The "computers" at the Harvard College Observatory, standing in front of the observatory entrance, 1917. Henrietta Leavitt is fourth from the left. Courtesy Harvard College Observatory.

Great Scientific Discoveries of the Twentieth Century

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Several years ago, I decided to explore some of the great discoveries in science in the twentieth century. I wanted to know: How do scientific discoveries happen? Which discoveries are accidental and which are intentional? Are there common patterns of discovery? How do styles of working and thinking vary from one science to the next and from one scientist to the next? How does the creative process in science compare to the creative process in the humanities and the arts?

I started by asking my friends – astronomers, physicists, biologists, chemists – to nominate the greatest discoveries in the twentieth century in their fields. I received about a hundred nominations, and I winnowed the list down to twenty-two.

Each of these twenty-two discoveries has profoundly changed the way we view ourselves and our place in the world. The original discovery papers themselves had a magic for me. I've often been puzzled why, in the humanities, we always read the original literature, but in science we rarely do. I think it's partly associated with the myth that in science it's only the bottom line that matters. But in the original papers we can hear the voices of the scientists; we can follow their lines of thought; we can see the great thinkers struggling to understand their place in the world. The original papers have something that no textbook summary can replace.

How do scientific discoveries happen? How does the creative process in science compare to the creative process in the humanities and the arts?

The great discoveries in the twentieth century that I chose to study are:

1. Max Planck's discovery of the quantum in 1900 revealed that energy is not continuous as people believed, but actually comes in little lumps called quanta. His findings revolutionized quantum physics and much of the computer technology that we have today.

2. In 1902, two British physiologists, William Bayliss and Ernest Starling, discovered the first human hormone. A few years later, we realized that hormones constitute a second mechanism, after the nervous system, for the body to communicate with itself.

3. Albert Einstein's 1905 discovery that light is not a continuous stream, but comes in little particles, laid the foundations of quantum mechanics.

4. Einstein's second great discovery that same year – probably the greatest discovery in physics of all time – was special relativity. He showed that the flow of time is not absolute, as it seems, but is actually relative to each observer.

5. In 1911, Ernest Rutherford found the nucleus of the atom – a tiny fraction of the volume of the atom that contains almost the entire atom's mass. If the entire atom were the size of Fenway Park, the nucleus would be the size of a marble.

6. Henrietta Leavitt, an astronomical assistant at the Harvard College Observatory, published a paper in 1912 that showed how to measure the distance to the stars, a finding of immense importance in astronomy.

7. In 1912, also, Max von Laue discovered a method for measuring the arrangement of atoms in solid matter using x-rays.

8. Neils Bohr, the great Danish physicist, put together the ideas of Planck, Einstein, and Rutherford in 1913 to construct, theoretically, the first quantum model of the atom.

9. In 1921, Otto Loewi discovered that nerves communicate with each other by secretion of a chemical.

10. Werner Heisenberg, one of the founders of modern quantum physics, published his famous Uncertainty Principle in 1927. It maintains, among other things, that we cannot predict with complete accuracy the future from the present, even if we knew all the laws of physics. The problem is that we cannot measure, or know, the positions and velocities of particles, or even a single particle, at any initial moment of time. In addition to having meaning for physics, this discovery has great philosophical, theological, and ethical meaning.

11. Linus Pauling, in 1928, published his first paper on the understanding of the chemical bond, the forces holding two or more atoms together to form a molecule. Pauling is the only person to have won the Nobel Prize in both a field of science and in peace.

12. Making extensive use of Henrietta Leavitt's earlier work, California astronomer Edwin Hubble, in 1929, found evidence showing that the universe is expanding.

13. In 1929, Alexander Fleming published his paper on penicillin, the first antibiotic, which led to the entire medical revolution that has saved millions of lives.

14. In 1937, Hans Krebs developed what is now called the Krebs cycle: the sequence of chemical reactions by which food is converted into energy in individual cells.

15. Physicist Lise Meitner and chemist Otto Hahn discovered nuclear fission in 1939 in an experiment that consisted of bombarding uranium atoms with neutrons. In previous experiments, when you bombarded a very heavy atom like uranium with a tiny subatomic particle, you only chipped off a bit of the larger nucleus. Hahn was expecting to find other atoms in the debris that were just a little less massive than uranium. But in his chemical test, he found that, after the bombardment, the remnants seemed to have the chemical properties of barium, which is half the mass of uranium. It was as if the uranium nucleus had been split in two by a diminutive neutron, similar to splitting a mountain in two with a stone from a slingshot. Hahn did the experimental work and Meitner made the theoretical interpretation.

