

Alan Turing

In Search of the Beginnings of Computers and Artificial Intelligence



Kyung-jin Kim, Attorney at Law

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The Person Who Opened New Ways of Thinking for a New Era

Before computers were widely used, Alan Turing asked what machines could do. His childhood curiosity led to mathematical research, and during the war, he worked with colleagues to break German military codes. After the war ended, he studied computer design and patterns in living things. However, Britain punished him because he was gay. His life holds both the quest for new knowledge and the portrait of a society that failed to protect an individual.

Turing examined the process of a human calculating according to rules by breaking it down step by step. In that process, he presented the principle of a universal machine capable of performing many different kinds of calculations. The idea that what a machine does can be changed by a program became the foundation for understanding computers today.

He also explored the possibility that machines could converse with humans and learn from experience. Although today's artificial intelligence is an achievement built together by many researchers, Turing's questions were among its starting points. Following his life, this book explores how ideas about computation, intelligence, and life developed.

Turing questioned the principles behind familiar things anew and sought to verify the answers through mathematics and experiments. This is also why we read about him. Going beyond merely learning technology that is already given, we learn how to think anew from a person who opened new ways of thinking for a new era.

Kyung-jin Kim, Attorney at Law

Chapter 1. Childhood Curiosity and Self-Taught Learning (1912–1926)



Figure 1. An illustration depicting young Turing observing plants.

From around the age of one, Alan Turing grew up apart from his parents. Because his father's duty station was in India, Alan was entrusted to another family in England, keeping in touch with his parents mainly through letters. After starting school, he was often seen as an odd child. It was not a glamorous childhood.

This child would later become a mathematician who deciphered secret codes and came to be regarded as someone who laid the foundation of computer science. Today, we live alongside computers, smartphones, and artificial intelligence, and Alan Turing is one of the very first people who deeply investigated the principles by which these machines work. This chapter covers the years from Alan's birth in 1912 to his entry into secondary school in 1926. Tracing surviving records, we look at how Alan's curiosity grew amidst the loneliness of living far away from his parents.

1.1. Birth in London and Foster Care

Alan Mathison Turing was born on June 23, 1912, in Maida Vale, London, England. His place of birth was a building called Warrington Lodge, which later became the Colonnade Hotel. Today, a round blue plaque is attached to the exterior wall of that building. In Britain, such plaques are placed on homes where famous people were born or lived, and they are called blue plaques.

Although Alan was born in London, his family's livelihood was based in India. His father, Julius Mathison Turing (1873–1947), was a British civil servant working in India. At that time, India was under British rule, and Britain selected its own citizens and sent them as civil servants to administer India. The organization responsible for this was the Indian Civil Service, abbreviated in English as the ICS. Julius worked in the Madras Presidency in southeastern India. Chatrapur, the coastal town where Alan's parents lived, belongs to present-day Odisha State, India.

The family of his mother, Ethel Sara Turing (1881–1976), also had deep ties to India. Sara's maiden name was Stoney, and her father, Edward Waller Stoney, was the chief engineer of the Madras Railway. The Stoney family had roots in Ireland. Julius and Sara were married on October 1, 1907, at a church in Dublin, Ireland, and the following year, in 1908, they welcomed their first son, John Ferrier Turing. Alan was their second son, four years younger than John.

Julius and Sara decided to raise their children in Britain rather than in India. This was because they considered India a difficult place for young children to grow up, given the hot climate and frequent outbreaks of disease. They also strongly wished for their children to be educated at traditional British schools. That was why Sara had returned to Britain to give birth to Alan. However, the father's workplace was still in India. When Alan was about one year old, his parents left for India once again, and the two brothers remained in Britain.

The brothers were placed in St Leonards-on-Sea, a seaside town in southern England. On a hillside road in this town stood a large house called Baston Lodge, where retired Army Colonel Ward and his wife lived. The Wards' own children and a nurse who looked after the children also lived there. Raising children in another family on behalf of the parents like this is called foster care. Alan grew up in this home from around 1913 until 1921—that is, from age one to nine. On June 23, 2012, the centenary of Alan's birth, a blue plaque was also placed on Baston Lodge.

His parents came to Britain on leave only once every few years, and those were the only times the sons could see their parents' faces. During the rest of the time, what connected parents and children were letters. Alan had to grow accustomed to another family's household rules before the embrace of his parents. Although there were several children in the same house, Alan preferred spending time gazing into things alone rather than running around playing with his peers. Numbers, symbols, maps, and calculations were Alan's playthings.

Several anecdotes are told about Alan during his Baston Lodge years. First, Alan learned to read remarkably quickly. According to records left by his mother Sara, Alan taught himself how to read in about three weeks using a book titled *Reading Without Tears*. He was a child who discovered rules on his own, without anyone having to teach him step by step.

He also had a stubborn insistence on knowing a story completely through to the end. Around 1918, when his mother was visiting Britain, Sara read aloud John Bunyan's *The Pilgrim's Progress* to Alan at Baston Lodge. When a long, dry religious explanation appeared in the middle of the book, Sara casually skipped over that passage. At this, Alan became furious, saying that leaving things out like that ruined the entire story, and stormed off to his room. To Alan, a story was a single coherent structure connected from beginning to end, and he felt that if even one piece was missing, the whole thing fell out of alignment.

Alan also coined words of his own. In the seaside town, seagulls squawked noisily as they fought over food, and Alan invented the word 'quockling' to describe that sound. When he encountered something that had no name, he gave it a name himself.

Returning to Britain in 1921, his mother felt that her son had changed. A once lively, chattering child had become quieter, spending his time lost in thought on his own. Being separated from his parents for so long must have left its mark on the young child's heart. That year, Alan left the Wards' home. His childhood letters reveal a child eager to investigate what he was curious about on his own.

1.2. Early School Life and Exceptional Curiosity

The first school Alan attended was St Michael's, located at 20 Charles Road in St Leonards-on-Sea. Alan attended this school from 1918 to 1921, from age six to nine. In class, Alan often appeared distracted. This was because, rather than following the teacher's instructions to the letter, he solved problems in his own way. Yet the headmistress of this school recognized something extraordinary in Alan. According to what his mother Sara recounted, the headmistress said that while she had seen clever children and hardworking children, Alan was a genius. She used the word genius for a child not even nine years old.

In January 1922, nine-year-old Alan entered Hazelhurst School in the village of Frant, Sussex. Hazelhurst was a boarding preparatory school. In Britain, a preparatory school is a school attended before entering a major private secondary school, where students lived away from home, boarding and studying at the school. His brother John had also attended this school; when Alan enrolled, John was in the highest grade and Alan was in the lowest. Alan remained at this school until the spring of 1926.

At Hazelhurst, Alan's academic marks were not remarkable. In subjects the school valued, such as languages and literature, he was average or slightly better. But when he became absorbed in topics of his own choosing outside the curriculum, it was a different matter entirely. At such times, Alan would lose all track of time, completely dedicated to a single pursuit.

It was a single book that opened up one such subject. In 1922, ten-year-old Alan encountered *Natural Wonders Every Child Should Know*, written by American author

Edwin Tenney Brewster. This book explained through scientific eyes how living things are born and grow, and how our bodies function. It conveyed the idea that life could be viewed not as a mysterious force, but as a kind of machine operating according to the laws of nature. Alan was completely captivated by this book. Later, his mother Sara recalled that this book was the first to open Alan's eyes to science.

What Alan pursued outside his textbooks can be seen in the letters he sent to his parents in India. These letters survive to this day and are preserved in the archives of King's College, Cambridge, England. Reading these letters in chronological order offers a glimpse into the mind of a young inventor.

The first thing that stands out is writing implements. In April 1923, ten-year-old Alan wrote in a letter about a fountain pen he had made, even including a drawing of how ink flowed down to the nib. Between 1923 and 1924, he wrote letters using ink he had made himself, calling it 'patent ink.' He also sent drawings contemplating how the parts inside a typewriter meshed and moved together.

In the summer and autumn of 1924, he was captivated by mountains and maps. On maps, lines connecting points of equal elevation are called contour lines. Alan calculated how the height of a mountain could be measured using contour lines and enclosed two hand-drawn contour maps with his letter. It was also around this time that he wrote to his parents about his eccentric idea of a bicycle that could ride on water.

Between September 1924 and March 1925, he became deeply absorbed in chemistry. Alan wrote in letters about how carbon dioxide changes in human blood, and pleaded with his parents to buy him experimental equipment so he could study chemistry on his own. What Alan wanted was an earthenware distilling vessel. Distillation is a method of boiling a liquid, cooling the resulting vapor, and collecting only the desired substance. He also wrote several times about the rules of chemical reactions and the exceptions that defied those rules. There is also a story that he conducted an experiment extracting a substance called iodine by burning seaweed gathered from the seashore.

In October 1925, he devised a mechanism to charge an accumulator by pedaling a stationary bicycle. An accumulator is a battery that can be recharged and reused. His idea was to turn human leg power into electricity.

His letters were not solely about inventions and experiments. Alan also took up chess with enthusiasm. Chess is a game of finding the best move within set rules. Each piece has prescribed paths of movement, and making a single move changes everything that follows. Alan entered a school chess tournament, and in November 1924, he wrote about entering the tournament on a postcard to his parents. He also took part in the school debating society. Later in life, Turing would also contemplate how to play chess using a computer.

Looking in sequence at fountain pens, ink, typewriters, maps, chemistry, accumulators, and chess, the interests of this ten-year-old boy might seem scattered in all directions. Yet these interests shared something in common. As revealed in his letters about the path ink takes, the way typewriter parts mesh, and the rules and exceptions of chemical reactions, Alan always wanted to know the principles by which things operate. Seeking the hidden rules beneath appearances rather than merely looking at the surface was where Alan's curiosity was directed.

1.3. The Genius of a 'Rough Gem'

A rough gem is a gemstone newly dug from the ground. Its surface is rough and covered in dirt, making it look no different from an ordinary stone at first glance, but when ground and polished, light shines from within. Young Alan Turing was just such a rough gem. In the eyes of others, he was an odd and clumsy child, but within him lay a hidden power to understand the world in his own unique way.

The school standards of the era also played a part in making Alan appear clumsy. At that time, British private schools sought to cultivate students who studied Latin, Greek, and ancient literature, and who strictly observed the rules of communal life. Science and mathematics were accorded lower status. Team sports such as hockey and rugby were also highly valued. From the very beginning, what Alan loved and what the school valued were at odds.

In truth, Alan was far from the model student the school desired. His handwriting was crooked and difficult to decipher, and he was clumsy at keeping things neatly organized. Team sports played with others were even more difficult for him, and he could rarely find any enthusiasm for such games.

A single drawing survives that vividly captures this side of him. It is a pencil drawing made in 1923 by his mother, Sara. On the playing field in the drawing, boys are running around chasing a hockey ball. Alan alone is crouched slightly away from the game, peering at a daisy blooming on the ground. Sara gave this drawing the title 'Hockey, or watching the daisies grow.' Even in his mother's eyes, her son was a child far more curious about how a flower grew than about the ball. About thirty years later, the adult Turing would mathematically study how leaves and petals arrange themselves in pattern and sequence as plants grow; one of the plants he examined in that research was the daisy.

The reason he clashed in class lay in his way of learning. Alan disliked memorizing answers that others had established. Instead, he sought to start from the most fundamental principles and find answers step by step on his own. This attitude is sometimes called 'thinking from first principles.' This approach took a long time and often diverged from the solution format the teacher expected. As a result, he clashed frequently at school. However, principles he discovered on his own became firmly rooted in Alan's mind.

There is a story showing how this method was put to use outside the classroom. It happened when young Alan went outdoors on an outing with his family. Alan watched the flight of honeybees for a long time. After gathering nectar from flowers, honeybees fly almost straight toward their hive. After observing the directions the bees were flying from several different spots, Alan mentally connected those directions with lines. He reasoned that the hive would be located where the lines intersected. Alan found wild honey at that very spot and brought it back to his family. While the adults saw merely flying bees, Alan saw a pattern within their movements and converted that pattern into geometry and calculation to arrive at the answer.

This was why Alan appeared different from others. Most children learn and follow the methods shown to them by adults. Alan trusted what he saw with his own eyes and reasoned through with his own mind far more than adults' explanations. When there was no word, he coined one; when he lacked laboratory equipment, he wrote letters asking for it to be bought; and when questions arose, he found books and read them on his own. Giving a name to the cries of seagulls, drawing the path of ink inside a pen, and tracing the flight paths of bees with lines all sprang from the exact same impulse: a desire to understand the underlying principles of how the world works.

Naturally, the adults raising and teaching such a child had many worries. His mother Sara had deep concerns about whether her son could adapt well to school life. Since the type of student the school aimed to foster and Alan's interests were completely at odds, there was good reason for that concern.

His childhood letters preserve a child curious about how things work and eager to experiment firsthand. Later in life, Turing investigated what calculations could be performed by machines and whether machines could think. It is difficult to explain these questions solely by childhood loneliness or any single experience.

At age thirteen, after passing the Common Entrance Examination, Alan gained admission in 1926 to Sherborne School in Dorset, southwestern England. Sherborne was a boarding school with centuries of history. Alan left Hazelhurst and set off for his new school.

Chapter 2. Sherborne School and the 60-Mile Bicycle Journey (1926–1931)



Figure 2. A reconstruction of the bicycle journey to Sherborne School.

In the spring of 1926, thirteen-year-old Alan Turing was preparing to enter a new school: Sherborne School, located in the small town of Sherborne in Dorset, southwestern England. Sherborne School was a boarding school with centuries of history, where students ate, slept, and studied in dormitories within the school. The boarding house where Alan was to live was Westcott House.

In Britain, such schools are called 'public schools.' From the name alone, it might sound like a state-run school that anyone could attend, but in reality, they are expensive private boarding schools. At that time, public schools were regarded as places that cultivated the talent to lead the nation and the Empire. Students learned Latin and Greek, studied ancient poetry and history, and absorbed rules and manners through team sports such as rugby and cricket. There was a strong atmosphere that viewed mathematics and science as subjects a tier below such studies.

Alan spent from May 1926 to July 1931 at this school. Rather than simply following the solutions given by his teachers, he was a student who examined everything for himself from the very beginning, which frequently brought him into conflict with his teachers. Yet it was precisely during this period that Alan studied Einstein's theory of relativity entirely on his own, putting down the roots of thought that would later form the foundation of his growth as a mathematician. His five years at Sherborne began with a single bicycle.

2.1. The General Strike and Going to School by Bicycle

At that time, Alan's parents were living in France. The new term at Sherborne School was scheduled to begin on May 4, 1926. Alan crossed the English Channel alone by boat from the French port of Saint-Malo, arriving at Southampton, a port city in southern England. According to the original plan, he was supposed to take a train from there to Sherborne.

Yet on that day, the whole of Britain had ground to a halt. This was because the British General Strike had begun on May 4, 1926. The strike originated in the coal mines. When mine owners attempted to cut miners' wages and extend their working hours, the miners resisted, and workers from other industries stood with them, walking off the job as well. Countless people stayed away from work—railway workers, bus drivers, dockers, and even printers. Trains came to a standstill, and newspapers could not be published properly. This strike continued for nine days, until May 12.

With no trains running, there was no suitable way to reach Sherborne. Southampton to Sherborne is about 60 miles. Depending on the record, it is cited slightly differently as 60 miles, 63 miles, or 65 miles. Since one mile is roughly 1.6 kilometers, this was a distance of nearly 100 kilometers—similar to traveling from Seoul to Cheonan. Even for an adult, it was a daunting distance to cover by bicycle in a single day.

Many students waited at home until the strike was over. Alan chose a different course: he decided to ride his bicycle to school. His mother, Sara Turing, recorded this event in detail when writing a biography of her son years later. According to her account, as soon as Alan disembarked at Southampton around midday, he first sent a telegram to his housemaster, Mr. Geoffrey O'Hanlon, saying he would arrive the next day. He then had his large luggage sent separately, took a map, and got on his bicycle. For Alan, it was a completely unfamiliar route.

Alan split this journey over two days. This was because when he had suggested riding his bicycle, his mother had urged him not to cover all 60 miles in one day. She worried that her son might have to attend classes early the following morning. Following her advice, Alan stayed overnight along the way at the Crown Hotel in Blandford. Dinner, lodging, and breakfast altogether cost him just six shillings, and the next morning the entire hotel staff came out to see him off. In the eyes of the hotel staff, a thirteen-year-old boy cycling alone along an unfamiliar road must have seemed quite remarkable. Alan wrote about this in a letter to his parents.

Alan arrived at Sherborne School on May 5, 1926. The story of his journey to school by bicycle was even reported in the local newspaper.

This journey clearly illustrates the kind of person Alan was. He did not halt just because the road was blocked. He unfolded a map, gauged the distance, chose a place to rest for the night, and pedaled forward on his own two legs. This attitude of finding his own way when no established path existed remained with Alan throughout his life. Strong legs were also a lifelong asset of his. As an adult, Alan became deeply passionate about long-distance running, developing marathon skills so formidable that he was considered for selection for the Olympic team.

This bicycle journey was long remembered, both inside and outside the school. According to his mother's account, when Alan's grades sank to the bottom a year or two later, his housemaster, searching for something to praise, remarked that at least this boy had ridden a bicycle all the way here. And in May 2026, exactly one hundred years later, students and teachers from Sherborne-area schools retraced Alan's journey. Cycling 100 kilometers from Southampton to Sherborne, they arrived in Sherborne at 6:00 p.m. on May 5 and commemorated the day with a small parade through the town streets.

2.2. Friction Between Classical Education and Self-Taught Science

The report card Alan received after his first term at Sherborne was not bad. His housemaster, Mr. O'Hanlon, described Alan as an original and very interesting boy, and Headmaster Nowell Smith added that it was a very promising start. Other records from the same period noted that Alan preferred to keep to himself. His teacher believed this was due not to a gloomy temperament, but to great shyness.

As time passed, problems began to surface one by one. Classes at Sherborne centered on Latin and Greek. Latin was the language spoken by the ancient Romans, and Greek by the ancient Greeks. Students memorized the grammar of both languages, translated ancient poetry and speeches, and composed Latin sentences of their own. Alan found no interest in memorizing grammar rules established by others, and he often received grades near the bottom of his class in Latin and English. His handwriting was difficult to read, and his notebooks were covered in ink stains. Teachers repeatedly criticized Alan for his messy notebooks and untidy habits.

Friction arose even in the subjects Alan loved. Although he loved mathematics, he did not solve problems using the methods set out in textbooks. When presented with a problem, he first examined what the problem was asking, and then found the answer via a route he had devised himself. Even when his answers were correct, teachers hesitated to award good marks on the grounds that his methods were not the prescribed ones. In the chemistry laboratory as well, Alan was frequently reprimanded for getting absorbed in experiments of his own design rather than those assigned by the teacher.

The school viewed Alan with concern, and the headmaster sent a letter to Alan's parents. This letter, cited by Andrew Hodges in his biography of Alan Turing, contained the following message: "I hope he will not fall between two stools. If he is to remain at a Public School, he must aim at becoming educated. If he is to be solely a Scientific Specialist, he is wasting his time at a Public School."

To fall between two stools is an English proverb meaning that by trying to achieve two things, one ends up missing both. The educated person referred to by the headmaster was a gentleman capable of reading Latin poetry and quoting the classics. Through such eyes, Alan, who delved only into mathematics and science, was merely half a student. Alan did not reshape himself into what the school desired. Nor did he engage in serious conflict with the school. Once classes ended, he quietly returned to the studies he loved.

Those studies were far in advance of his school curriculum. Even in 1927, Alan had not yet been taught even the basics of calculus at school. Calculus is a branch of mathematics that calculates values such as the rate at which quantities change and the area enclosed by curves. Even so, he solved difficult mathematical problems entirely on his own. There were even occasions when he independently discovered formulas expressing a value as an infinite series of additions. It was material of a level that only someone who had studied calculus at university would normally handle.

Around the age of fifteen, he began studying Albert Einstein's theory of relativity on his own. The theory of relativity, published by Einstein in 1905 and 1915, posits that time and space can vary depending on the motion of the observer. At the time, it was a theory so difficult that even university professors shook their heads over it. Alan not only read Einstein's writings and grasped their meaning, but also read between the lines to discern what was not explicitly stated in the book. He realized entirely on his own that Einstein was questioning Newton's laws of motion, which had served as the foundation of physics for more than two hundred years.

Alan wanted to share what he had understood with his mother. When he was fifteen and a half, he organized the theory of relativity chapter by chapter in a small notebook with a red cover. Titled 'A Summary of Albert Einstein's Theory of Relativity', it was 31 pages long. Alan gave this notebook to his mother as a present. In addition to the contents of the theory of relativity, the notebook contained Alan's thoughts on the sequence and mindset with

which one should read this theory. This notebook is preserved today in the archives of King's College, Cambridge.

Alan's interests did not end with relativity. He read 'The Nature of the Physical World', published in 1928 by the British astronomer Arthur Eddington. Eddington was the scientist who had found evidence verifying Einstein's theory through solar eclipse observations in 1919. Through this book, Alan encountered quantum mechanics. Quantum mechanics is the new physics explaining how matter behaves in the unimaginably tiny world of atoms. Around 1929, Alan wrote in a letter to his parents that he wanted to seek out and read the writings of Austrian physicist Erwin Schrödinger on quantum theory and the wave equation. A seventeen-year-old student was attempting to read directly the cutting-edge physics research of his time.

While studying the theory of relativity and quantum mechanics, Alan came to harbor profound questions: Does the world operate strictly according to predetermined laws? What is the relationship between matter and the mind? What mathematical principles govern our bodies and thoughts? Such questions later paved the way for Alan to imagine thinking machines.

2.3. The Formation of an Independent Mind

Clashing frequently with his teachers did not mean that Alan's school life was purely lonely or rebellious. In his own way, Alan took part in various school activities and gradually carved out his own place within the school community.

Such qualities were visible even in records from his early days at the school. For his first three terms after entering Sherborne, Alan sang in the school chapel choir. The part he sang was treble, the high vocal range of boys whose voices have not yet broken. He also took part in school concerts, and his name remains on the program of a concert held on December 20, 1926, where he appeared on stage as a treble singer. On November 7, 1927, he was confirmed in the school chapel. Confirmation is a rite in which a Christian believer personally affirms their faith. Alan, who might have appeared absorbed only in mathematics and science, lived as an integral member of the school, singing in the chapel and taking part in school rituals.

In sports, his preferences were clear. Alan did not enjoy team sports like rugby or cricket, preferring solitary pursuits such as golf and long-distance running. Even so, he represented his house twice in inter-house rugby matches, dutifully doing his part.

From around 1928, Alan grew close to Christopher Morcom, a boy in the class ahead of him. The two shared conversations about science and mathematics, exerting a profound influence on each other. Morcom was the first friend to whom Alan had opened his heart deeply. In February 1930, however, Morcom suddenly passed away.

As an upperclassman, Alan frequented the school library. Between October 1928 and May 1931, he borrowed 33 books from the library, of which only three were works of fiction. On November 4, 1930, he checked out three books at once by Lewis Carroll, the author of 'Alice's Adventures in Wonderland'. Lewis Carroll was not only a children's writer, but also a mathematician who researched both logic and mathematics.

Around this time, Alan did not confine himself to studying alone; he expanded his roles within the school as well. He frequently helped other students with their mathematics homework, something his housemaster regarded with favor. In the autumn term of 1930, he became a school prefect. A prefect was an upperclassman who helped maintain order in the school and guided younger boys. In the same term, he joined a student discussion society called 'The Duffers' and delivered a presentation titled 'Other Worlds'. He was also active in a science society known as the 'Alchemists'.

