississauga
²Department of Historical Studies – History of Religions, University of Toronto Mississauga
³Department of Geography, Geomatics, and Environment, University of Toronto Mississauga
⁴Department of Biology and Institute for the Study of University Pedagogy, University of Toronto Mississauga

Abstract

Learning from failure is critically important to the processes of scientific inquiry, discovery, and invention. However, students are not routinely taught how to reflect on, learn from, and ultimately embrace failure, and relatively few curricular examples and teaching tools exist for reflecting on failure and its relationship to discovery. In fact, many science textbooks are stories of past successes in science and often neglect the failures or missteps that led to major discoveries. Yet examples of failures, errors, setbacks, and accidents that led to innovation and discovery abound for use in instruction. Moreover, research suggests that students benefit when failure is openly discussed and reframed as integral to learning. We have curated a bank of examples as a teaching tool to encourage and guide discussions about learning from failure. We highlight systemic barriers to embracing failure and note resources (time, funding, security, cultural capital) that facilitate second chances; we cannot encourage students to embrace failure without acknowledging these needs. Nevertheless, reflecting on failure in science courses can hone the evaluative and creative capacities of students, aid in the development of procedural and metacognitive knowledge, and invite improvement in many science process skills including research, analysis, and experimental design and implementation. Importantly, reflecting on failure can also decrease stigma, promote resilience, and positively impact student wellbeing.

INTRODUCTION

Learning from failure is part of science, though we do not often acknowledge this in our teaching. M. A. Henry et al. describe failure in “the broadest sense” as “the gap between an expected or desired result and what one ultimately experiences,” and more narrowly as “the inability to meet the demands of an achievement context, with the result of not achieving a specific goal” (1). This definition departs from others that reserve the term “failure” for a complete disengagement of effort or iteration (2). It also distinguishes “failures” from “errors,” which can be corrected and “do not necessarily preclude accomplishment of a goal” (1). Nevertheless, “failures,” “errors,” “setbacks” and “accidents” all generally connote unintended outcomes. In this teaching tool, we opt for an expansive view of failure, exploring how a variety of unintended outcomes have contributed to scientific process. Scientific discovery involves navigating uncharted territory where there is no “right answer,” only good processes and methods that allow for reproducibility. While it must be rigorous and replicable, the scientific process is also open, fluid, and creative. When experimentation is reduced to rigid step-by-step formulas, students cannot effectively learn how to adapt to deviations from predicted outcomes, increasing the probability that obstacles will be interpreted as dead-ends, not opportunities for growth. Without adequate emphasis placed on experiencing, acknowledging, and learning from failure when designing and conducting experiments, analyzing data, evaluating methods, and communicating results, students have limited exposure to (and thus fewer resources to contend with) the messy realities of the scientific process.

Introductory science teaching need not shy away from complexity (as this website demonstrates). In part, this means offering students opportunities to conduct hands-on practices that are inquiry-based, creative, and present the possibility of failure. Increasing efforts in this direction are evident in contemporary undergraduate biology teaching (3–7). However, efforts to foster student learning around the complexities of the scientific process by providing modelling and mentorship around missteps and failures are lacking. Students cannot benefit from models of generative failure when they are routinely...
omitted from narratives of discovery. It is thus imperative that we include failures, errors, setbacks, and accidents in our science “success stories.”

Most science textbooks tell stories of past successes in science, although nearly all these successes were built upon a multitude of failures. Textbooks often give the illusion that the scientific process is concrete and successful findings are permanent. Scientists know, however, that no discovery is ever complete. Scientific discovery is a process that does not end. Over time, new knowledge may modify, enhance, or refute past findings and scientists may change their interpretation of the data when presented with more information. For example, the COVID-19 pandemic. At the start of the pandemic, the World Health Organization (WHO) did not recommend masks—which we know today as a staple item in pandemic protections—because they believed there to be no evidence that healthy individuals would benefit from wearing them. They further advised against wearing masks to save precious resources for healthcare workers who would otherwise face shortages. The WHO later recanted this statement, instead urging everyone to wear masks to curb infections, and further suggesting that tighter fitting masks such as N95’s would be more effective. This is a potent example of data analysis as a dynamic and adaptive process reliant on ongoing processes of evaluation and reassessment, and of the challenges involved in the communication of scientific results which are neither settled nor straightforward. Discussing this example with students yields an opportunity to reflect on several science process learning skills in action: from predicting outcomes and gathering data/making observations, to analyzing data and communicating results. Moreover, it highlights the ways failed predictions or recommendations might give rise to improved evaluative capacities (through checking, reviewing, and forming new recommendations), and be used to generate alternative hypotheses. Restoring failures to our scientific narratives and teaching from contemporary and historical examples that model learning and recovery from failure allows students to better contend with the dynamic realities of the scientific process.

There are countless examples—some more well-known than others—of failures, errors, and accidents in scientific experimentation and everyday life that have given rise to revolutionary techniques and enabled complex new discoveries. Some discoveries are products of trial-and-error where failure leads to innovation. Others are accidental by-products that, while unforeseen, have contributed immensely to advances in human knowledge and achievement. Still others take longer than expected or require collaborative effort to make their desired impact. In scientific experimentation, sources of failure can range from overgeneralization (in which a limited understanding of all potential variables tied to a specific outcome creates gaps in research) to methodological failure caused by faulty or damaged materials, holes in experimental design, inaccurate testing techniques, or transcription errors. Many of the cases highlighted in our example bank (Table 1) involve factors that combine to yield unintended outcomes. Reflecting on the heuristic disaggregation of related concepts (“failure,” “error,” “setback,” “accident”) may well be one way to get students to productively engage in discussion. Students might also benefit from noting that when scientific discovery is conceived as a trajectory, time is often what distinguishes “accidents” from “failures.”

