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Deducing Weather

The Dawn of Computing

Our climate prediction story begins in the historic town of Princeton, New Jersey. The town was the site of a battle during the Revolutionary War; after the war, in 1783, Princeton served for four months as the provisional capital of the United States. Today it is best known as the home of Princeton University. Through the center of town runs Nassau Street, which began as part of a Native American trail that later became a stagecoach route between New York and Philadelphia. This street marks the divide between "town" and "gown": To the north lives the general population of Princeton, and to the south lies the picturesque campus of Princeton University with its neo-Gothic architecture.

On Nassau Street's north side, across from the university, there is a wonderful independent bookstore called Labyrinth Books. Here, for the affordable price of $7.95, you can buy yourself a whole year's worth of weather and climate forecasts. These forecasts are found in the annual edition of a little book called the *Old Farmer's Almanac*, which has proudly provided this service every year for more than two centuries.[1] For each of eighteen different regions of the United States, the almanac lists quantitative predictions of the average temperature and precipitation for each month of the year, as well as qualitative weather forecasts for individual periods of these months. The almanac even features a thoughtfully placed hole in its top left corner so that it can be hung from a nail in the barn or the outhouse, enabling convenient perusal of its folksy weather-related articles and tables.

Historically, the almanac used a secret formula for weather forecasts, devised in 1792 by its founder, Robert B. Thomas. This formula is based on the premise that "nothing in the universe happens haphazardly, that there is a cause-and-effect pattern to all phenomena."[2] Thomas believed that the sun had an effect on the Earth's weather, and he credited Italian astronomer Galileo Galilei's seventeenth-century study of sunspots as a key part of his secret formula. Farmers – the almanac's original target customers – needed to know,

for instance, when the first snow of the year would fall in order to plan their harvests. Even townsfolk could benefit from advance knowledge of sunny days on which to plan a wedding or a picnic. The longevity of the almanac demonstrates its success in catering to the practical needs of farmers and townsfolk over the years. But the venerable almanac does have competition in the folksy prediction market: Since 1887, a groundhog named Phil has been prophesying the start of spring in the town of Punxsutawney, Pennsylvania.[3] We shall make further acquaintance of this furry forecaster later on.

For decades, while the *Old Farmer's Almanac* and, later, Punxsutawney Phil made their prognostications, the "gown" part of Princeton – the scientists in the ivory towers of the university – remained largely silent on the subjects of weather and climate prediction. That began to change in the late 1940s, with the invention of the digital computer.

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Let us walk south from Labyrinth Books through the university campus, past Nassau Hall (which served as the capitol building while Princeton was briefly the nation's capital). We eventually arrive at Jones Hall. This well-appointed building with carved oak paneling modeled after colleges at Oxford University currently houses the departments of East Asian Studies and Near Eastern Studies. Let us go back in time to 1931, when this building was built. It was then the new home of the mathematics department. It also had a different name, Fine Hall, after the beloved and well-respected math professor Henry B. Fine.[4] (The building's name was changed to Jones Hall in 1969, when the mathematics department moved to a new building. That building inherited the name Fine Hall.)

One of the occupants of Fine Hall in 1931 was the man who helped design it, a mathematician named Oswald Veblen.[5] Mathematics faculty were generally burdened with heavy teaching duties. Therefore, Veblen nursed a grand vision of a new science institute, a true ivory tower, in which faculty would focus only on research.[6] He managed to persuade an educator named Abraham Flexner, who was already in the process of setting up an institute of this nature, to locate it in Princeton. Known as the Institute for Advanced Study (IAS), it would bestow renowned scientists with lifetime appointments as professors, with no teaching responsibilities. There would additionally be a regular flow of short-term visiting scientists to the institute.

Flexner, the founding director of the IAS, was a strong proponent of curiosity-driven research; he published an essay with the provocative title "The Usefulness of Useless Knowledge."[7] He persuaded a wealthy New Jersey family, the Bambergers, to contribute the equivalent of $200 million

today to his project. A permanent building was to be constructed for the IAS using these funds, about a mile from the main campus of Princeton University. In the meantime, though, Flexner needed to find a temporary office for the scholars who would comprise the institute. Fine Hall was ideal for this purpose; the new members of the IAS could interact with the mathematicians already there, as well as with the physicists in the adjacent Palmer Physical Laboratory (which is now the Frist Campus Center).