The boy who had refused to follow standard solutions in class graduated having won nearly all the mathematics and science prizes the school had to offer. Alan's list of awards preserved in the Sherborne School records is as follows:

1926 Lower School Kirby Mathematics Prize

1927 Lyon Examination Prize

1928 Middle School Plumtre Mathematics Prize

1930, 1931 Digby Mathematics and Science Prize

1930, 1931 Christopher Morcom Prize for Natural Science

1931 King's Medal for Mathematics

1931 Westcott House Goodman Leaving Scholarship

Among these, the Christopher Morcom Prize for Natural Science was established by Morcom's family in memory of their late son. Alan received this prize for two consecutive years.

Alan graduated from Sherborne School in July 1931. The school's view of him, which had been so full of concern just a few years earlier, had changed dramatically. On his final report, Headmaster Charles Boughey wrote that Alan was a boy of outstanding ability and character, and that he would follow his future path with keen interest. He noted that Alan was warm and kind, and had carried out his duties as a prefect admirably.

Mr. O'Hanlon, the housemaster who had watched over Alan most closely for five years, also wrote a letter. He thanked Alan for the help, loyalty, and pleasure he had given them during their time together, and assured him that the name Turing would be long remembered as long as the present generation lived.

Years later, in 1966, Sherborne School named its newly expanded science building the 'Alan Turing Laboratory.' According to the records of Sherborne School, this was the first building in the world to be named after Alan Turing. Today, anyone learning about computers and artificial intelligence knows the name Turing.

The five years spent at Sherborne were not an easy time for Alan. The school wanted a gentleman who excelled in Latin, while Alan wanted to examine the principles of mathematics and science for himself from the very beginning. Caught in between, Alan was scolded, received poor grades, and was called an odd boy. Yet he never abandoned his own way of thinking. He read books by Einstein and Eddington on his own, sang in the choir, helped his friends with homework, and won numerous awards in mathematics and science. The boy who had cycled 60 miles alone to reach school left five years later as a young man equipped with his own way of thinking. In October 1931, Alan entered King's College, Cambridge, taking his first steps forward as a mathematician.

Chapter 3. Christopher Morcom and the Nature of Spirit (1928–1930)



Figure 3. A reconstruction of Turing and Morcom studying together.

While attending Sherborne School, Alan Turing spent much of his time alone. During Latin and Greek classes, his mind wandered to other thoughts, and he solved math problems in his own way rather than following the methods in the textbook. His teachers viewed Turing as an obstinate and unfocused student, and his classmates could not understand why he was so absorbed in chemicals and constellations. Turing rarely had anyone with whom he could freely share the thoughts in his head.

In the autumn of 1928, when Turing was sixteen years old, a boy appeared in his life. The time the two spent together was less than a year and a half. Yet this brief meeting and abrupt parting profoundly transformed Turing's life. It was during this very period that the question Turing held onto for the rest of his life began: what is the human mind, and how are the mind and body connected?

3.1. Meeting a Soulmate

The boy's name was Christopher Collan Morcom. Morcom was born on July 13, 1911, at 'The Clock House' in Fockbury, Worcestershire, England. He was one year older than Turing and one grade above him. Morcom's family had deep ties to science. His father, Reginald Morcom, was an engineer who led a machinery company, and his maternal grandfather, Joseph Swan, was renowned as one of the scientists who developed the incandescent light bulb. His older brother, Rupert, also won a mathematics prize at Sherborne School before entering Trinity College, Cambridge.

Morcom entered Sherborne School as a scholar in May 1925 and lived in a boarding house called Lyon House. It was a different house from Westcott House, where Turing lived. Morcom excelled in mathematics and science and possessed exceptional knowledge of astronomy. At night, he would carry a telescope up to his dormitory room to observe the stars, drawing his own star charts based on those records. He also enjoyed photography and listening to music.

He was not a student who only studied. Morcom was also full of playfulness; in the winter term of 1928, he filled several balloons with gas, attached fuses made of waxed string, and sent them drifting into the wind. There was also an occasion when he secretly took a photograph of a teacher during class and gave it to him as a gift, which the teacher took not as impudence, but as a sign of respect.

Yet Morcom had a secret worry known to few. In his childhood, he had contracted bovine tuberculosis after drinking contaminated cow's milk. Bovine tuberculosis is a form of tuberculosis transmitted from cattle to humans. After that, Morcom's family raised goats instead of cows to obtain milk. Even during his first year at Sherborne, Morcom underwent major surgery and missed two terms of school. Still, he quickly caught up with his studies and won a mathematics prize in 1927.

It was in September 1928 that Turing grew close to Morcom. At this time, Turing moved up to the Lower Sixth, where he studied mathematics and science, and began attending the same classes as Morcom. What brought the two together was a single question about planetary orbits. Their discussions continued even during breaks in football matches, and both devoted their shared interest to chemistry experiments as well. There was no end to the topics of their conversations. They would examine the ingredients of the iodized salt another student was eating, and then transition to discussing the age of stars.

The occasions for the two to study together gradually increased. Every Wednesday afternoon, they met in the school library to share their individual research, and during the spring and summer terms of 1929, they received private lessons in organic chemistry from their chemistry teacher, Andrews. It is also said that during class, they exchanged notes written in symbols only the two of them could understand to share mathematical ideas. Morcom, who loved music, also took Turing to the gramophone society run by their mathematics teacher, Epperson.

To Turing, Morcom was the first friend with whom he could truly communicate. Turing's nephew, Dermot Turing, later described Morcom as someone who did not view Turing as strange for being absorbed in equations and astronomy. That does not mean the two thought in the same way. Turing led with flashes of brilliant insight, but his final work was often unpolished. Morcom, even after grasping a principle, did not stop there, but carefully examined each step individually. When his housemaster asked about Morcom, Turing replied that what he admired most was Morcom's thoroughness.

How Turing viewed Morcom is also preserved in a letter he later sent to Morcom's mother. Turing wrote: "I have never known anyone who was so clever and yet so charming and unpretentious. I considered that my work and my interest in astronomy were things which had to be shared with him." It was Morcom who had introduced astronomy to Turing.

Turing's feelings did not stop at friendship. Turing was deeply fond of Morcom and later remembered these feelings as his first love. There is no record that Morcom knew of Turing's feelings. Morcom treated Turing as a precious friend with whom he connected intellectually. To the lonely Turing, Morcom was a presence that brightly illuminated his world.

In December 1929, the two traveled together to Cambridge to take the scholarship examinations for Trinity College, Cambridge. For a week, they absorbed the university atmosphere and envisioned the days they would continue studying together in the future. However, the results were mixed. Morcom was elected to an open scholarship and was scheduled to enter Trinity College the following October, while Turing failed to secure one. Left to stay at Sherborne for another year, Turing made up his mind that in a year's time, he would definitely follow his friend to Cambridge.

That plan went awry before even two months had passed. On the evening of Thursday, February 6, 1930, a concert by the Salisbury Singers choir was held in Sherborne School's great hall, the 'Big Schoolroom.' Morcom attended the concert together with friends, including Turing. That evening was the last time the two spent together.

3.2. Sudden Tragedy and Grief

That night after the concert, Morcom suddenly collapsed in severe pain. The next day, the school moved Morcom to the Yeatman Hospital in Sherborne to monitor his condition. On Sunday, February 9, Morcom was transferred to a hospital in London, where he underwent two operations. The tuberculosis he had contracted in childhood had caused inflammation in the lining of his abdomen, leading to an intestinal obstruction. Complications arose after the surgery, and Morcom ultimately failed to recover. At noon on February 13, 1930, Christopher Morcom passed away at a nursing home at 19 Manchester Street, London. Morcom was eighteen years old, and Turing was seventeen.

Tuberculosis, which took Morcom's life, is a disease caused by bacteria called tubercle bacilli entering the body. It primarily affects the lungs, but it can also develop in bones, the intestines, and the abdominal lining. As with the bovine tuberculosis Morcom contracted, many people in the past developed tuberculosis from drinking contaminated cow's milk as

it was. Today, milk is pasteurized at high temperatures and good medicines exist, allowing most cases to be cured. In 1930, however, medicines to cure tuberculosis did not yet exist.

Around the time Morcom collapsed, Turing experienced a curious event. Turing later recalled that on a certain night around that time, waking from sleep and gazing out the window at the setting moon, he felt that something had happened to Morcom. This experience, difficult to explain through science, remained in Turing's mind for a long time.

In the early morning of February 15, Morcom was buried in the churchyard of Christ Church in Catshill, near his family home. The following day, February 16, a memorial service honoring Morcom was held in the Sherborne School chapel. The entire school was plunged into grief over the loss of an outstanding student.

That day, Turing wrote a letter to his mother: "I feel sure that I shall meet Morcom again somewhere and that there will be some work for us to do, as there was for us to do here. Now that I am left to do it alone I must not let him down but try to get on with it all and put as much energy into it, if not as much interest, as if he were still here." Along with deep grief, this letter contained a new resolve. Turing resolved to carry on the studies that his friend had left unfinished.

Turing put that resolve into action. The first task he undertook was choosing the books his friend was to receive. Sherborne School decided to award the 1929 Digby Prize for Mathematics and Science posthumously to Morcom, and Turing selected the prize books on Morcom's behalf. The books Turing chose were Arthur Eddington's *The Nature of the Physical World* and *The Internal Constitution of the Stars*, and James Jeans's *Astronomy and Cosmogony* and *The Universe Around Us*. All were books dealing with stars, the universe, and the new physics—the very topics the two boys had discussed together.

In that same year, 1930, Morcom's parents established the 'Christopher Morcom Prize' at Sherborne School in memory of their son. This prize was not awarded based on examination scores. Instead, the science teachers reviewed a student's work over the year, evaluating progress, originality, and depth of understanding to award it to the most outstanding student. The winner also received a portrait of Morcom.

Turing was determined to win this prize. And in 1930, he became its first recipient with an original paper investigating the chemical reaction between sulphites and iodates in acidic solution. He also maintained his determination to go to Cambridge. Devoting himself to his studies, Turing sat for the Cambridge scholarship examination again in December 1930, and this time he was elected as a scholar at King's College. Turing won the Morcom Prize again in 1931. By receiving the prize bearing his friend's name for two consecutive years, Turing kept that promise.

3.3. The 'Nature of Spirit' Essay

After Morcom's passing, Turing began exchanging letters with Morcom's mother, Frances Isobel Morcom. Mrs. Morcom was a sculptor and painter. She warmly welcomed Turing, who had been her son's closest friend, and Turing also found comfort in Morcom's family. Turing borrowed the telescope and celestial globe Morcom had used and continued his astronomical observations. A celestial globe is an instrument with constellations depicted on the surface of a sphere, used to observe the positions and movements of stars.

The correspondence did not stop after a year or two. Every year on July 13, Morcom's birthday, and on February 13, the anniversary of his death, Turing sent a letter to Mrs. Morcom. They were letters conveying that he had not forgotten his friend. This correspondence continued for over ten years until Mrs. Morcom passed away in 1941. While the two boys' friendship had lasted less than a year and a half, Turing's bond with the Morcom family endured far longer.

Out of this connection came a piece of writing. Around April 1932, two years after Morcom passed away, Turing had become a student at King's College, Cambridge. Around this time, Turing stayed at The Clock House near Broomsgrove, spending time with Morcom's family, and there he wrote a short essay for Mrs. Morcom. The title was 'Nature of Spirit.' This manuscript, handwritten by Turing, remains preserved today in the King's College Archives at Cambridge.

To understand this essay, one must first recognize the changes that had taken place in physics around that time. For a long time, scientists explained the world based on Newtonian physics. According to this view, the universe operates according to predetermined laws, like a gigantic clock. If one knows the position and velocity of every

object at the present moment, everything that will happen in the future can be calculated without exception. This idea is called 'determinism.' Seeing astronomers accurately predict the dates of solar eclipses decades in advance, people firmly believed in this idea.

However, in the 1920s, a new physics called 'quantum mechanics' emerged. Quantum mechanics is the study of the microscopic world of atoms and electrons. Scientists discovered that in this minute realm, one cannot simultaneously determine both the precise position and velocity of an object. Events occurring in this subatomic world could only be expressed in probabilities. Eddington's *The Nature of the Physical World*, which Turing had chosen on Morcom's behalf, was a book that explained to general readers how this new physics was transforming the way we view the world.

In 'Nature of Spirit,' Turing sought to understand his friend's death through this new physics. What he addresses in the opening section of the essay is determinism. Earlier science held that if one knew the complete state of the universe, the future could be predicted. Yet when dealing with atoms and electrons, their exact state cannot be known. This is because the very instruments of measurement we use are themselves composed of atoms and electrons. On this basis, Turing reasoned that the idea that all human actions are predetermined, just like a solar eclipse, falls apart.

If actions are not predetermined, the question remains: what determines them? Here, Turing speaks of human 'will.' Turing proposed that human beings possess a will that determines the movement of atoms in a small part of the brain, or perhaps throughout the whole brain. He explained that the rest of the body functions like an apparatus that amplifies these minute movements. It is similar to a loudspeaker amplifying a faint sound. The tiny movement of a few atoms in the brain is amplified into major actions, such as moving arms and legs. Turing added that because other atoms in the universe lack such an amplifying apparatus, their movements appear purely random.

In the middle section of the essay, Turing moves from the will to the spirit, examining the relationship between spirit and matter. Drawing upon the ideas of Cambridge philosopher McTaggart, Turing maintained that without spirit, matter is meaningless. He also thought that while spirit is eternally linked with matter, it does not always remain in the same body. He wrote that although people previously believed that after death the spirit might depart

for a universe entirely different from ours, such an idea is now inconsistent because spirit and matter are inseparable.

If spirit cannot leave matter behind, one must explain what happens to the spirit after the death of the body. Turing sought the answer in the way body and spirit are connected. A living body, precisely because it is alive, attracts and holds the spirit. As long as the body is alive and awake, body and spirit are firmly united. Turing honestly wrote that he could not guess what happens during sleep. But when the body dies, the bodily 'mechanism' that held the spirit disappears, and he believed the spirit would soon, perhaps immediately, find a new body.

At the end of the essay, Turing asks why spirits have bodies at all, and whether spirits could not live freely and converse with one another without bodies. The answer Turing offered was this: while that might be possible, there would be nothing for them to do. The body provides something for the spirit to care for and use. This answer reflects Turing's longing for the times he had spent experimenting and stargazing with Morcom. For Turing, life was about sharing ideas and working together.

'Nature of Spirit' is a short essay of barely a single sheet. Yet it distinctly preserves the traces of a nineteen-year-old Turing struggling to cope with the sorrow of losing a beloved friend. Turing did not rely merely on vague faith to overcome his grief. He studied quantum mechanics, the most cutting-edge scientific knowledge of his day, and attempted to understand the relationship between mind and body through it. Because it was written by a nineteen-year-old student, there are aspects that do not hold up from the perspective of modern science. Even so, in this essay, Turing asked questions no one knew the answers to and attempted to work through them with logic.

The ideas contained in this essay did not remain unchanged. As Turing continued his studies at Cambridge, his thinking gradually shifted. He gradually moved away from the belief that the spirit survives after death, leaning toward the view that even the workings of the mind could be explained through matter and physical laws. Yet the question itself never left Turing. It was the question of whether human thought processes could be represented as rules, and whether the mind could be constructed as a machine.

In 1936, Turing conceived an imaginary machine that represented human computational processes through simple rules. This concept, known today as the Turing machine, became the theoretical foundation of computer science. In 1950, in his paper 'Computing Machinery and Intelligence,' he addressed whether machines can think. The essay written after losing Morcom retains the thoughts of a young Turing grappling with the relationship between mind and body. However, it cannot be asserted with certainty that those reflections led directly to his later research.

Chapter 4: The Freedom of King's College, Cambridge (1931–1935)



Figure 4. An illustration depicting Turing studying at Cambridge.

It was in the autumn of 1931, at the age of nineteen, that Alan Turing packed his bags and set off for Cambridge. The five years he had spent at Sherborne School before that had not been smooth. Sherborne was a school that placed great importance on Latin and Greek, and the teachers looked with worried eyes at Turing, who was absorbed only in mathematics and science. Christopher Morcom, the friend who understood Turing best there, passed away from tuberculosis in February 1930. Carrying that sorrow with him, Turing began his university life.

The place Turing entered was King's College at the University of Cambridge. The University of Cambridge is one of the oldest universities in Britain, made up of several colleges. A college refers to a small community where students and professors eat, sleep, and study within the same grounds. During his four years at King's College, Turing found for the first time a place where he could freely unfold his thoughts. He achieved his first successes as a mathematician and gradually came to accept who he was. The ideas that would later present the principles of the computer to the world also sprouted during this period.

4.1 Entering King's College

Two Scholarship Examinations

Turing had to take the scholarship examination twice before entering King's College. The first examination was in December 1929. Turing took the scholarship examination for Trinity College, Cambridge, together with Morcom. Trinity College was where Isaac Newton had studied, a college that any student fond of mathematics longed to enter. As a result of the examination, Morcom secured a scholarship place, but Turing did not. The two looked forward to the day they would study together at Cambridge. But when Morcom passed away two months later, that wish could not come true.

After remaining at Sherborne School for one more year to study, Turing took the examination again in December 1930. This time too, he was not admitted to Trinity College. Instead, King's College, which he had applied to as his second choice, accepted him as a scholar. The scholarship was 80 pounds a year. It was money that provided great help in paying for his tuition and living expenses.

Becoming a scholar at King's College was not easy either. Because King's College had long given many places to graduates of the prestigious Eton College, there were not many places available for those from other schools. Yet the examiners at King's College looked carefully at whether a student had the capacity for independent thought, rather than how well they memorized formulas. They highly valued students who approached problems by paths that others did not take. Turing's method of solving problems, which had led him to be called a clumsy student at organizing his work at Sherborne, became an asset here instead.

A Liberal Academic Atmosphere

In October 1931, Turing became a student in the mathematics department at King's College. King's College was famous for its liberal and tolerant atmosphere. Among the scholars who led this atmosphere was the economist John Maynard Keynes. Keynes was a figure who would later propose theories that transformed the economic policies of many nations around the world. At King's College, students and professors ate together in the dining hall and shared ideas without regard to age or family background. Nor did they consider strange anyone who thought differently from others.

This environment suited Turing well. Turing paid no attention to his attire and often hesitated when speaking. While he had often been scolded for such manners at Sherborne, no one at King's College blamed him for them. Undaunted by the opinions of others, Turing read and thought freely across mathematics, physics, logic, and philosophy.

Answers Found on His Own

How Turing studied during this period can be glimpsed in a letter written on January 31, 1932. According to the letter, Turing proved a mathematical problem entirely on his own. Yet as it turned out, it was a theorem that the Polish mathematician Waław Sierpiński had already proved. Without anyone's help, he had reached the exact same conclusion as a renowned mathematician.

Such things happened to Turing multiple times. Turing had a habit of trying to solve things for himself before looking for answers in books, and so he often rediscovered results that others had already found. It was a method that took more time. But through this method,

Turing built the strength to forge his own path rather than follow a path paved by others. This habit of forging his own path later led to his election as a fellow.

Questions Drawn from Books and Lectures

Having the habit of working things out on his own did not mean Turing stayed away from books. Turing also read many difficult books. He studied *Mathematical Foundations of Quantum Mechanics*, published in 1932 by the Hungarian-born mathematician John von Neumann. Quantum mechanics is a physics that explains what happens in an extremely small world like atoms. After losing Morcom, Turing had wondered about the relationship between mind and body, and quantum mechanics touched upon this question. In 1933, he read *Introduction to Mathematical Philosophy* by the British philosopher Bertrand Russell. This book investigates what foundations mathematics stands upon. Such reading served as fertile ground when Turing conceived the principles of the computer several years later.

Turing also attended lectures and academic society meetings. In the autumn of 1933, he attended the astronomer Arthur Eddington's lectures on scientific method, and late that year, he gave a presentation on mathematics and logic at the Moral Sciences Club, a group for discussing philosophy. Among these, Eddington's lectures led to Turing's first major piece of research.

An Interest in the World

In the early 1930s, when Turing attended university, Europe was unsettled. The Great Depression caused many people to lose their jobs, and Hitler took power in Germany in 1933. Among Cambridge students as well, voices opposing war and fascism grew louder. Fascism is an ideology in which the state crushes individual freedom and suppresses other nations by force. Turing took part in this movement as well. In May 1933, he joined a student group called the Anti-War Committee, and in November of that year, he joined a demonstration protesting a movie that incited war.

A Brilliant Graduation

A Cambridge mathematics student must take a graduation examination called the Tripos. It is an examination notorious for the difficulty of its questions. In June 1934, Turing

achieved a first-class degree in this examination and received his bachelor's degree. He also received a special distinction awarded only to students with exceptionally outstanding marks. The student who had caused worry at Sherborne had become one of the top graduates in the Cambridge mathematics department.

4.2 Independent Mathematical Achievements

A Question Sparked by Eddington's Lectures

Turing's first major piece of research began before his graduation examination, stemming from the lectures by Eddington he attended in the autumn of 1933. In his lectures, Eddington explained how values measured through experiments are dispersed. If you measure the length of the same object several times, the values turn out slightly different each time. When multiple small errors in measurement overlap, the measured values often gather in the center and become rarer toward both ends. Eddington only introduced this phenomenon without proving it deeply. Turing began to investigate on his own under what conditions such a distribution of errors appears.

The Secret of the Bell-Shaped Curve

The problem Turing tackled can be explained with dice. If you roll a single die, any number from 1 to 6 comes up with equal probability. Now consider the case of rolling two dice and adding the two numbers together. For the sum to be 2, both dice must be 1. On the other hand, there are many ways for the sum to be 7, such as 1 and 6, 2 and 5, or 3 and 4. That is why 7 appears most often. While each individual die favors no particular number, the sum concentrates around the middle value.

If you increase the number of dice to ten or a hundred, calculate their sums, and plot a graph by repeating this countless times, a distinctive shape appears. It is a bell-shaped curve that bulges in the center and slopes downward toward both ends. A similar shape can also be seen in measurement errors where multiple small factors are added together. However, simply collecting a large amount of data does not always produce this shape. Mathematicians call this curve the normal distribution. Because the German mathematician Carl Friedrich Gauss studied this curve deeply, it is also called the Gaussian distribution.

What clarifies the conditions under which the distribution of sums approaches a bell shape is the central limit theorem. A simple example is rolling the same die multiple times without the rolls affecting each other. Under the conditions that each outcome follows the same probability rules and that the mean and the degree of dispersion are finite, when comparing after adjusting the center and width of the sum, the distribution of the sum approaches the normal distribution. Even when different probability rules are followed, such a result holds if additional conditions are met. Turing studied these conditions. This theorem is widely used in statistical methods that evaluate errors in opinion polls and experimental results.

Turing finished the proof of this theorem around February 1934. He was still an undergraduate at the time.

A Theorem Already Proved by Someone Else

But there was one problem. This theorem had already been proved and published in 1922 by the Finnish mathematician Jarl Waldemar Lindeberg. Turing did not know this fact until he completed his proof. Just as in the case of Sierpiński, he had arrived on his own at an answer that someone else had discovered first.

In research where new discoveries are expected, presenting an already known result again is usually unlikely to receive a favorable evaluation. But the scholars at King's College looked at the power of thought that reached that result, rather than the result itself. The mathematician Philip Hall advised Turing to write up this research as a fellowship dissertation.

The Fellowship Dissertation

After graduating, Turing decided to become a fellow of King's College. A fellow is a researcher selected directly by the college. Becoming a fellow means obtaining rooms inside the college, dining with professors in the dining hall, and being able to devote oneself to research while receiving a stipend. One also gains the qualification to teach students. It was a position that any young scholar coveted.

To become a fellow, one had to submit a research dissertation. In November 1934, Turing submitted a dissertation titled "On the Gaussian Error Function." In this paper, Turing proved the central limit theorem from beginning to end using his own method. The mathematician Abram Besicovitch, who reviewed the dissertation, evaluated Turing's proof as original. In his referee report, he wrote that had this paper appeared before Lindeberg's, it would have been considered one of the foremost achievements in the mathematical world that year.