The last two decades have seen a rise in scholarly research emphasizing the pedagogical value of failure (9–15) and encouraging instructors to incorporate failure pedagogies such as “desirable difficulties” (11, 15), “constructive error climate” (12), and “productive failure” (9, 10, 13) into their classrooms. Nevertheless, widespread engagement with such approaches is not yet evident across postsecondary STEM teaching—although such engagement is increasing, as evidenced in a handful of recent publications (1, 3). In a 2019 work modelling hypothetical student responses to challenges and failures in undergraduate STEM learning contexts, Henry et al. note that while “navigating challenges, persevering through difficulties, and coping with failure are cited as some of the most important dispositions distinguishing outstanding scientists […] this is rarely an explicit area of instruction or development emphasized in STEM classrooms” (1). Ultimately, Henry et al. encourage further interventions designed to help students in STEM contexts develop a “persevering and challenge-engaging disposition” (1). These aims, likewise animating recent works (3, 16), are complementary to our own.

Crucially, however, and contra this emphasis on individual disposition, we wish to highlight that students do not experience the stigma of failure, fear of failure, and the stakes of failure evenly. Some students do not have the financial means to retake a course, and first-in-the-family students are less likely to know of or engage with available supports (17–19). Alongside advocating for and working towards interventions that would de-stigmatize failure and encourage perseverance in our students, we draw emphatic attention to the social realities that severely limit opportunities to try again. Such concerns are addressed in further detail in the final section of this work, Notes About Incorporating Learning From Failure Into Science Teaching.

A study conducted by Nunes et al. (17) examined first-year undergraduate students’ perspectives on where their fear of failure originates and how the stigma surrounding it can be reduced in a university setting. Most students suggested they would benefit from having more discussions about failure in ways that remove the judgment or shame associated with it and embrace it. Knowing that peers, upper-year students, or even professors have experienced failure can help remove the feeling of being alone in one’s struggles and produce an empowering sense of solidarity. Students additionally noted the benefits of changing course design to better equip them with the skills to bounce back and self-regulate and to provide opportunities that foster learning from failures and correcting mistakes (17).

Minimizing preoccupation with grades also emerged as a noteworthy theme in student responses about de-stigmatizing failure (17). However, providing opportunities for students to experience failure as generative rather than harmful can be immensely challenging in educational systems where grades loom large. Offering low-stakes or iterative assignments is one way to allow for students to take chances in their learning without grave impact to their final grades. Other possibilities include allowing for assignment re-submissions, perhaps with the lowest grade dropped; offering practice or trial assessments;
and offering credit for effort and/or participation (pass/fail). Such measures at the level of course design can help alleviate fear of failure and encourage experimentation and innovation by lowering the stakes of failure within a given classroom or lab. However, this is not the same as de-stigmatizing failure, an endeavour which requires larger systemic change (20). As long as grades are understood as accurate reflections of student capacity, and as long as they continue to determine access to further educational and professional opportunities, what Feigenbaum calls “stigmatized failure” remains operative, yielding dissonance for students who are encouraged to view failure as an opportunity for learning yet ultimately experience failure as punitive (20). It has long been noted that performance can be a “highly unreliable index” of learning (11, 21). Proponents of “ungrading” build on this longstanding distinction between learning and performance to argue that grading systems yield students more preoccupied with performance than immersed in authentic, long-term learning (22). For many instructors, however, working with some variety of grading remains an institutional necessity. In such contexts, careful course and assessment design and explicit discussion about the relationship of failure to scientific discovery can help mitigate the harms of a system where stigmatizing failure prevails.

EXAMPLE BANK AS TEACHING TOOL: SUMMARY AND IMPLEMENTATION

This teaching tool identifies and responds to a need for resources that highlight the role failure plays in scientific discovery and enable students to see failure as a potential stepping-stone for learning and growth. We offer a compilation of accessible examples (Table 1) for discussing failure as part of the scientific process and as endemic to innovation and discovery. A few examples are discussed in the following section, with recommendations for how they can be used to spur initial student engagement on the topic of failure and scientific learning or further developed into low-stakes assessments or curricular supplements (as outlined here, with adaptable templates provided as Supporting Files S1–S4).

Related active learning activities or assignments might include:

- **Excavating little-known failures** (Supporting File S1): students are asked to research and present on the backstory of an invention/discovery/experiment of their choosing, highlighting the presence of failures, errors, setbacks and/or accidents. Our in-class discussions have shown that students are unaware of the role failure has played in many scientific discoveries and inventions.
- **Reflecting on personal failure** (Supporting File S2): students are asked to reflect on a story about a failure of their own; think-pair-shares (21) with a partner may be an option depending on comfort level. What factors contributed to this failure? How was it experienced? What was learned from it? What factors, if any, (strategies, structural supports, material realities) facilitated this bounce-back? How might power and privilege have played a role in failure recovery?
- **Science process log** (Supporting File S3): students are asked to keep a log of their process throughout the various stages of a project or experiment (reviewing prior research; interpreting results/data; designing/conducting experiments; gathering data/making observations; analyzing data; communicating results). Students are encouraged to note not only steps in the process but their feelings in response to them: how did they react to unforeseen outcomes? Were they able to formulate alternative hypotheses and adapt procedures? Was it difficult to communicate experimental failure in their results? What were the most challenging and the most generative aspects of experiencing failure (or the prospect of failure) as part of this project? This log can be incorporated into inquiry-laboratory activities that are part of the curriculum.
- **Science success survey** (Supporting File S4): in this activity, students are asked to select a textbook chapter and count the number of “science successes” or experimental findings that are portrayed. Next, students are asked to identify the number of “science failures” or “learning from errors” or “learning from negative results” that are portrayed. A subsequent discussion in class about how learning from failure plays a core role in the scientific process but how it is not portrayed in many of our textbooks can be helpful. Part of the purpose of this activity is to normalize the role failure plays and have open discussions that can reduce associated stigma.
- **Weaving failure-examples through each class**: a simple and effective way to use this resource is to weave the provided examples into classes throughout the entire term or take inspiration to search out further examples tailored to your own teaching needs. No matter the specific topic, it is possible to find examples of how scientists learned through failure. Follow-up discussion or reflective writing can help to highlight the role failure plays in the process of science.