All was settled, and the IAS began operations in Fine Hall in 1933. Among its early recruits was the world-famous physicist, Albert Einstein. Another was a young mathematician named John von Neumann, who published his first mathematics paper before the age of eighteen. Von Neumann, the son of a wealthy banker, was born in 1903 in Budapest, Hungary. He was a prodigy who reportedly had the ability to recall entire books; before he joined the IAS, he had already written an influential book on the *Mathematical Foundations of Quantum Mechanics.* In 1935, von Neumann visited the University of Cambridge in England. There he met a young mathematician named Alan Turing, who was working on fundamental problems relating to the mathematics of computability.[8] Intrigued by Turing's research, von Neumann encouraged him to come to Princeton.

After receiving his degree from the University of Cambridge, Turing arrived in Princeton in 1936 to start his Ph.D. under Alonzo Church, a professor in the Department of Mathematics.[9] Between 1936 and 1938, Fine Hall housed Einstein, von Neumann, and Turing, three of the most legendary names in physics, mathematics, and computer science – the last being a field which did not even exist at the time. These three fields would come together in Princeton to birth the fields of numerical weather prediction and numerical climate prediction.

In a landmark 1936 paper, "On Computable Numbers, with an Application to the Entscheidungsproblem," Turing conceived of a universal computing machine with an infinite tape – a tape that the computing machine could read symbols from, write symbols on, or erase repeatedly. The tape could move forward or backward under the direction of the machine. This conceptual machine, now known as a Turing Machine, could carry out any computation which involved well-defined steps. Turing used this hypothetical construct to show that there were numbers that could not be computed using this machine. This led to the conclusion that there was no general computing procedure to prove if a computer program would eventually halt. In essence, Turing had invented a universal computing machine to prove the limitations of computing. This paper forms one of the foundations of the field of computer science.

In Princeton, Turing continued to work on problems related to computation. However, with the offices of luminaries such as von Neumann and Einstein just down the corridor from him, he felt that his own work would not be recognized.[10] After Turing completed his Ph.D. in 1938, von Neumann tried to persuade him to stay by offering him a research position at the IAS, but Turing decided to return to England. In the years following, von Neumann continued to be fascinated not only by the idea of building computing machines but also by the possibility of their practical utility.

Among the mathematicians of the IAS, von Neumann was somewhat of an oddity. He could hold his own among theoreticians like Einstein and Kurt Gödel, the great mathematical logician who had visited and later been recruited to the IAS. Gödel's work is about as theoretical as it gets: He is famous for proving the Incompleteness Theorem, which demonstrated the limits of mathematics and inspired Turing's work on the limits of computation. But, unlike either Einstein or Gödel, von Neumann was very much interested in useful applications of "useless knowledge," that is, the practical applications of science[11] such as hydrodynamics, meteorology, and the design of ballistic and nuclear weapons.

Being both a physicist and a newly minted computer scientist, von Neumann realized computers could be used to predict weather from basic physical principles.[12] But the Turing Machine, while a beautiful concept, was not a practical computer design. (It required an infinite tape, for instance.) So, von Neumann set out to design and build an electronic computer at the IAS. Due to such a computer's potential military applications, von Neumann was able to convince the US Atomic Energy Commission and various military agencies to fund this expensive endeavor.[13] While he waited for the IAS machine to be built, von Neumann would use the world's first general-purpose computer, the Electronic Numerical Integrator and Computer (ENIAC) – which was designed by another scientist interested in weather prediction.

1.1 From Sunspot Cycles to Compute Cycles

The cycles of heavenly objects have long fascinated humans. Inherent in cycles is their predictability: A peak in a ten-year cycle will be followed by a trough five years later, and by another peak ten years later. The English astronomer Edmond Halley was able to calculate the orbit of the comet eventually named after him and to predict its next appearance – fifty-three years in advance!

