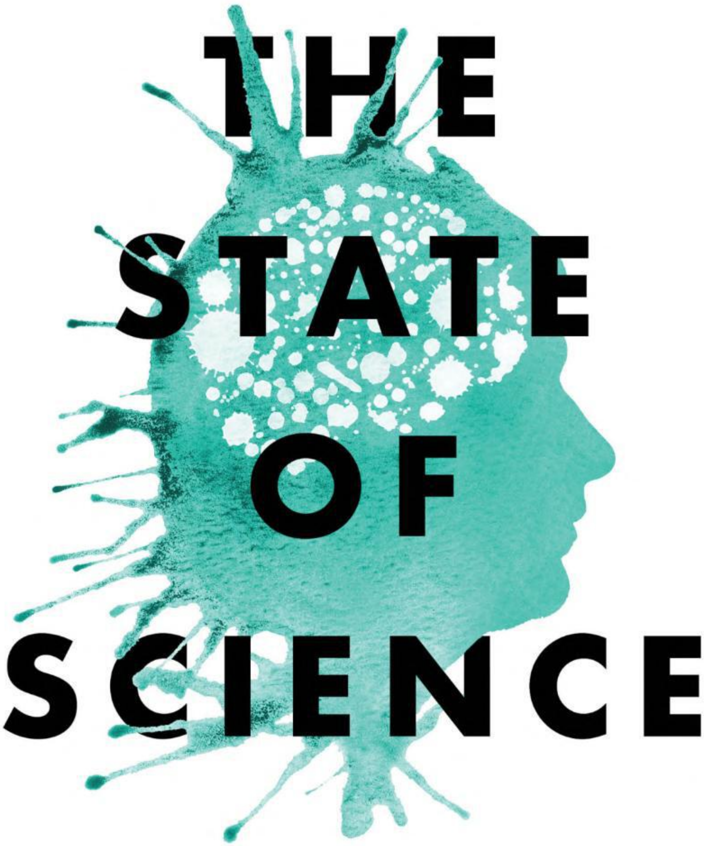
"The author starts a provocative conversation we should all engage in!"
–**Bill McKibben**, author of *Falter: Has the Human Game Begun to Play Itself Out?*



THE STATE OF SCIENCE

WHAT THE FUTURE HOLDS AND THE SCIENTISTS MAKING IT HAPPEN

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Chapter One

The Big Picture

> State of the Union address: A yearly speech given by the U.S. president to Congress and the people to tell them about important things that are affecting the country.—*Merriam-Webster Collegiate Dictionary*

Every year the leaders of countries, corporations, and universities present their views of the current conditions of their respective institutions. Given the function of these statements, they are often a top-down view with a biased perspective designed to make their current administrations look good.

There is no such annual report on science. This book is a report on the state of science from a practicing scientist, a view from the trenches. It is not meant to be a top-down view, nor is it meant to make anyone look good or bad.

I have written this book because science is not the same as it was in the first 20–25 years of my career. The way science is done, funded, and disseminated is evolving. At the same time, science is being politicized, and the public's trust in science is being undermined. Yet science remains the engine of our economy and is responsible for our improved well-being. And perhaps now more than ever before, it is at the cusp of altering the most fundamental aspects of our daily lives.

WHAT IS SCIENCE?

This is probably a good point in the book to define "science" and "scientist." The *Merriam-Webster Collegiate Dictionary* defines science as "the state of knowing" as distinguished from ignorance or misunderstanding." However, I much prefer Karl Popper's perspective, according to which a hypothesis has to be inherently disprovable for it to be a scientific theory. It is difficult to imagine an experiment that can disprove the existence of beauty and God. Hence the study of beauty and God is not science. Albert Einstein proposed the existence of gravitational waves. Their existence was provable, although the equipment to do so didn't exist when Einstein came up with his general theory of relativity, and it took close to 100 years to actually prove that they exist (chapter 6). It was disprovable and therefore a scientific theory. Scientists use experiments to test their theories and hypotheses. No map shows the way to prove or disprove a theory; the scientific process is not linear. Neil Gershenfeld, director of MIT's Center for Bits and Atoms, writes that "to find something that's not already on the map, you need to leave the road and wander in the woods besides it." He feels that nonscientists do not recognize that "science appears to be goal-directed only after the fact. While it's unfolding, it is more like a chaotic dance of improvisation, than a victory march."[1] It is also important to realize that uncertainty is an inherent and unremovable component of scientific experimentation. It is not a weakness; it is a strength. Critics of science often disparage scientific results on the basis of included uncertainties. This is a mistake born from a lack of understanding.

Before 1833, people who conducted experiments—who mixed, observed, and synthesized chemicals—were called natural philosophers. Newton, Galen, Galileo, and Mendel were all natural philosophers. In 1833 William Whewell, a professor at Cambridge University, coined the term "scientist" to highlight the fact that these were empirical folks and not philosophers of ideas. Like an artist works with art, a scientist works with science. As an analogy of "artist," the word "scientist" was infused by Whewell with creativity, intuition, and professionalism.

There is a commonly told tale that Whewell derived and popularized the term "scientist" because he needed an alternative to the commonly used phrase "man of science" to describe Mary Somerville in a positive review he was writing about her.[2] If true this would be a great story, and Mary Somerville was worthy of the honor. Her book *On the Connexion of the Physical Sciences* was instrumental in making modern physics into a discipline and was frequently revised and republished, with nine separate editions. In 1879, the first women's college at Oxford University was named in her honor. A main-belt asteroid (5771 Somerville) and a lunar crater in the eastern part of the moon are also named after her, and she graces all Scottish ten-pound notes printed from October 2018 onward. However, according to James Secord, professor of philosophy of science at the University of Cambridge, "Nowhere did Whewell or anyone else in her lifetime ever call Somerville a scientist, nor is it a word, so far as we know, that she ever used herself. By our current understanding of the term, Somerville can certainly be called a scientist, but for her contemporaries she belonged to a higher and more profound category entirely."[3]

No matter whether Mary Somerville was the woman for whom the word "scientist" was made, we can think of scientists as empiricists who use their creativity to prove or disprove theories. Of course scientists are human, as they can discover gloriously complex theories while also misinterpreting and presenting data in wondrously imperfect ways that lead to fantastic new models that are wrong and subsequently disproven. That is the way scientists perform science.

Before going on a trip through the scientific world and trying to judge its impact on our lives, as well as its reputation and health, it is a good idea to take a few steps back and look at the big picture. Because when we talk about science, it is impossible to ignore the political, environmental, economic, and global surroundings. We need to know how science has gotten us here and what challenges it faces in today's world.

SCIENCE AND THE ANTHROPOCENE

Since the arrival of the first *Homo sapiens* 40,000 years ago, a total of 108 billion humans have lived on Earth. A 15th of all these people are alive and kicking right now. Science and technology are the reason the numbers have undergone such robust growth.

Thanks to the development of weapons, protective houses, medicine, fertilizer, and so forth, humans have moved from being an occasional snack for predators to being at the top of the food chain. We have overcome constraints imposed by nature and evolution. There are no predators, other than ourselves, to limit our growth. Humans have become, in the worst sense of the word, the dictators of nature. Thanks to science, we can impose our will on nature and determine our own destinies. We are not doing a great job. Currently we are losing species 1,000 times faster than the natural rate of extinction. Humans represent just 0.01 percent of all living things by mass, yet during our time on Earth we have caused the loss of 83 percent of all wild mammals and half of all plants.[4]

Natural selection has been around for four billion years, since life on Earth began. But humans as a species are no longer governed by it. Not only are we in charge of our own evolution, but we have also changed how nature evolves. Ever since the continents broke apart, delicate ecosystems have been isolated by mountain ranges and oceans. Increased human movement has made the borders between ecosystems more porous. We have both inadvertently and purposefully introduced new species into ecosystems they could never have visited without hitching a ride on our cars, ships, and planes. In some sense, we have created a whole new global pseudo-ecosystem.[5] At the same time, thanks to modern science (CRISPR, gene drives, etc.; chapter 9) we have the ability to control the evolution of other species.

In 2000 Paul Crutzen, an atmospheric chemist and Nobel laureate, started popularizing the concept of the Anthropocene, a new geological age, during which human activity has been the dominant influence on climate and the environment. The International Commission on Stratigraphy, which is in charge of approving and naming subdivisions of geological time, hasn't yet officially approved the use of "Anthropocene" but is working on it. In an important first step, a preliminary Anthropocene working group supported the proposal and suggested the epoch start in the mid-20th century, in part because radioactive debris from the first atomic bomb is a distinct part of the geological record. Artificial radionuclides are just one of many traces we will leave as signatures in the strata of time. Traces of plastics, nitrogen-rich fertilizers, and fossils of domesticated animals and livestock species are just some of the many remnants we will leave behind in the anthropogenic layers of rock.

The International Commission on Stratigraphy will most likely vote on introducing the label for the new epoch in 2021.[6] For now, we are still officially in the Holocene era. Nevertheless, there can be little doubt that we are in an age in which humankind, through science and technology, possesses unprecedented control over its surroundings and nature.

Science, Economy, and Equity

Science and its resultant technologies are also responsible for the well-being of our economies. Our financial systems rely on growth. To be successful in today's global market, the economies of our countries are expected to grow at increasing rates. Games such as The Settlers of Catan, Civilization, Risk, Monopoly, and Minecraft, in which one has to expand one's possessions to win the game, are microcosms of this need. There isn't much room today to grow our agriculture or industries, and fortunately the days of colonization are over, so finding new science-based technologies is one of the few ways we can increase our economies. This places pressure on scientists to produce, which can result in corners being cut and science moving too fast for the global community to establish ethical and safe boundaries.