FAILURE: LEARNING IN PROGRESS (FLIP)

Class discussion and activities incorporating examples from this teaching tool may be further supported by open educational resources available on the FLIP (Failure: Learning in Progress) website: Resources for students and instructors include:

- A Learning from Failure Journal template with detailed reflective writing prompts for first-year students
- A podcast by students for students
- Publications disseminating qualitative research undertaken by the FLIP Project
- A glossary of terms for learning from failure across the disciplines
- An annotated bibliography for further reading about failure pedagogies and their implementation
- In-class Learning from Failure interventions: five decks of PowerPoint slides that can be individually tailored to your particular discipline/course and incorporated into class discussion

Each of these resources can be individually incorporated into active learning activities for students.
For example:

- Students may be progressively assigned reflective writing prompts drawn from the Learning from Failure Journal template. A follow-up assignment may ask students to come up with additional prompts stemming from their own experiences;
- Students may be asked to pitch podcast episodes aimed at students (or instructors!) in their own discipline;
- Students may be tasked with researching and annotating an additional resource related to learning from failure.

CLASSROOM INTERVENTIONS AND A POST-INTERVENTION REFLECTION

The FLIP Project website also shares five adaptable modules of PowerPoint slides designed to facilitate introductory in-class discussion around learning from failure (and the ways learning from failure is framed in higher education). The modules, accompanied by an instructor guide, are as follows: “Learning from Failure in X (insert your course here);” “Reflecting on Failure;” “Power and Privilege;” “Perfectionism and Procrastination;” and “Failing Forward.” Reflecting on undergraduate student reception of the “Power and Privilege” module in an online classroom setting, Professor Ken Derry (an affiliate of the FLIP Project) observed deep and ready engagement with the issues at hand: students “were totally down for this conversation...they very quickly came up with things like mental health, food insecurity, language issues, family abuse, etc.[...] they came up with everything I was prepared to mention and more (e.g., I hadn't listed food insecurity)” (K. Derry, personal correspondence, November 3 2022). Notable also was their kindness: participating students “really seemed to understand that some people are really needing to overcome significant hurdles PLUS school (when compared to some others)” (K. Derry, personal correspondence, November 3 2022). Importantly, Professor Derry noted that this discussion took place largely in the Zoom chat; “very little” of this discussion entailed “live people talking.” Instructors experimenting with implementation of these modules may consider documenting and reflecting on student response across various contexts (oral discussion, in person or in breakout rooms; online chat; shared doc/form; reflective writing questions).

In sum: building purposeful reflection on failure as part of the scientific process into lesson plans can productively contribute to the development of students’ procedural knowledge (including knowledge of criteria for determining the appropriateness of a given procedure) and metacognitive knowledge (including strategic knowledge, knowledge about cognitive tasks, and self-knowledge). Importantly, it can also contribute to decreasing stigma around failure and increasing resilience.

ILLUSTRATIVE EXAMPLES OF FAILURES IN SCIENCE

Shining a light on the failures and setbacks left out of “success stories” across diverse disciplines and contexts helps normalize failure as endemic to processes of learning and growth. The examples treated in our bank of “Science Fails” (Table 1) are compiled from several fields, including pharmacueticals, medicine, public health, ecology, technology and materials science, toys and consumer products, and food science. Two final categories consider examples of equipment, clinical testing, and research failures resulting from a lack of diversity, and highlight twists and turns in a selection of scientific career trajectories (often the result of systemic barriers). The range of examples surveyed is deliberately broad; the intention is to offer accessible examples that might appeal to the diversity of student interests and experiences represented in the undergraduate science classroom and that might be easily transferable across courses and disciplines.

Here we offer some illustrative examples selected from our example bank. From them, readers can gain a sense of what follows in Table 1 and how each of those brief examples might be expanded into fuller discussion.

Pharmaceuticals

Penicillin

In 1928, Alexander Fleming discovered the first antibiotic, penicillin. A foreign fungus invaded an agar plate and created a purified area in which no bacteria could grow. Fleming extracted a sample of this mold and determined it belonged to the Penicillium genus, thus giving rise to its name. However, Fleming failed to isolate penicillin as a purified compound, rendering his work incomplete for years. He did, however, save the agar plate in case subsequent studies proved to be successful. In 1939, Howard Florey and his team worked with this compound in large quantities in attempts to isolate it. Team member Ernst Chain finally succeeded in isolating purified penicillin. The new antibiotic was considered a miracle (24), and today antibiotics are commonly prescribed to treat many different bacterial infections. By highlighting the importance of Fleming’s optimism that others after him might be successful where he was not, we see how collaborative scientific discoveries can be.

Medicine

Pap Smear

The Pap smear, “the most successful cancer screening tool in history,” revolutionized the diagnosis and treatment of uterine and cervical cancers and reduced the mortality rate for women with cervical cancer by 70%. However, this relatively simple procedure took decades of collaborative work to develop. Greek immigrant Dr. George Papanicolaou’s pioneering research relied on samples of vaginal fluid both produced and meticulously processed for analysis by his wife and assistant, Andromache (“Mary”) Papanicolau (25). Papanicolau first realized he could visually identify cancerous cells by chance, after an acquaintance with uterine cancer volunteered samples for further study. After his initial findings failed to impress, Papanicolaou shifted his research focus, not reviving attempts to disseminate his results until a full decade later (25). While Papanicolaou blamed himself for failing to adequately communicate the significance of his findings to “clinical men,” it should be noted that the venue for his first presentation (a national “Race Betterment Conference” where several eugenicists held court) made for a highly problematic reception context (26). Successful dissemination of the procedure eventually resulted from collaborative efforts with Herbert Traut—a pathologist at Cornell University who worked to optimize the technique and co-publish the findings in 1941—and with the gifted scientific illustrator Hashime Murayama (25, 26). A Japanese-American artist who in these years of war endured harassment, arrest and detainment for
being Japanese, Murayama's detailed and visually striking renderings made the process of cellular analysis easier and more attractive to clinicians, improving its viability as a diagnostic tool.