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Hahn wrote in his paper: "As chemists, we really ought to revise the decay scheme given above and insert the symbol for barium instead of the symbol of radium, which is very close to uranium. However, as 'nuclear chemists' working very close to the field of physics, we cannot bring ourselves yet to take such a drastic step, which goes against all previous experience in nuclear physics. There could, perhaps, be a series of unusual coincidences which have given us false indications." Of course, we learn shortly later that his tests were correct: he was detecting barium, and this was the beginning of the nuclear age.

16. Barbara McClintock in 1948 discovered that genes could move around on individual chromosomes. Before that, people thought the chromosome was like a fixed chain, with fixed links.

17. Rosalind Franklin, James Watson, and Francis Crick discovered the structure of DNA in 1953.

18. Max Perutz, a physical chemist, discovered the structure of hemoglobin in 1960.

19. In 1965, Robert Wilson and Arnold Penzias accidentally discovered the radio waves left over from the Big Bang. Robert Dicke, a Princeton physicist, who was both an experimentalist and a theorist, first interpreted their discovery. In fact, a few months earlier, Dicke had predicted that radio waves left over from the Big Bang should be pervading all of space. He was building an experimental apparatus that would detect these radio waves when Penzias and Wilson told him that they had found this radio hiss in their antenna that they didn't recognize. Dicke realized that they had indeed made the discovery that he was only a month or two away from making himself. Penzias and Wilson eventually won the Nobel Prize.

20. In 1967, Steven Weinberg independently discovered the first modern unified theory in physics, showing that two fundamental forces were actually part of the same force.

21. In 1969, Jerry Friedman, with Henry Kendall and Richard Taylor, discovered quarks. The quark is the smallest known elemental bit of matter. When we were in school, we were told that the proton and neutron are the smallest particles in the nucleus of the atom. Since then, we have learned that each proton and neutron is composed of three quarks.

22. In 1972, Stanford biologist Paul Berg discovered recombinant DNA, where two strands of DNA from different organisms are joined together to create a new strand of DNA and an altered life form that never existed before in nature.

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There are two particular discoveries that I'd like to describe in more detail: One is Otto Loewi's discovery that nerves communicate with each other by the secretion of a chemical. The other is Henrietta Leavitt's discovery of a method to measure the distances to stars.

In one of the most remarkable narratives of scientific discovery, Otto Loewi recalled how the idea for testing the way nerves communicate came to him in a dream: "The night before Easter Sunday of [1921] I awoke, turned on the light, and jotted down a few notes on a tiny slip of paper. Then I fell asleep again. It occurred to me at six o'clock in the morning that during the night I had written down something most important, but I was unable

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to decipher the scrawl. The next night, at three o'clock in the morning, the idea returned. It was a design of an experiment to determine whether or not the hypothesis of chemical transmission [of the nervous impulse, from nerves to their organs] was true. I got up immediately, went to the laboratory and performed a simple experiment on a frog part, according to the nocturnal design. . . ."

At the time of his dream in 1921, it was well known that the nervous system is the primary means of communication in the body. It was also known that, in an individual nerve, the communication signal is electrical. What was not known was how the nerves conveyed their impulses from one nerve to the next, or from a nerve to an organ. In other words, how do nerves talk to the rest of the body? Most biologists believed that nerves communicated with other nerves and with organs by electricity. In this view, tiny electrical currents would flow from one nerve to the next.

Loewi's late-night experiment was not only simple but elegant. He took the hearts out of two frogs and removed all the nerves from the second heart. Into both hearts he inserted a metal tube filled with Ringer solution, which matches the concentration of salts in the body and keeps isolated hearts alive. It's hard to imagine, but these hearts were still beating outside of the animals. Loewi then stimulated the vagus nerve of the first heart – the heart that had the nerves still attached. The vagus nerve slows down the functions of organs, and the heart's rate of beating slowed down as expected.