Keynes's Lunch Invitation

John Maynard Keynes also participated in the election of fellows. Keynes was a scholar who held great influence at King's College. On March 11, 1935, Keynes invited Turing, a candidate, to lunch. And that day, he wrote a letter to his wife, the ballerina Lydia Lopokova. In the letter, Keynes wrote that he had met in person the candidate who seemed the most outstanding on paper and had even examined his fingernails; he was a very nice young man, and his name was Turing.

There was a reason Keynes looked at his fingernails. Keynes had a habit of carefully observing a person's hands upon first meeting them, and he was said to dislike people who bit their fingernails. While it may seem like a trivial anecdote, it clearly shows that a senior member of the college took enough interest in Turing to meet the twenty-two-year-old candidate in person. This anecdote is also recorded in biographies covering Keynes's life.

A Fellow at Twenty-Two

Five days later, on March 16, 1935, King's College elected Turing as a fellow. Turing was twenty-two years old, and less than a year had passed since he graduated from his undergraduate studies. Becoming a fellow at such a young age was uncommon.

Having become a fellow, Turing threw himself straight into research. In April 1935, he submitted a paper titled "Equivalence of Left and Right Almost Periodicity" to the Journal of the London Mathematical Society. It was the first paper Turing published in an academic journal. The following year, in 1936, he received the Smith's Prize for his research on the central limit theorem. The Smith's Prize is an award given by the University of Cambridge to outstanding young scholars in mathematics.

The research on the central limit theorem itself was largely forgotten thereafter. People do not remember Turing as a mathematician who studied probability and statistics. However, the knowledge of probability accumulated at this time was used several years later to break German military ciphers during World War II. His experience of deeply understanding how chances accumulate demonstrated its power in a completely different area.

4.3 Academic Freedom and Homosexual Identity

A Place Where One Did Not Have to Hide

What King's College gave Turing was not just mathematical achievements. Here, Turing was able to look honestly at what kind of person he was. Turing was someone who felt love for men rather than women. The feelings he had harbored for Morcom during his Sherborne School days were of that very nature.

In Britain at the time, this was something that had to be hidden. British law punished certain sexual acts between men as crimes. The Criminal Law Amendment Act 1885 made "gross indecency" between men punishable, and it applied even to acts committed in private places. If caught, one could lose one's job and be sent to prison. Therefore, most people who loved someone of the same sex lived hiding that fact.

The atmosphere at King's College was different from the outside world. Many scholars at the college, including Keynes, did not take issue with who loved whom. Among them were people who loved someone of the same sex. Outside the college walls, the law remained terrifying, but among close friends inside the college, there was no need to hide it. In this atmosphere, Turing gradually accepted himself as homosexual. He did not feel ashamed of himself or try to change himself by force. Turing maintained this attitude throughout his life.

Friends with Whom He Shared His Heart

At Cambridge, Turing made friends with whom he could open his heart. David Champenowne was a mathematics scholar who entered King's College in the same year as Turing. Friends called him Champ. Turing trusted Champ enough to show him writings revealing his inner thoughts. Champ later became an economist, but their friendship lasted

for a long time. In 1948, they even designed a computer program to play chess together. Combining their two names, this program was called Turochamp.

In 1933, he went on a walking tour to the Lake District in northwestern England with his mathematics friend James Atkins. The Lake District is a beautiful region where lakes and mountains blend together. Through this trip, the two developed an affection for each other, and their relationship continued for several years.

Turing also remained close to Fred Clayton, a young scholar studying classics. Clayton was someone who, like Turing, opposed war and fascism. Turing broadened his eyes to the world beyond mathematics as well, socializing with friends who shared his perspectives.

Sports and Stargazing

Turing also enjoyed physical exercise. In May 1935, he competed as an oarsman for the King's College Boat Club, rowing in races. He also enjoyed running long distances alone. Running became an exercise Turing treasured throughout his life, and later, he ran well enough to produce records rivaling those of marathon runners.

Turing also had an unusual hobby. It was observing the stars in the night sky to set his wristwatch with precision. Stars pass fixed positions at fixed times. Turing used this rule to correct the error of his watch. The thought that the world moves according to regular rules, and the act of discovering those rules to make them useful, were things Turing enjoyed all his life.

Thoughts Nurtured by Freedom

In this way, what Turing nurtured at King's College was not just mathematical ability. He also learned how to believe in his own thinking and the mindset that it was all right to be different from others. The boy who had studied alone and lonely at Sherborne gained friends and mentors here. Yet this freedom could only be enjoyed inside the college walls. The laws of British society remained unchanged, and these laws would later leave great sorrow in Turing's life.

Encounter with the Decision Problem

In the spring of 1935, having become a fellow and able to immerse himself in research, Turing attended lectures by the mathematician Max Newman. The course was titled the Foundations of Mathematics. In this lecture course, Newman introduced the incompleteness theorems presented in 1931 by the Austrian mathematician Kurt Gödel. The incompleteness theorem states that in any consistent mathematical system capable of containing the basic arithmetic of natural numbers and whose axioms can be mechanically determined, there will always remain propositions that are true but cannot be proved within that system alone.

Newman also addressed the decision problem posed by the German mathematician David Hilbert. The decision problem is a question concerning first-order logic. First-order logic is a fundamental logical system that deals with the properties of entities and their relationships. Asking whether there exists a procedure that can always decide if a given statement in this system can be proved using logical rules is what constitutes the decision problem. Hilbert believed that such a method must exist. Turing began to delve deeply into this question.

In the summer of 1935, while resting in the meadows of Grantchester near Cambridge after a run, Turing turned this problem over carefully in his mind. Then, he discovered a clue to solving the problem. It was the idea: what if the process of a human computing with pencil and paper were broken down into very simple actions? This thought led to his 1936 paper, "On Computable Numbers, with an Application to the Entscheidungsproblem." The imaginary machine we call a Turing machine today, along with the universal machine that became the foundational principle of all computers, was born right in this paper.

Chapter 5: Computable Numbers and the Universal Turing Machine (1935–1936)

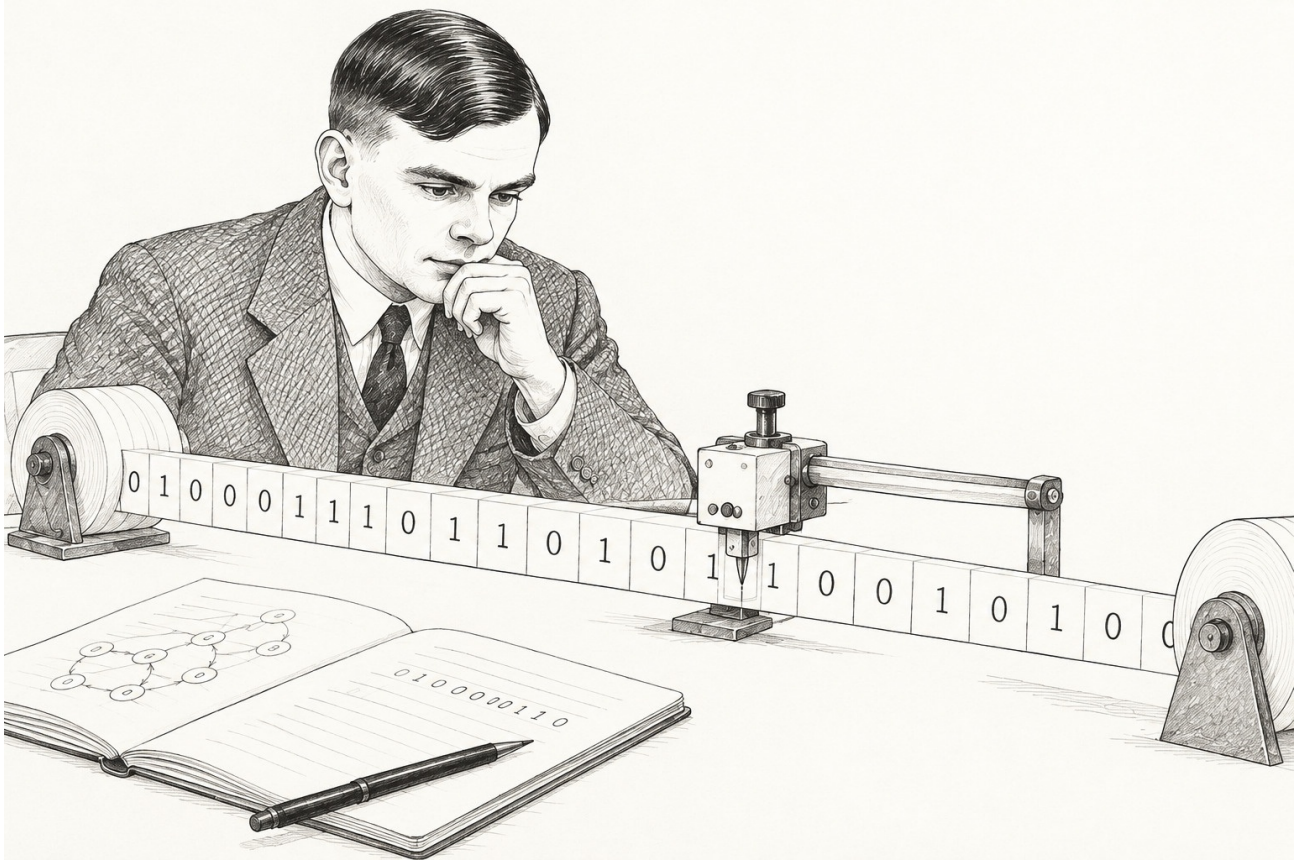


Figure 5. Conceptual diagram of a Turing machine that calculates with a tape and rules.

In March 1935, King's College, Cambridge, elected Alan Turing as a fellow. That spring, Turing was twenty-two years old. Having become a fellow, Turing received accommodation and research funds from the college, allowing him to pursue his desired studies to his heart's content. That very spring, Turing encountered a question that mathematicians had long been unable to solve. Seeking to answer this question, he envisioned a machine in his mind, and this computational model on paper later became an important foundation for understanding the principles of general-purpose computers.

5.1. Hilbert's Decision Problem

That question came from the German mathematician David Hilbert. Hilbert was a scholar who led many fields of mathematics in the early twentieth century. He wanted to build mathematics like an airtight building. Starting from a few basic rules that mathematicians call 'axioms,' he hoped that every mathematical statement could be proved or disproved.

To achieve this goal, mathematics had to answer three questions. First was the question of whether mathematics is complete—namely, whether all true statements can be proved. Second was the question of whether mathematics is consistent—namely, whether it never happens that both a statement and its opposite are proved at the same time. Third was the question of whether mathematics is decidable. This asked whether there is a method such that, no matter what mathematical statement is given, simply following the steps in order will produce an answer as to whether that statement can be proved or not.

The specific problem Hilbert posed in connection with the third question targeted statements in first-order logic. First-order logic is a fundamental logical system that deals with the properties of objects and relationships between them. This problem asks whether there is a procedure that can always determine whether such statements are provable according to the rules of logic. In German, it is called the 'Entscheidungsproblem,' and in Korean, the 'decision problem.' In a logic book written in 1928 with his colleague Wilhelm Ackermann, Hilbert presented this problem as an important challenge in mathematical logic. What the decision problem demands is easy to understand if you think of an instruction manual. Anyone could put in a mathematical statement, follow the steps written in the manual exactly, and at the end, the answer 'provable' or 'unprovable' would come out. If such a manual existed, mathematicians would have no need to ponder all night. It

would be enough just to put in the statement and follow the steps in order. Hilbert believed that such a method would definitely appear one day.

In 1931, however, the young Austrian mathematician Kurt Gödel made a crack in Hilbert's dream. The 'incompleteness theorems' published by Gödel targeted mathematical systems meeting certain conditions. Those conditions were systems that contain the basic arithmetic of natural numbers, whose axioms can be determined mechanically, and that are free of contradictions. Gödel showed that in such a system, there must always be statements that are true but cannot be proved using only the rules of that system. He also revealed that such a system cannot even prove using only the methods of its own system that it contains no contradictions in itself.

Gödel did not prove that all of mathematics contains contradictions. Rather, the answer to Hilbert's first question clearly became 'no,' and regarding the second question as well, the limitation was revealed that a consistent system cannot prove its own consistency by itself. However, the third question, the decision problem, remained unsolved by anyone.

Where Turing encountered this problem was in the lecture room of Max Newman. Newman was a Cambridge mathematician who studied both topology, which investigates the properties of geometric figures, and mathematical logic. In the spring of 1935, Newman offered an advanced course entitled 'Foundations of Mathematics,' and Turing attended this lecture. After explaining Gödel's incompleteness theorems in detail, Newman introduced Hilbert's decision problem. He then asked whether there was a 'mechanical method' that could tell whether a mathematical statement could be proved or not.

A 'mechanical method' means a method where one does not need to rack one's brain or puzzle things out, but only needs to follow rules written down in advance. Column addition learned in elementary school is a good example. You add starting from the ones place, and if the sum exceeds 10, you carry 1 to the next digit. As long as the rules are followed, whoever does it will arrive at the same answer. Such a method is called an 'algorithm.'

The problem was that mathematicians at the time had not determined exactly what a 'mechanical method' was. Everyone understood it intuitively, but no one had written it down thoroughly in the language of mathematics. To answer 'yes' to the decision problem, one did not need such a definition, because it was enough to find and present one such

method. But to answer that 'no such method exists in the world,' the situation was different. One had to examine every possible method, and to do that, one first had to define what a 'method' was. It was like having to define who counts as an athlete before one can say that no athlete may enter the sports field.

Turing grappled with this problem, lost in thought by himself. Andrew Hodges, who wrote Turing's biography, recorded a scene from the early summer of 1935. While strolling along the banks of the River Cam at Grantchester Meadows near Cambridge and lying down in the grass to rest, Turing came up with the key idea. Rather than defining a 'mechanical method' with difficult formulas, his idea was to break down what a human being actually does when calculating into tiny actions and translate them into the movements of a machine.

5.2. The Birth of a Historic Paper

From the summer of 1935 to the spring of 1936, Turing conducted his research almost entirely alone. He rarely exchanged views with other scholars. As if watching a person calculating beside him, he looked into what was happening inside his own head.

In the 1930s, the word 'computer' referred not to a machine, but to a person. Workers in government offices or observatories who calculated numbers all day long were called computers. Turing pictured such a person calculating with a pencil in a notebook of graph paper. When calculating, a human writes numbers in squares, erases them, shifts their eyes to adjacent squares, and remembers what they are currently doing.

In this process, Turing retained only what was essential to calculation and broke it down into even smaller parts. Although the squares of a notebook spread out horizontally and vertically, joining the squares end-to-end in a single long strip presents no problem for calculation. Since a human can look at only a few squares at a time, a machine needs to look at only one square at a time. Since human memory has a limit, a few states remembered by the machine are sufficient. A few usable symbols are also enough.

In this way, the machine in Turing's imagination took shape. This machine consists of four parts. The first is the tape. It is a long strip of paper divided into squares, which can be extended as much as needed in either direction. In each square, one symbol can be written.

The second is the read-write head, called 'head' in English. The head rests over one square of the tape and reads the symbol in that square. It can write a new symbol or erase an existing one, and can move one square to the left or right.

The third is the state of the machine. Just as a person remembers 'I am currently carrying over a digit,' the machine also remembers which step it is currently in through its state. There is a limit to the number of states. The fourth is the table of rules. It is a table that gathers rules such as: 'If the current state is A and the symbol read by the head is 0, write 1 in that square, move one square to the right, and change the state to B.'

Looking at the table of rules, the machine moves step by step and does nothing else. As his first example in the paper, Turing included a machine that endlessly writes 0 and 1 alternately. With only four states and four lines of rules, this machine writes 0, 1, 0, 1 endlessly on the tape.

Turing called this machine an 'a-machine,' meaning 'automatic machine.' The name 'Turing machine' that we use today was first used by the American logician Alonzo Church in a 1937 review introducing Turing's paper.

Turing's machine looks humble on the surface. Yet Turing asserted that whatever calculation a human could perform according to rules, this machine could also do. For no matter how complex a calculation may be, it is ultimately just repeating many times reading one square, writing one square, moving one square, and changing state. In effect, Turing defined the 'mechanical method,' which had remained undefined in Newman's lecture, as what this machine could do.

The 'computable numbers' appearing in the title of the paper were also defined through this machine. Turing called numbers whose decimal digits could be written out endlessly one by one by a machine according to rules 'computable numbers.' Pi (π) continues endlessly as 3.14159..., but a machine with an appropriate table of rules will keep writing those digits one after another. Therefore, π is a computable number. The same is true for the mathematical constant e . Yet Turing also showed that there are numbers that, although explainable in words, cannot have their decimal digits written out by any machine. It was the first sign that there was an edge to the world of what can be calculated.

In April 1936, Turing showed his nearly completed manuscript to Newman. Right around that time, a piece of news arrived from the United States. It was the news that Alonzo Church of Princeton University had solved the decision problem with his own method called the 'lambda calculus (λ -calculus).' In 1936, Church published 'An Unsolvable Problem of Elementary Number Theory' in the American Journal of Mathematics, showing that there were problems in number theory that could not be solved by the lambda calculus, and in a short paper that same year, 'A Note on the Entscheidungsproblem,' he dealt directly with Hilbert's decision problem. Church's answer was also 'no such method exists.'

Turing was greatly disappointed by the news that someone else had arrived at the answer first in research he had been devoted to for nearly a year. But Newman viewed Turing's paper differently. Even if the conclusion was the same, the path taken to reach it was different. Church's lambda calculus was an abstract language of functions that transformed symbols. Turing's machine directly mirrored the way a human calculates, so that anyone could understand what a 'mechanical method' was as if picturing it before their very eyes. Newman sent a letter to the London Mathematical Society explaining that Turing had conducted his research alone, independently of Church, and earnestly requested that they publish the paper. He also wrote a letter to Church to introduce Turing.

On May 28, 1936, the London Mathematical Society received Turing's paper, 'On Computable Numbers, with an Application to the Entscheidungsproblem.' At this time, Turing was twenty-three years old. In August of that year, Turing added an appendix to the end of the paper. It was a proof that what could be calculated by his machine and what could be expressed by Church's lambda calculus were exactly identical. It showed the fact that the two men had climbed to the same mountaintop by different paths.

The London Mathematical Society published this paper in two installments, on November 30 and December 23, 1936, in Volume 42 of its journal, Proceedings of the London Mathematical Society. The length was thirty-six pages in total. The following year, in 1937, Turing published an additional short note in the same journal correcting minor errors.

Later, scholars combined the ideas of Church and Turing, calling it the 'Church–Turing thesis.' It is the idea that anything a human can calculate by a mechanical method can be calculated by a Turing machine. Computer science still defines the meaning of what it means to be 'computable' based on this idea.

5.3. The Halting Problem and the Archetype of Modern Computers

In Section 6 of the paper, Turing introduced the 'universal machine.'

In the Turing machines seen earlier, each machine had only one task it performed. The machine that alternately writes 0 and 1 did only that task, and the machine that writes π wrote only π . To perform addition, an addition machine was required, and to perform multiplication, a separate multiplication machine was needed. Computing machines in the physical world were also like that. Calculators driven by gears could perform only the calculations determined when they were made.

Turing took this a step further. The starting point was the fact that for any Turing machine, its table of rules could ultimately be written as a string of symbols. Turing established a method for converting a table of rules into a string of characters and called this a 'standard description.' Converting this string into a single large number was called a 'description number.' Doing this turned each individual machine into a single number.

If a table of rules could be written in symbols, those symbols could also be placed on the tape of another machine. Taking advantage of this, Turing designed a special machine. On the front part of this machine's tape, the table of rules of another machine is written in symbols. On the rear part, the data for that machine to calculate is placed. The special machine reads the table of rules in the front part line by line and mimics on the rear part exactly what that machine would have done. If you put the table of rules of an addition machine onto the tape, it performs addition, and if you put the table of rules of a π machine, it writes π . Turing called this machine a 'universal computing machine,' and today it is called a 'universal Turing machine.' In his paper, Turing wrote that a single machine could be constructed that calculates any computable sequence.

Translating this idea into today's terms means that only a single machine is needed, and programs determine the work it does. This is the reason why a single smartphone can be a calculator, a camera, and a gaming device. Even without changing the components inside the smartphone, simply changing the app changes what it does. Turing mathematically presented this principle in 1936, before electronic general-purpose computers ever appeared.

There is one more noteworthy point about the universal machine. The universal machine writes both 'instructions' and 'data' together on the same tape using the same symbols. Instructions, after all, are simply a type of data. Today's computers also work by storing programs and data together in the same memory. This method is called the 'stored-program concept.' Turing's universal machine was the theoretical starting point for this method.

In 1936, the Turing machine was an imaginary machine with neither physical tape nor head. Yet before long, this imagination became reality. Between 1945 and 1946, after World War II ended, Turing designed an electronic calculator called ACE at the National Physical Laboratory in Britain. In June 1948, the 'Manchester Baby' at the University of Manchester ran a program stored in memory for the first time. Today, laptops, smartphones, and computers for artificial intelligence also perform diverse calculations by changing programs. The universal Turing machine is the theoretical model explaining such computational power. The structure and component design of actual computers were advanced by many researchers and engineers.

Returning to the 1936 paper, the universal machine was also the tool Turing used to answer the decision problem. With the universal machine in hand, Turing now set out to look for things a machine could not do. For to answer 'no' to the decision problem, he had to demonstrate a problem that no machine could solve.

Turing first divided machines into two kinds. One is a machine that endlessly keeps writing digits after the decimal point, and the other is a machine that writes only a finite number of 0s and 1s and cannot write any more digits. The latter machine includes not only cases where it stops completely partway through, but also cases where it keeps moving yet cannot write out any more digits. Turing called the former a 'circle-free machine' and the latter a 'circular machine.' He then examined whether it was possible to create a decision machine that, given the description number of any machine, could always determine whether that machine was circle-free or circular.

Turing's answer was 'it cannot be made.' Turing's original proof developed in quite a complex manner regarding this problem of distinguishing between circular and circle-free machines. Today, when explaining the limits of computation, the related 'halting problem' is frequently used. The halting problem states that given any program and input, it is

impossible to create a program that will always tell whether that program will eventually finish its task and halt, or whether it will never halt. The term 'halting problem' does not appear in Turing's paper. The halting problem later became a widely used explanation in computability theory.

The proof of the halting problem is as follows. Suppose there is a machine that, given a program and an input, always yields an answer and accurately determines whether execution will halt. Using this decision machine, we create a new program that acts in the opposite way. When the new program receives the number of any program, it asks the decision machine whether that program will halt if given that number itself as input. If the answer 'halts' comes back, it works endlessly; if the answer 'does not halt' comes back, it halts immediately. Now, we put the new program's own number into the new program. If the decision machine says it halts, the new program does not halt, and if it says it does not halt, the new program halts. Either way, the prediction is wrong. Therefore, the initial assumption that one can accurately determine this for all programs and inputs cannot hold.

This proof resembles the statement, 'I am lying right now.' If this statement is true, it becomes a lie, and if it is false, it becomes the truth. Words referring to themselves generate a contradiction. Turing refined this idea mathematically based on the 'diagonal argument' created by the German mathematician Georg Cantor while studying infinity.

Turing did not stop here. He also showed that the problem of determining whether a machine writes a 0 on the tape even once cannot be solved by any machine. And he rewrote this problem into a statement of logic of the kind Hilbert dealt with. If there were a mechanical method to solve the decision problem, it would also have to be able to solve the problem of 'does this machine write 0?' with that method. But that problem cannot be solved. Therefore, there is no mechanical method to determine in all cases whether a statement of first-order logic is provable. The answer Turing offered to Hilbert's decision problem was 'impossible.'

This result did not leave mathematicians with only disappointment. Knowing what cannot be computed is just as useful as knowing what can be computed. Today, programmers know that they cannot create a checking program that finds every single error in all programs without omission. That is why they use methods of testing and inspecting

repeatedly together. The research of Church and Turing became the foundation for understanding both the power and the limits of computation.