In Canada, Dr. Marion Hilliard developed a further simplified method for detecting early symptoms of cancer (particularly of the cervix). She established Canada's first Cancer Detection Clinic in 1948 and lobbied unsuccessfully for a decade (often facing indifference and dismissal) to have Women's College Hospital (where she was head of gynecology and obstetrics) accepted as a teaching hospital affiliated with the University of Toronto—a goal finally accomplished in 1956. As a result of her tireless efforts in and out of the hospital and lab, the period of 1948 to 1952 saw nearly 30,000 simplified Pap Tests processed at Women's College Hospital, saving many lives.

Technology and Materials Science

Apollo 13

The Apollo 13 mission of 1970 was well underway as three NASA astronauts set out to explore a new region of the Moon. Not long after its take-off, the mission was aborted because the Cryogenic Oxygen Subsystem failed during takeoff which led to a total loss of oxygen, water, and electrical power. These conditions were life threatening and NASA was forced to act fast. The spacecraft used the Sun to position itself on a trajectory back to Earth, leading to the safe arrival of all 3 crew members. This failure resulted in new knowledge and greater understanding that improved the structural and mechanical build of successive spacecraft.

Food Science

Aspartame

Aspartame was unintentionally discovered in 1965 by scientist James M. Schlatter while trying to synthesize a peptide sequence of gastrin. Aspartame powder residue splashed onto the outside of the flask Schlatter was working with and consequently onto his finger. Later, he licked his finger to catch the corner of a piece of paper and noticed a sweet taste. After retracing his steps in the lab, he realized this sweet sensation was from the aspartame he made (27).

Lack of Diversity

Pulse Oximeters

Some dangerous failings may result from lack of diversity and racial and gendered bias in the development of medical research and technology. Consider the failings of the widely-used pulse oximeter. These devices (which clip onto the finger and measure oxygen levels in the bloodstream by way of light absorption) have been found to produce less accurate measurements for patients with dark skin, a result of design which does not take into account the effects of skin pigmentation on light absorption. Such inaccurate measurements can mean that patients of color receive less supplemental oxygen than they actually need—a dangerous situation that highlights the urgent need to educate both patients and medical professionals about the failings of the pulse oximeter and to design new models that work reliably for patients of all skin tones. The failings of the pulse oximeter also demonstrate an urgent need for diversity in engineering and medical design as well as in clinical trials.

Aspirin

The developing understanding of the benefits—and potential risks—of low-dose daily Aspirin is another case demonstrating the need for diversity in clinical trials. The Women's Health Study—a ten-year study of healthy women over 45—was the first large clinical trial looking specifically at effects of aspirin on women. Overall, findings showed that low-dose daily aspirin did not reduce the risk of heart attacks, but it did increase the risk of bleeding (results consistent with the more recent ARRIVE and ASPREE trials). While some benefit was seen for women over the age of 65, Dr. Erin Michos, associate director of preventive cardiology for the Ciccarone Center for the Prevention of Heart Disease, warns that there is “good reason to be wary of Aspirin” for younger women and for most adults without a history of heart disease. Landmark earlier studies were focused largely on men: the 1989 Physicians’ Health Study of healthy men from 40–85 found 44% reduction in risk of heart attack for those who took a standard pill of aspirin every other day. Subsequent studies using smaller doses showed similar benefit. Shifting—and broadening—the pool of research subjects has changed clinical practice around this drug.

Career Trajectories

Scientists and Grant Funding

Failures—or perceived failures—can also influence career trajectories. A study conducted by Wang et al. (28) examined Robert K. Merton's Matthew effect, which suggests that more talented scientists have better opportunities and greater access to resources such as grants. This early success provides recognition that only makes them more successful as compared to unrecognized scientists that struggle for the same opportunities. Survivorship bias—the tendency to focus on those who are successful and disregard those who have failed—may contribute to the stigma attached to failure. Wang et al. countered this by suggesting that experiencing early failure can lead to greater success in the long term than experiencing initial success (28). Researchers examined the career trajectories of scientists whose grant applications were successful, and scientists whose applications were equally strong, but just missed the mark. While those who were initially rejected were more likely to give up, those who showed resilience and continued applying surpassed their competitors who received grants the first time (26). Failure can indeed be a character-building experience. However, opportunities to regroup and recover from failure are not evenly distributed; demonstrating resilience in the face of failure is not simply a matter of character, it is also a matter of resources (29).

The examples in this section illustrate struggle on the path to achievement, barriers to achievement, unrecognized achievement, or continued struggle despite achievement. Notably, these examples often show barriers to achievement or recognition resulting from systemic, not individual failures (often racism and sexism). They demonstrate that innovation and discovery can emerge along uneven paths strewn with setbacks, obstacles, and failures, both personal and systemic.

Dr. Irene Ayako Uchida

Dr. Irene Ayako Uchida introduced cytogenetics, the study of chromosomes and heredity, to Canada. Her career trajectory, while remarkable, was bumpy: early on, she
worked to advance the rights of Japanese Canadians alongside her university studies and, returning from a trip to Japan in 1941, was forcibly removed (along with her family and 22,000 other Japanese Canadians) to internment camps in British Columbia, where she opened a school for interned children and served as teacher and principal until 1944. Despite persistent anti-Japanese racism, Uchida continued her education in Canada after the war, working on the side as a seamstress, and graduating with a BA in English literature in 1946. Swayed from pursuing a master’s degree in social work, Uchida earned her PhD in zoology in 1951. Despite successfully developing a genetics lab in Winnipeg, Manitoba, and winning a Rockefeller Foundation grant to fund further study at the University of Wisconsin, Uchida (regarded as Japanese though she was born in Canada) was initially refused entry to the United States; she gained entry only when the university president intervened. A year later, Uchida became director of medical genetics at the Children’s Hospital in Winnipeg, where she went on to develop a clinical test for trisomy-18 (Edwards syndrome) and found Canada’s first cytogenetics program.