After a few minutes, he took the fluid from the first heart and poured it into the tube going into the second, nerveless, heart. The second heart slowed down, just as if its own vagus nerve had been stimulated. Then he focused on the accelerator nerve, which speeds up all functions. When he stimulated the accelerator nerve of the first heart, it sped up. He then took the liquid out of the tube that had been stuck in the first heart and poured it into the tube going into the second heart, which sped up as well. The results provided conclusive evidence that the transmission from a nerve to an organ, or from a nerve to another nerve, is chemical, not electrical. The stimulated nerve secreted a chemical. Loewi had discovered neurotransmitters.

Henrietta Leavitt remains largely unknown to the public. Most astronomy books, even today, contain only a few sentences about her. She received no medals, no honors, no awards, and no honorary degrees during her lifetime. She left behind only a very small number of letters, mostly written to Edward C. Pickering, the director of the Harvard College Observatory, where she worked. There is a recent book about Henrietta Leavitt by George Johnson, which contains most of what little is known about her.

Leavitt developed an important new method for measuring distance in astronomy. When you go outside on a clear night and look up in the sky, you see only a two-dimensional image. You don't know how far away those tiny points of light are. If all stars had the same luminosity – think of luminosity like wattage – then the closer ones would appear brighter and the further ones dimmer, and you could judge distance by brightness. But, in fact, stars come in a wide range of luminosity. So if you see a little light there in space, you don't know whether it's the equivalent of a 1-watt penlight that's very nearby, or a 10,000-watt floodlight that is far away.

Without knowing the distance to objects in space, we didn't know anything about the cosmos beyond the solar system: we didn't know how big our galaxy is or whether there are other galaxies in addition to ours. What we need is a little label on each star telling us what its wattage is. Henrietta Leavitt found a way of putting that little label on each star. She gave astronomy the third dimension.

Leavitt was born on July 4, 1868, in Lancaster, Massachusetts. She was the daughter of a Congregationalist minister, and she remained religious her entire life. She never married. From 1888 to 1892 she studied classics, languages, and astronomy at the Society for Collegiate Instruction of Women in Cambridge, which is now Radcliffe College.

In 1895, she became a volunteer assistant at the Harvard College Observatory, joining a dozen other women who were working for its dictatorial director, Edward C. Pickering. Such women were called computers: they literally computed. Working in two rooms at the Harvard College Observatory with about eight women to a room, they did incredibly painstaking work. Photography had just come into astronomy around 1900 or so. With it came the ability to analyze vast quantities of data, because one photographic plate could hold the images of a thousand or more stars. These women computers were hired to calibrate and analyze each of these little points of light on the photographic plate. Since these were negatives, they were black points. You can imagine how tedious and painstaking this work was. Pickering hired these women

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because he could pay them much less than he would have had to pay a man to do the same work – and when you had all this data to analyze, you needed a cheap source of labor. On the other hand, this was the first opportunity for many women in the United States to start scientific careers.

A family crisis in 1900 called Leavitt away from the observatory. After an absence of two years, she wrote to Pickering: "I am more sorry than I can tell you that the work I undertook with such delight, and carried to a certain point, with such pleasure, should be left uncompleted." But in 1902, at the age of thirty-four, she came back to the Harvard College Observatory and was hired full-time, at a salary of thirty cents an hour, which corresponds in today's dollars to about eight dollars an hour. She gradually became deaf. So now imagine her working on these photographic plates with a thousand little spots on each plate in a world of silence.

The fourth category is analogy, in which the scientist applies a concept or a pattern from a previous problem.

The project Pickering assigned her, resulting in her great contribution in astronomy, was to analyze a certain kind of star called a Cepheid variable. These stars, unlike our sun, do not remain constant in brightness; instead they get brighter, then dimmer, then brighter, then dimmer, in a regular, periodic way, in cycles ranging from one day to thirty days. Leavitt's assignment was to measure the cycle times, and the brightnesses, of a group of faint Cepheid stars, all huddled together in a particular region of space called the Small Magellanic Cloud. Leavitt did this work by comparing photographic plates taken at different times and determining which little black spots had become bigger and which ones were staying the same. She noticed a pattern, an unexpected one: the brighter Cepheid stars had longer cycle times. The correlation was sufficiently good that she could infer a Cepheid's brightness by measuring its cycle time.