In September 1936, Turing boarded a ship, crossed the Atlantic, and departed for Princeton in the United States. It was to meet Alonzo Church, who had solved the decision problem before him, and conduct research together.

Chapter 6. Studying at Princeton and the Oracle Machine (1936–1938)

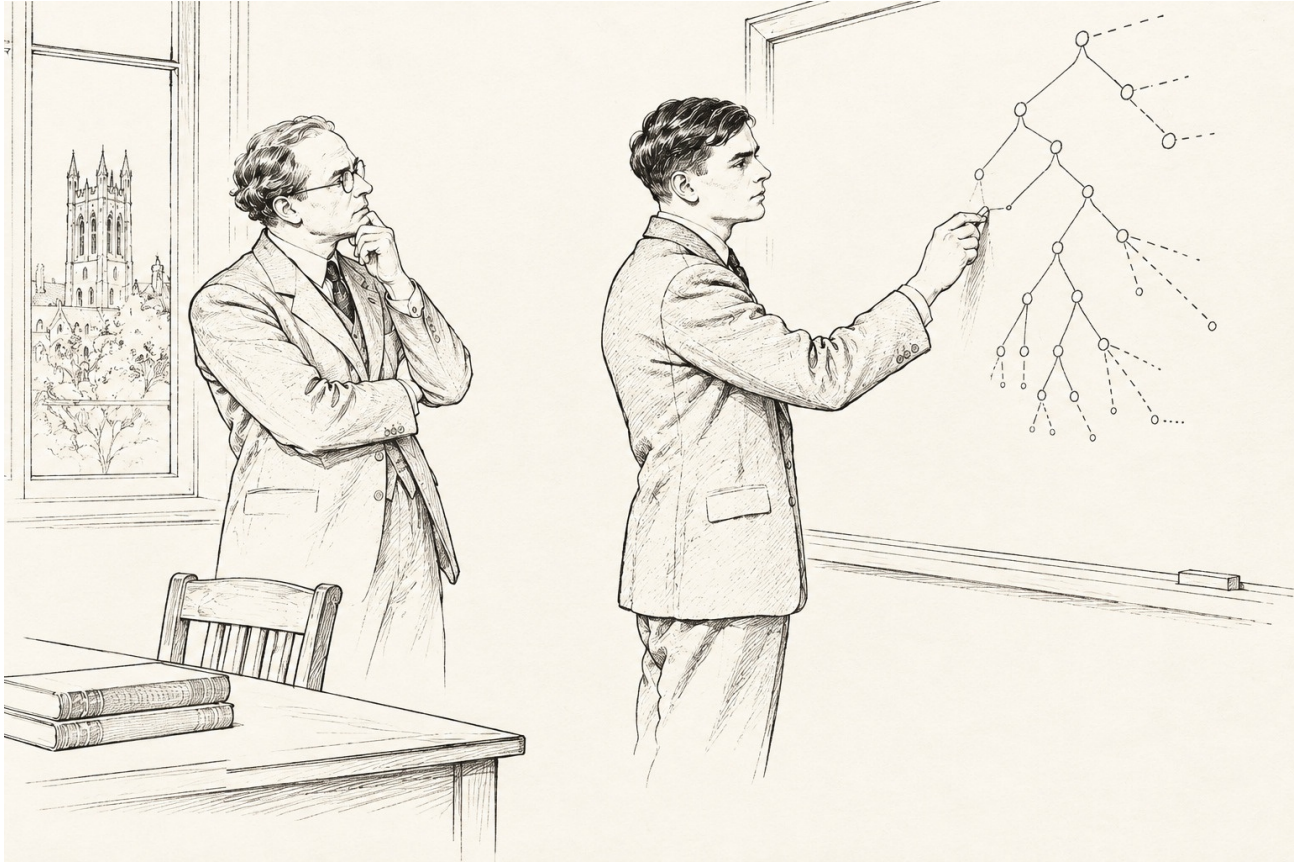


Figure 6. A reconstruction of Turing studying logic at Princeton.

In the spring of 1936, Alan Turing, a young fellow at King's College, Cambridge, provided an answer to Hilbert's decision problem using a machine he had imagined in his mind. Yet at nearly the same time, Alonzo Church, a logician at Princeton University in the United States, reached the exact same conclusion using an entirely different method. Turing was, in effect, a step behind. Max Newman, who had taught Turing at Cambridge, saw this development as an opportunity rather than a setback. Turing had a habit of doing research entirely on his own, and Newman believed he could grow significantly if he learned alongside Church, who had studied the same problem deeply. Newman arranged for Turing to go to Princeton and study under Church.

At that time, Church was not the only scholar at Princeton. In the mid-1930s, as Hitler and the Nazis seized power in Germany, a dark shadow fell over the European academic world. Brilliant scholars working in Göttingen, Berlin, and Vienna crossed the Atlantic to escape persecution, and many of them settled in Princeton, a small university town in New Jersey. As the world's greatest mathematicians gathered at Princeton University and the newly opened Institute for Advanced Study, Princeton became the new capital of mathematics.

The period of study at Princeton that began this way lasted nearly two years, from September 1936 to the summer of 1938. During this time, Turing earned his doctorate, proposed a new concept called the oracle machine, and built an electrical machine with his own hands. And in the end, he made an important decision that would change the course of his life.

6.1. Research with Church and the Doctoral Degree

In late September 1936, Turing crossed the Atlantic aboard the passenger liner *Berengaria*. Even on the ship, Turing could not sit idle. He used an instrument called a sextant to measure the altitude of the sun and stars, calculating for himself roughly where the ship was sailing. A sextant is a tool that sailors in old times used to determine their position at sea. Turing wrote about this in a letter to his mother, Sara Turing. It was a classic display of Turing's character, having loved to make and verify everything firsthand since childhood.

Upon arriving in New York, Turing unpacked his bags at the Princeton University Graduate College dormitory. At that time, Princeton's mathematics department was located in a building called Fine Hall. The university's mathematics department and the Institute for

Advanced Study shared this building, and tea was served every afternoon. Holding their teacups, scholars gathered to exchange ideas freely on mathematical problems. In a letter to his mother dated October 6, 1936, Turing listed the names of scholars he had met there: John von Neumann, Hermann Weyl, Richard Courant, Godfrey Hardy, Albert Einstein, Solomon Lefschetz, and his advisor Alonzo Church. Scholars whose names appear in textbooks were right beside him.

Turing began his doctoral studies under Church's guidance. While the two had answered the same question, their approaches to handling computation differed. Church studied computation using a method called lambda calculus. Lambda calculus is a method of creating and evaluating functions using only symbols and rules. Turing solved the same problem by imagining a machine that reads and writes squares one by one on a tape. Though their paths were different, the destination they reached was the same.

However, life at Princeton was not glamorous from the start. In December 1936, at Church's suggestion, Turing gave a presentation to the Mathematical Club on his paper "On Computable Numbers." Yet not many people came to hear the lecture, because few people knew the name Turing yet. Though disappointed, Turing did not stop his research.

It was Church who clearly pointed out the merits of Turing's method. Church acknowledged that Turing's approach was far easier to understand and more intuitive. In 1937, in a review introducing Turing's paper, Church referred to the machine Turing had imagined as a "Turing machine" for the first time. This is how the name that appears in computer science textbooks around the world today came into being.

Around this time, mathematicians came to realize that the range of what could be computed was identical across Church's lambda calculus, the recursive functions refined by Kurt Gödel, and Turing's machine. Recursive functions are a method of starting from simple functions and repeatedly applying set rules to build more complex functions. It was as if three people had climbed a mountain by different routes and all reached the exact same peak. Because three methods with entirely different starting points arrived at the same scope, mathematicians came to believe that anything a human can compute by following a fixed procedure can also be computed by a Turing machine. This idea is known as the Church–Turing thesis. It became possible to compare different methods of computation against a single standard.

Turing's research was not confined to logic. He also studied group theory, another branch of mathematics. Group theory is a field dealing with objects that are bound together by consistent rules, such as numbers or symmetries. Turing published the results of that research in several papers.

The achievements of his first year received high praise. For his second year, spanning 1937 to 1938, Princeton University appointed Turing as a Jane Eliza Procter Visiting Fellow. Thanks to this position, Turing could immerse himself entirely in research without worrying about tuition or living expenses. Records from the IEEE Computer Society also state that Turing spent two years at Princeton from 1936 to 1938, serving as a Procter Fellow during the second year and researching alongside Church.

6.2. The Oracle Machine and Ordinal Logics

To understand the problem Turing addressed in his doctoral dissertation, one must first go back to 1931. In that year, Kurt Gödel, a young Austrian mathematician, proved a fact that shook the mathematical world: in any system of rules that can encompass basic arithmetic such as the addition and multiplication of natural numbers, whose rules are precise enough to be listed one by one by a machine, and that is internally free of contradictions, there will inevitably remain statements that are true but cannot be proved using those rules alone. This is known as Gödel's incompleteness theorem.

One can compare the axioms of such a mathematical system to the rulebook of a game. In a system meeting the conditions described above, statements remain that cannot be decided using the rulebook alone. If so, one might consider the idea of writing in one more rule to resolve that situation. Turing researched this very method in depth. If an unprovable true statement is added as a new rule, the rulebook becomes a little stronger. However, because the new rulebook still satisfies the earlier conditions, unprovable statements arise within it once again. Then that statement is added as well. In this way, the rulebook is expanded continuously, step by step.

These steps continue endlessly, like 1, 2, 3. But Turing did not stop there. The German mathematician Georg Cantor had shown that order could be assigned even to infinities. In this view, the first position that comes after passing through all of 1, 2, 3, and so on is called omega, the next is called omega plus one, and so forth. Sequences that extend beyond

infinity in this manner are called transfinite ordinals. Turing created a system that expanded the rulebook infinitely along these ordinals and called it ordinal logics. He then investigated whether such an endlessly strengthened rulebook could fill the gaps Gödel had revealed.

The outcome was not complete success. Turing himself showed that even this method could not cleanly bridge every gap. Yet in the process, he left behind an important observation about the way mathematicians think. Turing viewed mathematical reasoning as the interplay of two faculties: one is ingenuity, and the other is intuition. Ingenuity is the ability to carry out a proof step by step according to set rules. This is something a machine, such as a Turing machine, can perform in place of humans. Intuition is the ability to recognize at a glance which new rule ought to be added or whether a certain statement is true. Turing explained that, in light of Gödel's theorem, mathematics as a whole cannot be completed through ingenuity alone; intuition is inevitably required somewhere along the way. The question of how machine thought differs from human thought would follow Turing for the rest of his life.

There is another part of this dissertation that is best known today: the oracle machine. Turing himself only briefly used the oracle machine as a tool to aid proofs within the paper, without exploring it more deeply. An oracle refers to a seer at a temple—a divine revelation—where people in ancient Greece consulted the will of the gods. Turing imagined an ordinary Turing machine accompanied by such an oracle-like helper. An oracle is a hypothetical device that provides precise answers to a predetermined class of questions. A modern example would be an oracle that answers the halting problem for ordinary programs: assuming that when given a program and an input, it tells you whether it will eventually halt. This setup was designed to explore how far problems that an ordinary Turing machine cannot answer in all cases could be solved if such help were available.

The way an oracle machine works is simple. Normally, it computes by reading and writing on a tape just like an ordinary Turing machine. Then, when it is time to query the oracle according to its table of rules, it submits a predetermined type of question, receives an answer, and continues its computation. The oracle is not a physical device that was actually discovered, but an assumption made for research. Therefore, the physical principles behind how it produces answers are not explained here.

This imaginative concept opened a new path in mathematics. Thanks to oracle machines, mathematicians could pose new questions: if there were a helper that provided the answer to Problem A, could Problem B also be solved with that help? This is known as relative computability. To use an analogy with a math exam, it is like asking whether knowing the answer to an earlier question allows you to solve a later one. In this manner, one can compare computational capability between problems. However, not all problems can be lined up in a single order. There are also relationships where neither problem can be solved even with access to the other's answers.

Turing demonstrated that attaching an oracle does not make the limits of computation disappear. Explained in terms of the modern halting problem, one cannot always decide whether all programs utilizing a specific oracle will halt using only the help of that same oracle. Even when one kind of help is added, problems that lie beyond its reach still remain.

It was later scholars who greatly developed this idea that Turing had used only briefly. Through the work of scholars including the American logician Emil Post, concepts emerged such as Turing degrees, which classify the difficulty of problems into levels, and Turing reductions, which solve one problem by transforming it into another. The methods computer scientists use today to compare problem difficulty also have their roots in this thinking.

Turing completed his dissertation and sent it to the London Mathematical Society in late May 1938. In June 1938, he received his doctorate from Princeton University. The title of the dissertation was "Systems of Logic Based on Ordinals." After being refined, this paper was published in 1939 in the Proceedings of the London Mathematical Society, Volume 45, running 68 pages.

6.3. The Decision to Return Home

At Princeton, Turing did not confine himself to paper and pencil. His interests extended beyond logic, and one of them was cipher. A letter dated October 14, 1936, shortly after his arrival in Princeton, contains an intriguing passage. Turing wondered what the most general form of cipher might be, informing his parents that he was designing a cipher that would be difficult for others to break yet fast to construct. At the time, no one could have known that this interest would draw Turing into the center of war just a few years later.

Turing did not leave his ideas merely on paper. Since childhood, he had been the kind of boy who repaired fountain pens and built chemistry lab equipment himself. That habit remained unchanged at Princeton. Turing borrowed the physics department's machine shop to build relays by hand to use as switches.

A relay was an electrical switch used in telephone exchanges at the time. When an electric current flows, a small electromagnet attracts a piece of metal to close the circuit; when the current is cut off, the metal drops away and breaks the circuit. There are only two states: on and off. Turing took note of the fact that these two states could be viewed as the numbers 1 and 0. The method of representing all numbers using only the two digits 0 and 1 is called the binary system. Turing began building a machine that performed binary multiplication by connecting relays with wires and soldering them. He actually completed three or four stages of the overall machine. Biographer Andrew Hodges explains that this multiplier was connected to Turing's concept of constructing ciphers by multiplying large numbers. Alongside his abstract studies of computation, Turing was also conducting experiments to build physical computing devices.

Around this time, Turing also took an interest in the Riemann hypothesis, an old enigma of mathematics. The Riemann hypothesis is a problem concerning the patterns by which prime numbers are distributed. A prime number is a natural number greater than 1 that is divisible only by 1 and itself, and the Riemann hypothesis remains unsolved to this day. Turing conceived of a machine that would perform calculations related to this problem using gear wheels, and after returning to Britain in 1939, he actually drew blueprints and began cutting gears. With the outbreak of war, this machine was never completed.

Among those who took keen notice of Turing's work at Princeton was John von Neumann. Von Neumann was a Hungarian-born mathematician who would later make his name by formulating the architecture of modern computers. The two had first met in Cambridge in 1935, and Turing reconnected with von Neumann at Princeton. Von Neumann noted with appreciation that Turing had produced new results even in the theory of continuous groups, his own primary field of research.

In 1938, as Turing was completing his doctoral studies, von Neumann made him an offer: to remain in the United States and work as his research assistant at the Institute for Advanced Study in Princeton. It was a position offering an ample research environment,

collaboration with world-renowned scholars, and a secure future. Turing's father, Julius Turing, also hoped his son would leave an increasingly perilous Europe and settle down in the United States.

However, Turing declined this offer. In a letter to his mother dated May 17, 1938, he wrote that although he had been offered the position of assistant to Professor von Neumann, he had turned it down and decided to return to Cambridge.

There were several reasons behind Turing's decision to return. First, the situation in Europe was deteriorating rapidly. In March 1938, Hitler annexed Austria into Germany and soon began threatening Czechoslovakia. Many people felt that a major war was approaching.

Second, King's College, Cambridge, was Turing's intellectual home. King's College was a place where, in an atmosphere of freedom, Turing could truly be himself. In the spring of 1938, King's College renewed Turing's fellowship. Princeton alumni records also report that Turing was homesick. One biographical dictionary notes that Turing chose to return even though there was no lectureship awaiting him at Cambridge.

In the summer of 1938, Turing returned to Cambridge with his doctorate in hand. It was not merely the mathematics lecture halls that awaited him. The Government Code and Cypher School, the British government's secret cryptanalytic agency, summoned Turing to prepare for the looming war with Germany. After returning home, Turing attended training courses in codebreaking there and began assisting their work without telling anyone. The curiosity about ciphers he had written about in his letters from Princeton was now about to turn into a matter upon which the nation's destiny hinged.

During his two years at Princeton, Turing carried out research in logic and experiments on computing devices side by side. His doctoral dissertation written alongside Church, together with the oracle machine, demonstrated that there are countless gradations between what can and cannot be computed. The relay multiplier he built with his own hands in the physics department's workshop was his first step toward bringing machines from the mind into reality. And his decision to turn down von Neumann's offer and return to Britain would lead Turing to Bletchley Park and the battle against the Enigma cipher.

Chapter 7. Entering Bletchley Park and the Beginning of the Code War (1938–1940)



Figure 7. An illustration depicting the researchers gathered at Bletchley Park.

After earning his doctorate from Princeton University in the United States, Alan Turing returned to Britain in the summer of 1938. At twenty-six years old, he was a Fellow of King's College, Cambridge. A Fellow is a scholar who resides at a college to conduct research and teach students.

A heavy air of war hung over the Europe he returned to. In the spring of that year, Germany's leader Hitler annexed Austria into Germany and subsequently demanded territory from Czechoslovakia. In September, Britain and France signed an agreement with Hitler in Munich, Germany, agreeing to hand over part of Czechoslovakia's territory to Germany. Although this was a choice made to avoid war, many felt that a major war was not far off.

Around this time, a change also took place in the work Turing did. Until then, he had been a quiet mathematician who wrote mathematical formulas on blackboards and researched imaginary machines. But the British government sought to entrust him with breaking enemy codes, and Turing took on a secret mission that he could not speak of to anyone. That mission began as the government's codebreaking agency prepared people and a location in anticipation of war.

7.1. The Call of the Government Code and Cypher School

To win a war, one must first know what the enemy intends to do. Entering the twentieth century, militaries exchanged orders via radio communication. Because radio waves could be intercepted by anyone, armies sent their messages converted into code. The opposing side had to break those codes to learn the enemy's plans. Such a struggle waged in unseen places is called a code war.

In Britain, the agency responsible for this work was the Government Code and Cypher School, abbreviated as GC&CS. Although its name included the word 'School,' it was not a place for teaching students, but an intelligence agency that secretly deciphered other countries' codes. It is the predecessor of today's British intelligence agency, the Government Communications Headquarters (GCHQ). Established in 1919, the organization was headed operationally for a long time by Alastair Denniston, a former naval officer.

As war approached, the Government Code and Cypher School had to prepare two things: one was personnel to confront new ciphers, and the other was a safe place to work even during wartime.

First was the matter of people. At that time, most codebreakers at the Government Code and Cypher School were classical linguists. As scholars who studied ancient languages like Latin and Greek, they excelled at inferring the meanings of words and sentences. However, the German military was using a cipher machine called the Enigma. Unlike ciphers made by humans with paper and pencil, the Enigma scrambled letters countless times using electrical circuits and wheels. Denniston judged that linguistic skill alone could not defeat this machine. He drew up an emergency roster of people to summon immediately if war broke out. The list included mathematicians, logicians, and chess masters from Cambridge and Oxford. Denniston called them the 'professor types.' For Britain to gather so many mathematicians for codebreaking was something rare before that time.

Turing was recruited by the Government Code and Cypher School in 1938. He participated in a special training course organized by the Government Code and Cypher School. While continuing his research at Cambridge as usual, he occasionally visited headquarters in London to confer with cipher experts. Ciphers were not an unfamiliar field to Turing. He had been deeply interested in ciphers and symbols since his student days. At Princeton, he had even built a small machine that performed multiplication using electrical switches. In a paper published in 1936, he had conceived of an imaginary machine that read and wrote symbols according to rules. His ability to handle machines, symbols, and rules all at once was ideally suited to battling the Enigma.

Next was the matter of location. If war broke out, London could be bombed, so a place was needed to relocate the codebreaking agency to the safe countryside. In May 1938, Admiral Hugh Sinclair, head of the British Secret Intelligence Service (MI6), purchased a country mansion and its grounds in Buckinghamshire, northwest of London. When the government said it lacked the budget, he paid £6,000 of his own money. The estate's name was Bletchley Park. Situated between Oxford and Cambridge, with a railway station and major roads nearby, Bletchley was convenient for gathering scholars from both universities.

In the autumn of that same year, personnel from the intelligence services and the Government Code and Cypher School gathered at Bletchley Park. To conceal their

identities, they called themselves 'Captain Ridley's Shooting Party,' even bringing along a chef from a luxury London hotel to pose as guests enjoying a weekend retreat. At the height of the Munich Crisis, they prepared for war by conducting actual cipher work here. People later also referred to Bletchley Park by the code name 'Station X.' Here, X did not mean the letter X, but the Roman numeral 10.

The personnel and location prepared in this manner were put into actual use in late summer 1939. The Government Code and Cypher School left London and relocated to Bletchley Park on August 15. On September 1, German forces invaded Poland, and two days later, on September 3, Britain declared war on Germany. World War II had broken out. Turing reported to Bletchley Park to begin work on September 4, 1939, the very day after the declaration of war. He rented a room at the 'Crown Inn' in Shenley Brook End, a small village west of Bletchley, and stayed there until the summer of 1944.

Everyone who came to Bletchley Park signed an undertaking under the Official Secrets Act. It was a promise not to speak of what they saw and heard there, even to their families. Turing kept this promise to the end. That is why what he did during the war was revealed to the world only bit by bit in the 1970s, some twenty years after his death.

7.2. The Gift Left by Dilly Knox and the Polish Cipher Bureau

Upon arriving at Bletchley Park, Turing joined the Enigma research section led by Dilly Knox. Knox's full name was Alfred Dilwyn Knox. Like Turing, he was a scholar who had studied ancient Greek literature at King's College, and he was a seasoned expert who had broken enemy ciphers since World War I. During the Spanish Civil War in 1937, he made a name for himself by breaking the Enigma used by the Italian Navy. That machine, however, was a commercial model with a simpler structure than the military Enigma.

Knox's research section worked in a small cottage in the stable yard behind the mansion. Alongside Knox, John Jeffreys, Alan Turing, and Peter Twinn set up their quarters here. People simply called this building 'the Cottage.' Turing wrestled with the Enigma in this cottage from the winter of 1939 until early the following year. Before long, Knox reported that Turing was continuously producing ideas.

The Enigma they faced looked outwardly like a typewriter. When a key for a letter was pressed on the keyboard, electric current passed through the machine, and another letter lit up on the lampboard above. Inside the machine were three wheels called 'rotors.' Complexly intertwined wires inside each rotor substituted one letter for another. With every keystroke, the right-hand rotor stepped, and the other rotors turned according to predetermined conditions. Because the wiring state substituting the letters changed accordingly, pressing the same letter A repeatedly could produce entirely different letters. At the end of the rotors was a 'reflector' that sent the electrical current back through. The military Enigma had an additional mechanism attached: the 'plugboard.' It was a board where patch cables were plugged in to swap pairs of letters.

The reason the cipher was difficult to break lay in its settings rather than the machine's mechanical structure. Every day, German signal operators set up the machine according to prescribed settings. Which rotors to insert in which order, which letter to align each rotor to, and which sockets to connect on the plugboard were changed daily. Around 1939, the number of possible configurations that could be chosen this way was approximately 159 quintillion. It was a number with 18 zeros following the number 159, larger than multiplying 100 million by 1 trillion. If a person were to test them one by one, it was a quantity that could not be finished even in millions of years. This was why the German military believed the Enigma to be an unbreakable machine.