In 1933, John Mauchly was the head (and sole member) of the physics department at Ursinus College[14] in Collegeville, Pennsylvania, about 50 miles west of Princeton. He had tinkered with electronics throughout his youth and enrolled in the engineering school at Johns Hopkins University, but, turned off by the "cookbook style" of engineering courses, he ended up switching fields to physics and was awarded a Ph.D. in 1932.[15] Mauchly's research involved harmonic analysis – looking for periodic oscillations – in weather data. He built an analog harmonic analyzer machine, and he published a paper on oscillations in rainfall. The number of sunspots – dark areas on the surface of the sun – also exhibited 11-year oscillations, and Mauchly was looking for evidence that solar variations could be used to predict weather years in advance. (Recall that sunspots were also part of the secret formula used by Robert B. Thomas, the founder of the *Old Farmer's Almanac.*)

Mauchly wanted to analyze weather data to scientifically demonstrate a relationship between weather and the number of sunspots. The data was too voluminous for Mauchly to manually calculate the necessary statistical correlations; he figured that he could build an electronic computing device to speed up the calculations, but he needed support. Ursinus College was too small an institution to host such an endeavor. Mauchly persisted, and, in 1942, during the Second World War, he moved to Philadelphia to join the faculty of the Moore School of Engineering at the University of Pennsylvania.[16] During the war, the Moore School worked closely with the US Army, which required extensive computations for firing tables to find, for instance, the range of artillery shells. Using humans to perform these computations had proved too slow. Mauchly's proposed electronic computing device could solve the Army's problem. With an initial grant of $61,700 from the Army,[17] Mauchly partnered with J. Presper Eckert, an engineer, to design the ENIAC in 1943. The ENIAC was the first general-purpose electronic computer in the world, meaning it could be used for any type of calculation. Its predecessors were all computers custom-built for specific types of calculations.

Mauchly and von Neumann soon crossed paths. Purely by chance, a member of the ENIAC team recognized von Neumann on a railway platform in 1944 and invited him to meet with the team.[18] This led to von Neumann joining the team as a consultant. The ENIAC project itself ran behind schedule and was only completed in December 1945. The ENIAC was a behemoth, weighing 30 tons and containing 18,000 vacuum tubes.[19] Its final cost was about $500,000 (the equivalent of $7 million in 2019). It occupied an area of 30×60 feet and consumed about 160 kW. It had a memory of 40 bytes and could perform about 400 floating-point (or arithmetic) operations per second

(flops). For comparison, a modern desktop computer can have almost a billion times more memory and can run more than a billion times faster.

The war was over by the time ENIAC was operational, and there was no longer an urgent need for ballistics computations. But the ENIAC would still be put to military use: A new type of weapon, the hydrogen (or fusion) bomb, was now in development, and its design would require complex calculations of shockwaves and explosions. Von Neumann used the ENIAC to carry out these top-secret calculations. Mauchly and Eckert went on to form a private company to commercialize their invention,[16] although Mauchly continued to work on the statistical analysis of sunspot cycles.[20] Later in this book, we will revisit the possible role of sunspot cycles in climate. But first, we turn to a problem that motivated both Mauchly and von Neumann: weather prediction.

1.2 Philosophy Break: Inductivism versus Deductivism

Computer pioneers von Neumann and Mauchly (Figure 1.1) were both interested in the accurate prediction of weather, but they approached the problem from diametrically opposite directions. Mauchly, the former engineer, wanted to analyze large volumes of weather data to reveal relationships between

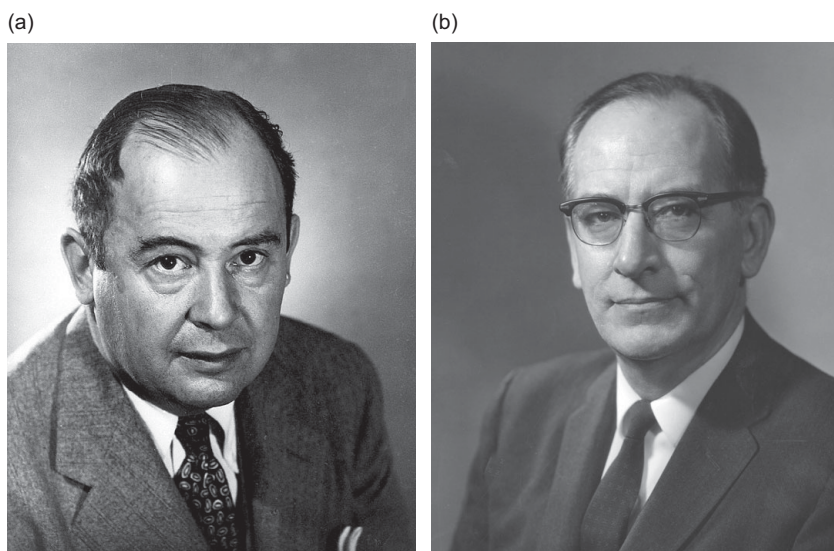(a)   (b)

Figure 1.1 (a) John von Neumann (Photo: US Dept. of Energy). (b) John W. Mauchly. (Photo: Charles Babbage Institute Libraries, University of Minnesota Libraries)

weather cycles and sunspot cycles, and then use those relationships to predict weather. Von Neumann, the grand theoretician and genius mathematician, hypothesized that the atmosphere could be divided into a grid of points and that weather could be predicted by applying the laws of physics at each point. Both approaches required an immense number of calculations, a number beyond human capability – hence the need for the electronic computer.