Scientific discoveries have not only enabled the expansion of the human population but are also the key to expanding economies in the postindustrial world. To keep the financial systems growing, such findings need to come faster and faster. At the same time, scientific discoveries will have to curtail the environmental and ecological degradation associated with growth. These expectations are unrealistic and a sign of a broken system; science cannot deliver all this. Expecting science to rescue us from the consequences of our overconsumption is just as dangerous as failing to acknowledge its great potential. In *Falter: Has the Human Game Begun to Play Itself Out?*, Bill McKibben argues that we have to move from a growth economy to a mature economy.[7] To illustrate his thinking, he uses a human analogy: as teens we are expected to grow and would be taken to the doctor if we didn't; however, as mature adults we have reached stasis, and our families and doctors would be very concerned if we continued to get taller. McKibben argues, and I agree, that our economies are now mature.

At best science may be a bandage on an unsustainable, growth-based economy, but it won't be the cure. Our economies and societies are complex ecosystems constrained by thermodynamics, and from thermodynamics we know that all this growth requires energy and generates waste (entropy). According to Philip Ball, former *Nature* editor, "creating a true science of sustainability is arguably the most important objective for the coming century; without it, not an awful lot else matters. There is nothing inevitable about our presence in the universe."[8]

Throughout the 20th century, children enjoyed better lives than their parents. However, this pattern cannot continue forever; something has to give: the economic system built on growth, the environment, our energy consumption, and/or our eating habits. There is no denying that an increase in scientific knowledge will increase the quality and length of our lives, but it will also bring increasing environmental and ethical problems. It will widen the gap between the haves and have-nots, both within the United States and between nation-states. Developments in science won't just improve transportation (cars, trains), communication (phones, internet), and consumption (fertilizers), as they did in previous generations; instead new advances have the potential to improve our bodies (CRISPR; chapter 9) and minds (optogenetics; chapter 8).

In *Homo Deus: A Brief History of Tomorrow*, Yuval Harari argues that existing inequities will be compounded by the fact that in the past, medicine's main purpose was to heal the sick, whereas in the future medicine will increasingly be designed to enhance the healthy. Treating the sick is an egalitarian process, while upgrading the healthy will be a luxury available only to the elite. Medicine will increase existing inequities by giving an edge to the rich. "People want superior memories, above-average intelligence and first-class sexual abilities. If some form of upgrade becomes so cheap and common that everyone enjoys it, it will simply be considered the new baseline, which the next generation of treatments will strive to surpass."[9] For the first time, the rich will have not only significant material benefits but also genetic improvements. As in the past, they will have better lives than the poor, but thanks to new techniques such as CRISPR, they may actually *be* better, too. In the extreme case, this could ultimately lead to a new species: *Homo superior*. Today the richest 100 people have more assets than the poorest 4 billion. In the future this financial inequality may lead to biological inequalities.[10]

ETHICAL AND SAFETY CHALLENGES OF SCIENTIFIC GROWTH

Authors and thinkers, including Ray Kurzweil and Bruno Giussani, suggest that science and technology are growing exponentially, while the structures of our society (government, education, economy, etc.) are designed for predictable linear increases, which are dysfunctional in today's exponential growth.[11] This is why our nation-state system can't deal with the challenges of modern science. The challenges presented by modern science (climate change, CRISPR, gene drives, and artificial intelligence) are much larger than those brought about by the Industrial Revolution (steam engines and electricity). Even if we find ways of globally regulating science, there will always be a country marketing itself as a place to do research that is banned elsewhere. And it just takes one country pursuing a high-risk, high-profit path for all the other countries to follow. In fact, the nation-state/growth economy that exists today requires that countries follow such paths to avoid falling behind.

Many governments, including that of the United States, control research by intentionally not funding certain areas that are either dangerous and unethical or difficult to regulate. This technique doesn't work when foundations or start-up companies fund the work. It also fails when the techniques and materials being used are inexpensive, as is the case with CRISPR (chapter 9), and government funding isn't needed (The Amateur Scientists; chapter 3). In the absence of clearer guidelines or regulations, scientists have to rely on themselves, on their own scientific norms. This doesn't work too well in modern science because of the intensely competitive nature of academia, in which "the drivers are about getting grants and publications, and not necessarily about being responsible citizens," notes Filippa Lentzos of Kings College London, who specializes in biological threats.[12] High-profile results matter. In addition, to prevent their competitors from knowing what they are doing and prevent being scooped, scientists keep their experiments under wraps until they are ready to publish, at which point the cat is let out of the bag, and it is too late to think about the ethical impact of the work or to try to stop the research.

Dual-use research, which could be used for either good and ill, presents its own challenges to the safe and ethical regulation of global scientific research. Occasionally scientists work their way to an invisible dual-use research line and cross it. In response, surprised, shocked, and scandalized scientists have urgent meetings to discuss the moral and safety implications. Scientists often proudly point to the 1975 Asilomar conference on recombinant DNA as a model response for dealing with science that has reached new and challenging boundaries in ethics and safety. They perceive the conference as a successful self-regulation in the public's interest. Senator Ted Kennedy and other politicians of the time saw it differently; they considered the scientists a group of unelected experts making public policy without public input. Scientists need broader input from the general public and ethicists, but they are hamstrung by the goals and modus operandi of the expert collaborators they need. Philosophers and ethicists take a contemplative, long-term perspective, while engineers are eager to take results from the laboratory to the market, and investors are always in a hurry and looking for short-term financial gains. Consequently, we have been very good at commercializing scientific discoveries but less proficient at predicting their consequences and proposing the appropriate guidelines (e.g., DDT, fracking, nuclear chemistry). The increasing speed at which scientific breakthroughs are being made will also make it harder and harder to predict and regulate them in the future.

Scientists, despite their desire to have inputs into policy related to their community's discoveries, are not trained to anticipate the consequences of their research, and their solutions are often ineffective, as evidenced by the frequency of such "transgressions' and mini "Asilomars." For example, in 2002 scientists from the State University of New York, Stony Brook synthesized a polio virus from scratch; in 2005 researchers from the Centers for Disease Control and Prevention (CDC) reconstructed a particularly virulent form of the 1918 flu virus; in 2012 two teams mutated the bird flu virus to make it more virulent in mammals; in 2017 a group at the University of Alberta resurrected a horsepox virus, a close cousin of the smallpox virus; and in 2018 CRISPR was used for the first time to create genetically modified human babies. Each of these experiments crossed a line that may have unforeseen consequences, and each led to an emergency conference. Each case leads us closer to the point at which one small accident or well-placed malicious scientist can affect a large portion of the human population or even accidentally wipe out an entire species. In an interview with the *Atlantic*'s Ed Yong, Kevin Esvelt, a CRISPR/gene drive expert at MIT, succinctly summarizes the problem: "Science is built to ascend the tree of knowledge and taste its fruit, and the mentality of most scientists is that knowledge is always good. I just don't believe that that's true. There are some things that we are better off not knowing."[13] On the other hand, we have to remember that some research, such as in vitro fertilization, was once seen as a transgression of scientific norms but is now scientifically and socially acceptable.

CHALLENGES TO SCIENCE

President Donald Trump is not a strong supporter of science, the scientific method, or facts. In his tweets he promotes conspiracy theories and implores Americans to distrust conventional sources of information and traditional institutions. In his first 5,000 tweets as president, the words "science" and "technology" were never used. It took two years before he appointed a science adviser. Deregulation has been a priority of the Trump administration, and by July 2019 it had rolled back more than 80 environmental rules and regulations.[14] It has weakened the Environmental Protection Agency (EPA), cutting staff and budgets and undercutting the agency's ability to use science in its policy making, resulting in steep drops in civil and criminal enforcement of violations of laws such as the Clean Air and Clean Water Acts.[15] According to the EPA, the number of "unhealthy-air days" has increased by 14 percent under this administration, and ozone, nitrous oxide, and particulate matter are more common than in 2016.[16] One of the most telling facts is that both the EPA and CDC have been prohibited from using the phrase "evidence-based" in their publications and press releases. So far, thanks to congressional intervention, the budgets of the National Science Foundation (NSF) and the National Institutes of Health (NIH) have survived, despite three requests by the Trump administration to reduce their size and their budgets.

Ironically, although he has claimed that climate change is "bullshit," "pseudoscience," and "a total hoax," President Trump's representatives have applied for permission to erect a sea wall to protect one of his golf courses in Ireland from rising seas due to "global warming and its effects."[17] (Although this book could easily have been a rant about the Trump administration and its attitudes toward science, I have tried to show some restraint and have limited my comments about the president to the first and last chapters.)

President Trump's opinions weren't formed in a vacuum. He was elected by the American public and still has support. This reflects the increasing public mistrust and resentment of experts. This rejection of scientific thinking and evidence comes from many directions: postmodernist academics and journalists, Christian fundamentalists, liberal new-age purists, and industrial interests and lobbyists. A 2015 Pew Research Center poll showed that "a sizable opinion gap exists between the general public and scientists on a range of science and technology topics," and that "compared with five years ago, both citizens and scientists are less upbeat about the scientific enterprise."[18] In *The Workshop and the World: What Ten Thinkers Can Teach Us about Science and Authority*, Robert Crease writes, "Some people, including many scientists, seem resigned to this. They hope that scientific authority is a natural thing that will shortly reassert itself, like a sturdy self-righting boat knocked over by a rogue wave." He argues that this is not going to happen because the scientific process described earlier in this chapter is inherently vulnerable to attacks. "The fact that it is done by collectives, is abstract and always open to revision" provides fuel for science deniers. To change their minds, we can't just explain the science over and over again; we have to learn how they think and why they are rejecting science.[19]

Many scientists and science supporters have rallied against the antiscience bias, climate denial, flat-earthers, and anti-vaxxers. For example, the first March for Science was held on April 22, 2017; many scientists ran for office in the 2018 elections; and there have been many initiatives to improve scientific outreach.