This finding was critical because all of these stars were in the same region of space, and so it could be assumed that they were all physically close together. If they're all very close together, that means that the brighter stars actually have a higher luminosity. It's like seeing a bunch of lights in a distant office building. Since the light bulbs are all in the same location, you know the brighter ones have greater intrinsic luminosity, or greater wattage.

Leavitt had, in effect, found a way to put that tag on a Cepheid star by discovering a correlation between intrinsic luminosity and cycle time. Once we know the intrinsic wattage of a star, we can measure its distance by how bright it appears.

Her work was published in a three-page paper in the *Harvard College Observatory Newsletter*, signed by Pickering. In 1918, Harlow Shapley, who would later become director of the Observatory and President of the American Academy, used her method of measuring cosmic distance to measure the size of our galaxy, the Milky Way. In 1924, Edwin Hubble used Leavitt's findings to show that other galaxies lie beyond ours, and in 1929, he used her work to show that the universe as a whole is expanding. Playing that expansion backwards in time, we were able to conclude that the universe as a whole began about 10 billion years ago. All of those incredible discoveries came from Henrietta Leavitt's initial finding of how to measure the distances to stars.

Leavitt's title at the Harvard College Observatory, from the beginning to the end, was "assistant." She never asked for anything more. She died of cancer on December 12, 1921, at age fifty-three, unknown by almost everyone except a few astronomers who were aware of her work. Shortly before her death, Henrietta Leavitt wrote out her will, leaving her possessions to her mother: bookcase and books, $5; folding screen, $1; rug, $40; table, $5; chair, $2; desk, $5; bedstead, $15; two mattresses, $10; one bond at $100 face value; one bond at $48.56; one bond at $50.

Harvard astronomer Solon Bailey wrote this about Leavitt in her 1922 obituary: "Her sense of duty, justice, and loyalty was strong. Miss Leavitt was of an especially quiet and retiring nature, and absorbed in her work to an uusual degree." Three years after her death, in 1925, Professor Mittage-Leffler of the Swedish Academy of Scientists wrote a letter to Henrietta Leavitt, saying that he would like to nominate her for a Nobel Prize. He didn't know that she had died three years earlier.

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From my sample of these twenty-two discoveries, I've tried to see if I can make any generalizations. I have developed what one might call a taxonomy of scientific discovery, in which I've grouped all of the discoveries into six categories. Of course, any such taxonomy is subjective; no one knows exactly what's going on in the creative process. The real test is to see if this system applies to discoveries in the nineteenth century, the eighteenth century, and so on.

The first category is the accident, in which the scientist discovers something that he or she was not looking for. About a quarter of the discoveries that I looked at fall into this category. The discovery by Penzias and Wilson in 1965 of the cosmic background radiation – those radio waves – is an example of an accident. Alexander Fleming's discovery of penicillin in 1928 was also an accident. He came into his laboratory one day and found white fluff growing on his staphylococci colonies; where it touched the colonies, they were killed.

The second category, which is very rarefied, is 'principles first.' Here the scientist begins with a philosophical principle and then explores the consequences of that principle. The premier example of this is Einstein's discovery of the way time behaves, the Special Theory of Relativity. Here, Einstein started with the philosophical principle that there is no such thing as a state of absolute rest in the universe. If you were in a car going at a constant speed and pulled the shades down so that you could not look out of the window, you would not be able to tell how fast you're moving, or even if you're moving at all. From this principle, Einstein deduced all of the equations of special relativity.

The fifth category is new tools. Sometimes a new instrument comes along, to which a particular scientist has exclusive access, and he or she uses it to make a great discovery.

The third category is the timely clue, in which the scientist is confronted with an important clue just at the moment when he's struggling with a recognized problem. Barbara McClintock's discovery in the late 1940s that genes could move around on chromosomes is an example of this type. She was attempting to understand how pigment-controlling genes were turning on and off in the growth cycle of a single corn plant. The phenomenon appeared not in a random mutation but in some regular way. One day in 1946, while looking at the colored stripes on the leaves of her corn plant, she noticed that these mutations came in pairs. That was the critical hint she needed.

The fourth category is analogy, in which the scientist applies a concept or a pattern from a previous problem. A good illustration of this is Krebs's discovery of the cycle of chemi-

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cal reactions in which energy is released in an individual cell. A few years earlier, he had discovered another cycle in biochemistry, the "ornithine cycle," which starts with a chemical called ornithine, then changes into citrulline, which changes into arginine, before turning back into ornithine. In the process, ammonia, which is toxic to the body, is absorbed and urea is given off. Krebs had the idea of cycles in his mind.