Mary W. Jackson

Mary W. Jackson’s path to a rewarding career at the Langley Research Center was similarly indirect. She graduated from Hampton Institute in 1942 with a dual degree in Math and Physical Sciences and taught math in Maryland for a year before returning home to Hampton to aid in war efforts. Before landing at Langley Memorial Aeronautical Laboratory’s segregated West Area Computing section in 1951, Jackson worked as a receptionist at the King Street USO Club, as a bookkeeper for Hampton Institute’s Health Department, raised a son, and served as army secretary at Fort Monroe. At Langley, after two years in computing, Jackson was offered a job with engineer Kazimierz Czarnecki, who eventually suggested she join a training program that would enable promotion from mathematician to engineer. Though she had to obtain special permission from the City of Hampton to join her white peers in the grad-level math and physics after-work courses managed by the University of Virginia, Mary completed the courses and, in 1958, became NASA’s first black female engineer. She enjoyed two productive decades of engineering in which she authored and co-authored over a dozen research reports. She enjoyed two productive decades of engineering in which she authored and co-authored over a dozen research reports. However, as the years progressed, her frustration at not being able to break into management roles mounted. In 1979, Jackson boldly moved out of engineering, taking a demotion and winning a Rockefeller Foundation grant to fund further studies at the University of Virginia, Uchida (regarded as Japanese though she was born in Canada) was initially refused entry to the United States; she gained entry only when the university president intervened. A year later, Uchida became director of medical genetics at the Children’s Hospital in Winnipeg, where she went on to develop a clinical test for trisomy-18 (Edwards syndrome) and found Canada’s first cytogenetics program.

It is thus not just the erasure of failed attempts on the unsteady path to accomplishment that we begin to highlight for students with this bank of examples, but also the erasure of contributions by marginalized figures and cultures from scientific “success stories” that have dominated Western histories to date. We hope students will continue to seek out, discuss and shine a light on such contributions, drawing on and furthering endeavors such as Scientist Spotlights.

NOTES ABOUT INCORPORATING LEARNING FROM FAILURE INTO SCIENCE TEACHING

In looking at the many examples of innovation and discovery that have come out of failures, missteps, and setbacks, it is critically important to recognize that power, privilege, and access to resources greatly influence one’s ability to bounce back from missteps and uncertainty (29). Starting from the understanding of privilege as an unmerited benefit received solely due to the class that one was born into or the possession of a socially desired characteristic (30), it is not surprising that the discoveries deemed most influential often do not represent the work of marginalized populations. Privilege makes it so that individuals belonging to dominant groups in society not only have more opportunities to try, fail, and try again, but their endeavors are often more celebrated within mainstream historical narratives (31). Systems of oppression tied to race, gender, class, ability, sexuality, and religious affiliation as well as many other forms of discrimination intersect to create barriers for marginalized populations while privileged individuals are given greater access to opportunities, such as education (32). Most of the scientists credited with historically-celebrated inventions are white men, privileged to have the opportunity to receive an education, make mistakes and have opportunities to try again (33). To put it plainly, privilege empowers some and silences others, which is important to acknowledge and incorporate into lessons on the potential of failure in the scientific process (31). This principle can also be applied to contemporary university settings where students who finance their own tuition may not have the luxury of retaking a course if they do poorly or have the time or resources to participate in research opportunities if they hold a job to pay their way through school. While some students come from families where their parents went to college or university and benefit from their experiences, support and resources, other students may be the first in their families to undertake post-secondary education and navigate this experience alone (17).

It is also important to note the roles that time pressures and research grants play in scientific discovery. Innovation is an ongoing process which takes time and resources that may not be available to everyone. In a contemporary university setting, for example, the need for grants to conduct research has become increasingly pressing due to budget constraints, with greater emphasis put on funding the “right” or “strategic” research areas and increasing demands to conduct research in a privatized, commercialized setting (34). This setting fosters heightened competition, less camaraderie and, as a by-product, a tendency to fixate negatively on failure as evidence of inferiority (34). Efforts to reframme failure as generative remain critically important in such settings.

In the classroom, textbook approaches to the scientific method can yield so-called “cookbook labs,” where testing a hypothesis occurs along a straight path and following specific steps yields predictable results (1, 3). “Cookbook labs” such as these, while effective at modelling hypothesis-testing, can miss out on modeling and fostering the evaluative and creative learning inherent to science. Such limitations have been broadly recognized (4, 6). While the realization of large-scale
pedagogical shifts takes time and resources, a gradual shift away from cookbook-style labs towards inquiry- and discovery-based courses in undergraduate biology instruction over the last three decades is observable (3, 4). Further attention to the role of failure in the scientific process can be effectively integrated into inquiry- and discovery-based teaching. Recent research shows that students in CURE (Course-based Undergraduate Research Experiences) and inquiry-based courses experience experimental failure and iteration as particularly “authentic” components of scientific research (3). Further efforts are needed to support the circulation of such generative understandings of failure in introductory science teaching. Our bank of examples is a simple teaching tool contributing to this effort. It is an easily adaptable and accessible resource demonstrating that innovation and discovery are dynamic, unpredictable processes: some of today's most popular science “success stories” were “fails” before they were successes.

CONCLUSION

In terms of the scientific process, reflecting on failure can invite further consideration of our materials, hypotheses, procedures, and findings and generate improvements in research and analysis as well as in experiment design and implementation. In more general terms, failure provides opportunities to reflect on our missteps and struggles and transform them (with adequate support) into productive experiences. Unfortunately, failure is so often stigmatized as a negative experience that it can incite fear, anxiety, dampened motivation for success, risk avoidance, and lower self-esteem (17). Failures need to be acknowledged, celebrated, and valued in diverse learning contexts. Models of failure need to be integrated and present in every level of education, from kindergarten to graduate school, because understanding and embracing failure, not just in a scientific or academic setting but in day-to-day life, is crucial to experiencing success. The bank of “fails” provided here is intended as a simple and pragmatic tool to introduce such models to science courses.

SCIENTIFIC TEACHING THEMES

Active Learning

This bank of examples is meant to stimulate active reflection, discussion, and creative application. Instructors are encouraged to apply and adapt these examples as they best see fit for diverse classroom use. Ideally, after initial guided or group reflection, students will continue to reflect on these examples when confronting their own failures, honing their procedural and metacognitive knowledge, and encouraging them to adapt their designs and strategize new ways forward. Furthermore, students can actively contribute to the expansion of scientific discovery narratives proposed here by conducting their own research and reporting or presenting on additional examples of scientific learning or innovation through failure. See section entitled Example Bank as Teaching Tool: Implementation for further discussion and Supporting Files S1 through S4 for adaptable assignment templates.