FAKE NEWS AND SCIENCE

In an essay in the *New York Times Magazine* in 2016, Jonathan Mahler writes that people "are abandoning traditional sources of information, from the government to the institutional media, in favor of a D.I.Y. approach to fact-finding" and are "forming a radical new relationship between citizen and truth."[20] In addition, over the last decade science has been revolutionized by the development of new techniques that allow scientists to conduct experiments bordering on the fantastic, increasing the difficulty for the layperson to distinguish between fact, hyperbole, quackery, and fake news (chapters 9 and 11).

Fake news and pseudoscience occasionally get the better of scientific facts in Congress, too. Congress also struggles with the fact that the amount of scientific knowledge in the world is not only increasing but growing faster and faster. At the same time, science is becoming more complex thanks to a spike in interdisciplinary work between previously disparate fields, such as optics, electrical engineering, and neuroscience joining forces in optogenetics (chapter 8). This has resulted in an ever-widening gap between the scientific knowledge of legislators, religious leaders, and voters and the total available science knowledge.

In Congress, which is ultimately in charge of regulating and defining the direction of science research in the United States, these difficulties are amplified by the fact that there are only 3 scientists and 8 engineers in the 115th Congress of the United States, while there are 218 lawyers. The 7 radio talk show hosts, 26 farmers, and 8 ordained ministers all outnumber the scientists as well. Similarly low numbers are found in Australia and Canada, where scientists make up just 4 percent of each country's parliament. The vast predominance of lawyers in the House of Representatives and Senate sets the tone of the debate in the U.S. Congress. Trial lawyers are trained to win debates, they use facts selectively, and they aren't looking for the truth, nor are they interested in presenting the whole picture. In contrast, science relies on gathering evidence, weighing that evidence, and validating theories.[21] Scientists and science in general don't do well in politics (Angela Merkel and Margaret Thatcher, both chemists, are obvious exceptions). Scientists believe in the importance of facts and think they can win public debates by using facts, despite empirical evidence that suggests passionate opinion will often overcome scientific facts. We can no longer rely on Congress to provide the leadership and guidelines for scientists and industries to deal with the problems and ethical dilemmas associated with gene editing (chapter 9), climate change (chapter 11), and quackery (chapter 12). Scientists have to become more media savvy. They have to learn how to interact with journalists, regulators, and politicians, and they need to have a larger presence on social media. Scientists make good administrators, and many are university presidents; it is time some make the transition into politics.

Having placed today's science in a wider context, it is time to see the *new* science, contrast it with the *old* science, see all that *good* science can do, and lament how it can be abused as *bad* and pseudoscience. (In an earlier incarnation, this book was subtiitled "New Science, Old Science, Good Science, Bad Science.")

Chapter Two

The Professional Scientist

Is the disheveled, gray-haired, Einstein-like character in a lab coat still a good representation of a scientist? Who are our scientists, and who should they be?

In an interview with the *Guardian*, Donna Strickland, 2018 physics laureate and the third woman to ever receive a Nobel Prize in physics, says, "I don't see myself as a woman in science. I see myself as a scientist."[1]

As discussed in this chapter, the situation for women and people of color in science may have improved over the last decade, but inequities still exist. Many people still see the woman before they see the scientist. The United States and the world as a whole have not been taking full advantage of the diverse pool of potential scientists. We may have found and nurtured many future Einsteins, but we have fallen behind in cultivating new Marie Curies and George Washington Carvers. To stay competitive in the current economic system, to solve our global food needs, and to overcome our environmental problems, countries, companies, and academic institutions need to make use of all scientific talents available across a vast array of gender identities, races, and ethnicities.

From the 1970s to 2019, the number of current college graduates has flipped from being 58 percent men to being 56 percent women.[2] However, the gender distribution is not uniform; while women receive 59 percent of bachelor's degrees awarded in the biological sciences, they receive only 40 percent of physical science and mathematics degrees and much less than 20 percent in the computer sciences and engineering.[3] Women make up half of the total U.S. college-educated workforce but only 29 percent of the science and engineering workforce. A 2017 National Center for Science and Engineering Statistics report shows that although white men make up only one-third of the U.S. population, they constitute at least half of all scientists.[4]

SCIENTISTS OF COLOR

Although students from underrepresented groups aspire to careers in science, technology, engineering, and mathematics (STEM) fields at the same rates as their nonminority peers, minorities, who comprise 30 percent of the U.S. population, make up only 14 percent of master's students and just 6 percent of all PhD candidates.[5] This gap hasn't changed much in the last 15 years.[6] In 2017, there were more than a dozen areas in which not a single PhD was awarded to a black person, primarily within the STEM fields.[7] There are many reasons for this. In a paper examining underrepresented minority participation in biomedical research and health fields, Rosalina James, a member of the University of Washington Bioethics and Humanities department, states, "Inadequate preparation is a major limiting factor in efforts to increase the pool of qualified minority applicants for advanced education. Poverty, sub-par resources in minority-serving schools and poor mentorship contribute to losses of minority students at each level of education."[8] Stereotype threat,[9] impostor syndrome, and numerous microaggressions[10] also prevent scientists from minority groups from performing anywhere close to their potential.

According to a report by the American Institute for Research, a third of all black STEM PhDs earned their undergraduate degrees at historically black colleges and universities (HBCUs), institutions of higher education founded to serve primarily African American students.[11] Xavier University of Louisiana, located in New Orleans, is an HBCU and Catholic institution nationally recognized for its STEM programs. "Of the 3,231 students enrolled at Xavier in fall 2018, approximately 72 percent were African American, and about 79 percent of the 2,463 undergraduates majored in the biomedical sciences (bioinformatics, biochemistry, biology, chemistry, computer science, data science, mathematics, neuroscience, physics, psychology, public health sciences, and sociology)."[12] Xavier is best known for its education in the health professions, and, according to 2018 *Diverse Issues in Higher Education* data, ranks second in the nation in the number of African Americans who earn bachelor's degrees in the physical sciences and fourth in the number earning bachelor's degrees in the biological and biomedical sciences.[13] A 2013 National Science Foundation report confirms Xavier's success in educating science graduates, ranking Xavier first in the nation in producing African American graduates who go on to receive life sciences PhD degrees, fifth in producing African American graduates who go on to receive science and engineering PhD degrees, and seventh in producing African American graduates who go on to receive physical sciences PhD degrees.[14] The 2012 Report on Diversity in Medical Education published by the Association of American Medical Colleges (AAMC) ranks Xavier first in the number of African American alumni who successfully complete their medical degrees.[15] Xavier is one of 101 HBCUs in the United States. I went to visit Xavier to get the university's perspective on minority representation in STEM fields and to see what it does so well.

In 2014, the National Institutes of Health (NIH) announced 10 BUILD (Building Infrastructure Leading to Diversity) awards, ranging from $17 million to $24 million over five years. In his announcement of the awards, NIH director Francis Collins explained that the program was designed to increase the representation of African American, Hispanics, and Native Americans in science. Collins is particularly concerned because "although 12.6% of the U.S. population is African-American, only 1.1% of our NIH principal investigators are African-American."[16] One of these awards, in the amount of $19.6 million, was presented to Xavier.

Professor Maryam Foroozesh is the chemistry department chair and the lead principal investigator of Xavier's NIH BUILD award. Like Professor James, she feels the root of the problem is in K–12 education. The public school system needs serious improvement across the country. If we are all paying taxes, then every one of our children should have the right to the same type of education. The underrepresentation of students of color in the sciences is not due to their ability but to a lack of preparation and the reduced expectations that can come with an inferior education. "I think if there was a standard K through 12 national education program with federal oversight, then all the students including the ones from the inner cities or rural areas of the country would get a better education," Foroozesh told me. "A federal education system would hopefully also address some of the diversity issues you see in science at the higher levels, because once you provide all the students in the U.S. with the education they deserve, then you would get a higher number of scientists coming out of the groups currently underrepresented in science."

Foroozesh is also very concerned that the 116th Congress is extremely focused on short-term returns on their investments. They are pressuring funders to do short-term assessments, but it takes a long time to see the results of diversity programs. Increasing the diversity of the faculty and grant writers is a long-term project that involves K–12 reforms, changes in both undergraduate and graduate programs, and faculty hiring and retention. These factors are interlinked, and changes are difficult to evaluate because the numbers we are talking about are small. In 2012, 267 African Americans and 329 Hispanics received PhDs in the biological sciences. Even a small increase or drop can represent a large percentage change. Foroozesh worries that funding to programs that foster diversity and help STEM undergraduates from underrepresented groups are being cut before the programs have adequate time to prove their worth, which will disproportionally affect HBCUs that are highly reliant on them because they don't have hundreds of millions of dollars in endowments.

There are many reasons students do not continue in STEM, and any one is sufficient to dissuade a student from persevering. Initial assessments of Xavier's BUILD program have shown that mentorship is a major factor. Mentoring is crucial in retention of underrepresented students in STEM fields. Ideally the mentors need to serve as role models and have to understand the importance of cultural issues, family ties, financial needs, and expectations. Xavier's researchers undergo special mentoring training to achieve this understanding.