Mauchly and von Neumann exemplify two contrasting approaches to scientific progress: the *data-driven* approach and the *hypothesis-driven* approach. The data-driven approach to science may be referred to as *inductivism*, a branch of empiricism, which is the study of knowledge from experience. The hypothesis-driven approach may be referred to as *deductivism*, a branch of rationalism, which is the study of knowledge from reasoning.

A classic example of inductive reasoning is as follows: We watch one hundred swans pass in sequence, note that they are all white, and conclude therefore that all swans are white. What we might call the "theory of white swans" was indeed the accepted wisdom in the Western world regarding swans through the end of the seventeenth century[21] – until the exploration of Australia, when a black swan was spotted. The observation of a black swan falsified the theory of white swans. The Austrian–British philosopher Karl Popper, in his 1935 work *The Logic of Scientific Discovery*, emphasized that the falsifiability of theories is a key requirement of science.[22] Unlike mathematical theorems, scientific theories cannot be proven true, but they can be falsified. More and more observations of white swans can confirm the theory of white swans, but they cannot prove it.

The black swan has now become a metaphor for an unprecedented cataclysmic event, such as a stock market crash. Inductive reasoning cannot predict these kinds of events. This is a shortcoming known as the "problem of induction."[23] As discussed in the Introduction, the Great Galveston Hurricane of 1900 was not well predicted because it took a path across the Gulf of Mexico that went against the conventional wisdom at the time. But, unlike inductive reasoning, deductive reasoning can predict unprecedented events. The rainfall over Houston due to Hurricane Harvey in 2017 was (literally) off the charts, but the weather forecasts based on deductive computer models were able to predict it by solving the equations governing air motions.

Science progresses by creating new theories or models. In this book, the terms "theory" and "model" are used almost interchangeably. There is no real difference between the two. A model is an abstraction of reality; so is a theory. It is true that models are more commonly quantitative abstractions of reality, while theories are more commonly qualitative descriptions of reality. However, this distinction is far from absolute: Einstein's special theory of relativity involves rather complicated mathematical equations!

Discussions of scientific theories or models often emphasize their *predictive power*. In 1915, Einstein developed his general theory of relativity, hypothesizing that the sun's gravity could bend light and thus alter the apparent position of a star in the sky. This theory was verified by British astronomer Arthur Eddington's measurements during an eclipse in 1919.[24] The hypothesis-driven deductive approach emphasizes bold predictions. We can separate good theories (or models) from bad theories (or models) by looking at how accurate these bold predictions turn out to be.

The data-driven inductive approach, on the other hand, emphasizes the *explanatory power* of theories or models. The British naturalist Charles Darwin collected thousands of specimens and filled notebooks with careful observations and sketches of plants and animals during his five-year voyage on the ship the HMS *Beagle*. After studying the data he had amassed to understand how organisms had changed over time, Darwin (along with another British naturalist, Alfred Russel Wallace) proposed the theory of evolution through natural selection. The theory provides an elegant explanation of the observed characteristics of existing as well as extinct animals, and serves as a fundamental principle of modern biology.

In this book, we will frequently make distinctions for the purposes of analysis. We will use the concept of the analytic knife, also known as Phaedrus's knife (after the character in Robert M. Pirsig's 1974 book *Zen and the Art of Motorcycle Maintenance*). Our analytic knife[25] is the distinction between inductivism and deductivism. With it, we cut through the tangled web of multifarious approaches to scientific research.[26] It is admittedly a simplistic distinction, black and white without shades of gray. Much of real science involves a combination of both inductive and deductive approaches:[27] Theoreticians use old data to build scientific models, make predictions to test them, and refine them as new data are obtained from experimentalists. Asking whether the theory or the observation came first is like asking whether the chicken or the egg came first.