Assessment

This teaching tool is meant to inspire and facilitate further curriculum design. Suggested applications include: class discussion; written or oral responses to metacognition/reflection prompts; think-pair-share exercises; research and short presentations or reports on further examples of failure in scientific experimentation and discovery; science process log entries documenting student experiences through various stages of a given project/experiment. See section entitled Example Bank as Teaching Tool: Implementation for further discussion and Supporting Files S1 through S4 for adaptable assignment templates.

Inclusive Teaching

The examples discussed in this bank of science “fails” represent a variety of fields, figures, and products. We aimed for our examples to be accessible and easily recognizable for undergraduate students with diverse experiences and educational backgrounds. We also aimed for this bank of examples to be easily applicable and transferable to discussion/reflection contexts across a variety of courses.

We explicitly treat issues of power, privilege, and resources as they relate to teaching about failure in the section entitled Notes About Incorporating Learning From Failure Into Science Teaching. As noted there, “individuals belonging to dominant groups in society not only have more opportunities to try, fail, and try again, but their endeavors are often more celebrated within mainstream historical narratives” (16). We emphasize the importance of acknowledging barriers faced by minority groups with regard to education, training, research opportunities, access to resources, and structural supports, and we stress that teaching about failure and resilience must take these barriers into account. Instructors and students are encouraged to actively reflect on questions of representation when consulting this bank of examples and to contribute additional examples from marginalized voices and histories.

SUPPORTING MATERIALS

- S1. Science “Fails” – Excavating little-known failures (research activity)
- S2. Science “Fails” – Reflecting on failure (writing/discussion prompts)

ACKNOWLEDGMENTS

As crafted by the Circle of Elders of UTM, ‘We wish to acknowledge this land on which the University of Toronto operates. For thousands of years, it has been the traditional land of the Huron-Wendat, the Seneca, and the Mississaugas of the Credit. Today, this meeting place is still the home to many Indigenous people from across Turtle Island and we are grateful to have the opportunity to work on this land’.
Table 1. A bank of examples for learning from failure in science.