Seventy-five percent of the undergraduates enrolled at Xavier in fall 2018 were African American women, most of whom were STEM majors. These women in STEM largely fell between two departments at the university. The chemistry department, the largest department at Xavier in the number of faculty and research staff and the second largest in the number of majors, has 28 faculty members, half of whom are women. Even though Xavier is an HBCU, the department only has six African American/black faculty (1 woman and 5 men). The biology department, the second largest department at Xavier based on the number of faculty members and the largest based on the number of majors, has 23 faculty members, 6 of whom are African American/black (4 women and 2 men). The causes for this disparity are systemic and have roots in retention and recruitment, as well as the small numbers of African Americans/blacks, especially women, looking for jobs in academia. Another chemistry faculty member, Professor Mehnaaz Ali, is a coprincipal investigator on a National Science Foundation (NSF) ADVANCE grant, "which is focused on creating an equitable, inclusive and energizing climate for female STEM faculty members by addressing systemic barriers which currently lead to higher attrition rates of female faculty and women of color." Dr. Ali told me, "There are many speed bumps for female faculty in academia. It could be child care, it could be family care. If you are a minority in a school such as this one, where the numbers are low, you end up doing a lot of service, if you are a female faculty of color you are a role model for everyone, you are on a lot of service-oriented committees. But are you on the committees that are high impact? This is significant because committees, mentoring, and other unseen burdens result in burnout that can lead to retention issues."

Another reason Xavier has such high graduation rates for African American women in science is that it has a critical mass of students of color doing science. The students have each other, they can talk to each other, and they look to each other and Xavier alums as role models in science. This can make all the difference in the world. The critical mass required for this type of group-wide support is absent in most non-HBCUs. The ADVANCE team aims to create similar environments for faculty to have a safe space where they can talk and address important issues with people who are like minded and share intersectional boundaries and thus be connected to a larger campus-wide faculty network.

I grew up in South Africa. While at university I tutored students from Soweto who were boycotting their apartheid education. Each Saturday they traveled more than two hours to learn math and science from a naive undergraduate, who was younger than most of them. This experience made me realize how important education is and the lengths some people go to get it. At Connecticut College I do a lot of chemistry outreach and get to see the different levels of preparation students receive. Based on 25 years of personal experience, I argue that the inequities (facilities, class size, and equipment) between the richer and poorer schools that I visit in the Northeast are growing worse. In 2007 I started, and today still direct, an undergraduate program that prepares students from underrepresented groups for a variety of science-related careers and provides a solid foundation for graduate study or medical school. Participants in the Science Leader program come from socioeconomically disadvantaged backgrounds, and priority is given to students of color, first-generation college students, students with disabilities, and women in mathematics, computer science, and physics. The program is based on cohort formation through a first-year seminar, an associated field trip, and research. As students go through the college acclimation experience together, they quickly become part of the larger Science Leader community. They learn from advanced students about what to expect in certain courses. Older students organize study groups, peer tutoring sessions, and social gatherings and assist with the orientation of incoming students. This creates a supportive network of science professionals and graduate and undergraduate students that grows and strengthens organically. Since 2007, 104 students have entered Connecticut College under the Science Leader program, an average of approximately 15 students per year. The six-year graduation rate for students in the Science Leader program is 97 percent. As of spring 2019, Science Leader students have obtained six medical degrees, one doctorate, and eight master's degrees in STEM fields and six other graduate degrees. Twenty-four Science Leader alums are currently enrolled in graduate schools. The Science Leader program has been named a recipient of *INSIGHT into Diversity* magazine's 2019 Inspiring Programs in STEM Award.

I wish we didn't need this program, but it has become increasingly important and relevant. Most universities have been forced to introduce similar initiatives. The program is both one of the most rewarding and most depressing facets of my job.

NOBEL PRIZES

What Do They Say about Diversity?

As I write this we have just gone through another Nobel Prize season. The three Nobel Prizes in chemistry, physics, and medicine are the scientific equivalents of the Academy Awards. Just as for the Oscars, there is a pre-Nobel buzz; scientists are trying to predict who will be awarded the year's prizes. In the days and weeks following the announcement of the awards, there is a thorough analysis of the winners and their research and sympathizing with those who, unjustly of course, didn't get an award. It doesn't take a very detailed investigation to discover that women and black scientists are not proportionally represented among the laureates, the United States does better than most countries, and China has surprisingly few science Nobel laureates.

In 1895, five Nobel Prizes were established according to Alfred Nobel's will. The first prizes in chemistry, literature, physics, and medicine were awarded in 1901. Each prize can be awarded to no more than three people, and prizes may not be awarded posthumously.

The annual Nobel announcements occur in October, which is Black History Month in the United Kingdom. This is rather ironic, as no black scientist has ever won a Nobel Prize in science. Zero of the 617 STEM laureates! The reasons for this are the limited opportunities black (especially African) students have and the biases, hurdles, and lack of role models that they experience in science. Not enough young black students are choosing science, and there are not enough black full professors in the sciences at elite universities, where the networks and reputations required for winning a Nobel are made. Unfortunately, it is impossible to give Africa the same economic and political power as the global North. But "if we want more black scientists and eventually Nobel laureates, then similar direct strategic action (as has been used to increase the numbers of women in science) is urgently needed."[17]

Immigrants to the United States

Thirty seven of the eighty-nine U.S. citizens awarded a Nobel Prize since 2000 were foreign born. Most notably, all six American winners of the 2016 Nobel Prize in economics and STEM fields were immigrants to the United States.

American universities consistently perform extremely well in all global rankings of academic institutions. Foreign graduate students flock to the United States. In 2015, more than half the computer science, engineering, mathematics, and statistics graduate students were international students. Most of these students return to the countries of their birth upon completing their graduate studies, but a significant number of the very best stay in the United States and become naturalized citizens. In a disturbing trend, the NSF reports that the number of international graduate students coming to the United States dropped by 22,000 (5.5 percent) in 2017.[18] *Inside Higher Education* reports that the high cost of US higher education, visa denials and delays, the political and social environment in the United States, and increasing competition from other countries are responsible for this decrease.[19] Had the proposed tax on graduate fellowships passed Congress (it barely failed in 2017), the decrease would surely have been greater than just 5.5 percent. In 2018, the number of international students dropped again, especially in universities in the central parts of the United States and at lesser ranked universities. The numbers of students coming from Canada and Mexico also declined.[20]

What will this drop in international STEM graduate students, often the best from their countries, mean to science research? This change in demographics does not bode well for science in the United States. We need to be careful we don't lose touch with this very important talent pool. Not only do immigrants contribute to an inordinately high number of Nobel awards, but they also bring new ways of thinking to their research labs. They come from other cultures and have learned their science in different educational systems, which place different emphases on rote learning, historic understanding, and interdisciplinary research. They often bring an alternative and important perspective that a homogeneous scientific community cannot match.

WOMEN IN SCIENCE

Between 1901 and 2019, there were 213 Nobel awardees in physics, 184 in chemistry, and 219 in medicine. Over that period women were only awarded 3 Nobel Prizes in physics, 5 in chemistry, and 12 in medicine.

Donna Strickland was awarded the 2018 Nobel physics prize with her PhD mentor, Gérard Mourou. Strickland was the first woman to be awarded a physics prize in 55 years. At the University of Rochester, Strickland and Mourou together developed the most intense and shortest laser pulses ever produced in a laboratory. Mourou had the idea, and Strickland made it work. Besides being an impressive scientific advance, their technique has resulted in high-intensity lasers that have been used in millions of corrective eye surgeries.[21] Ironically, Donna Strickland wears glasses and refuses to get the laser eye surgery that her research made possible: "I have great faith in lasers, but no one's putting one near my eye."[22]

Many women could have, and probably should have, been awarded a Nobel Prize in physics. The *Guardian* published a 2018 article titled "Five Women Who Missed Out on the Nobel Prize."[23] Lise Meitner, who laid the groundwork for understanding nuclear fission, is my favorite of these. An element, meitnerium, was named for her posthumously. She is the only woman to have earned such an honor (curium is named after both Marie and Pierre Curie). But no Nobel. Both Lise Meitner and Jocelyn Bell, who discovered the first radio pulsars in 1967, missed the Nobels while their male collaborators, Otto Hahn (1944) and Anthony Hewish (1974), were each honored with an award. Lene Hau, a physicist at Harvard University, is another woman mentioned in the *Guardian* article. In 1999, her team was able to slow a beam of light to 17 meters per second, which she topped in 2001 by stopping a beam of light completely. This work has implications for quantum computing and quantum encryption. Hau's work is fairly recent, so she may yet get a Nobel Prize.

There can be no denying that just three women in 213 physics Nobel laureates is a disproportionately low number and that many distinguished and immensely qualified female physicists must have been overlooked. But is this a big deal? Yes, of course it is. It is grossly unfair to the women who didn't get the award and sends the wrong message to young people, funding agencies, editorial boards, and others about who does noteworthy science. Perhaps much more important, it is indicative of many biases and inequities that plague women and minorities in science.

In 2008, I served as a consultant for the Royal Swedish Academy of Sciences' deliberations about the chemistry award; as a result, my wife and I were invited to attend the Nobel ceremonies. We stayed in the Grand Hotel with all the awardees. We got to see how scientists, excellent but unknown outside their fields, suddenly became superstars. They were interviewed on radio and television and hobnobbed with Swedish royalty. The events of Nobel week were shown live on Swedish television, and the newspapers were atwitter about the clothes worn by the Swedish princesses at the awards ceremony. Nobel laureates immediately become role models who are invited to give seminars all around the world. In an interview with *Nature* magazine, Donna Strickland, was asked how her life had changed since being informed that she had won the award. She said, "Oh, completely! This is just completely crazy, you know; I got to talk to the Prime Minister of Canada for the first time ever. He was very nice about it. I said, 'This must be how your life is like all the time.' And he replied, 'No, I don't always get to speak to a Nobel laureate.'"[24] Her answer shows the stature the prize imparts and why women Nobel laureates are such important role models.