An ancient example of an inductive discipline is meteorology, the study of weather. The name itself is derived from the ancient Greek word *meteora*, referring to that which is high in the sky or the heavens. In the fourth century BCE, the Greek philosopher Aristotle wrote a treatise called *Meteorologica*, which remained the definitive work in the field for two millennia.[28] At the start of the twentieth century, meteorology was largely data driven, and more an art than a science: Meteorologists gathered observations of weather, mapped pressure and temperature, and made forecasts based on their previous experience.[29] This inductive approach to making forecasts was not very reliable. For instance, weather systems are often thought of as moving roughly with the

prevailing winds. But prevailing winds near the surface can be quite different from prevailing winds higher up and can affect weather systems in different ways. Furthermore, weather systems can themselves alter the prevailing winds as they move. Human experience alone could not account for the variety of possible effects.

During this time, the physical sciences were making remarkable progress in explaining the fundamental behavior of nature, with the formulation of both quantum mechanics and the theory of relativity in the early twentieth century. The predictive power associated with some of these developments was spectacular: The theory of relativity, for example, accurately predicted small perturbations in the orbit of Mercury. Many physical scientists began to wonder why the same hypothesis-driven approach could not be applied to weather.[30] After all, weather was nothing more than air flow, driven by pressure forces and subject to Newton's laws of motion.

The mathematical equations governing the physics of weather were understood at this time; but solving these equations to forecast weather for the entire world was too much work for a single person. One British scientist, Lewis Fry Richardson, decided to try anyway.[31] He used a simple equation, called the *continuity equation*, to make a six-hour weather forecast for a day in the past (May 20, 1910). Richardson spent more than two years completing a long and tedious set of hand calculations. The results he obtained were, in the end, completely unrealistic. In fact, his forecast was so bad that he published a book about it, titled *Weather Prediction by Numerical Process*, in 1922. After his failed one-man effort, Richardson concluded that the computations he had attempted on his own would need to be farmed out to a large team of about 64,000 people in order to make a timely forecast (Figure 1.2a). This proposed

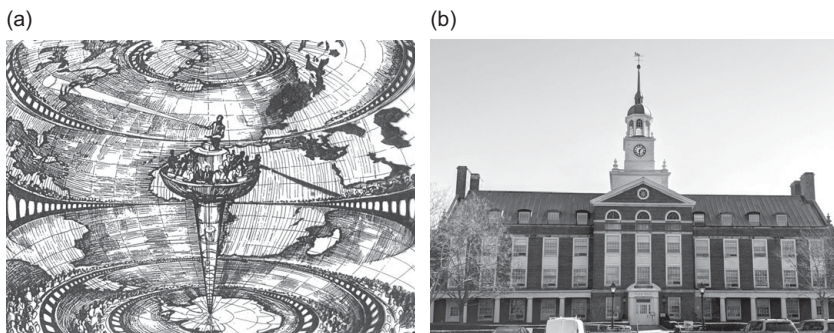(a)   (b)

Figure 1.2 (a) A depiction of Richardson's proposed "forecast factory" (A. Lannerbäck, Dagens Nyheter, Stockholm). (b) Fuld Hall, Institute of Advanced Study, Princeton, New Jersey. (Photo: Shiva Saravanan)

"forecast factory" was impractical, but it set the stage for the use of digital computers in weather prediction. Richardson's ideas would play an influential role in the evolution of meteorology into a science.

1.3 The Weatherperson and the Computer

Let us return to Fine Hall (now Jones Hall) in Princeton. We walk a mile and a half southwest along College Road, past the Graduate College, turning left on Springdale Road, and then turning right on Ober Road, which becomes Einstein Drive. We have reached Fuld Hall, the permanent home of the IAS (Figure 1.2b).[7] The IAS faculty and staff moved into this Georgian-style building in 1939, soon after Turing's departure. While the ENIAC was being completed in 1945, von Neumann initiated the Electronic Computer Project to build a computer at the IAS, hiring many scientists and engineers for that purpose. Soon after that, in 1946, von Neumann formed the Princeton Meteorology Group, which would use the new computer to predict weather by solving the equations that govern atmospheric motions.