Yet the first people to defeat this machine were not the British, but the Poles. Because Poland shared a border with Germany, it worried about the movements of the German military more than anyone. The Polish Cipher Bureau recruited three young men who had studied mathematics at Poznań University: Marian Rejewski, Jerzy Różycki, and Henryk Zygalski. In the autumn of 1932 in Warsaw, Rejewski was tasked with studying the German military Enigma, and in December of that year, he achieved a major breakthrough in decipherment. Using the mathematical theory of 'permutations,' he worked out the wiring inside the rotors. A permutation is a mathematical concept dealing with the ways of arranging multiple objects in a particular order. Documents obtained by French intelligence from an informant inside the German cipher office also proved of great help. Based on this, Poland even built replica machines that identically mirrored the Enigma.

Over the subsequent years, the Polish team read German military ciphers and built tools of their own to assist in decryption. In the autumn of 1938, they built an electrical machine to

aid the decryption process, and the name of this machine was the 'Bomba.' In Polish, it means bomb. Various stories are told regarding why it was given this name. Zygal'ski devised a method of superimposing multiple perforated paper sheets. People called these 'Zygal'ski sheets.'

However, the German military did not sit idly by. In December 1938, the Germans increased the available rotors from three to five. Although only three rotors were still inserted into the machine, three had to be chosen out of five and their order determined. Consequently, the number of ways to insert the rotors increased tenfold, from 6 to 60 ways. In January 1939, they also increased the number of cables connected to the plugboard. For the Polish team to keep up with this, they needed to build ten times more bombas than before. For a small country's budget and manpower, this was a difficult burden to bear.

As war drew near, Poland made a major decision. On July 25 and 26, 1939, cipher experts from Poland, France, and Britain met near Warsaw. The meeting place was a secret Polish Cipher Bureau facility in the Pyry forest south of Warsaw. From Britain, Denniston, head of the Government Code and Cypher School, and Knox, who led the Enigma research, attended. Poland revealed its achievements to date without withholding anything. They shared the rotor wirings, the design of the bomba, and the principles of the Zygal'ski sheets. And they handed over one replica Enigma each to Britain and France.

At this gathering, the British and French representatives learned that Poland was far ahead of them. Not only had Poland already read many German military messages, but they had also designed and built electrical machines to aid in codebreaking. Britain's share of the replica machine arrived in London in mid-August via the French intelligence officer Gustave Bertrand. This was about two weeks before Germany invaded Poland.

In the Cottage at Bletchley Park, Turing studied the materials provided by Poland meticulously. He held Rejewski's mathematical prowess in high regard. At the same time, he also identified a hidden weakness in the Polish method. At the time, German signal operators typed the three letters indicating the starting positions of the rotors twice in succession at the very beginning of a message. It was a habit meant to ensure the receiving party understood without mistake. Poland's bomba and Zygal'ski sheets used the regularities arising from this repetition as their clue. Turing foresaw that if the German

military abandoned this habit, the Polish method could no longer be used. His prediction was correct. The German military abolished this repetition in May 1940.

Therefore, Turing sought another path that did not rely on repetitions at the beginning of messages. He turned his attention to words likely to appear in the ciphertext. In German military messages, similar expressions were repeated daily. Examples included words reporting the weather, unit names, and phrases like 'nothing to report.' Codebreakers called such guessable fragments of the original text a 'crib.' When placing a crib side by side with the ciphertext and examining them, many machine settings would be contradictory and could be eliminated from consideration. Turing wanted a machine, rather than a human, to rapidly perform this search for contradictions. The method of using cribs could continue to be used no matter how the Germans changed the beginnings of their messages.

From the autumn of 1939 until the end of the year, Turing refined the design of such a machine. In homage to Poland's bomba, he named the new machine the 'Bombe.'

Meanwhile, the Polish cipher team had left their country. When war broke out, they escaped through Romania to France, and continued their Enigma decryption alongside the French at a secret base about 40 kilometers southeast of Paris. Turing met the Polish cipher experts in person in Paris in January 1940, and from this meeting, he obtained clues to push his research one step further.

The blueprints for the Bombe were handed over to Harold Keen, an engineer at the British Tabulating Machine Company (BTM). He was a man known to his colleagues by the nickname 'Doc.' The first Bombe arrived at Bletchley Park in March 1940, and people named this machine 'Victory.'

7.3. The Eccentric Professor of Bletchley Park

As the war continued, the number of people working at Bletchley Park grew rapidly. In September 1939, there were only several dozen, but by the end of the war, nearly 10,000 people worked here. Mathematicians, linguists, chess players, crossword puzzle champions, mechanical engineers, and numerous female staff worked together.

Even among this multitude of people, Turing stood out easily. Colleagues called him 'the Prof,' a nickname short for the English word 'professor.' Although Turing was not a formal professor, he earned this nickname because of his scholarly demeanor, always lost in thought. He prioritized what was rational over how others might view him. Several stories passed down by colleagues and biographers illustrate this trait of his well.

The first is the story of the gas mask. Turing suffered from severe pollen allergies. Every June, he struggled with a runny nose and sneezing. To keep out pollen while commuting by bicycle, he wore a gas mask. Because it was wartime, everyone had been issued a gas mask in preparation for poison gas attacks, and Turing used his as a pollen mask. Stories also recount that villagers who saw him riding along country roads wearing a gas mask were alarmed, thinking something terrible had happened.

The second is the story of the bicycle chain. Turing's bicycle had a malfunction where the chain kept slipping off. An ordinary person would have taken it to a repair shop or replaced the chain. Turing first looked for the rule governing when the chain came off. He counted how many revolutions of the pedals caused the chain to slip. Thereafter, he counted the pedal revolutions in his head, dismounted right before the chain slipped off, adjusted the chain, and got back on. Later, it is even said that he attached a small counting device to his bicycle to track the number of pedal turns. It is an anecdote that clearly reveals his habit of searching for cycles and rules, even when dealing with a mechanical breakdown.

The third is the story of the tea mug. At Bletchley Park, the mugs used for drinking tea often went missing. To protect his mug, Turing put a padlock on the handle and chained it to a radiator pipe. A radiator is a heating unit that warms a room by circulating hot water. The sight of him resorting to a chain and padlock just to protect a single mug remained long in the memories of his colleagues.

The fourth is the story of running. Turing enjoyed long-distance running. Whenever he felt fatigued from work or his thoughts grew tangled, he went on long runs along the country roads around Bletchley. It is even said that he once ran approximately 64 kilometers (40 miles) from Bletchley Park to London to attend a meeting. After the war ended, he developed his skills enough to compete in marathon races.

Hearing only these stories, Turing might seem like an eccentric person. Yet there was always a reason of his own behind his behavior. If a gas mask kept pollen away, he wore it; if he knew the cycle of the chain slipping, he acted accordingly. This attitude of prioritizing principle over the eyes of others carried over directly to his approach to the Enigma. When others called it an unbreakable machine, Turing calmly sought out the rules the machine followed and its vulnerabilities.

Bletchley Park was a place that embraced such an eccentric. Here, ability and ideas took precedence over attire or etiquette. Knox was also a man well known for peculiar behavior, and Bletchley Park was filled with people of strong, distinctive individuality. In this atmosphere, Turing was able to think and calculate to his heart's content and fully deploy his abilities.

Between the summer of 1938 and the winter of 1939, Turing's life changed dramatically. The mathematician who had studied imaginary machines on paper became a codebreaker confronting real machines. He did not forge this path alone. There were the Polish mathematicians who paved the way ahead, Knox who shared his long experience, and Denniston who recognized the power of mathematicians and brought them in. Building upon what he received from them, Turing established a broader and more robust method. The culmination of that effort was the Bombe.

Chapter 8. Design and Exploits of the Bombe Codebreaker (1939–1941)

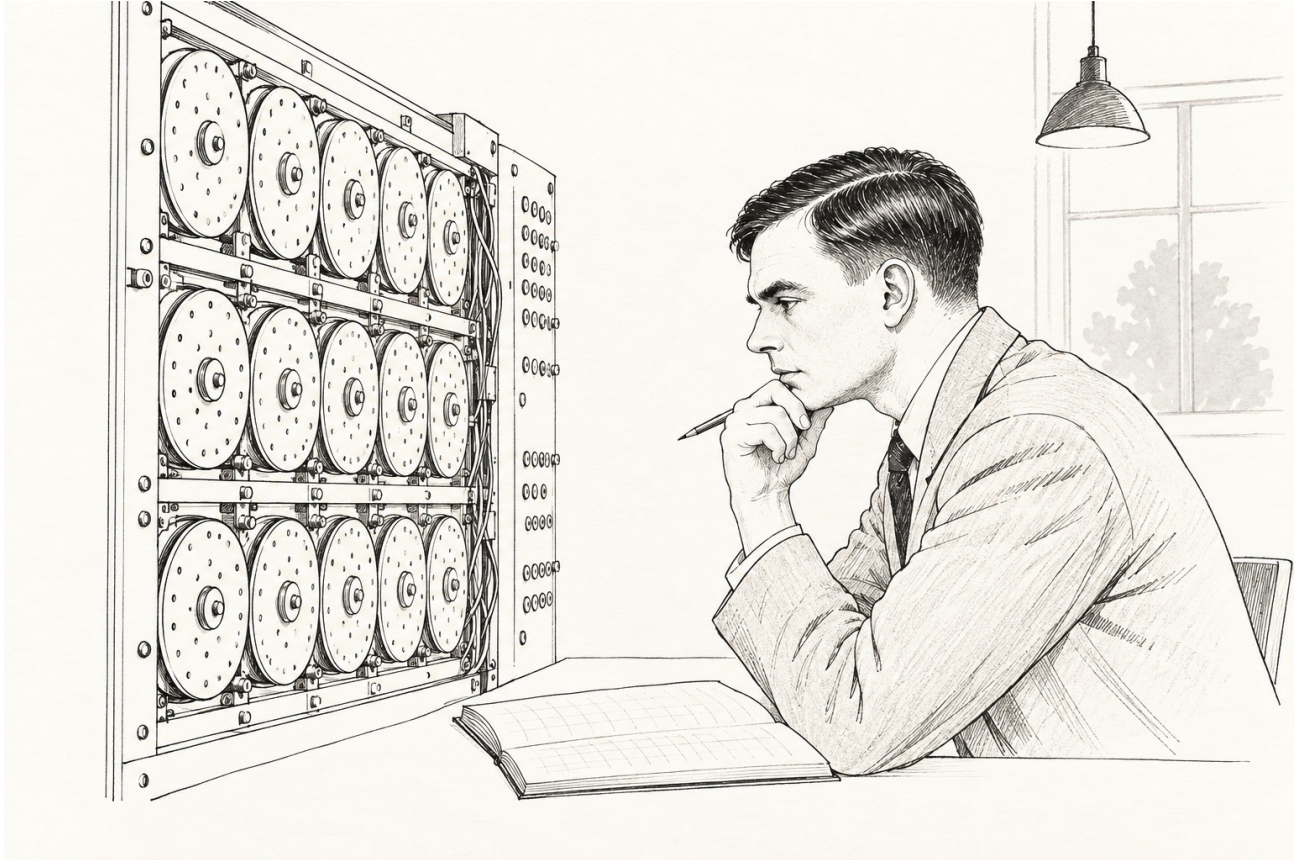


Figure 8. Depicting codebreaking research using the Bombe.

On September 3, 1939, Britain declared war on Germany and entered the Second World War. From that day on, Bletchley Park, an old estate in Buckinghamshire northwest of London, became a battlefield where no gunfire was heard. The people gathered here fought not with guns, but with pencils, paper, and their minds.

Their adversary was the German military's cipher machine, the Enigma. The Enigma was a wooden box that looked like a typewriter. When a key was pressed, electrical current passed through three rotating circular wheels called rotors and through cables on a plugboard at the front, turning it into a different letter, and that letter lit up on the lampboard above. Because a rotor turned by one position every time a letter was struck, pressing the same letter A twice would produce a different letter each time.

Furthermore, the German military changed the machine's settings every day. They chose anew which rotors to insert in which order, the starting letter position for each rotor, and which letters to pair up with the plugboard cables. Calculated from choosing 3 out of 5 rotors and plugging in 10 cables, the possible settings reached approximately 159 quintillion combinations. It was a number that several people working by hand could never finish checking even in an entire lifetime. This was precisely why the German military believed the Enigma was an unbreakable machine.

Twenty-seven-year-old Alan Turing thought differently. He believed that if a riddle was made by a machine, it could be solved by a machine. Three years earlier, in his paper 'On Computable Numbers,' Turing had explained all computation as a sequence of very simple mechanical operations. Now, it was time to move that idea from paper into metal and wire.

8.1. Designing an Electromechanical Codebreaker

Starting from the Polish Bomba

The first task Turing faced at Bletchley Park was examining the technology handed over by Poland. In July 1939, just before war broke out, British and French cipher experts gathered at a secret base in the Pyry forest near Warsaw, Poland. There, the Polish Cipher Bureau presented the methods they had used to break Enigma over several years, along with replica machines.

At the center of this achievement was the Polish mathematician Marian Rejewski. In the autumn of 1938, Rejewski built a decryption device driven by an electric motor and named it the 'bomba.' The bomba exploited a single habit of German radio operators. At the time, when German operators transmitted a message, they typed the three-letter key chosen for that message twice in succession at the very beginning. This was meant to ensure the receiving end understood it without mistake. For example, if the key was DKV, they enciphered and transmitted DKV DKV. Sending the same letters twice revealed an underlying pattern between them, and the bomba took advantage of this opening.

Turing immediately recognized the weakness of this method. Because the bomba relied on a single habit of the German operators, it would become useless if they changed that habit. Indeed, the German military had already made things difficult for Polish codebreakers by altering their procedures. In December 1938, when the Germans increased the variety of rotors from three to five, the number of possible choices multiplied greatly, meaning Poland would have needed to build many times more machines under their method. And in fact, starting on May 1, 1940, the German military ceased sending the key twice across most of their networks.

A New Key Called the Crib

Turing sought a method that would still work even if German habits changed. It was a way of guessing in advance words that were almost certainly contained in the ciphertext. The people at Bletchley Park called such guessed words a 'crib.' The word 'crib' originally referred to a cheat sheet that British schoolboys glanced at secretly during exams.

They were able to guess cribs because German reports routinely contained similar words. The weather reports transmitted every morning at the exact same time almost never omitted the German word for weather, WETTER. Turing saw that by matching such words letter-by-letter against the actual ciphertext and tracing the relationships among those pairs, they could work backward to deduce the machine's settings.

Two Weaknesses of the Enigma

In this method, Turing relied on two properties inherent to the Enigma.

First, on the Enigma, no letter could ever be turned into itself. This was because the reflector at the far inner end of the machine invariably rerouted the electrical current back through a path for a different letter. If you pressed A, one of the remaining 25 letters would light up, but never A. Therefore, if a crib was aligned over the ciphertext and the same letter appeared in the same position, that position was definitely incorrect. Codebreakers slid the crib along one space at a time, eliminating such positions.

Second, the cables on the plugboard worked symmetrically in both directions. If A and E were connected by a cable, A turned into E, and E turned into A. Furthermore, only one cable could be plugged into any single letter.

A Machine That Eliminates False Answers

Using these properties, Turing translated into mechanical circuitry the method of making an assumption and then discarding it if a contradiction emerged. This was the same principle as proof by contradiction used in mathematics. In proof by contradiction, one assumes a premise to be true and reasons through it; if an inconsistent result is reached, the initial assumption is judged to be false.

For example, suppose that at a certain rotor position, A is connected to E on the plugboard. As one continues the deduction by applying this assumption successively to the letter pairs in the crib, a result might arise indicating that A must also be connected to F. Because only one cable can be plugged into a single letter, such a result is impossible. That means the initial assumption was false. At this point, the entire setting—including that rotor position—could be discarded, and they could move on to the next setting.

The letter pairs between the crib and ciphertext, across which assumptions were sequentially applied, could be linked together in a diagram. The staff at Bletchley Park called this diagram a 'menu.' The more loops the menu contained—where letters linked in a ring back to the starting letter—the better the Bombe was at filtering out false settings.

The Bombe processed this entire search electrically. It took less than the blink of an eye for electrical current to travel around a circuit. Rather than a machine designed to find the correct answer directly, the Bombe was a machine that ruled out wrong answers at high speed. Whenever it encountered a setting that produced no contradiction, the machine

stopped. A human operator would then note down the rotor positions at that moment and test them on an Enigma replica to confirm whether it was the true answer.

A Machine Made of Metal and Wire

Turing's blueprints were passed to the British Tabulating Machine Company (BTM) in Letchworth. Harold Keen, an engineer at the company, was known among his peers by the nickname 'Doc.' Keen took on the job of translating Turing's logical circuits into actual switches, relays, and gears.

The standard Bombe that was later widely used was a massive metal cabinet nearly two meters tall and two meters wide, weighing about one ton. Across its front panel were rows of circular drums that served the function of Enigma rotors. Three drums performed the role of one Enigma, and a single Bombe contained circuitry equivalent to 36 Enigma machines. Attached to the back of each drum were 104 fine wire brushes that carried electrical connections for the 26 letters of the alphabet. In accordance with the menu, these circuits were interconnected using cables bundled with 26 individual wires.

On March 18, 1940, the first Bombe arrived at Hut 1 in Bletchley Park. People named this machine 'Victory.'

8.2. Gordon Welchman's Addition of the Diagonal Board

Victory's Shortcoming

While Victory was theoretically flawless, problems arose when it was put into actual practice. The German military paired up 20 of the 26 letters using 10 plugboard cables. With so many possibilities, for Victory to effectively filter out false settings, the menu needed to contain several closed loops of letters. And creating such loops required long cribs.

Yet finding long, reliable cribs in actual cipher messages was no easy task. When the Bombe was run with a menu that lacked sufficient loops, the machine repeatedly stopped at settings that were not the correct answer. These were known as 'false stops.' Because a

human operator had to verify the settings by hand every time it stopped, decryption speeds did not improve as much as hoped.

Welchman's Idea

The person who solved this problem was Gordon Welchman. Born in 1906, Welchman was six years older than Turing, and had taught mathematics at Cambridge University before coming to Bletchley Park. He led Hut 6, which was responsible for German Army and Air Force Enigma ciphers.

Between late 1939 and early 1940, as Welchman closely examined Turing's Bombe design, he realized that the machine was not making full use of the bidirectional nature of the plugboard. If A was connected to E, then E was also connected to A. By applying this self-evident fact simultaneously across the entire machine, contradictions could be discovered far more rapidly.

Welchman turned this idea into a device called the 'diagonal board.' The diagonal board was a panel of 26 by 26—meaning 676—terminals arranged like a grid, with diagonally opposite terminals interconnected by wires. The moment the Bombe's circuitry sensed a connection between B and E, the diagonal board simultaneously fed the connection between E and B into the circuit. Information gained at one point immediately rippled throughout the entire machine.

When Welchman presented this idea, Turing was at first incredulous, but soon welcomed it enthusiastically, as Welchman later recorded in his memoirs. Turing gladly embraced the colleague's insight that improved his own design.

The Birth of Agnus

Equipped with the diagonal board, the Bombe could filter out almost all false settings even with short cribs containing few loops. False stops decreased dramatically, and with them, the amount of manual verification needed by operators.

On August 8, 1940, the second Bombe, built from the start with a diagonal board, began operating at Bletchley Park. It was named 'Agnus,' after 'Agnus Dei,' Latin for 'Lamb of

God.' People also affectionately called the machine Agnes or Aggie. The earlier machine, Victory, was also sent back to the factory to be retrofitted with a diagonal board.

The machine that united the minds of Turing and Welchman in this way is known today as the 'Turing-Welchman Bombe.' For each rotor order, this Bombe tested all 17,576 rotor positions ($26 \times 26 \times 26$) in just over twenty minutes. It was a feat that humans working by hand could never have dreamed of matching.

The number of Bombes continued to grow thereafter. Operating the machines was mainly entrusted to members of the Women's Royal Naval Service (WRNS). They plugged in cables according to the menus, swapped drums, and recorded the results whenever a machine stopped. By the end of the war, more than 200 Bombes were running in Britain.

8.3. Crib Attacks and Real-Time Decryption

The People Who Found Crib

No matter how fast the Bombe was, it was useless unless it was fed the right crib. Finding cribs was a task for humans, not machines. The codebreakers doggedly studied the habits and mistakes of German radio operators.

The Germans repeated reports in identical formats every day. There were weather reports, 'nothing to report' messages indicating that nothing unusual had happened, and words like unit names and commanders' ranks that always appeared in the same spots. Some bases transmitted virtually the same sentences every day, and such messages provided excellent cribs for the codebreakers.

There were also operations designed to deliberately generate cribs. The Royal Air Force dropped naval mines at specific locations in waters used by the Germans. The German military would then transmit warning messages mentioning the name of that specific location, and the codebreakers used that place name as a crib. This operation was nicknamed 'Gardening.'

The greatest successes came from the German Air Force. The German Air Force cipher that Bletchley Park codenamed 'Red' suffered frequent operator errors and provided abundant cribs. From May 22, 1940, onward, Hut 6 broke this cipher almost every single day.

The Toughest Adversary: The German Navy

The opponent Turing confronted was the far more formidable German Naval Enigma. Bletchley Park called this naval cipher used by U-boats 'Dolphin.'

Naval ciphers became critically important because of the war situation in the Atlantic. When France surrendered in June 1940, Admiral Karl Dönitz, commander of the German submarine fleet, established U-boat bases along the French Atlantic coast, including Lorient. German U-boats were now able to reach the middle of the Atlantic with ease. Dönitz scattered multiple U-boats across the ocean; when one spotted an Allied convoy, it radioed the others to assemble for a coordinated mass attack. This tactic was known as the 'wolfpack.' Because island Britain had to import food, fuel, and weapons by ship from the United States and Canada, every sunken merchant ship severed another piece of Britain's lifeline.

However, the German Naval Enigma was far more securely defended than the Army and Air Force versions. While the Army and Air Force chose 3 rotors out of 5, giving 60 possible wheel orders, the Navy introduced 3 additional rotors and chose 3 out of 8. The number of possible orders jumped to 336. Moreover, the Navy disguised message keys a second time using separate codebooks and bigram tables. As a result, even if a crib was found, many hurdles remained before it could be fed into a Bombe.

Many people at Bletchley Park shook their heads, believing Naval Enigma to be unbreakable. That was precisely what drew Turing to it. Turing later remarked that because no one else was working on it, he could have it all to himself. Taking charge of Hut 8, Turing began a long duel against naval ciphers. To reduce the time required to run the Bombes, he also devised new calculation methods based on probability and statistics.

Keys Salvaged from the Sea

Mathematics alone was not enough. They needed to get their hands directly on German naval cipher materials. On April 26, 1940, the British destroyer HMS Griffin captured the German vessel Polares, disguised as a Dutch fishing trawler, off the coast of Norway. Thanks to documents recovered from this ship, Hut 8 succeeded in breaking naval messages for several days in late April 1940. Although the decryption took too long to be used operationally at the time, it gave Turing and his colleagues a profound understanding of Naval Enigma's structure.

The decisive material arrived the following year. On May 9, 1941, the British warships HMS Bulldog and HMS Aubrietia attacked the German submarine U-110 south of Iceland, forcing it to surface. Its commander, Fritz-Julius Lemp, lost his life while abandoning ship, and British sailors led by Sub-Lieutenant David Balme boarded the sinking submarine. They retrieved an intact Enigma machine and codebooks.

By combining these materials with the Bombes and Turing's statistical methods, decryption speeds accelerated dramatically. In June and July 1941, Hut 8 was at times able to decrypt intercepted naval communications within an hour.

Turning the Tide in the Atlantic

The intelligence obtained from decryption was codenamed 'Ultra.' Ultra intelligence was passed immediately to the Admiralty in London. Pinpointing the maritime zones where U-boats lay in wait, the Admiralty rerouted merchant convoys away from danger. The wolfpacks were left patrolling empty waters. During the second half of 1941, the number of Allied merchant ships sunk in the Atlantic dropped significantly compared to the first half of the year.