Because only 3 percent of the science awardees have been women and there have been no black winners, there are very few role models for the new generation. The entertainment industry is no help; media depictions of male scientists and engineers outnumber those of women by a ratio of 14 to 1.[25] Frances Arnold, winner of the 2018 Nobel Prize for chemistry, had a guest appearance on *The Big Bang Theory*. She was the first woman scientist to make a guest appearance in 12 seasons of the show. If we want to solve our climate change problems, cure Alzheimer's, expand our economies, and so forth, we can't afford to completely ignore a large proportion of the population. In the words of Virginia Valian, who has spent the past 25 years studying the structural and psychological reasons for the paucity of women in the upper reaches of science, "If we want talent, we have to welcome it and nurture it, in all its diversity."[26]

Nomination to receive a Nobel Prize in science or medicine is by invitation only. Each year, thousands of members of academies, university professors, scientists, previous Nobel laureates, members of parliamentary assemblies, and others are asked to submit candidates for the Nobel Prizes for the coming year. The names of the nominees and other information about the nominations cannot be revealed until 50 years later.[27] Despite this confidentiality, we know that nominations tend to favor scientists working at elite research institutions, famous scientists who are good at self-promotion and are well known to their peers. Predictably, these tend to be older, established white males. The Royal Swedish Academy of Sciences, for chemistry and physics, and the Nobel Assembly at the Karolinska Institute, for medicine, are in charge of selecting the Nobel winners from the nominations. They are aware that they have a "white male problem," and starting with the 2019 nominations they have asked nominators to consider diversity in gender, geography, and topic in their future nominations. It didn't work. There were no female awardees in physics, chemistry, or medicine at the December 2019 Nobel award ceremonies.

"The Leaky Pipeline"

The disproportionately low number of female Nobel laureates in the sciences and the absence of black science laureates is an extreme example of the "leaky pipeline" in science. The NSF coined the phrase for this phenomenon in the 1980s. It comes from a report in which the NSF also predicted an upcoming shortage of scientists and engineers that would grow to over 500,000 by 2006. The shortage never materialized, but the metaphor stuck. It presents a vivid visual image of women and people of color entering the sciences but then "leaking out of the pipeline" at greater rates than white males as they progress along their educational and career paths. This pipeline should lead to awards and board memberships in science, the ultimate being the Nobel Prizes, but the number of women and people of color consistently decreases as we move along the pipeline. More than 14,000 academic articles have been written about the "leaky pipeline."[28] However, while the phrase is also very popular with the media and politicians, it is a flawed metaphor. Although it is often used in connection with a perceived future shortage of scientists, it is less commonly used to show the need for increased diversity and equitable representation in STEM, the more important pressing problem. At the same time, a leaky, dripping pipeline has the obvious negative connotations of a dysfunctional pipe; it implies that there is a single direct pathway from preschool to PhD, and that the PhD is a more valuable endpoint than other educational degrees.[29] Although the leaky pipeline is not necessarily a good metaphor, it certainly describes something real. Therefore, I use the phrase in this chapter, although I place it in quotes to acknowledge its inadequacy.

The percentages of women decrease from a bachelor's degree to a PhD, tenure, full professorship, and major awards in the sciences. A 2015 NSF report shows that women accounted for 45 percent of PhDs in the STEM fields. The percentage falls to 42 percent for female junior faculty members and to 30 percent for female senior faculty members.[30] A similar drop-off is observed in biotech companies, where women just hold 20 percent of leadership roles and 10 percent of board seats. *Chemistry & Engineering News* reviewed the boards of 75 biotech companies that had raised series A funding since 2016 and found that 39 have only men on their boards, while just 2 have boards with over 30 percent women.[31]

There are numerous reasons for the decrease in the percentage of women in more senior positions and receiving major awards. The remainder of this chapter divides them into three main categories: (1) a structure (PhD, tenure, funding, and publication) that is not compatible with a family life; (2) implicit biases against women by other scientists (both men and women); and (3) a system that favors men and masculine confidence.

Science and a Family Life

The easy and convenient explanation for the low numbers of women in the upper levels of science is that they have more family responsibilities . Many will even argue that this is a fait accompli and that nothing can be done about it. I disagree. Some of the differences may be due to family reasons, but with proper incentives these differences can be made negligible, and there are other, more significant factors that cause women to exit the pipeline. If family issues are the only problem, why have the last 30–40 years seen such great improvements in gender diversity (and even racial diversity) in the life sciences, while the physical sciences, computer science, and engineering have lagged behind? Physics and astronomy require very similar skills, yet astronomy has twice the percentage of women faculty as physics.[32]

A study of gender diversity in the life sciences sector in Massachusetts was conducted by Liftstream and MassBio, in which over 900 people working in the biotech sector were surveyed. The 2017 report found that women have career breaks more often than men, related not just to parenthood but also to caring for elderly parents. More important, the researchers found that parenthood isn't the only cause for the "leaky pipeline." In fact, more women leave the biotech sector because they are opting out of the corporate culture than for parenting reasons.[33]

Patricia Fara is the president of the British Society for the History of Science and a fellow at Clare College, Cambridge. She has an undergraduate degree in physics from Oxford but is one of the many who leaked out of the "pipeline." In a February 2018 National Public Radio interview, she talked about why she had dropped out of the system. For her it was a choice between quality of life and status. To succeed in science and academia routinely requires a 24/7 commitment. Fara feels that she and many other women have wisely opted for a better quality of life and that "perhaps in time, the really smart men will realize that's a better option than earning more money but having no time to spend it."[34] She might be right that faculty at the elite institutions have little or no life outside of work and that getting tenure requires extraordinary sacrifices, especially in one's family life. Progressive policies such as paid parental leave, high-quality, on-site child care, and tenure 'clock stops" will improve the quality of living of STEM faculty and make STEM careers more appealing to new generations, but they won't completely close the gender gap.

In their aptly titled paper "Do Babies Matter? The Effect of Family Formation on the Lifelong Careers of Academic Men and Women," Mason and Goulden have shown that women with children don't advance any slower than women without children. That doesn't mean having babies doesn't matter; it matters a great deal. The study showed that there is large gap in achieving tenure between women and men who have babies within five years of getting their PhDs. But most important, based on all the data in their study, Mason and Goulden conclude that "babies are not completely responsible for the gender gap, and that there are other factors at work, perhaps including the thousand paper cuts of discrimination."[35] Most of these "paper cuts" are a result of implicit bias. They are unconscious, involuntary, natural, and unavoidable assumptions that all of us make on the basis of subconscious assumptions, preferences, and stereotypes.

Implicit Bias

Gender disparities are decreasing in academia. However, many biases and gender inequities remain. This section looks at some of these "paper cuts." Frances Trix and Carolyn Psenka of Wayne State University examined 300 letters of recommendation for medical faculty. They found significant differences between letters written for men and women. The average length of letters for female applicants was 227 words, whereas the average length of letters for male applicants was 253 words. Not only are the letters for women shorter, they also use descriptors such as "determined" and "dependable" more often and "outstanding" and "brilliant" less often than the equivalent letters for men. Letters for women are more likely to mention family situations and personal characteristics. And here is the kicker: it makes no difference whether the letters are written by men or women.[36]

The peer-review publishing model that the scientific publication system is based on is a single-blind process. Upon receiving a manuscript, a journal editor sends it to external reviewers with expertise in the research area. The reviewers know the identity of the authors, but the reviewers remain anonymous. They read the paper, recommend whether it should be published or not, and identify what changes are needed to make the paper acceptable if it is not quite ready for publication. To examine reviewer bias, Silvia Knobloch-Westerwick, Carroll Glynn, and Michael Huge of Ohio State University[37] recruited graduate students to rate conference abstracts authored by researchers with distinctively male or female names. The fake author identities on the abstracts were varied such that the same abstract would be attributed to a male-sounding name or a female-sounding name in a given test. Scientific abstracts submitted by "male" authors were considered of higher scientific quality than those submitted by authors with feminine names even though there was no difference in content. The gender of the reviewers did not influence these patterns. The differences were small but statistically significant. I am confident the same implicit biases appear when papers or presentations indicate that a work was done at a lesser ranked institution or in a developing country, or if the author has a foreign last name. Bias in peer review can affect the publication record of young scientists and impact their chances for promotion and tenure, a painful paper cut indeed.