Since he himself had little detailed knowledge of atmospheric flows, von Neumann enlisted experts in that area.[32] The first such expert was Phil Thompson,[12] an Air Force meteorologist who learned about von Neumann's computer project from an article in the *New York Times Magazine*. Thompson joined von Neumann in 1946 and remained with the project for two years, during which time he learned about numerical analysis, the technique of solving mathematical equations using a digital computer. Before Thompson returned to the Air Force in 1948, he recruited one of his academic acquaintances, Jule Charney, to the Princeton Meteorology Group. Charney had recently derived a simple set of mathematical equations that could be very useful for computing weather forecasts of the sort envisioned by von Neumann.

Charney served as the anchor of the Princeton Meteorology Group, and he would go on to become a major figure in weather and climate science. His doctoral thesis on wavelike motions in the atmosphere was a groundbreaking work in the field, occupying the entire October 1947 issue of the *Journal of Meteorology*.[33] Upon completing his doctorate, Charney visited the University of Chicago to work with Carl-Gustaf Rossby, the preeminent meteorologist of the time. Rossby was one of the leading architects of the midcentury transformation of meteorology from an uncertain art into a certain science, one based on mathematics and physics. After Charney arrived in Princeton during the summer of 1948, he and von Neumann recruited several other atmospheric

scientists from the United States and Europe to the Princeton Meteorology Group.[34]

The mathematical equations governing the motion of air, known as the Navier-Stokes equations, are derived from Newton's laws of motion applied to a fluid. Given the state of the atmosphere at a given time, these equations predict how the air will move under the action of the various forces. In principle, we can use a computer to solve these equations and forecast the weather for the next 24 hours. However, we cannot do this in a single step; we need to subdivide the problem into smaller steps. Say we make a forecast for the next hour. Then we can use that forecast to make a forecast for the following hour, and so on, until we have forecast 24 hours into the future. Choosing the number of steps for a forecast is like choosing the frame rate for a video. If there are too few frames per second, the motion will become increasingly jerky and inaccurate, and eventually cause the program to crash. If there are too many frames per second, the motion will be smooth, but it may overload the computer.

The time interval between the frames of a forecast, known as the *time step*, needs to be as large as possible, to minimize the total number of steps and the associated computational work. But for the computational work to be stable and accurate, the time step needs to be short enough to capture the evolution of each of a number of processes in the atmosphere. The processes governed by the Navier-Stokes equations include weather systems, fronts, and even sound waves. Sound waves have periods of much less than a second. This means that to solve the full Navier-Stokes equations directly on the computer and make a forecast, we need to use a time step of a fraction of a second.

With the computing power available in 1948, it was not feasible to make a 24-hour weather forecast with such a short time step. There would be far too many frames for the computer to handle. (Actually, even modern computers are not capable of such a short time step!) But sound waves are not important for weather forecasts. Charney analogized the atmosphere to a musical instrument that can play many tunes.[35] Sound waves are like the high notes, and weather systems are like the low notes. To forecast weather, the atmosphere only needs to play the low notes, because the high notes do not affect the weather.

The Navier-Stokes equations had to be simplified to eliminate "extraneous" processes, which would allow a longer time step for the forecast and a lower frame rate for the computer. The Princeton Meteorology Group considered two ways to accomplish this simplification. They could (1) use a two-dimensional model that took the drastic step of ignoring the vertical dimension of the atmosphere, thus eliminating the extraneous processes or (2) use a more
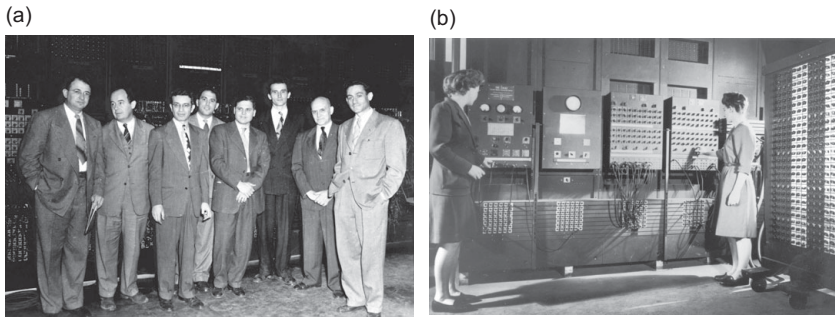
(a)   (b)