The impact of codebreaking on the overall war can only be stated through estimates. One widely cited estimate is that codebreaking at Bletchley Park shortened the war by about two years. Turing scholar Jack Copeland estimated that had the war dragged on for two more years, more than 14 million additional lives might have been lost. While these figures are estimates that vary depending on calculation methods, most researchers agree that cryptanalysis was a decisive force that turned the tide of the Battle of the Atlantic.

In the autumn of 1939, faced with the Enigma that was widely deemed unbreakable, Turing chose the path of confronting a machine with a machine. Along that path came together the pioneering work of Polish mathematicians, Welchman's diagonal board, Keen's engineering, and the dedicated hands of countless operators who ran the Bombes day and night. Though the Bombe was a machine built for a single purpose, the experience of translating human thought into electrical circuits served as a stepping stone toward the true computer that Turing sought to build after the war.

Chapter 9. Hut 8, Naval Enigma, and Banburismus (1940–1942)



Figure 9. Illustrates the relationship between codebreaking and the protection of convoys.

When the German army occupied France in the summer of 1940, Britain was left to stand alone against Germany in Europe. As an island nation, Britain imported much of its food, oil, and weapons from across the sea, and ships carrying these supplies crossed the Atlantic Ocean in groups. Such groups of ships sailing together are called convoys.

Admiral Karl Dönitz, who led the German navy's submarine fleet, sought to sever these sea routes. He established submarine bases in ports such as Lorient on the western coast of France. German submarines were called U-boats, and packs of U-boats would surround and attack convoys just as wolves hunt in packs. People called this tactic 'wolf pack' operations. After the war, Prime Minister Winston Churchill recalled that the only thing that had truly frightened him during the conflict was the threat of the U-boats.

To stop the U-boats, it was first necessary to know where they were. At sea, U-boats communicated with headquarters by radio, and Britain was able to intercept those transmissions. The trouble was that the contents of the radio messages were concealed by a cipher called Naval Enigma. Naval Enigma was more difficult to break than the Enigma used by the Army and the Air Force, and talk circulated even among senior figures at Bletchley Park that the naval cipher would ultimately prove unreadable.

Alan Turing saw things differently. He reasoned that since no one else was taking on the naval cipher, he could investigate it entirely on his own to his heart's content. A problem that others had abandoned was, for him, a welcome opportunity. Thus, Turing took charge of the team dedicated to Naval Enigma. Because the wooden hut where this team worked was numbered 8, the team came to be called Hut 8. At the time, Turing was a young mathematician in his late twenties.

9.1. Hut 8 and the U-boat Cipher

There were several reasons why Naval Enigma was so difficult to break. The first was the number of rotors. Inside the Enigma machine were three circular wheels that substituted letters; these wheels were called rotors. The Army and the Air Force chose three out of five available rotors and inserted them in order. This yielded 60 different ways to insert the rotors. The Navy, by contrast, chose three out of eight rotors, which expanded the possibilities to 336 arrangements. From the codebreaker's perspective, this meant more than five times as many cases to examine.

The second reason was the method used to conceal indicators. Messages sent by Enigma had a short cluster of letters attached to the beginning. Known as an indicator, this signal told the recipient from which position the message should be deciphered. The Army and the Air Force concealed indicators using relatively simple methods. The Navy, however, selected indicators from a special book and then disguised them once more using tables that swapped pairs of letters with other pairs of letters. Without knowing these tables, no matter how many messages one gathered, it was impossible to find a starting point to begin deciphering them.

By combining earlier materials left behind by Polish cryptanalysts with mathematical reasoning, Turing had worked out in his mind nearly all of how this indicator system functioned by the end of 1939. Yet understanding its structure was one matter, and getting hold of the tables actually in use was quite another. Britain needed to seize cryptographic material directly from German ships. People at Bletchley Park called such operations a 'pinch'—meaning to quietly swipe or snatch something.

The first opportunity came on April 26, 1940, off the coast of Norway. The British destroyer HMS Griffin intercepted the German naval patrol vessel Polares, which had been disguised as a Dutch fishing boat; among the documents the German crew failed to destroy were cipher settings for several days in late April. Using this material, Hut 8 worked backward to decipher past communications. In November 1940, Hugh Foss decrypted a naval transmission dated May 8 of that year. What his colleagues called 'Foss's Day' was the date of this communication. Although much time had already elapsed since the transmission, it was an important achievement proving that Naval Enigma could be broken.

The second opportunity came the following spring. On March 4, 1941, British and Norwegian commandos raided Norway's Lofoten Islands and recovered a set of Enigma rotors and cipher materials from the German armed trawler Krebs. Although the captain of the Krebs threw the Enigma machine into the sea, the surviving materials contained the German Navy's cipher settings for February.

The greatest opportunity came on May 9, 1941. In the waters south of Iceland, the U-boat U-110, stalking a convoy, surfaced after being attacked with depth charges by the British warships HMS Bulldog and HMS Aubrietia. A depth charge is an explosive detonated underwater to attack submarines. Believing the vessel would sink shortly, the captain,

Kapitänleutnant Julius Lemp, ordered his crew to abandon ship. Yet U-110 did not sink. British sailors led by Sub-Lieutenant David Balme braved the danger, boarded the submarine, and brought out the Enigma machine and codebooks intact from the radio room. Britain kept this capture strictly secret. This was because if Germany learned its ciphers had been seized, it would change them immediately.

When these seized materials were coupled with the Bombe designed by Turing and the statistical technique called Banburismus (to be explained in the next section), the situation was transformed. Beginning in June 1941, Hut 8 read the naval cipher used by the U-boats almost daily. Bletchley Park called this cipher Dolphin. The deciphered intelligence was relayed to the Admiralty under the secret codename Ultra, allowing the Admiralty to pinpoint where wolf packs were assembling and reroute convoys around those waters. In the second half of 1941, the number of Allied ships sunk in the Atlantic dropped noticeably.

Even so, work was not always smooth. Hut 8 was perpetually short-handed. Because there were not enough people to organize and type up decrypted messages, one day's work frequently spilled over into the next. On September 6, 1941, Prime Minister Churchill visited Bletchley Park and encouraged the staff. A little over six weeks later, on October 21, Turing—along with Hugh Alexander, and Gordon Welchman and Stuart Milner-Barry from Hut 6, which handled Army and Air Force ciphers—wrote a letter directly to Churchill. The letter explained that staff shortages were delaying the finding of naval cipher settings by at least twelve hours each day. Milner-Barry personally carried this letter to 10 Downing Street in London. Upon reading the letter, Churchill instructed his chief military assistant, General Ismay, to take action that very day and give them everything they required. Thereafter, personnel and machines at Bletchley Park expanded substantially.

The following year, decryption was blocked once again. This was because on February 1, 1942, U-boats in the Atlantic began using a new Enigma equipped with four rotors. Bletchley Park called this new cipher Shark. For nearly ten months, Hut 8 was unable to read this cipher, and during that period, Allied shipping losses mounted again. The breakthrough once more came from material brought from the sea. On October 30, 1942, in the Mediterranean, British sailors boarded the sinking U-boat U-559 and retrieved codebooks. In carrying out this task, officer Anthony Fasson and seaman Colin Grazier lost their lives when they went down with the submarine, while sixteen-year-old Tommy Brown

survived. Thanks to the codebooks they recovered, Hut 8 was able to resume reading Shark in December 1942.

Around this time, Turing was stepping back from the day-to-day operations of Hut 8. While he was brilliant at delving deeply into problems, he was not adept at managing large numbers of people, and practical operations were frequently run by deputy head Hugh Alexander. When Turing left for the United States in November 1942, Alexander officially assumed leadership of Hut 8.

9.2. The Banburismus Statistical Method

The Bombe was a machine that tested rotor settings one by one. Yet in 1940 and 1941, Bletchley Park possessed only a handful of Bombes, leaving a shortage of machines even for cracking Army and Air Force ciphers. Testing all 336 rotor arrangements of Naval Enigma on the Bombes was impossible because it took far too much time.

Turing therefore proposed eliminating unlikely arrangements through calculation before running the Bombes. If they could narrow down the 336 possibilities to just a few plausible ones to pass on to the Bombes, the time required to run the machines would be vastly reduced. The method born of this idea was Banburismus. Turing drew a crucial clue from a technique called the 'clock method,' developed by Polish cryptanalyst Jerzy Różycki.

Banburismus targeted a specific weakness in Naval Enigma. Each day, the German Navy set a basic setting shared by all radio operators. This basic setting was called the Grundstellung in German. Operators chose a separate starting position for each message, enciphered that starting position using this very Grundstellung, and prefixed it to the message. Thus, the actual starting position for enciphering each message was different. However, if two messages transmitted on the same day had starting positions close to each other, sliding one by several spaces and aligning them correctly would create an overlapping stretch where the machine had encrypted letters under the exact same state. Aligning stretches encrypted under the same machine state in this way revealed hidden patterns.

To figure out how two messages should be aligned, Turing's team used elongated paper cards. The alphabet was printed in columns on the cards, and operators punched holes in the corresponding boxes for each letter of the ciphertext. These cards were printed at a

print shop in the town of Banbury, Oxfordshire. Consequently, the cards were named Banbury sheets, and the entire method using them was called Banburismus.

The operating procedure was as follows: cards for two messages were placed one on top of the other, with a light shining from underneath. Then, sliding the top card sideways one space at a time, the operator counted the spots where holes overlapped in both cards. An overlapping hole meant that the same letter appeared at the same position in both messages.

The number of overlaps was meaningful because of probability. If two strings of letters generated by selecting randomly from the 26 letters of the alphabet with equal probability are overlapped, the probability of identical letters appearing at the same position is 1 in 26. This is because there are 26 letters in the alphabet. However, when two German naval messages enciphered under the same machine state are aligned correctly, this probability rises to about 1 in 17. This was an approximation based on the letter distribution of naval communications at the time. Because German has frequently used letters such as 'E', the rate at which letters coincide in plain text carries over into the ciphertext. Operators counted not only single-letter overlaps, but also instances where two or three consecutive letters matched. The more overlaps there were, the greater the likelihood that the two messages were properly aligned.

The remaining question was how many overlaps were needed for the result to be reliable. To answer this question, Turing created a unit to measure the weight of evidence. If a piece of evidence multiplied the ratio of the odds that a hypothesis was true versus false by a factor of 10, he defined the weight of that evidence as 1 ban. The name 'ban' was taken from the town of Banbury. However, since 1 ban was too large a unit for practical use, Turing mainly used one-tenth of it, the deciban. This was similar to the decibel, a unit used to measure the intensity of sound.

The advantage of the deciban was that one needed only to add them up. Suppose the initial odds of being right or wrong were fifty-fifty. When 10 decibans of evidence accumulated, the odds of being right became 10 times greater than being wrong. At 20 decibans, it was 100 times greater; at 50 decibans, 100,000 times greater. Operators added points each time they found an overlapping letter, and reached a conclusion once the score exceeded a

predetermined threshold. Jack Good, who was Turing's assistant, explained that roughly 1 deciban was the smallest change in belief that a human being could perceive.

This method of gradually revising one's judgment as new evidence comes in is known as sequential analysis. The American mathematician Abraham Wald also developed and published a similar method, but Turing was already using it in the field of codebreaking beforehand. However, because Turing's work was a wartime secret, the outside world remained unaware of this for a long time.

Once Banburismus revealed how multiple pairs of messages overlapped, codebreakers could use the results to narrow down which rotors occupied the right and middle positions. This reduced the 336 possible arrangements to just a few candidates to be tested on the Bombes. The person most adept at Banburismus was Hugh Alexander, who was also a chess champion, and Joan Clarke was likewise an outstanding Banburist. Alexander and Jack Good viewed this work less as a job than as an intellectual game. It was work that was neither so easy as to be boring nor so difficult as to be exhausting.

Hut 8 used this method continuously for two years, discontinuing it only in 1943 when Bombes became plentiful. During that time, Banburismus saved an immense amount of Bombe operating time. After the war ended, most of the Banbury sheets were destroyed to preserve secrecy. In September 2013, however, workers renovating the huts at Bletchley Park discovered several Banbury sheets in the gaps of a Hut 6 ceiling. People working in the frigid hut had stuffed the discarded sheets into cracks to block the draft.

9.3. The Prof's Book

People at Bletchley Park called Turing 'the Prof,' short for professor. Although he was not an actual professor, he always seemed like one because he was constantly pondering mathematical problems.

In the autumn of 1940, Turing compiled the principles of Enigma decryption he had discovered into a single report. Its official title was 'The Mathematical Theory of the Enigma Machine,' but within Bletchley Park, the report was known as 'the Prof's Book.' Turing typed the text on a typewriter and drew the formulas and diagrams by hand.

This book contained mathematical explanations of how the Enigma's rotors and plugboard scrambled letters. It also included methods for testing guessed phrases against ciphertext to uncover contradictions, explained the principles on which the Bombe operated, and described how to attack naval indicators. Mathematicians newly arriving at Bletchley Park learned Enigma cryptanalysis from this book. The Prof's Book remained a classified document for many years before being declassified in the United States in 1996. It is now kept at the British National Archives under the reference number HW 25/3.

In addition, Turing wrote two papers dealing with the use of probability in codebreaking. One addressed the application of probability to cryptography. In this paper, Turing explained how Bayes' theorem and deciban calculations could be applied to various types of ciphers. Bayes' theorem is a probability formula that describes how initial beliefs should be updated when new evidence is obtained. The other paper dealt with the frequency of repeated letters within a text. Both papers were kept secret for nearly 70 years at Britain's Government Communications Headquarters, or GCHQ. Only in April 2012, marking the centenary of Turing's birth, were the two papers transferred to the National Archives and made public. At the time, a GCHQ mathematician commented that the very fact these papers had remained secret for so long demonstrated their value.

Turing's idea of quantifying information numerically, just as he measured the weight of evidence in decibans, resembled the information theory developed independently around the same time by Claude Shannon in the United States. Shannon also devised a unit for measuring amounts of information. The two men even met and conversed in the United States in 1943 during the war.

Turing's statistical methods did not stop with Enigma. In July 1942, Turing developed a method to determine by hand the wheel cam settings of the Lorenz cipher machine—another machine used by the German High Command—that is, the arrangement of pins around the wheels that modified the signals. His colleagues dubbed this method 'Turingery' after his name. The technique of accumulating evidence using decibans was also employed in other methods of breaking the Lorenz cipher. This line of development led between 1943 and 1944 to Colossus, an electronic codebreaking machine built by engineer Tommy Flowers. Colossus was an electronic machine operated by vacuum tubes.

The process through which Hut 8 broke Naval Enigma from 1940 to 1942 brought together the efforts of many people. Turing took on the naval cipher that people even within Bletchley Park said would never be read, analyzed the indicator system, designed the Bombe, narrowed down candidate settings for the Bombe using probability calculations, and left behind a book so that his colleagues could use these methods together. Added to this were the deeds of sailors who seized cipher materials from German ships, and the labor of the Hut 8 staff who counted holes in Banbury sheets and tallied the scores. It was because all of these efforts came together that the Admiralty was able to steer convoys away from waters where U-boats had gathered.

Chapter 10. Secret Technology Exchange and Project Delilah (1942–1945)

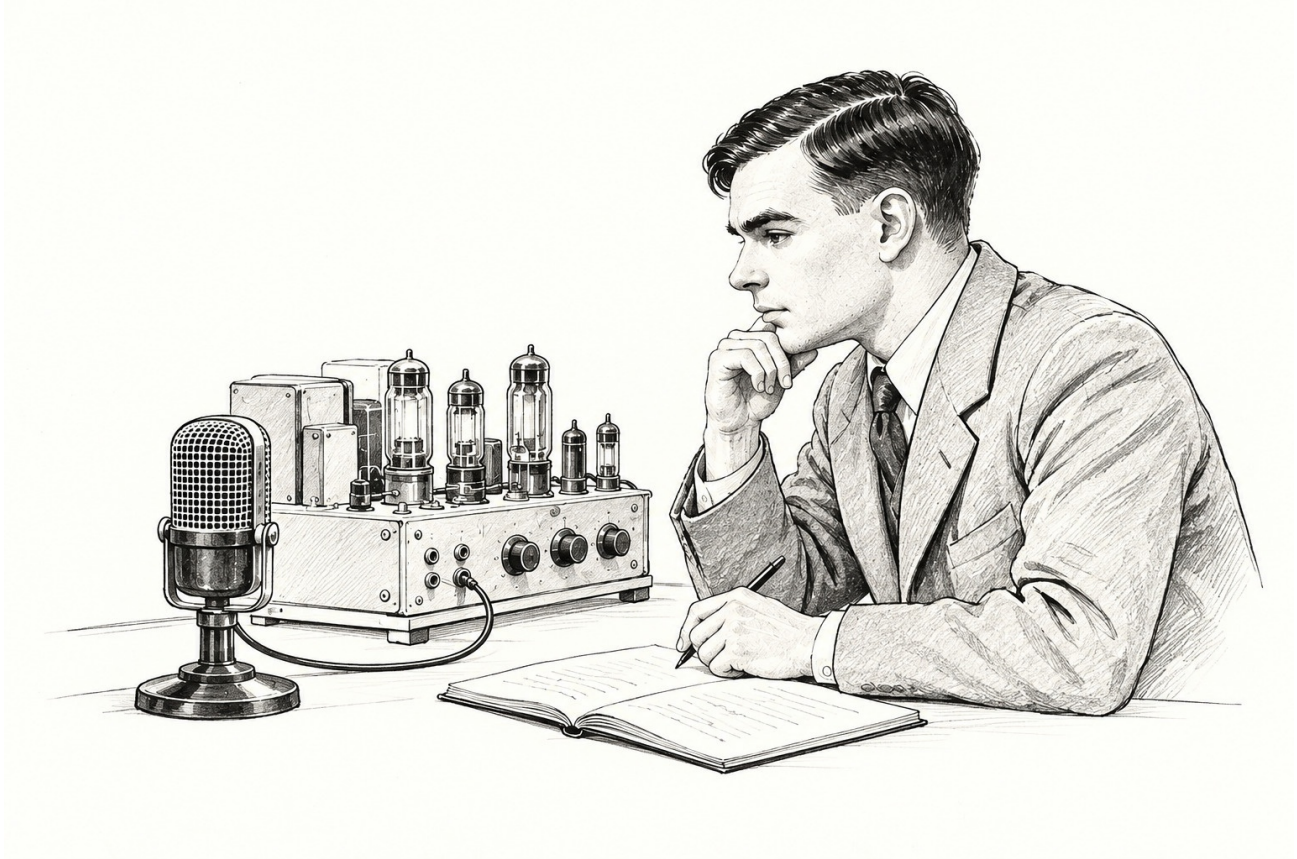


Figure 10. A reconstruction of the Delilah speech-scrambling research.

In the autumn of 1942, German U-boat submarines were sinking Allied transport ships one after another in the Atlantic Ocean. Alan Turing was working in Hut 8 at Bletchley Park, deciphering the German Naval Enigma. Then, a new mission was assigned to him: to cross over to the United States and share with his American colleagues the cryptanalytic techniques Britain had built up.

Behind this mission was the entry of the United States into the war. The United States had entered the war triggered by Japan's attack on Pearl Harbor in December 1941. If two nations fighting the same enemy broke ciphers separately, it would take twice as much time and effort. The two countries decided to join forces, and Turing became one of the vital links connecting them.

Between 1942 and 1945, Turing's work largely fell into three parts. First, he visited the United States to share cryptanalytic techniques and inspect speech-scrambling equipment. After returning to Britain, he built Delilah with his own hands—a machine that turned human speech into cipher. After the war ended, he received an honor, but for a long time, what that honor commemorated could not be revealed.

10.1. Visits to American Cryptanalytic Agencies and Laboratories

A Guest Arriving Without Papers

Turing crossed the Atlantic by ship in November 1942. It was a perilous sea where U-boats preyed upon transport ships. He arrived in New York on November 12, and this visit lasted until March of the following year.

As soon as he arrived, a minor commotion broke out. Because Turing did not have proper documents proving his identity, immigration officials hesitated for a while over whether to admit him. This incident was recorded in detail in a report written by Turing himself two weeks later.

To Turing, the United States was not an unfamiliar place. Between New York and Washington lay Princeton, where he had pursued his doctoral studies six years earlier. Back then, he was a young student writing mathematical papers. This time, he set foot on

American soil again as a secret envoy representing the British government's cryptographic expertise.

OP-20-G in Washington

The first place Turing visited was OP-20-G, the U.S. Navy's cryptanalytic section in Washington, D.C. Although the name sounds unfamiliar and code-like, it was the designation assigned to a team within the division responsible for communications at U.S. Navy headquarters. Like Britain's Hut 8, this team was also trying to decipher the German Naval Enigma.

Turing put his head together with American cryptanalysts and explained the British methods. These included how to operate the Bombe and how to narrow down candidate settings using Banburismus. Initially, he did not evaluate the capabilities of the U.S. Navy team very highly. However, as brilliant young mathematicians like Andrew Gleason joined, the team's caliber rose rapidly.

The Bombe Factory in Dayton

On December 21, 1942, Turing visited the National Cash Register (NCR) factory in Dayton, Ohio. This company, which had manufactured cash registers, was producing Bombes for the U.S. Navy during the war. Engineer Joseph Desch led this work.

The U.S. Navy's plan was vast in scale. That scale stemmed from the structure of the Enigma. Even in the four-rotor Enigma faced by the U.S. Navy, the three primary moving rotors were chosen from eight options and inserted in order. The fourth rotor was selected separately from these three. Since there were 8 choices for the first position, 7 remaining for the second, and 6 remaining for the third, $8 \times 7 \times 6$ yielded 336 combinations in all. The American Bombe project aimed to assign one machine to each combination, building 336 machines.

Turing thought differently. Rather than multiplying the number of machines, he believed it was better to increase the speed of each individual machine and use mathematical deduction to reduce in advance the combinations that needed checking. In his Dayton visit report, he also stated that the American side should concentrate its efforts on increasing the

Bombe's speed. Desch and Turing clashed over the design. In the end, the Dayton laboratory built a total of 121 Bombes, not 336.

Bell Labs and Voice Encryption

Turing had a second mission: to inspect the speech encryption system under development at Bell Labs in New York. British Prime Minister Churchill and American President Roosevelt spoke across the Atlantic via radiotelephone, but the speech-scrambling device in use at the time carried the risk of German eavesdropping. To solve this problem, Bell Labs was building a new system that would later be known as SIGSALY.

The laboratory doors did not open easily. The American side insisted that they could not show top-secret equipment even to an allied expert. For Turing to view this device, Britain's Field Marshal Sir John Dill had to step in and make a personal request directly to America's General George Marshall. A major dispute erupted between the intelligence agencies of the two nations over this issue.

In January 1943, Turing finally began work at Bell Labs. SIGSALY was a massive system that filled an entire room, weighing tens of tons. The device converted voice into digital signals and then scrambled them using phonograph records containing purely random noise as a key. The receiving end had to have an identical phonograph record to restore the original voice.

Turing analyzed mathematically whether this device was truly secure. The evaluation report he wrote played a pivotal role in the decision to adopt the system and install it in London. Starting in the summer of 1943, SIGSALY was used for secret communications connecting London and Washington.

Conversations in the Cafeteria

At Bell Labs, there was a young researcher named Claude Shannon. Shannon would later establish information theory, laying the foundations of digital communication. Turing met Shannon during this visit, and the two had lunch together in the laboratory cafeteria, deep in conversation.

Neither could discuss his classified duties with the other. Therefore, their conversations drifted to topics like thinking machines and the similarities between the human brain and machines. Turing also spoke about his 1936 paper on universal machines. Right in the middle of the war, the two individuals who would later blaze the trail for computers and artificial intelligence were seated face-to-face.

Return to Bletchley Park

Turing returned to Britain in March 1943. In the meantime, the head of Hut 8 had been taken over by Hugh Alexander, a former chess champion. Alexander had already been managing the day-to-day operations of Hut 8 and was also skilled in handling people. For Turing, this change was actually a welcome one, as he preferred solving problems to dealing with paperwork and meetings.