The reviewing biases discussed here are not limited to graduate students. In 2012, Jo Handelsman and coworkers at Yale University showed that faculty at research-intensive universities favor male students. In a randomized double-blind study, 127 science faculty rated the application materials of a student, randomly assigned either a male or a female name, for a laboratory manager position. They found that "faculty participants rated the male applicant as significantly more competent and hireable than the (identical) female applicant. These participants also selected a higher starting salary and offered more career mentoring to the male applicant. The gender of the faculty participants did not affect responses, such that female and male faculty were equally likely to exhibit bias against the female student."[38]

In 1998, Virginia Valian published *Why So Slow?*, a landmark book on bias.[39] In 2018, she and her coworkers analyzed gender differences in 3,652 colloquium speakers who presented their work at 50 prestigious U.S. colleges and universities in 2013–2014.[40] The proportion of women presenting colloquia was significantly smaller than for those presented by men. There was no difference in the extent to which male and female professors at these elite universities valued or declined speaking invitations. The difference was in the number of invitations offered. These biases have significant consequences, because as the authors say, "Colloquium talks are an important part of academicians' careers, providing an opportunity to publicize one's research, begin and maintain synergistic and productive collaborations, and enhance one's national reputation; those results in turn typically lead to retention, promotion, or greater salary increases. . . . Colloquium talks also signal to audience members who is worthy of being invited."[41]

Ending implicit biases is not going to be easy. Combating implicit bias is difficult at the best of times, but it is particularly hard in the sciences, where scientists believe that the process of doing science is rigorous and objective and as a consequence are convinced that they are not prone to bias. "Gender discrimination is everywhere," says Christine Williams, a sociologist at the University of Texas at Austin. "But what makes the experience unique among scientists is their almost unflappable belief in objectivity and meritocracy."[42] Another complication is the fact that in acknowledging implicit bias against underrepresented groups, established white male researchers have to accept that they may have been privileged in the attainment of their positions. "Some scientists might be slow to consider that the system could be rigged because it implies that their own accomplishments might not be totally deserved," says Deborah Rhode, a legal ethicist at Stanford University. "They might also be less willing to see how helping their closest peers (mainly males) might simultaneously exclude others."[43]

Biases can lead to discrimination, a much deeper cut than implicit bias. A 2018 Pew Research Center report finds that the majority of black people in STEM fields (62 percent) report having experienced some form of discrimination at their work due to their race or ethnicity. The survey also finds that half of women working in STEM jobs report experiencing discrimination at work due to their gender, more than women in non-STEM jobs (41 percent) and far more than men working in STEM jobs (19 percent).[44] As mentioned previously, more women working in the Massachusetts biotech sector left their places of employment because of workplace issues than for family reasons. Discrimination does not lead to an inviting workspace, and it encourages scientists with important ideas and skills to leave the field.

SCIENCE AND MASCULINE (OVER)CONFIDENCE

Society, and science specifically, rewards masculine (white American) confidence. Numerous studies have shown that in mixed-gender groups, men talk more than women, and that when women do speak they are more likely to be interrupted than men. In contrast, women are considered rude and abrasive if they interject when men are speaking. These behaviors all add to the perceived influence of men.[45] Science is no different.

In May 2018, five months before Donna Strickland was awarded the Nobel Prize, a page about her was submitted to Wikipedia but was rejected because she and her research had not garnered enough internet coverage,[58] another clear example of women not self-promoting as much as men.

CONCLUSION

Eric Lander, founding director of the Broad Institute of MIT and Harvard, wrote an opinion piece in the *Boston Globe* in which he said, "The United States has only 5 percent of the world's population. To stay ahead, we'll need to use all our assets. That means leveling the barriers for women in science and engineering, and closing the participation gap for underrepresented minorities. It also means expanding tech-driven prosperity beyond the two coasts."[59] This is particularly important because the economic center of gravity of the world is shifting as the populations and personal income of Africa and (especially) Asia are increasing. If the United States wants to stay competitive in the world economy, it will have to rely on technological and scientific advances. Science and technology are related to each other, and both will advance faster and further with an expanded and diversified talent pool.

For better or worse, the world economic system is based on growth. In the current system, countries and companies need to expand in order to thrive. Staying the same may be sustainable, but it is not economically desirable. The U.S. agricultural and manufacturing sectors have reached their maximum capacity; they can no longer expand. America's economic growth is predicated on the production/design of new products (iPhones, solar panels, cars, etc.). We need new and improved products, high-tech merchandise enhanced beyond previous models. In other words, the expansion of the U.S. economic system is reliant on scientific knowledge and know-how.[60] The use and insights gained from scientific breakthroughs such as CRISPR, optogenetics, and gravitational waves will keep the United States competitive in tomorrow's economy. To do this we need to maximize our scientific talent.

All the hurdles and biases described here don't apply only to women and scientists of color; they also apply to some white male scientists. Chapter 5 discusses Doug Prasher, who wasn't confident enough to go for tenure at Woods Hole; didn't continue working on green fluorescent proteins because he wasn't being supported; and finally dropped out of science, missing the hundredth Nobel Prize in chemistry in 2008 by the tiniest of margins. His is another, very different, example of a "leaky pipeline": the importance of "loudership" and old-boy network connections.

Frances Arnold, 2018 chemistry laureate, is optimistic. She thinks we may have turned the corner, "as long as we encourage everyone—it doesn't matter the color, gender; everyone who wants to do science, we encourage them to do it—we are going to see Nobel Prizes coming from all these different groups. Women will be very successful."[61] Women perhaps, but I am not convinced that people of color will be fairly represented among STEM Nobel laureates in the next 10–20 years. Unfortunately the systemic, societal, economic, and educational (K–12) differences are too large and too entrenched to expect parity in the next two decades.

Chapter Three

Do-It-Yourself Science

Citizen Science, the Amateur Scientist, Biohacking, and SciArt

Chapter 2 looked at the demographics of today's scientists and the need to increase the proportion of people of color and women in science. These scientists were employed in institutions such as industry, academia, national labs, and research hospitals. The vast majority had graduate degrees in science. A group of very interesting, very important scientists is making a resurgence: amateur scientists. They often have no postgraduate degrees in science and are not employed in the scientific sector. They do their scientific research purely for the love of science. They are amateur in the true sense of the word, the etymology of which harkens back to the Latin *amatore*, which means "lover or friend."

HISTORY OF AMATEUR SCIENTISTS

Amateur science has a storied past. Much of our early science was done by amateur scientists. Here I briefly introduce four of these pioneering amateurs—Michael Faraday, Charles Darwin, Henrietta Swan Leavitt, and Robert Evans—before turning to the new breed of amateur scientists we have come to know in modern science.

Michael Faraday, born in 1791 in Newington, England, had no formal education. He grew up poor and learned to read and write in Sunday school. At age 14 he was apprenticed to a bookbinder. Through reading in his spare time he taught himself about electricity and chemistry. When one of chemist Humphrey Davy's assistants was dismissed for brawling in 1812, Faraday managed to get a position working for Davy at the Royal Institution of Great Britain. Though an amateur in the sense that he had no formal education, Faraday would become one of the greatest experimentalists of the 19th century. Among his many breakthroughs was the invention of the first electric motor and dynamo. He pioneered the field of electrochemistry and discovered diamagnetism and benzene. Some have gone so far as to suggest that Davy's greatest contribution to science was his discovery of Faraday, even though Davy himself discovered five new elements.

Mary Ellen Hannibal, author of *Citizen Scientist: Searching for Heroes and Hope in an Age of Extinction*, describes Charles Darwin as the archetypical amateur scientist: "He did not have an advanced degree, and he worked for no one. He worked for himself—no institution."[1] To be fair, he did have a rich father to support him. The days when amateur scientists such as Darwin and Faraday were revolutionizing science are probably over. However, one area in which amateurs have made and still are making substantial breakthroughs is astronomy.

Henrietta Swan Leavitt was an astronomer in the early 1900s. She was a Harvard "computer," one of many women hired to examine the relative brightness of stars in thousands of photographic plates. The hours were long and the work tedious, and they were paid a pittance. Between 1907 and 1921, Leavitt discovered 2,400 variable stars. She didn't just do tedious, repetitive work; she also discovered a relationship between the period of a star's brightness cycle and its absolute magnitude that made it possible to calculate its distance from Earth.

The record for visual discoveries of supernovae is held by another amateur astronomer. Robert Evans was born in 1937; he is a minister of the Uniting Church by profession. He graduated from the University of Sydney, majoring in philosophy and modern history. Two of my favorite authors have discussed Evans's talents. In *An Anthropologist on Mars*, Oliver Sacks describes Evans's ability to find subtle changes in the starfield as "savantlike."[2] In *A Short History of Nearly Everything*, Bill Bryson presents a great analogy for Evans's ability to detect changes: it is like being able to spot an added grain of salt on a tabletop of salt.[3]

In 1992 Daniel Koshland Jr., the editor of *Science* magazine, published an editorial in which he argued that modern science "can no longer be done by gifted amateurs with a magnifying glass, copper wires, and jars filled with alcohol."[4] To do modern science 1990s style, one needed high-tech equipment, significant funding, graduate and postdoc students, a lab, and a graduate degree in science. It seemed as if the days of the amateur scientist were over. However, Koshland was wrong. Amateur astronomers are still contributing important findings. In the 2010s, amateur astronomers have found 42 new planets, spotted a new dwarf galaxy, and sighted "yellow spaceballs that funding the research rather than doing it, that they are science supporters rather than amateur scientists.

The Global Biodiversity Information Facility (GBIF) and iNaturalist rely on traditional amateur scientists and are perhaps better examples of citizen science in action. iNaturalist.org was founded in 2008. The premise of the site is that citizen scientists take photos of plants and animals, which they post with their locations and observations. Other naturalists and scientists on the site identify the species and can use the information to monitor changes in biodiversity. iNaturalist.org has also used the vast amounts of photos and information gathered from its citizen scientists to train an artificial neural network to identify the species of the organisms in most of the animal/plant pictures. In June 2017 the site released an app that uses an artificial intelligence algorithm to identify the species of plant or bird photographed.[9] Many of the iNaturalist.org postings are deposited in the GBIF, where they are part of a database of hundreds of millions of "species occurrence" records. Half the observations come from citizen scientists. In its own words, the GBIF "is an international network and research infrastructure funded by the world's governments and aimed at providing anyone, anywhere, open access to data about all types of life on Earth."[10] The facility estimates that its database has been used for more than 2,500 peer-reviewed papers in the last 10 years.[11] The GBIF and iNaturalist.org use the large number of citizen science postings to give us a global picture of what's happening to our biodiversity, while at the same time educating us and enticing us to participate in the protection of the planet's biodiversity.