<table>
<thead>
<tr>
<th>Example</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Pharmaceuticals</strong></td>
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<td>Viagra</td>
<td>In 1996, Pfizer created this pill as a heart medication. Although it failed to be effective for this purpose, it became the first widespread oral treatment for erectile dysfunction. Patented in 1996 and approved by the FDA just two years later, it is worth considering what factors may have contributed to this drug’s expedited approval.</td>
<td><a href="https://www.history.com/today-in-history/fda-approves-viagra">https://www.history.com/today-in-history/fda-approves-viagra</a></td>
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<td>LSD</td>
<td>Albert Hoffman initially intended this drug to treat fungal infections. However, in 1943, Hoffman experienced intense hallucinations after accidentally exposing himself to a small amount of the drug. LSD ended up a hallucinogen whose uses in psychiatric therapy and beyond are still being investigated.</td>
<td><a href="https://www.scientificamerican.com/article/inventor-of-lsd-embarks-on-final-trip/">https://www.scientificamerican.com/article/inventor-of-lsd-embarks-on-final-trip/</a></td>
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<td>Penicillin</td>
<td>In 1928, Alexander Fleming first noted irregular bacterial activity in an agar plate but failed to isolate the compound that created it. In 1939, another team of scientists successfully accomplished Fleming’s work, giving rise to the first antibiotic, Penicillin.</td>
<td>Gaynes, R. (2017). The Discovery of Penicillin—New Insights After More Than 75 Years of Clinical Use. Emerging Infectious Diseases, 23(5), 849–853. <a href="https://doi.org/10.3201/eid2305.161556">https://doi.org/10.3201/eid2305.161556</a></td>
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<td><strong>Medicine</strong></td>
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<td>Anesthesia</td>
<td>In 1844, Horace Wells put himself under nitrous oxide and underwent a dental extraction without feeling any pain, but it took several failed sedations to perfect the process on patients.</td>
<td>Smith, C. A. H. (1927). The Discovery of Anesthesia. The Scientific Monthly, 24(1), 64–70. <a href="https://www.jstor.org/stable/7799">https://www.jstor.org/stable/7799</a></td>
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<td>Coronary Angiogram</td>
<td>In 1958, during a routine heart procedure, Dr. Mason Sones accidentally injected dye into a coronary artery due to a slipped catheter. Surprisingly, the heart continued to pump, giving rise to this diagnostic procedure, and enabling more advanced surgical procedures.</td>
<td>Cheng, T.O. (2003). First Selective Coronary Arteriogram. American Heart Association Journal, 107(5). <a href="https://www.ahajournals.org/doi/full/10.1161/01.CIR.0000053958.38681.81">https://www.ahajournals.org/doi/full/10.1161/01.CIR.0000053958.38681.81</a></td>
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<td>X-Ray</td>
<td>This revolutionary discovery was made in 1895 when physicist Wilhelm Roentgen accidentally put his hand under a cathode and found the rays easily penetrated the skin to show the underlying bones.</td>
<td><a href="https://columbiasurgery.org/news/2015/09/17/history-medicine-dr-roentgen-s-accidental-x-rays">https://columbiasurgery.org/news/2015/09/17/history-medicine-dr-roentgen-s-accidental-x-rays</a></td>
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<td>Pacemaker</td>
<td>The first implantable pacemaker was developed in 1960 by Wilson Greatbatch after he unintentionally put a stronger than intended transistor into a heart monitor.</td>
<td><a href="https://www.intellectualventures.com/buzz/insights/the-heartbeat-of-invention-how-pacemaker-creator-wilson-greatbatch-saved-co/">https://www.intellectualventures.com/buzz/insights/the-heartbeat-of-invention-how-pacemaker-creator-wilson-greatbatch-saved-co/</a></td>
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<td>Pap Smear</td>
<td>This lifesaving procedure took decades of collaborative work. Dr. George Papanicolaou discovered he could track cellular changes in vaginal fluid first in his research on guinea pigs, then using samples produced over the course of twenty-one years by his wife and assistant, Andromache Papanicolaou. However, his findings were not successfully disseminated until 1941, a decade after their discovery. Critically important to their successful dissemination were the contributions of scientific illustrator Hashime Murayama. A further simplified version of the Pap test was developed by Dr. Marion Hilliard, head of gynecology and obstetrics at Women’s College Hospital in Toronto. Hilliard opened Canada’s first Cancer Detection clinic in 1948, processing over 30,000 simplified PAP tests in a five-year period and saving many lives. Despite these accomplishments, it took Hilliard a decade of persistent lobbying to gain Women’s College hospital affiliation with the University of Toronto in 1956.</td>
<td><a href="https://www.sciencehistory.org/distillations/hashime-murayama-and-the-art-of-saving-lives">https://www.sciencehistory.org/distillations/hashime-murayama-and-the-art-of-saving-lives</a></td>
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<td><strong>Public Health</strong></td>
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<td>COVID</td>
<td>The World Health Organization (WHO) gave advice to not wear masks at the start of the COVID-19 pandemic because they believed there to be no evidence that healthy individuals would be more protected from the virus by wearing them. They later recanted this statement, instead urging everyone to wear masks to curb infections, and further suggesting that tighter fitting masks such as N95s would be more effective.</td>
<td><a href="https://www.scientificamerican.com/article/scientists-failed-to-use-common-sense-early-in-the-pandemic/">https://www.scientificamerican.com/article/scientists-failed-to-use-common-sense-early-in-the-pandemic/</a></td>
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<td><strong>Ecology</strong></td>
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<td>#FieldWorkFails</td>
<td>A popular Twitter hashtag for ecologists sharing daily setbacks in the field. These lighthearted “fails” go a long way towards generating community and normalizing failure as an inevitable part of the research process.</td>
<td><a href="https://twitter.com/a_dorrestein/status/123213238985878738">https://twitter.com/a_dorrestein/status/123213238985878738</a></td>
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<td><strong>Technology and Material Science</strong></td>
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<td>Apollo 13</td>
<td>This 1970 mission to the moon is known for how quickly after departure it failed, as the Apollo 13 spacecraft experienced a total loss of oxygen, water, and electrical power. A quick and adept response saved the crew. This failure ultimately led to significant advancements in successive spacecraft composition.</td>
<td><a href="https://www.nasa.gov/centers/marshall/history/apollo/apollo13/index.html">https://www.nasa.gov/centers/marshall/history/apollo/apollo13/index.html</a></td>
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<td>Vulcanization</td>
<td>This procedure was discovered in 1839 when rubber and sulfur were accidentally left on a stove for too long and produced a rubber with greater resilience and flexibility.</td>
<td><a href="https://trp.co.uk/the-best-accidental-discoveries-in-polymer-chemistry/">https://trp.co.uk/the-best-accidental-discoveries-in-polymer-chemistry/</a></td>
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<td>Safety Glass</td>
<td>This accidental discovery came about in 1903 when a glass flask containing cellulose nitrate was dropped but did not shatter.</td>
<td><a href="https://www.mcgill.ca/oss/article/history-you-asked/what-safety-glass">https://www.mcgill.ca/oss/article/history-you-asked/what-safety-glass</a></td>
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<td>Microwave Oven</td>
<td>Percy LeBaron Spencer developed this household appliance in 1945 after using a magnetron which gave off magnetic radiation so strong it accidentally melted a chocolate bar in his pocket.</td>
<td><a href="https://www.popularmechanics.com/technology/gadgets/a19567/how-the-microwave-was-invented-by-accident/">https://www.popularmechanics.com/technology/gadgets/a19567/how-the-microwave-was-invented-by-accident/</a></td>
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<td>Plastic</td>
<td>This well-known accident was produced in 1907 when Leo Baekeland attempted to create a more economical shellac by combining formaldehyde and phenol.</td>
<td><a href="https://trp.co.uk/the-best-accidental-discoveries-in-polymer-chemistry/">https://trp.co.uk/the-best-accidental-discoveries-in-polymer-chemistry/</a></td>
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<td>Superglue</td>