The change in leadership did not mean Turing's contributions were valued any less. When Alexander later compiled the history of Hut 8, he wrote that there was no doubt that the greatest single factor in the section's success was Turing's work. No longer bound to a single department, Turing now took on an advisory role assisting with difficult cryptographic problems across all of Bletchley Park.

10.2. The Delilah Speech-Scrambling System

The SIGSALY system Turing saw at Bell Labs left him with a challenge. SIGSALY was secure, but it was far too large. A device filling an entire room could hardly be carried into battle by soldiers. Could the task of completely disguising human speech with electronic circuits and then reconstructing it be accomplished with a much smaller apparatus? That was the challenge. Turing decided to build a speech-scrambling device himself that was small and light enough to be used in actual military operations.

The Secret Laboratory at Hanslope Park

The location where Turing set up his new laboratory was Hanslope Park. This was a facility used by the Radio Security Section of Britain's Secret Intelligence Service, equipped with workshops where electronic equipment could be built and tested directly. Today, the British Government Communications Centre stands on this site.

Hanslope Park was about 16 kilometers away from Bletchley Park along country roads, and Turing commuted back and forth between the two places by bicycle. He began work on Delilah here in 1943, and from 1944 onward, he stayed and worked entirely at Hanslope Park.

Donald Bayley, the Young Engineer

In 1944, Donald Bayley, an electrical engineer who had graduated from the University of Birmingham, arrived as Turing's assistant. Born in 1921, Bayley was nine years younger than Turing. When he first saw Turing's circuit, the wires were tangled in a complex jumble. Bayley later recalled that the circuit was tangled like a spiderweb.

The two men were teachers to each other. Bayley taught Turing workbench skills such as soldering and wiring. He addressed Turing as 'Prof,' meaning professor, just as everyone at Bletchley and Hanslope did. Turing taught Bayley and fellow technicians the mathematics needed for circuit design. After dinner was over, Turing gave lectures, and Bayley meticulously took notes. These notes became an advanced mathematics textbook for circuit engineers.

How Delilah Worked

The operating principle of Delilah can be understood in three stages.

First, the voice is converted into an electrical signal. A voice is a vibration of air—that is, a wave. Delilah extracted the amplitude of this signal at regular time intervals and used it for encryption. This is called sampling. Although this concept is used in modern digital recording, Delilah used analog electronic circuits to combine signal amplitudes. Turing also left mathematical notes examining how frequently the signal had to be sampled in order to restore the original sound.

Next, a key signal is blended in. The transmitting machine generates an irregular-looking key signal and adds it to the voice signal in a predetermined manner. This turns the original spoken words into unintelligible noise.

Finally, the receiving side generates the identical key signal at the exact same moment to recover the original voice from the combined signal. Synchronizing the key signals and timing of the two machines with precision was the core of Delilah's design.

This principle was connected to the ideas Turing had developed while tackling German teleprinter ciphers at Bletchley Park. It applied the same concept to voice instead of letters. However, unlike letters, voice flows continuously without pause, so the vacuum tube circuits had to operate rapidly and precisely. Turing and Bayley recorded each experimental result in a logbook as they modified and refined the circuits.

The Name Delilah

Delilah is the English name of the biblical figure Delilah. Delilah was the one who deceived the mighty Samson to discover the secret of his strength. The name of a deceiver suited a machine designed to fool eavesdroppers completely by letting them hear only noise. Turing did not choose this name alone. He held an open competition for the name of the device, and his friend Robin Gandy—who would later become his executor—won the contest.

Concealing and Restoring Churchill's Voice

Delilah was finally completed. The two men held a demonstration before British government officials. When a recording of Prime Minister Churchill's speech was fed into Delilah, only noise came out of the speaker. Once routed through the receiving machine, Churchill's voice was clearly audible once again. The timing of this demonstration varies slightly depending on sources: the auction house Bonhams described it as late 1944, while other researchers date it to early 1945.

On May 8, 1945, the war in Europe came to an end with Germany's unconditional surrender. Turing and Bayley took a long walk together to celebrate the victory.

An Unused Machine, Enduring Experience

Delilah never saw action on the actual battlefield. By the time the machine was completed, the war was already nearly over, and there was no time to manufacture it in large quantities and distribute it to military units. There were also design limitations. Because Delilah was

designed for short-range telephone lines or radio, it was difficult to use for long-distance communication across the Atlantic. In fact, only a single prototype was ever built.

Even so, these two years served as an immense learning experience for Turing. The mathematician who once calculated on paper had become an engineer who handled vacuum tubes directly, soldered, and troubleshoot malfunctioning circuits. He learned firsthand how fast electronic circuits operated and where trouble tended to arise. In the autumn of 1945, Turing would go on to design the electronic computer ACE at the National Physical Laboratory (NPL). That design was thoroughly infused with the practical experience he had gained at Hanslope Park.

Notebooks Resurfacing After More Than 70 Years

For a long time, the story of Delilah was virtually unknown. Bayley kept the relevant documents until his death in 2020. In November 2023, this collection, known as the 'Bayley Papers,' came up for auction in London and sold for £381,400. It contained Turing's handwritten calculations and notes, laboratory logbooks, and the lecture notes Bayley had transcribed.

The British government intervened to prevent these precious materials from leaving the country. In August 2024, a temporary export bar was placed on the documents. Subsequently, over £397,000 was raised, and in March 2025, King's College, Cambridge—where Turing had studied and conducted research—purchased the papers. The documents were digitized and added to the Turing archive, accessible to researchers and students worldwide.

10.3. The Medal of Silence (OBE)

A Single Line on the Honours List

When the war ended, the British government awarded honours to those who had served the country. Turing was among them. The honor he received was Officer of the Order of the British Empire, abbreviated as OBE.

The British government publishes the names of honours recipients in the official gazette, The London Gazette. In The London Gazette, Issue 37617, page 3124, dated June 18, 1946, it is recorded that Alan Mathison Turing, 'employed in a Department of the Foreign Office,' was awarded an OBE. While some sources describe the award decision as dating to 1945, the date published in the gazette is June 1946.

In this single line, there was not a single word about what he had actually done. Neither Enigma, nor Bombe, nor Banburismus, nor Delilah could be mentioned. The manner in which he received the medal was equally quiet. Turing did not go to Buckingham Palace to receive his honour. The medal arrived by mail accompanied by a letter from the King, and Turing reportedly kept it in a tin box along with screws, nails, and bolts.

The Padlock of the Official Secrets Act

The reason Turing could not speak of his achievements lay in the Official Secrets Act. Everyone who worked at Bletchley Park and Hanslope Park had sworn an oath of secrecy under this law. Even after the war ended, that oath remained unbroken. They could not reveal what they had done to family, to friends, or to newspaper reporters.

Turing's mother was no exception. His mother, Sara Turing, later wrote a biography of her son. In that book, she wrote that she had never received the slightest inkling of what her son's secret work was. She also noted that because of this enforced silence, her son's letters had become infrequent and brief. Even his own mother lived on without knowing what her son had achieved during the war.

Unrecognized Contributions

Scientists who developed radar or the atomic bomb during the same war became renowned and went on to direct major laboratories after the war. Turing's circumstances were very different. Although he had contributed to saving countless transport ships and human lives through codebreaking, only the few who shared the secret knew of this truth. Many historians believe that the achievements of Bletchley Park's codebreakers shortened the war by about two years. At the very center of that effort was Turing.

The silence also affected Turing's postwar research. In the autumn of 1945, Turing joined the National Physical Laboratory and began work on building a computer. Most people there had no idea that Turing had built electronic circuits with his own hands during the war. Unable to present his experience as proof, Turing had to persuade them all over again from scratch.

The secrets of Bletchley Park only began to emerge to the world in the 1970s. In 1974, with the publication of a book detailing wartime codebreaking, the secret intelligence operation known as 'Ultra' became widely known. This was twenty years after Turing had passed away. The detailed workings of Delilah came to light only nearly half a century later still, when Bayley's notes surfaced at auction.

The medal tucked away inside a tin can was the official recognition Turing had received, but for a long time, no one knew what that medal commemorated.

Chapter 11: The NPL and the Design of the Early Computer ACE (1945–1948)

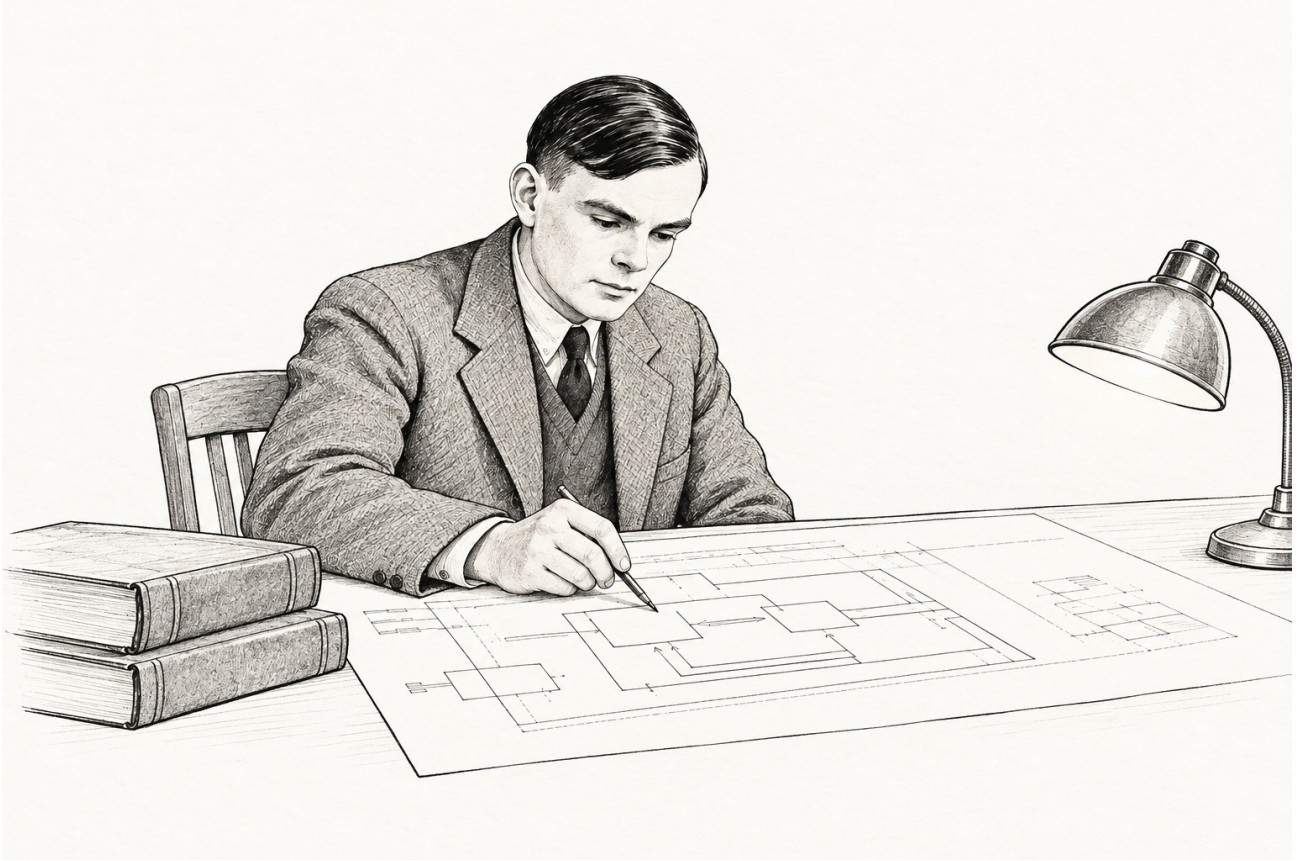


Figure 11. An illustration depicting Turing conceiving the design of a computer.

World War II, which had lasted for nearly six years, came to an end in Europe in May 1945. With the war over, the people who had worked at Bletchley Park and Hanslope Park returned one by one to their former positions, and Alan Turing also had to find a new path. That June, Turing celebrated his thirty-third birthday.

During the war, Turing had worked closely with and observed various machines. He had designed the Bombe to break Enigma, and he had seen Colossus—built by his colleagues with thousands of vacuum tubes—calculate at high speed. Toward the end of the war, he had even done his own soldering to build Delilah, a voice encryption device. Through these experiences, Turing became convinced of one thing: using electronic circuits made with vacuum tubes, the 'universal machine' he had sketched on paper in his 1936 paper could actually be built in reality.

The universal machine was the idea that a single machine could perform any calculation whatsoever. Even if the calculation to be performed changed, there was no need to build a new machine; one only had to change the instructions fed into it—that is, the program. The computers and smartphones we use today operate on this very principle. This is why we can play games, look at maps, and do our homework all on the same smartphone. In the autumn of 1945, Turing gained the opportunity to turn this idea into a real machine.

11.1 Joining the National Physical Laboratory (NPL)

In Teddington, west of London, lies the National Physical Laboratory of the United Kingdom. It is commonly called the NPL, taking the initials of its English name, the National Physical Laboratory. The NPL is a government research institute that establishes national standards for things such as length, weight, and time, and conducts a wide variety of scientific research.

As the war was drawing to a close, the British government decided to create a new Mathematics Division within the NPL. The plan was to apply computing technology, which had advanced significantly during the war, to science and industry. The head of this new division was the applied mathematician John R. Womersley. Womersley was one of the few people who had read Turing's 1936 paper, "On Computable Numbers, with an Application to the Entscheidungsproblem," and early on recognized its value.

At that time, most people thought of calculating machines as tools designed to do just one specific task. A machine that calculated the trajectory of artillery shells did only that calculation, and doing a different calculation required a different machine. The large electronic calculator ENIAC, completed in the United States in 1945, was similar. ENIAC was a colossal machine using about 18,000 vacuum tubes, yet each time it had to solve a new problem, people had to manually unplug and replug cables and flip switches. Preparing for a calculation could take several days.

Womersley wanted to build a large electronic computer at the NPL, and he chose Turing as the person to entrust with this task. Visiting Turing, Womersley showed him a report that had just come out of the United States. It was the "First Draft of a Report on the EDVAC," written in June 1945 by the Hungarian-born American mathematician John von Neumann. This report described the basic architecture of a stored-program computer—a computer that works with programs stored inside the machine itself. Von Neumann had been familiar with Turing's work since Turing's days studying at Princeton. Womersley believed that many of the core ideas in the EDVAC report had originated with Turing.

On October 1, 1945, Turing reported for his first day of work as a Senior Principal Scientific Officer in the Mathematics Division of the NPL. Womersley gave the new computer project the name ACE. It stood for Automatic Computing Engine, meaning an 'automatic calculating machine.' There was a story behind the word 'Engine.' In the nineteenth century, the British mathematician Charles Babbage had designed calculating machines driven by gears, naming them the 'Difference Engine' and the 'Analytical Engine.' In honor of Babbage, Womersley included the same word in ACE. It was a name that also symbolized Turing carrying forward the dream Babbage had cherished a century earlier.

Unlike ENIAC, the computer Turing envisioned did not require replugging wires. Leaving the machine as it was, one would simply feed in new programs and data. Then the same machine could calculate the weather today, calculate the load a bridge could bear tomorrow, and play chess the day after tomorrow. Turing did not view ACE merely as a calculator that quickly crunched numbers. He saw it as a machine capable of carrying out a variety of intellectual tasks performed by the human mind. Bringing the universal machine of 1936 into reality using vacuum tubes and wiring—that was the task Turing took on at the NPL.

11.2 The ACE Report

Turing worked rapidly. Toward the end of 1945, less than three months after joining the NPL, Turing completed his ACE design report. Its title was "Proposed Electronic Calculator." Running 48 typewritten pages, this report included circuit diagrams, component descriptions, memory storage design, a budget, and even examples of programs that could actually be run. While von Neumann's EDVAC report was an unfinished draft outlining the overarching architecture, Turing's report was close to a workable blueprint that could be built directly from.

On March 19, 1946, Turing presented the ACE plan to the NPL Executive Committee, and the committee agreed to move forward with the project. Turing estimated that building ACE would cost £11,200. The report also detailed what ACE would be capable of doing. Turing believed that ACE could handle not only complex scientific calculations, but also solve puzzles and even look several moves ahead in chess.

A part of the report that Turing addressed in great detail was the storage device. For a computer to work, it must hold programs and numbers somewhere, and this device is called a storage unit or memory. Turing believed that memory was the most difficult problem in computer design, and that once this problem was solved, the remaining circuits would be relatively straightforward. In those days, semiconductor memory like what we have today did not exist. If memory was made from vacuum tubes, storing even a single number required multiple tubes, making both the cost and size unmanageable.

The method Turing chose was the mercury delay line. The mercury delay line was a device that emerged from wartime radar technology. A steel tube about 1.5 meters (5 feet) long was filled with mercury, a liquid metal, and quartz crystals were attached to both ends. The quartz converted electrical signals into sound signals, and sound signals back into electrical signals. When sound pulses representing 0s and 1s were sent from one end, the sound traveled through the mercury and reached the opposite end. By routing this signal back to the starting point, the numbers circulated continuously through the tube. The machine memorized numbers by keeping them in constant circulation. It is easy to picture runners circling endlessly around a sports track, with each runner carrying a single number as they run.

Turing planned to connect about 200 of these tubes. Since a single tube could hold about 1,024 zeros and ones, altogether they could store about 200,000. Converted to modern units, this is about 25 kilobytes. While far smaller than a single photo taken on a smartphone today, in 1946 it was a massive memory capacity that no one had ever possessed.

Turing was also aware of the weakness of mercury delay lines. Because the numbers circulated inside the tube, one had to wait until the desired number reached the tube's exit. If the waiting time was long, the calculation slowed down. Therefore, Turing meticulously arranged the positions inside memory so that the next instruction and number needed would arrive at the exit at the exact moment they were required. Later, people called this method 'optimum programming.' This approach was designed to reduce waiting time in the delay lines and thereby increase computing speed.

Turing also set the machine's speed. Computers operate to a steady beat, which is called the clock. Turing set the clock of ACE at 1 megahertz. This meant keeping rhythm one million times per second. By the standards of that era, it was a high speed.

The design of ACE embodied another characteristically Turing idea: use as few mechanical and electronic parts as possible, and leave the complex tasks to the software. American engineers built dedicated hardware circuits for multiplication and division, and as circuits multiplied, so did the number of vacuum tubes. Turing chose not to follow this approach. He had the hardware handle only simple instructions such as addition, subtraction, and moving numbers, while calculations like multiplication, division, and square roots were handled by programs stringing together those simple instructions multiple times. Turing called these programs 'instruction tables.'

There was good reason for this design. Vacuum tubes were components that burned out easily like light bulbs, so the more there were, the more often the machine broke down. Fewer vacuum tubes meant fewer malfunctions and easier construction. Turing wanted to keep the machine lean and compensate for its limitations with well-crafted programs. He felt that writing programs was precisely what he had been doing since 1936. Decades later, computer architects rediscovered the method of simplifying instructions to increase speed, and Turing's design is regarded as an early demonstration of that concept.

Relying on programs to handle so much work also required an efficient way to write them. The report introduced the idea of subroutines: creating separate small programs for frequently used calculations, calling upon them whenever needed, and then returning to the original place in the program. It is similar to writing a recipe for 'How to make sauce' just once in a cookbook and referring to that page in many different recipes. Today, programmers use this method every single day.

On February 20, 1947, Turing gave a lecture on ACE to the London Mathematical Society. On this occasion, Turing went one step further than merely explaining the design. He stated that what we desire is a machine that can learn from experience. It was the idea that a machine could gradually improve itself by modifying its own instructions. At a time when not a single properly functioning stored-program computer existed anywhere in the world, Turing was already speaking about a learning machine.

11.3 The Wall of Bureaucracy and a Cambridge Sabbatical

The blueprints were brilliant, but the work of actually building the machine made little headway. There were several stumbling blocks.

The biggest problem was people. While there were plenty of mathematicians in the NPL Mathematics Division, there were no electronic engineers who could physically build vacuum-tube circuits. Turing wanted help from Tommy Flowers and Allen Coombs, the engineers at the Post Office Research Station (Dollis Hill) who had built Colossus during the war. However, the Dollis Hill station was tied up with repairing the telephone network damaged by the war.

Secrecy was another obstacle. Colossus was a state secret. Turing could not tell the people at the NPL that an electronic machine with thousands of vacuum tubes had already run continuously during the war. His NPL colleagues, knowing nothing about Colossus, thought ACE was far too grandiose a dream.

The laboratory's bureaucracy was also slow. The director of the NPL was Sir Charles Darwin, grandson of the Charles Darwin famed for the theory of evolution. Director Darwin was a cautious administrator who decided matters one by one through meetings and paperwork. Lengthy discussions dragged on over which division would build the machine

and how work would be shared with other research institutes. Some suggested starting by building a small test machine first. But Turing wanted to go straight to a complete machine rather than spending time on a test machine. In the end, even that test machine was never completed.

Turing grew increasingly exhausted. While his designs languished beneath piles of paperwork, research teams in other countries and universities were forging far ahead. Turing channeled his frustration into running. During his years at the NPL, he joined the nearby Walton Athletic Club and ran long distances. Stories even tell that on days when he had meetings in London, he ran all the way from the laboratory to the meeting hall. In August 1947, he competed in the Amateur Athletic Association (AAA) marathon championship, finishing in fifth place with a time of 2 hours, 46 minutes, and 3 seconds. It was a time strong enough to aim for selection on the British team for the 1948 London Olympics. However, after injuring his leg, that dream slipped away.

In the autumn of 1947, Turing applied to the NPL for a one-year sabbatical and returned to King's College, Cambridge. A sabbatical is a period during which a researcher temporarily steps away from their regular duties to rest or pursue new studies. After Turing departed, the ACE team at the NPL was led by his assistant, Jim Wilkinson.

At Cambridge, Turing began a new course of study. Wanting to understand how the human brain and nervous system work, he delved into physiology and neurology. He believed that to create a thinking machine, one had to first understand the brain, the organ of thought. This study later led to his research on explaining the patterns that appear on living organisms through mathematics.

In the summer of 1948, Turing organized his thoughts and submitted a report to the NPL. Its title was "Intelligent Machinery." It was an essay that specifically examined how to build the learning machines he had spoken about in his lecture to the London Mathematical Society. Today, many scholars consider this paper to be one of the very first reports to treat artificial intelligence in earnest.

In the report, Turing introduced the concept of 'unorganised machines.' This had a completely different starting point from machines elaborately designed from the outset to perform a specific task. Turing conceived of a network-like model where various electronic

components were connected at random. He proposed that if one trained this network using rewards and punishments, good connections would be retained while bad ones would be modified, allowing the network to grow on its own into a useful machine. It was much like a child learning through praise and scolding. This idea closely resembles the 'artificial neural networks' at the core of modern artificial intelligence.

Turing also wrote about the idea of 'genetical search' or 'evolutionary search.' This was a method where one could find good solutions by repeatedly making small random modifications to various answers, selecting the better ones, and modifying them again. In effect, it borrowed the way living organisms have evolved over vast stretches of time and applied it to computation. This was an idea that later developed under the name 'genetic algorithms.'

In this report, Turing saw two parallel paths toward endowing machines with intelligence. One path was for humans to determine rules in advance and program them into the machine; the other was for the machine to accumulate experience and learn on its own. Turing did not insist on one approach to the exclusion of the other. Just as a child learns set material at school while also discovering things independently through play and experience, he believed a machine could walk both paths together.

Director Darwin, however, did not welcome this report. He regarded it as little more than a sloppy schoolboy essay. The NPL did not publish the report, and "Intelligent Machinery" remained tucked away in the laboratory's filing cabinets for a long time. The paper was published in a book for the first time only in 1968, fourteen years after Turing had passed away.