There are some concerns with using citizen science. The animal sightings and geospatial information sent to sites like iNaturalist.org could be used by poachers to find rare and elusive wildlife. And there are no restrictions on the way health monitoring apps such as PatientsLikeMe use the medical data they collect.

SCIENTIFIC ART

Eduardo Kac (pronounced cats) is an example of a new breed of amateur scientist. He is the first and by far the most famous of the transgenic artists (artists who use cross-species genetic modifications in their art, genetically modifying living organisms so that they make proteins normally only found in other species). Kac was born in 1962 in Rio de Janeiro. During the 1980s he protested against the Brazilian dictatorship by giving "performance art" demonstrations on Ipanema Beach, reciting porn poems while wearing a pink miniskirt. He is currently a professor in the Art and Technology Department at the School of the Art Institute of Chicago. Although he has taken some bioengineering workshops, he has a PhD in art and never studied biochemistry, molecular biology, or chemistry.

Chapter 5 introduces green fluorescent protein (GFP). By tagging a protein with a fluorescent protein, one can see where and when a protein is made in a living organism. Most of my research is focused on fluorescent proteins, which have changed the way science is done, fascinating transgenic artists and DIY scientists along the way.

Kac produced two exhibits based on GFP technology, *GFP Bunny* and *The Eighth Day*, both part of his *Creation Trilogy*. While the first part of the trilogy, *Genesis*, didn't involve GFP, it is worth describing due to its relationship with the other two pieces and because it is thought-provoking.

In *Genesis* Kac translated Genesis 1:26, "Let man have dominion over the fish of the sea and over the fowl of the air and over everything living that lives upon the Earth," into Morse code. Since both DNA and the Morse code are made up of four different characters, Kac was able to convert the dots, dashes, and spaces between letters and words in the Morse coded version of this passage into the DNA nucleic bases C, T, G, and A, respectively. He then hired a biotech company to synthesize the "Genesis gene," which was injected into fluorescent bacteria. The gene was artificial and was probably not expressed in the bacteria. Visitors to the exhibit saw a projected view of the bacteria if, and only if, they switched on a UV lamp that briefly irradiated the bacteria and mutated them, thereby rewriting Genesis 1:26. The exhibit was shown at galleries in Linz, São Paulo, Chicago, New York, Yokohama, Athens, Madrid, and Pittsburgh. For each show, a new "Genesis gene" was created. In some cases a web link to the exhibit was established, and web surfers were given the opportunity to view and thereby mutate the bacteria. The Genesis exhibit premiered at Ars Electronica in 1999, and after the show Kac took the mutated bacteria back to the lab and had the modified "Genesis gene" sequenced, converted to Morse code, and translated back into English. Most of the mutations were nonsense mutations, but some made sense and were interesting; for example, "fowl" was mutated to "foul." In *Genesis*, Kac tried to break the barriers between art and life. It is important to note that this was done in the 1990s, when sequencing was expensive, and molecular biology was in its infancy. Today the project would be fairly trivial.

Alba is a cuddly albino rabbit that hops around, snuffles its nose, and munches carrots just like any other rabbit. Turn off the lights, switch on blue lamps, and it becomes *GFP Bunny*, a transgenic artwork. Alba, Spanish for "dawn," is both alien and cuddly. She changes from lovable family pet to a disconcerting vision of the future, a science fiction pet with an eerie green glow emanating from every cell, from her paws and especially her eyes.

Alba was created in 2000 by Louis-Marie Houdebine of the French National Institute for Argonomic Research.[12] The GFP bunny is part of the second work in the *Creation Trilogy*, but there was supposed to be more to the GFP bunny piece than just Alba. The dialogue created by the pet/alien dichotomy and the social integration of Alba were important parts of the exhibit. Alba's public debut was scheduled for an exhibition of digital art in Avignon, France. Kac and Alba were going to live in a faux living room created in the gallery, signifying how biotechnologies are entering our lives, even the privacy of our living rooms. However, on the eve of the show the director of the institute that had created Alba refused to release her to Kac. This fueled the dialogue portion of the exhibit, and soon Alba was competing with the Olympics for headlines in the *Boston Globe*, *Le Monde*, the BBC, and ABC News. *GFP Bunny* was meant to be a political project that would break down the barriers between art, science, and politics, and in this it succeeded. For many people, fears of genetically modified organisms, the human genome project, and cloning were realized when they saw photos of Alba's strangely fluorescent eyes. Kac used Alba as a symbol for all transgenically modified organisms and of what is possible with biotechnology; she was meant to be provocative. Despite many detractors, Kac's project also had many supporters. The science fiction writer Robert Silverberg was one person of note who entered the GFP bunny debate. He wanted to know why scientists can create transgenic organisms while artists can't and whether breeding a phosphorescent (his word) rabbit is any sillier than breeding a dachshund.[13]

For *The Eighth Day*, the last part of the *Creation Trilogy*, Kac modified some amoebae, fish, mice, and plants by adding the GFP gene to their genomes, then placed them in a clear, four-foot-diameter plexiglass dome, a transgenic biosphere. While most transgenic organisms have been developed in isolation, the dome in *The Eighth Day* is meant to symbolize a new ecology that is forming between genetically modified crops in the United States. It is the eighth day in the creation of man and Earth (a foreshadowing of CRISPR?). The centerpiece of the display is a robot that is driven by green fluorescent amoebae called *Dyctiostelium discoideum*. When they are active the robot goes up; when they are quiet it goes down. The robot also has a camera attached to it that can be controlled by web participants.

It took Kac and plant biologist Neil Olszewski six years to create Edunia, a petunia that has a part of Kac's immunoglobin gene expressed in its veins. According to Kac, "There's a duality here—on the one hand, it's a living thing like any other flower, it needs light and good soil, attentive watering to grow. On the other hand, the red veins in the flower carry my own DNA; I decided to give the Edunia the very same gene that in my body seeks out and rejects foreign matter."[14]

Eduardo Kac is a pioneer in the field of transgenic art, which enabled him to collaborate with interested scientists and labs. Today there are many more artists hoping to combine their art with science and scientists hoping to combine their science with art. A lot of this collaboration occurs in community labs, the scientific equivalent of maker spaces.

COMMUNITY LAB SPACES

Genspace is the first nonprofit community biotech lab established in the United States. It was started in 2009 in Brooklyn, New York. The idea for the project came from Ellen Jorgensen, who wanted a lab space that was open to everyone and would foster innovation, diversify biotechnology, and establish a space in which people could "take classes and putter around in the lab in a very open friendly atmosphere."[15] The time was right. There was a pool of disenfranchised graduate students, artists with an interest in using science as their new canvas, and highly skilled professionals with ideas and projects they couldn't pursue in their day jobs, all interested in the concept of a community lab. The 2008 recession had led to the downsizing and collapse of small biotech start-ups, which forced them to sell their equipment on eBay. Jorgensen, a molecular biologist with a PhD from New York University who has had various positions in the biotech industry, put out a call for like-minded people. They met in science journalist David Grushkin's apartment to talk about biotechnology, the need for lab space, and "to learn more about bioengineering by inserting a gene into bacteria that caused it to glow green."[16]

From that group Genspace slowly grew. In the core group that founded Genspace was Nurit Bar-Shai, an artist. She was interested in GFP and contacted me to talk about fluorescent proteins. We emailed back and forth, and I gave a few talks at the Genspace labs, which are located on an upper floor in the Metropolitan Exchange Building, a block away from the Brooklyn Academy of Music (BAM). The first time I went I got off on the wrong floor. One of the people in the building gave me a brief tour on the way to the Genspace labs. The owner of the Metropolitan Exchange, Al Attara, has attracted a variety of entrepreneurs to the building with cheap rent, communal kitchens, and a symbiotic workplace. This was the perfect location for a community biotech lab. The open-plan floors of this old bank building were packed with walls of old equipment separating groups of desks occupied by young architects, artists, and biotechnologists all bustling with energy and ideas. Al, the building's owner, is not happy with the building's name. "I want to rename it the Brooklyn Arts and Design Arena—or BADA. Since we're in the BAM District, it'll be BADA-BAM," he said in a *New York Times* article.[17] BADA-BAM would certainly capture the spirit of Genspace's energy. Most of the community lab's members are not scientists, and a lot of the energy is devoted to teaching and training members and students from local underfunded high schools. The lab only qualifies as a biosafety I lab, which means it is suitable for handling life forms that present no risk to humans.

From its very inception, Genspace and its founders have suffered from negative public misperceptions. Ellen Jorgensen recalls her first interactions with the press after forming Genspace: "The more we talked about how great it was to increase science literacy, the more they wanted to talk about us creating the next Frankenstein."[18] These fears that DIY biologists (DIYbio) or biohackers will be able to able to cause themselves or even others harm have grown, particularly since the advent and commercial distribution of CRISPR kits. In 2013, David Grushkin and Piers Millet, deputy head of the Biological Weapons Convention Implementation Support Unit of the United Nations, did a survey of DIY biologists.[19] They found that most work together, and only 8 percent of the respondents worked alone in their own home labs. Biohackers are very interested in idea sharing, open-sourcing techniques, and transparency. Community labs are sprouting up all over the country, and most cooperate with authorities to ensure that they have no accidents and that their facilities aren't abused.[20] However, biohackers have a large variety of motivations. Medical doctors and biochemists want to examine diseases that are of personal importance to them or their families; retired scientists want to continue their research; and bankers and software engineers switch careers to being transgenic artists, cyberpunks, and anarchic biohackers.