Figure 1.3 (a) Visitors and some participants in the 1950 ENIAC computations: (left to right) Harry Wexler, John von Neumann, M. H. Frankel, Jerome Namias, John Freeman, Ragnar Fjørtoft, Francis Reichelderfer, and Jule Charney, standing in front of the ENIAC. Wexler, Frankel, Namias, and Reichelderfer were visitors from the Weather Bureau. G. Platzman and J. Smagorinsky are absent. (Photo: Courtesy of John Lewis, reproduced from the Collections, Library of Congress). (b) Programmers Jean Jennings (left) and Frances Bilas operating the ENIAC (US Army photo)

elaborate three-dimensional model that incorporated a mathematical approximation (called quasi-geostrophy) that would also eliminate the extraneous processes. The two-dimensional model was already in use and therefore familiar to meteorologists, and Charney had just derived the equations of quasi-geostrophy necessary for the three-dimensional model.[12]

In 1950, the group decided to make an initial set of weather forecasts using the two-dimensional model. But the IAS computer was not ready yet. Von Neumann arranged to borrow some computer time from the ENIAC, which had by then been moved from Philadelphia to Aberdeen, Maryland. The group traveled to Aberdeen in March of that year to make the world's first set of numerical weather forecasts (Figure 1.3a). Three members of the Princeton team supervised the programming of the ENIAC for the forecasts: George Platzman, John Freeman, and Joseph Smagorinsky. Harry Wexler of the US Weather Bureau also worked with the team.

Group photos of scientists from the early days of computing and weather prediction (e.g., Figure 1.3a) may give the impression that all of the work was carried out by men. But photos of early computers like the ENIAC, with the first programmers standing next to the computers, often feature women (Figure 1.3b).[36] Despite the institutional barriers that inhibited their advancement in science, women often played important roles behind the scenes. While the engineers and scientists who worked on the computer hardware were almost exclusively men, the computer programmers were frequently women.

The wives of many scientists in the Princeton group[37] – including Klara von Neumann, Marj Freeman, and Margaret Smagorinsky – worked with computers as part of the research endeavor. Their contributions were significant but received little public recognition[38] aside from the occasional "thank you" in the acknowledgments section at the end of a paper. Klara von Neumann, in particular, played a crucial role in the project. Klara had previously worked with her husband, John, on classified atomic bomb simulations using the ENIAC.[39] She was a skilled programmer who taught other scientists how to code and was the one to check the final version of the program.

Programming in 1950 was a very different experience than it is today. Computers had neither keyboards nor monitors. Instead, there were massive banks of switches and large plug boards with connecting wires.[40] Platzman describes the ENIAC programming technique as follows:

> the programmer had available only about a half-dozen or at most 10 words of high-speed read/write memory. An intermediate direct-access but read-only memory of 624 six-digit words was provided by three so-called "function tables," on which decimal numbers were set manually by means of 10-pole rotary switches, a tedious and lengthy procedure.[41]

To transmit and receive data from the ENIAC, the well-established technology of punch cards was used. Each punch card, somewhat larger than a postcard, represented one 80-character line of input or output. For each character in the line, a unique combination of holes, readable by a machine, was punched in the card. While printing and magnetic tape were later invented for computer output, punch cards remained the preferred way to input data well into the 1970s.

The Princeton Meteorology Group worked intensely over a five-week period in Aberdeen. Since the ENIAC had very limited memory, about 100,000 punch cards were used to record the details of the weather forecasts.[42] The programming required round-the clock effort, with programmers working in shifts.[12] In the end, four 24-hour forecasts were made for selected days in the previous year. The forecasts had some skill, although it took ENIAC 36 hours to compute a 24-hour "forecast"[43] – too slow to be of practical use!

A paper describing these forecasts – which were the first numerical forecasts ever – was published, coauthored by Charney, von Neumann, and Ragnar Fjørtoft, a visiting scientist from Norway. Since the two-dimensional model was considered too drastic a simplification of the atmosphere, the Princeton group decided to use the three-dimensional model for numerical prediction, expecting that it would improve the skill of the forecasts. The vertical dimension in the three-dimensional model was represented using either two or three

grid points, or pressure levels.[44] The IAS computer, completed in 1952, was used to carry out three-dimensional forecasts to predict the famously intense storm that had occurred on Thanksgiving Day 1950.[45] Although the results initially appeared promising, further analysis indicated that three-dimensional forecasts were less skillful than two-dimensional forecasts, and the approach was abandoned for the time being.