<td>In 1942, Harry Coover was using cyanoacrylate monomers to create plastic scopes on firearms, and everything that touched the monomers stuck to them. The scopes failed, but Superglue stuck!</td>
<td>Coover HW. (2000). IRI Achievement Award Address: Discovery of Superglue Shows Power of Pursuing the Unexplained, Research-Technology Management, 43(5), 36–39. <a href="https://doi.org/10.1080/08956308.2000.11671379">https://doi.org/10.1080/08956308.2000.11671379</a></td>
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<td><strong>Toys and Consumer Products</strong></td>
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<td>Play Doh</td>
<td>This popular children’s toy was initially produced by a soap company in 1912 to be a cleaning product; it failed. It was later repurposed into the malleable non-toxic clay known today as Play Doh.</td>
<td><a href="https://www.smithsonianmag.com/innovation/accidental-invention-play-doh-180973527/">https://www.smithsonianmag.com/innovation/accidental-invention-play-doh-180973527/</a></td>
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<td>Slinky</td>
<td>Richard James made this accidental discovery in 1943 while attempting to create a more durable spring. When it dropped on the floor, it continuously rolled over itself instead of bouncing, giving rise to this toy.</td>
<td><a href="https://www.smithsonianmag.com/innovation/accidental-invention-slinky-180973016/">https://www.smithsonianmag.com/innovation/accidental-invention-slinky-180973016/</a></td>
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<td>Silly Putty</td>
<td>The result of a failed attempt to create a more economical version of synthetic rubber.</td>
<td><a href="https://kidsdiscover.com/quick-reads/weird-science-the-accidental-invention-of-silly-putty/">https://kidsdiscover.com/quick-reads/weird-science-the-accidental-invention-of-silly-putty/</a></td>
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<td><strong>Food Science</strong></td>
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<td>Artificial Sweeteners</td>
<td>This unintentional discovery was made by James M. Schlatter in 1965 during an experiment in which aspartame powder splashed out of the flask and onto his hand. Later, licking his finger to turn a page, Schlatter noticed the sweet taste and traced it back to the splash in the lab.</td>
<td>Stegink LD, Filer Jr LJ. (1984). Aspartame: Physiology and Biochemistry. Taylor &amp; Francis Group.</td>
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<td>Chocolate Chip Cookies</td>
<td>Created in 1930 by Ruth Wakefield when she substituted a Nestle chocolate bar instead of normal baker’s chocolate to make cookies. The chocolate did not melt as intended, instead remaining in small chunks within the cookies, which gave rise to chocolate chip cookies.</td>
<td><a href="https://www.cnn.com/2019/08/04/us/chocolate-chip-cookie-history-trnd/index.html">https://www.cnn.com/2019/08/04/us/chocolate-chip-cookie-history-trnd/index.html</a></td>
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<td><strong>Lack of Diversity</strong></td>
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<td>Pulse Oximeter</td>
<td>This common medical device clips onto the finger and uses light absorption to detect oxygen levels in the blood. However, recent studies reveal pulse oximeters produce less accurate measurements for patients with dark skin, as pigmentation affects light absorption. Failing to account for differences in skin pigmentation in the design of this technology puts patients of color at risk. This case highlights the urgent need for diversity in clinical trials and in the development of medical technology.</td>
<td><a href="https://www.nejm.org/doi/full/10.1056/NEJMc2029240">https://www.nejm.org/doi/full/10.1056/NEJMc2029240</a> <a href="https://www.npr.org/sections/health-shots/2022/07/11/110370384/when-it-comes-to-dark-skin-pulse-oximeters-fall-short">https://www.npr.org/sections/health-shots/2022/07/11/110370384/when-it-comes-to-dark-skin-pulse-oximeters-fall-short</a></td>
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<td>Aspirin</td>
<td>Landmark studies of this common over-the-counter medication showed that daily low doses reduced the risk of heart attacks; however, they were focused largely on men, failing to adequately consider women. Subsequent studies targeting women indicated minimal benefits and increased risk of bleeding, leading health care professionals to approach it with caution.</td>
<td><a href="https://www.hopkinsmedicine.org/health/wellness-and-prevention/is-taking-aspirin-good-for-your-heart">https://www.hopkinsmedicine.org/health/wellness-and-prevention/is-taking-aspirin-good-for-your-heart</a></td>
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<td>Bird Song</td>
<td>It was long thought that only male birds sang during mating season. A new wave of research led by female scientists has overturned this finding, showing that both males and females of many species sing, especially in the tropics.</td>
<td><a href="https://theconversation.com/women-have-disrupted-research-on-bird-song-and-their-findings-show-how-diversity-can-improve-all-fields-of-science-142874">https://theconversation.com/women-have-disrupted-research-on-bird-song-and-their-findings-show-how-diversity-can-improve-all-fields-of-science-142874</a></td>
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<td><strong>Career Trajectories</strong></td>
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<td>Scientists and Grant Funding</td>
<td>Wang et al. conducted a study in 2019 that challenged the Matthew effect by examining the role of resiliency in receiving grants, finding that scientists who experienced early failure were more successful long-term than their counterparts who achieved initial success.</td>
<td>Wang, Y., Jones, B.F., &amp; Wang, D. Early-career setback and future career impact. Nat Commun 10, 4331 (2019). <a href="https://doi.org/10.1038/s41467-019-12189-3">https://doi.org/10.1038/s41467-019-12189-3</a></td>
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<td>Dr. Irene Ayako Uchida</td>
<td>Introduced cytogenetics, the study of chromosomes and heredity, to Canada. Uchida endured forcible removal to an internment camp in WW2 and, as a Japanese-Canadian, was refused entry into the United States despite winning a prestigious grant to study there. Eventually, she became director of medical genetics at the Children’s Hospital in Winnipeg, where she developed a clinical test for trisomy-18 (Edwards syndrome) and founded Canada’s first cytogenetics program.</td>
<td><a href="https://womeninSTEM.ingeniumcanada.org/portfolio-item/irene-2-ayako-uchida/">https://womeninSTEM.ingeniumcanada.org/portfolio-item/irene-2-ayako-uchida/</a> <a href="https://www.thecanadianencyclopedia.ca/en/article/irene-uchida">https://www.thecanadianencyclopedia.ca/en/article/irene-uchida</a></td>
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<td>Dorothy Vaughan</td>
<td>Vaughan, a mathematician, became the first African American manager at the segregated “West Area Computing Unit” at NASA (then NACA), processing aeronautical research data, hiring and advocating for female scientists, and adeptly managing the unit for more than a decade. After segregated facilities were abolished, Vaughan sought but failed to receive another management position, facing enduring systemic barriers.</td>
<td><a href="https://www.nasa.gov/people/dorothy-vaughan/">https://www.nasa.gov/people/dorothy-vaughan/</a></td>
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<td>Katherine Johnson</td>
<td>Johnson earned one of three spots for African American graduate students at West Virginia University and landed at NASA's Langley Memorial Aeronautical Laboratory, where she collaboratively developed aerospace technology and was sought out to confirm trajectory equations for the famous 1962 “Friendship Mission.” Turned down for the job she initially applied to at NASA, Johnson ended up devoting 33 years to her career there and was awarded the Presidential Medal of Freedom, America’s highest civilian honor, in 2015.</td>
<td><a href="https://www.nasa.gov/content/katherine-johnson-biography">https://www.nasa.gov/content/katherine-johnson-biography</a></td>
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<td>Mary W. Jackson</td>
<td>A mathematician and scientist hired to the West Area Computing Section in 1951, Jackson overcame racist policies to join a graduate-level training program in engineering and physics, going on to become NASA’s first black female engineer in 1958. After two productive decades of engineering, Jackson still could not break into management; she opted to move out of engineering and into a lesser management role so that she could impact the hiring and promotion of NASA's next generation of female engineers, mathematicians, and scientists.</td>
<td><a href="https://www.nasa.gov/content/mary-w-jackson-biography">https://www.nasa.gov/content/mary-w-jackson-biography</a></td>
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REFERENCES