Biohacking provides a research space for high-risk projects that aren't always designed to lead to tenure or new products. Furthermore, it has allowed wannabe scientists, graduate students, transgenic artists, doctors, teachers, and industrial researchers to try out their own ideas in their own spaces. In garages and scientific maker spaces, individuals are altering their own genetic codes, building things, making cells glow, and democratizing science.

BIOHACKING

Josiah Zayner, age 38, is a biohacker interested in pushing boundaries. He has a PhD in molecular biophysics and his own company, The ODIN, which sells kits and instruments for home scientists. Zayner sees himself as a scientific adventurer and rebel researcher. He is willing to experiment on himself, to try new and experimental techniques, and to circumvent the Food and Drug Administration (FDA) in order to improve his own body. "I want to live in a world where people are genetically modifying themselves," he says.[21] In 2016, he released a YouTube video titled "How to Genetically Engineer a Human in Your Garage," showing his attempt to genetically modify himself so that cells in his arm would express GFP.[22] The self-

Part Two

Doing Science

Chapter Four

The Nuts and Bolts

This chapter describes how scientists know whether they can trust published results, how the peer-review system works, and where scientists get funding for their research.

PEER-REVIEWED PUBLICATIONS

In 2018, Susan Bourne, the interim dean of science at the University of Cape Town in South Africa, and I were talking about science journals. The scientific paper is the primary mechanism for both broadcasting one's own scientific results and determining what research has been done by others and how they did it. It is also a measurement used to assess a scientist's worth, whether for funding, tenure, promotion, or getting a job. I like how Susan succinctly summed up her thoughts on the scientific publishing process and probably those of most other scientists: "The system is completely crazy. The taxpayer funds the research, the scientists do the research, write it up for free, do all the editing, all the peer reviewing—the publisher gets everything for free. And then the taxpayer has to pay for us to get access to it again."

Prior to the 1600s, scientists privately communicated their findings and ideas in letters, gave public lectures, and wrote books once the experiments were all done and their ideas and theories had matured. There was no way of publishing increments of one's research. When the advent of scientific journals allowed scientists to publish chunks of their work, "scientists from that point forward became like the social insects: They made their progress steadily, as a buzzing mass."[1] At first the papers were shorter, less formal, and more readable than they are today. As the research became more specialized, papers became longer and contained more jargon.

I sometimes think of scientific papers as puzzle pieces. Nature is full of intriguing puzzles for researchers to solve. The jigsaw pieces don't come in a box, with the number of pieces listed and a picture of the solution on the lid. To solve any of nature's puzzles, researchers need to find the pieces, then try to put them in the correct place. Some puzzles are much more important than others, and within the puzzles themselves some jigsaw pieces are more central than others. Scientific research is all about finding the pieces, putting them together, and trying to extrapolate to determine the big picture even when some pieces are still missing. Some puzzles lead to new understandings, others form the basis of new theories, and yet others result in new techniques. When a puzzle reaches a certain stage, it becomes easier and easier to put in the pieces; the research accelerates. The breakthrough occurs when the pictures on the puzzle become visible, when a central piece is placed that allows whole new areas to emerge. An important puzzle can lead to the start of many other new puzzles.[2]

Each year about 1.8 million papers are published in roughly 2,800 journals.[3] The journals are not all equal. *Science*, *Nature*, and *Cell* are the most prestigious ones; the important puzzle pieces are published in them. Getting a paper published in one of these journals assures the authors of a wide readership and significant prestige, and in turn the reader knows that the papers have withstood rigorous peer review and have been judged to be of importance to all scientists. The "impact factor" of a journal (the annual average number of citations per paper published in the journal in the previous two years) is an attempt to quantify its prestige. (The 2018 impact factor for *Science* was 41.1, which means that the average paper published in *Science* in 2015 or 2016 was mentioned in 41.1 papers in 2017. The parallel impact factor for *Nature* was 41.6, almost the same.) Publishing one's work in the journal with the highest impact factor is important and something of an art. Being too ambitious in journal shopping leads to rejections and delays, while taking the safer route and submitting to a journal with a lower impact can lead to less of the needed exposure and prestige that parlay into grants, jobs, tenure, and fellowships.

Nature receives about 200 manuscripts a week but can publish no more than 8 percent of them. Upon receiving a manuscript, a staff editor with expertise in the area covered by the paper makes a first cut and within a week decides whether the paper should be sent for external review or be returned to the authors.[4]

In the next step, *Science* and *Nature*, like most other science journals, use a single-blind peer-review system to evaluate their manuscripts. The papers are sent to at least two external referees, who also have expertise in the research area covered in the paper. In the single-blind process the reviewers know who wrote the paper, but the authors never officially find out the identity of the outside experts (although journals have begun experimenting in 2016 *Nature* commissioned a study of the time taken for papers to move from submission to acceptance.[10] This period includes the time taken for authors to respond to the call for revisions and additions made by the external reviewers. For some journals there had indeed been an increase in waiting time; for example, the time between submission and acceptance of *Nature* papers increased from 85 days to 150 days in the decade before 2016, while over the same period the wait for *PLOS One* manuscripts rose from 37 to 125 days. However, for the preceding 30 years the median review time for all journals had remained constant at about 100 days. Although the median time had remained the same across all journals, it had increased for papers accepted by high-impact journals. This is most likely due to increased demands from external reviewers. Leslie Vosshall, a neuroscientist at the Rockefeller University in New York City, says, "We are demanding more and more unreasonable things from each other."[11] We are writing so many papers we don't have the time to find and read anybody else's work. Since the Second World War, the number of cited papers has doubled about every nine years.[12] Vosshall says we need peer-reviewed journals as "prestige filters." Without them, "How do we find the good stuff?"[13]

Ron Vale, a cell biologist at the University of California, San Francisco, compared biology papers published in *Nature*, *Cell*, and the *Journal of Cell Biology* in the first six months of 1984 and 2014. He found that both the number of panels in experimental figures and the average number of authors rose by a factor of two to four during that 30-year period.[14] He concludes, "More experimental data are now required for publication, and the average time required for graduate students to publish their first paper has increased and is approaching the desirable duration of PhD training." This time is often lengthened by authors "journal shopping" their manuscripts in an attempt to place their manuscripts in journals with the highest impact factors. This is a risky practice that can lead to research groups being scooped by their competitors and may lead to some of the gender inequities discussed in chapter 2.

My first papers were all submitted as hard copies, and the papers were typeset. Fortunately, those days are gone. Digital publishing has sped up and simplified both the submission and publication processes. From 2000 to today, the median time from acceptance to publication has dropped from 50 to 25 days.

Some publishers are trying to speed up and clean up the publication process by using artificial intelligence programs to screen submitted papers for plagiarism, select reviewers, summarize the content of the papers, check statistics, and ensure that the manuscripts adhere to the journal's guidelines. According to Neil Christensen, the sales director of one of these programs, UNSILO, "The tool's not making a decision, it's just saying: 'Here are some things that stand out when comparing this manuscript with everything that's been published before. You be the judge.'"[15]

Sarah Reisman is at Caltech, where she has excellent students, but she has to compete with the superstars of the chemistry world to get these students to work in her lab. She thinks the greatest benefit of her *Science* paper was that it raised her profile among prospective graduate students: "Incoming graduate students are not very sophisticated yet and put a lot of weight on where you publish."

The fact that a paper has been published in a highly selective journal is a good indicator that the work described is legitimate and has been considered significant by editors and peer reviewers. Another measure of a paper's importance is how often other articles acknowledge the paper as the source of ideas, techniques, or relevant information. These acknowledgments come in the form of citations. The Web of Science is a searchable database and one of the most popular citation indexes, containing information from more than 90 million publications. According to a 2014 article in *Nature*, "If you were to print out just the first page of every item indexed in Web of Science, the stack of paper would reach almost to the top of Mt Kilimanjaro. Only the top metre and a half of that stack would have received 1,000 citations or more."[16]

The number of citations a paper gets is only an approximation of its worth. The truly important papers, like those on Watson and Crick's discovery of the DNA double helix and Einstein's special theory of relativity, aren't cited that often because once they have become part of textbooks, they are accepted as part of general scientific knowledge. Instead, the most commonly cited papers tend to be those that describe useful methods or techniques used by many research groups. Furthermore, citations vary across disciplines because, for example, biology cites much more often than physics.

To me, the most astounding finding of the research was that more than 25 million papers have never been cited in any other papers. Think of all the effort, time, and money that has gone into doing the research and then writing up the results. Did anyone even read these papers? Were they written to disseminate results or just to pad someone's résumé? The situation appears even worse when one considers that the Web of Science tries to avoid indexing predatory journals, journals that charge a substantial publishing fee and have little to no peer review.

I discuss unethical journals in chapter 10 of this book. There are tens, maybe hundreds of thousands more papers published every year that haven't even been peer reviewed and aren't considered in this research because they weren't indexed. Librarian Jeffrey Beall has published a list of known predatory journals on his website, https://beallslist.weebly.com/.

The scientific publishing business is one of the most lucrative industries in the world, with total global revenue of over $25 billion. Five for-profit companies dominate, publishing more than 50 percent of all journals. The largest, Reed/Elsevier, has 24 percent of the scientific journal market. In 2012 and 2013, Elsevier had profit margins of more than 40 percent, higher