The forecasts made by the Princeton group in 1950 using the ENIAC were for research purposes only, but the field of meteorology was never the same again. The mathematical approach pioneered by the Princeton group provided the previously subjective discipline with an objective foundation. Meteorologists around the world read the papers published by the group and improved upon them, using faster digital computers and better algorithms. Today, this technique of making forecasts by solving the equations of motion using a computer is called *numerical weather prediction*.

Although the United States was the first country to research numerical weather prediction, it was not the first country to use it for operational forecasts. A Swedish scientist named Bert Bolin visited the IAS in 1950 to work with Charney to study the effect of mountains on weather.[46] When Bolin returned home, he joined a Swedish weather prediction effort led by Charney's Swedish-born mentor, Rossby. The first operational weather forecast in Sweden was made in late 1954, using a locally built computer called the Binary Electronic Sequence Calculator (BESK).[47]

The Princeton Meteorology Group continued for several years to carry out research on numerical weather prediction using the new computer. It eventually disbanded in 1956,[29] and its former members went on to have illustrious research careers elsewhere, many playing important roles in future scientific developments. Unfortunately, Von Neumann had been diagnosed with cancer by 1956. We will discuss his final days in Chapter 19.

1.4 The Dark Side of Weather Prediction

All stable processes we shall predict.
All unstable processes we shall control.

John von Neumann[48]

Predicting weather seems like a harmless application of science, but the motives behind some early efforts at weather prediction were not always benign. The military supported weather prediction because it could provide valuable intelligence to troops in the field, but that was not the only reason for

its interest. The early- to mid-twentieth century was the heyday of hypothesis-driven physical science, and many scientists, including von Neumann, believed that if the weather could be predicted, it could also be controlled for civilian and military purposes.[49] The *New York Times* wrote in 1946 that "some scientists even wonder whether the new discovery of atomic energy might provide a means of diverting, by its explosive force, a hurricane before it could strike a populated place."[50]

Like the hydrogen bomb, weather modification could prove to be the ultimate weapon if the enemy were to acquire it first during the Cold War. The early computers used overtly to make weather forecasts were also used covertly to design hydrogen bombs. Von Neumann himself had helped design these bombs, as part of the top-secret Manhattan Project. He is even credited with using his expertise in game theory to develop the doctrine of Mutual Assured Destruction (MAD) that maintained the uneasy peace between the United States and the Soviet Union. Mutual Assured Destruction relied upon the immense destructive power of nuclear bombs. The very first atomic bomb dropped on Hiroshima, codenamed "Little Boy," yielded the equivalent of 15 kilotons of TNT explosive; the first hydrogen bomb tested, codenamed "Ivy Mike," yielded 10 megatons; and the most powerful nuclear weapon ever tested, the Soviet weapon Tsar Bomba, yielded 50 megatons. (Most nuclear weapons currently mounted on ballistic missiles have yields of less than one megaton.)

As powerful as nuclear weapons are, nature can be much more so. The average Atlantic hurricane generates about 100 megatons of mechanical energy per day,[51] the equivalent of 100 ballistic missile detonations per day! Von Neumann was aware of the immense power of these natural processes, but he believed that they could either be predicted or controlled in the same way that an unruly horse could be steered or reined in, through the judicious use of small amounts of force – or, as he put it, "the release of perfectly practical amounts of energy."[52] Von Neumann envisioned a committee of experts who would decide how to release this energy at the right points in space and time: They could ensure that there was no rain during national celebrations such as the Fourth of July,[53] for example – but they could also ruin Soviet harvests with an artificially induced drought.

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Weather prediction was an important driver of, and one of the first applications of, digital computing. To this day, weather and climate scientists are among the first customers for the latest and greatest computers. Two pioneers of digital

computing, John von Neumann and John Mauchly, were both motivated by a desire to forecast weather. The philosophical battle for weather prediction between von Neumann's deductive approach and Mauchly's inductivist approach was, in simplistic terms, won by the deductive approach. (Ironically, the first deductive weather forecast was achieved using the machine created by Mauchly!) Von Neumann sought to use this approach not only to predict but also to control weather; thankfully, his dream of weather control would turn out to be impossible, sparing us the nightmare of weather warfare.

In Chapter 2, we describe how a very simple model of a very complex system was used to demonstrate the limits of weather prediction. In subsequent chapters, we chronicle how deductivism extended its reach to climate prediction. However, inductivism hasn't gone away: Data-driven approaches have continued to play a role in model calibration and may come to play a more prominent role in weather and climate prediction as well through machine learning.