The fifth category is new tools. Sometimes a new instrument comes along, to which a particular scientist has exclusive access, and he or she uses it to make a great discovery. An example is Edwin Hubble's discovery of the expansion of the universe. I'm not saying that Hubble wasn't a brilliant man, but he had exclusive access to the new hundred-inch Hooker telescope on Mt. Wilson. Other astronomers were working on the same problem, but Hubble had the largest telescope in the world.

The last category, one that gives hope to me and to many people, is what I call the 'long haul,' in which there's not a single insight, nor a single brilliant idea, but slow, steady, committed, incremental work over a long period of time that produces a great discovery. An example is Max Perutz's discovery of the three-dimensional structure of hemoglobin, which took him twenty-two years, from 1938 to 1960.

There are some common patterns across these six categories of discovery. Most discoveries involve a synthesis, in which the scientist brings together strands of information from previous discoveries. For example, Bohr's discovery of the quantum atom used the work of Planck, Einstein, and Rutherford.

Another pattern that occurs in many, but not all, discoveries is the following sequence of events: First comes the research and hard work, leading to what I call 'the prepared mind.' Then, a scientist will get stuck on a problem. Finally, after being stuck, he or she will have a shift in perspective, a new way of looking at the problem. Lise Meitner's understanding of nuclear fission followed this pattern. So did Watson, Crick, and Franklin's discovery of the structure of DNA. And others as well.

The prepared mind is critical. I don't know of any examples of major scientific discoveries in the twentieth century made by untrained amateurs. Even when the discovery was accidental, even when the scientist was not looking for the discovery, his or her mind was prepared to realize the discovery's importance. Being stuck is also a very important part of the creative process. This frustrating mental condition – after you've done your homework, after you know what the important problem to be solved is – somehow catalyzes the creative imagination.

I've seen this pattern of discovery in the arts as well as the sciences. As both a novelist and a physicist, I have experienced this pattern of discovery. I've recognized the same pattern when writers and actors talk about their creative process. Let me read a snippet from *The Paris Review*, which has a wonderful, long-standing set of interviews with writers. In 1990, Wallace Stegner commented: "I don't go in search of projects. Sometimes they appear before my eyes, and sometimes they grow over a long period of time, as I brood." With the case of *Crossing to Safety*, one of his novels, he said, "I knew from the beginning it was going to be a book. You have that feeling. It's like a fish on the line. But I didn't know what book it was going to be. I had to discover that by trial and error."

In Janet Sonenberg's book *The Actor Speaks: Twenty-Four Actors Talk About Process and Technique*, John Turturro (who was in, among other things, *Barton Fink* and *The Secret Window*) wrote: "Once the scene's dynamic is starting to occur, I'll go with it and then try to shift it, too, just like you would in life. The shifting is important. Then, if I can get to the point when I know that that's happening, and I don't know what I'm doing, that's inspiration. I've done all my work, and then I try to achieve this other living dimension."

Finally, there is no single scientific personality. A scientist can be bold and self-confident, like Einstein or Rutherford or Watson. A scientist can also be modest and quiet, like Leavitt or Krebs or Fleming or Meitner. William Bayliss, who discovered the first hormone in 1902, was cautious, meticulous, in love with the details. His collaborator, Ernest Starling, was just the opposite. He was brisk, impatient, engaged mainly in the broad sweep of things.

What all of these men and women shared – and this I saw in every single discovery, whether the people received encouragement or discouragement from their parents, whether they were the revolutionary type or the retiring type – was a passion to know, a sheer pleasure in solving puzzles, an independence of mind. The American biologist Barbara McClintock recalled that in high school science classes, "I would solve some of the problems in ways that weren't the answers the instructor expected. It was a tremendous joy, the whole process of finding that answer, a pure joy." When the German nuclear physicist Lise Meitner was a little girl, her grandmother warned her that she should never sew on the Sabbath because the heavens would come tumbling down. So the little girl decided to do an experiment. She touched her needle to her embroidery, waited, and looked up; but nothing happened. Then she took a single stitch, waited, looked up, and nothing happened. Finally, satisfied that her grandmother had been mistaken, she continued her sewing. ■