Around the same time, news arrived from Manchester. Max Newman, who had taught Turing logic during his Cambridge days and worked alongside him at Bletchley Park, had become a professor at the University of Manchester and established a computing machine laboratory. There, radar engineers Freddie Williams and Tom Kilburn built a small electronic computer. People called this machine the 'Manchester Baby.' On June 21, 1948, the Manchester Baby succeeded in running a program stored in its memory. It was the very first moment an electronic computer operating with a program stored inside the machine actually ran.

Turing's decision to change jobs came even before the Baby's first run. He accepted Newman's offer in the spring of 1948, and in May conveyed his intention to resign to the NPL. In September of that year, he began working at the University of Manchester.

Even after Turing left, the design of ACE lived on. Wilkinson, along with colleagues such as Donald Davies and Mike Woodger, scaled down Turing's design to build a smaller machine. This machine was the 'Pilot ACE.' Pilot ACE ran its first program on May 10, 1950. With about 800 vacuum tubes, it had far fewer than ENIAC's 18,000, but it ran at the 1-megahertz clock rate Turing had specified. In the early 1950s, Pilot ACE was one of the fastest computers in the world. Based on this machine, the British company English Electric built the commercial computer DEUCE and began selling it in 1955. The full-scale ACE that Turing had originally envisioned was completed only in 1958.

During his three years at the NPL, Turing never saw a single computer completed with his own hands. Even so, during this period he drew up detailed blueprints for a stored-program computer and posed a novel question to the world: the idea of a machine that learns. Today, Pilot ACE resides in the Science Museum in London. And on the back of the new £50 banknote issued by Britain in June 2021, an image of this machine appears alongside Turing's face.

Chapter 12. The University of Manchester and the First Stored-Program Computer (1948–1951)



Figure 12. Depicting the period of research into early computers.

In 1948, thirty-six-year-old Alan Turing had been immersed in computer design for over two years at the National Physical Laboratory (NPL) in Teddington, near London. The design proposal he had drafted for the Automatic Computing Engine (ACE) was a remarkably concrete computer design for its time. However, having a blueprint did not mean the machine would be built. There was a shortage of engineers to take charge of construction, and decisions were constantly delayed. Turing, who longed to turn the 'universal machine' he had conceived on paper in 1936 into an actual electronic machine, was growing weary.

Just then, a mathematician he had known for a long time called upon Turing. It was Professor Max Newman of the University of Manchester.

12.1. Max Newman's Invitation and the Move

The connection between Turing and Newman began at Cambridge. In 1935, Turing attended Newman's lectures on the 'Foundations of Mathematics.' In this course, Newman introduced the 'decision problem' posed by the German mathematician David Hilbert. It was the question of whether, given any logical statement, it could always be determined through a fixed, machine-like procedure whether that statement could be proven using set logical rules. After grappling with this question, Turing wrote his 1936 paper 'On Computable Numbers,' from which the concepts of the Turing machine and the universal machine emerged.

The two men met again at Bletchley Park during World War II. Leading a section known as the 'Newmanry,' Newman broke the Lorenz cipher used by the German High Command. For this work, engineer Tommy Flowers built an electronic codebreaking machine called Colossus using thousands of vacuum tubes. Colossus was fast, but it could only perform one task—codebreaking—and having it do anything else required manually changing switches and rewiring cables by hand. Here, Newman and Turing saw firsthand how rapidly electronic circuits could calculate. If a program could be stored in high-speed circuits, a single machine could handle various kinds of computable problems simply by changing the program.

After the war ended, Newman became a professor of pure mathematics at the University of Manchester. In 1946, he secured a substantial research grant of 35,000 pounds from the

Royal Society of London and established the 'Computing Machine Laboratory.' Meanwhile, two engineers who had worked on radar during the war joined the Department of Electrical Engineering at the University of Manchester: Freddie Williams and Tom Kilburn. Soon after, Geoff Tootill joined them.

Williams and Kilburn discovered a method to store 0s and 1s using cathode-ray tubes (CRTs), which had been used for radar screens. When a small dot of light is placed on the CRT screen, an electric charge briefly remains at that spot. By repeatedly reading and rewriting this trace, numbers could be remembered. This device was called the 'Williams-Kilburn tube.' At the time, other laboratories used a method of circulating acoustic signals through long tubes filled with mercury, but with this approach, one had to wait until the desired number reached the end of the tube. In contrast, the Williams-Kilburn tube could immediately retrieve and read a number from any location. Reading data from a desired location without waiting in sequential order is directly akin to today's RAM.

With funding, a laboratory, an engineering team, and memory devices all in place in Manchester, Newman invited Turing. Turing resigned from the NPL and, in September 1948, took up a position as a Reader in the Department of Mathematics at the University of Manchester. A Reader is the academic rank directly below professor. He was also given the title of 'Deputy Director of the Royal Society Computing Machine Laboratory.' However, this laboratory had no director. Old records of the University of Manchester state that this title was in name only, and that it was not even clear what Turing's official duties were at first.

Even before moving to Manchester, Turing showed interest in the machine there. He obtained in advance the list of instructions processed by the machine and wrote and sent a program to perform long division. Tootill modified this program so that it could run on the machine.

Work at the Manchester laboratory was broadly divided into two areas. The engineering team led by Williams and Kilburn built the physical hardware, such as vacuum-tube circuits and memory devices. Turing took charge of the programming side—that is, how to perform actual calculations with that machine. The engineers who soldered the machine with their own hands and the mathematician Turing who envisioned machines with paper and pencil

had different ways of working, and at times their ideas clashed. Even so, Turing liked working in Manchester, where an actual electronic computer operated right before his eyes.

12.2. The Manchester Baby, the Mark 1, and the Programmer's Handbook

About three months before Turing arrived in Manchester, a major milestone in computer history took place there. Shortly after 11:00 a.m. on June 21, 1948, a small experimental machine ran its first program. The machine's official name was the 'Small-Scale Experimental Machine (SSEM),' but people called it the 'Baby.'

The Baby was not built as a practical calculator from the start. It was a device made to test whether the Williams-Kilburn tube functioned properly. Its memory capacity was thirty-two 32-bit words, totaling 1,024 bits. Compared to today's mobile phones, this was an exceedingly tiny amount. Even so, the Baby retrieved, read, and executed programs stored inside its memory on its own. Without having to rewire cables like Colossus, it could be made to do different tasks simply by changing the contents of its memory. This is what is meant by a 'stored-program computer.' The Baby was the world's first electronic computer to actually operate in this manner.

The first program was written by Tom Kilburn. It was a program designed to find the highest proper factor of a number—that is, the largest divisor excluding the number itself. At first, they tested it on small numbers, and within a few days expanded the test range up to 262,144, which is 2 multiplied 18 times. The highest proper factor of 262,144 is 131,072. While a human could tell the answer almost instantly, the machine had to find it by testing divisions one by one, starting from large numbers. In this calculation, after operating continuously for 52 minutes, the Baby displayed the correct answer as dots of light on the screen. This event showed that the ideas Turing had proposed in his 1936 paper actually worked on a physical machine.

Following the Baby's success, the research team soon set out to expand the machine. The computer built in this way was the 'Manchester Mark 1,' and it became available for use in April 1949. The memory capacity was increased to 128 forty-bit numbers. They also added a 'magnetic drum,' which recorded numbers magnetically on the surface of a rapidly rotating cylinder. The scheme kept frequently used information in the fast cathode-ray tubes, while

larger amounts of information were stored on the drum. This is similar to how modern computers maintain separate memory and storage devices.

A device called the 'B-line' was also incorporated into the Mark 1. When repeating the same calculation multiple times, this device automatically modified the address of the number to be read next. Today, it is called an 'index register' and is found in almost every computer. Commemorating the Baby, the Institute of Electrical and Electronics Engineers (IEEE) recorded that the Mark 1 was the machine that first introduced the index register.

As soon as the Mark 1 became available, Turing began working with it. Until then, programs had to be entered by flipping switches one by one. In the summer of 1949, Turing helped obtain a device that could input and output programs and numbers using punched paper tape, and helped connect it to the Mark 1.

Around this time, Turing devoted his efforts to organizing methods for people to instruct computers. Today, programming languages use human-readable words like 'print.' Back then, however, computers processed only 0s and 1s. Turing grouped 0s and 1s in sets of five to represent a single letter or symbol. A five-digit sequence of 0s and 1s can represent thirty-two different combinations. Turing took teleprinter character codes and mapped them one-to-one to these thirty-two combinations. Programmers wrote programs with these symbols instead of long strings of 0s and 1s. While this method reduced human error, it still looked like an unfamiliar cipher to beginners.

Turing created separate small programs for frequently used calculations. These were called 'subroutines.' There were subroutines for calculating square roots, logarithms, and trigonometric functions, as well as subroutines for punching results onto paper tape. Programmers could simply call and use them whenever needed, eliminating the need to write the same calculations from scratch every time. This was the same concept as the 'libraries' used by programmers today. Turing also established rules for transferring numbers between the cathode-ray tube memory and the magnetic drum in units called 'pages.'

Turing did not do this work alone. Cicely Popplewell, who had studied mathematics, worked as Turing's assistant and wrote programs for the Mark 1. Records from the

University of Manchester state that Turing developed the early software for the Mark 1 with Popplewell's full-time assistance.

Turing compiled these organized materials into a booklet. Its title was 'Programmers' Handbook for Manchester Electronic Computer Mark II.' The reason 'Mark II' appeared in the title was that Turing referred to the Ferranti company's upcoming new machine by that name. He wrote the handbook in advance before that machine arrived, basing it on the experience gained from working with the Mark 1. One surviving copy of the first edition contains an errata sheet dated March 1951. Many historians regard this book as the world's first programming manual written for a stored-program computer.

In this handbook, Turing also explained what an electronic computer was. Paraphrasing his meaning: an electronic computer is a machine that takes over the calculations previously performed by a human who strictly follows set rules. This human knows how to calculate, but makes no independent judgments. Turing did not view the computer as a mystical brain. He saw it as an exceptionally fast human computer that follows rules without missing a single one.

There was also a notable instruction in the handbook: the 'hoot' instruction. It was a command that caused a speaker attached to the computer to emit a 'beep' sound, originally intended as a signal to alert the operator that a calculation had halted. However, by sounding this noise repeatedly at high speed, pitches of different notes could be produced. Turing noted this technique in the handbook, and it later became the starting point of computer music.

The Manchester computer also attracted attention outside the laboratory. On June 9, 1949, Manchester neurosurgeon Geoffrey Jefferson delivered a lecture entitled 'The Mind of Mechanical Man.' He stated that machines could not think or feel like humans. The next day, newspapers covered the lecture, and a reporter visited Turing. An article entitled 'The Mechanical Brain: Answer to 300-Year-Old Sum' appeared in The Times on June 11, 1949. Here, the '300-year-old sum' referred to the problem of finding which numbers of the form $2^n - 1$ are prime numbers. Such numbers are called Mersenne numbers. Newman and Turing had been preparing since the summer of 1948 to solve this problem on the Manchester machine.

In this article, Turing stated, 'This is only a foretaste of what is to come, and only the shadow of what is going to be.' He believed that machines would enter fields handled by human intelligence and eventually compete with humans. Seventy-two years later, in 2021, the United Kingdom issued a new 50-pound banknote featuring Turing's face. These words are inscribed on that banknote.

Turing also conducted his own research using the Mark 1. In 1950, he used this machine to perform calculations related to the Riemann hypothesis, a long-unsolved problem in mathematics. That same year, he published the paper 'Computing Machinery and Intelligence.' This paper addressed the question of whether machines can think.

12.3. Consulting on the Ferranti Commercial Computer

News of the Baby's success reached the British government as well. The government's Ministry of Supply decided to transfer the University of Manchester's technology to industry to build a commercially salable computer. In late 1948, the government signed a contract with Ferranti, an electrical engineering company in Manchester. The task was for the company to robustly reconstruct the machine created in the university laboratory and sell it. In July 1949, the basic design of the new machine was handed over to Ferranti.

Turing served as a consultant to Ferranti. He provided opinions to the company's engineers regarding the design of the new machine and programming rules, and his views were incorporated throughout the machine.

A prime example was the 'random number generator.' This is a device that produces unpredictable numbers, much like rolling dice. At Turing's suggestion, the Ferranti Mark 1 incorporated a device that generated random numbers using electrical circuit noise. Such numbers are useful for programs that play games or run calculations simulating phenomena involving randomness, such as weather or living organisms. In the new machine, the B-lines were also expanded to eight, and more instructions were added.

Turing took the stance that the machine's circuitry should be kept as simple as possible, leaving complex tasks to be handled by programs. Every additional vacuum tube introduced another potential point of failure and raised costs. In contrast, once a program was written well, it could be reused again and again. This position was a continuation of

Turing's perspective held since 1936, which envisioned that a single 'universal machine' could handle various kinds of computable problems simply by changing programs.

In February 1951, the first computer manufactured by Ferranti arrived at Turing's laboratory at the University of Manchester. People called this machine the 'Ferranti Mark 1.' The Ferranti Mark 1 was the world's first commercially available general-purpose electronic computer produced by a company. It preceded UNIVAC I, the first commercial computer built in the United States, by several weeks.

When the new machine arrived, Turing's handbook served as its user manual. Anyone wishing to use the machine learned programming from that handbook. Among them was Turing's friend Christopher Strachey. In 1951, Strachey wrote a checkers program for this machine and also created a program that played music using the hoot instruction. That year, the British BBC visited Manchester and recorded the computer playing the British national anthem, 'Baa Baa Black Sheep,' and 'In the Mood.' The Computer Conservation Society has stated that it knows of no earlier recording of computer-generated music.

The Ferranti Mark 1 was used for calculations by numerous scientists and engineers. Turing also used this machine to calculate the principles behind how patterns in living organisms develop.

Around 1951, Turing stepped back from the development of the Manchester computer. Assisting programmers was taken over by newcomer Tony Brooker. However, what Turing had established endured: the method of writing instructions in symbols, the practice of collecting subroutines, and the handbook for teaching programming to people. Even with a machine, a computer is useless without a way to give it instructions. In Manchester, Turing established the first framework for that method.

In 1948, the stored-program electronic computer built by the Manchester engineering team became operational, and by 1951, commercial machines also emerged. The theory of computation evolved into physical machines and programs through the work of numerous researchers and engineers. In that process, Turing contributed to theory, design, and programming, while continuing his research into machine intelligence.

Chapter 13. The Turing Test: Can Machines Think? (1950)

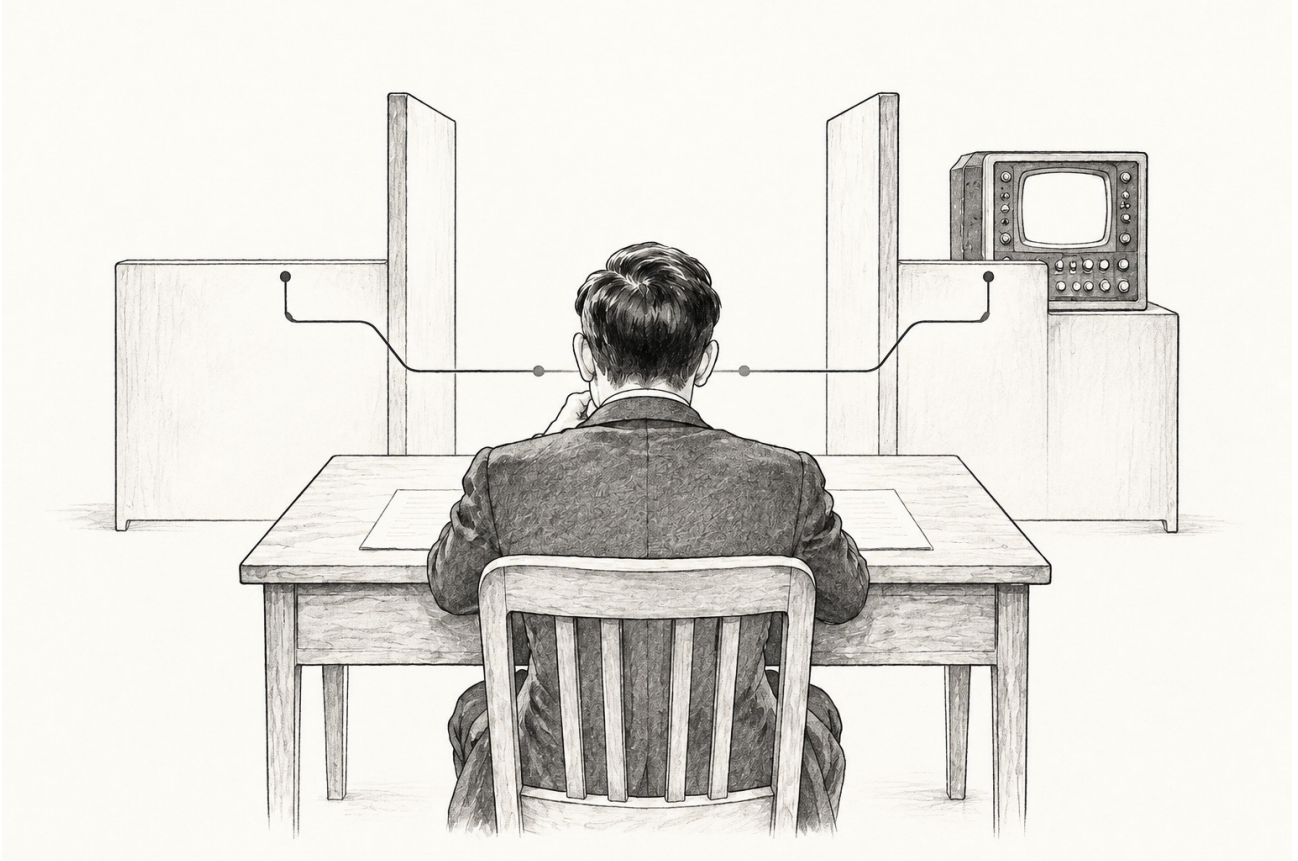


Figure 13. Conceptual diagram of the imitation game, which distinguishes between human and machine through conversation.

In October 1950, a 28-page paper appeared in Volume 59, Issue 236 of the British philosophical journal *Mind*. Its title was "Computing Machinery and Intelligence," and its author was the thirty-eight-year-old mathematician Alan Turing, then serving as deputy director of the Computing Machine Laboratory at the University of Manchester. The paper opened with a single short question: "Can machines think?"

Today, many people consider this paper the starting point of artificial intelligence research. But in 1950, when the paper was published, the term 'artificial intelligence' did not yet exist. The phrase first appeared in 1955 in a research proposal written by John McCarthy and his colleagues in the United States, and spread widely through a summer research workshop held at Dartmouth College in 1956. Turing had posed the question that the field would explore for decades to come, even before the discipline itself had a name.

13.1. The Philosophical Turn and the Mind Paper

A Mathematician Writes for a Philosophy Journal

Up until that time, Turing had worked primarily as a mathematician and an engineer. In 1936, he conceived of an imaginary machine that could imitate the computations of other Turing machines using paper tape and rules—the Universal Turing Machine. During the war, he designed the Bombe at Bletchley Park and devised a statistical technique called Banburismus to break German military ciphers. After the war ended, he designed the ACE computer at the National Physical Laboratory, and from 1948 onward, he programmed an actual working computer at the University of Manchester.

Yet alongside this work, Turing harbored another question that had stayed with him for years. Ever since losing his friend Christopher Morcom at age seventeen, he had long pondered what the mind and soul were, and where in the body thought originated. When computers transformed from concepts on blueprints into reality before his eyes, this long-held question returned in a new form: If human thought is ultimately something governed by fixed rules, couldn't a machine think as well?

This question was not Turing's interest alone; by 1949, it had made its way into newspapers. In June of that year, the neurosurgeon Professor Geoffrey Jefferson gave a lecture in London arguing that machines could never match the human brain. The *Times*

newspaper reported on the lecture alongside a story about the Manchester computer, and a reporter asked Turing for his thoughts. Turing replied to the effect that what was happening now was merely a foretaste of what was to come.

Turing did not leave the matter at a brief comment in a newspaper article. He decided to organize his thoughts carefully and publish them in a journal read by philosophers, resulting in the Mind paper. At the time, the journal's editor was Gilbert Ryle, a philosopher at Oxford University. A person who had personally designed computers and written programs for them was now addressing the philosophical question of the relationship between machines and thought in the pages of a philosophers' journal.

Beginning by Changing the Question

At the very beginning of the paper, Turing took issue with the question he himself had posed. The question "Can machines think?" was far too vague. Trying to define words like 'machine' and 'think' first would lead into endless quibbling. On the other hand, if one attempted to settle the answer by investigating how people commonly use these words, Turing felt that would be like trying to solve a scientific problem through an opinion poll.

Turing therefore set aside the original question and proposed a new one that had a clear meaning and could be tested in practice. Rather than trying to determine whether a machine is thinking by peering into its inner mind, his idea was to judge it by observing what the machine actually does. An issue mired in disputes over definitions of words was thus transformed into a question whose conditions could be set and outcomes verified. It was a transition that moved an age-old question of philosophy into a question for the laboratory.

The paper consists of seven sections in all. Turing first introduced the new question, the 'imitation game,' and explained that the machine to be used in this game was a digital computer, describing what characteristics digital computers possess. Next, he examined nine objections raised against machine intelligence one by one, and finally, he shared his thoughts on how to build a machine capable of learning on its own.

13.2. The Imitation Game and the Turing Test

A Game Played by Three People

To explain this new question, Turing presented a game. Three people take part in it: a man (A), a woman (B), and an interrogator (C), who stays in a separate room from the other two. C can neither see their faces nor hear their voices. Questions and answers are exchanged solely through typewritten text or a teleprinter, a telegraph typewriter. After conversing with them, C must guess which of the two is the man and which is the woman.

The two participants have different roles. The man, A, tries to deceive C into making a mistaken judgment. When asked about his hair style, A can answer falsely, pretending to be a woman. In contrast, the woman, B, tries to help C reach the correct answer. B can speak the truth, saying, "I am the woman, don't believe him!" but because A can say the exact same thing, C cannot easily decide.

Turing introduced a variation to this game: what would happen if a machine took the place of the man, A? The question was whether the interrogator C would make mistaken judgments just as often when conversing with a human and a machine as when conversing with a man and a woman. Turing stated that this was the new question to replace "Can machines think?" Turing himself called this test the 'imitation game,' and later people attached his name to it, calling it the 'Turing test.'

Why the Conversation Was Conducted Only in Writing

Turing had a clear reason for concealing faces and voices. He wanted to separate the machine's physical body from its intelligence. Creating artificial skin identical to human skin and wrapping it around a machine does not make the machine any smarter. Turing judged that to measure thinking ability, one must look solely at the content of the words, not appearances or voices.

This condition was also related to fairness. No one looks down on a human being for losing a footrace against an airplane. Likewise, there is no reason to blame a machine for not winning a prize in a beauty contest. The imitation game was a test designed so that neither human nor machine would be disadvantaged by outward appearance.

Concealing outward appearance did not make the test any easier, for in a written conversation, there is no end to the questions that can be asked. Turing gave several examples in his paper: the interrogator could ask the subject to write a poem on the Forth Bridge in Scotland, ask for the sum of two five-digit numbers, or pose a chess problem.

In Turing's example, the respondent declines to write poetry, saying they cannot, and hesitates for about thirty seconds before giving an answer to the addition problem. But that answer is not correct. Asked to add 34,957 and 70,764, the respondent answers 105,621, whereas the correct answer is 105,721. Some scholars read this as an example of a deliberate mistake made to seem human, while others believe Turing simply wrote down the numbers incorrectly. Whichever the case, this example shows that a humanlike answer is not always the same as an accurate one.

A Single Computer Can Mimic Any Machine

The next thing to decide was what kind of machine should enter the game. Turing chose the digital computer. A digital computer consists of a storage unit to hold information, an execution unit to perform calculations, and a control unit that ensures instructions are carried out in sequence. Here Turing revived the idea he had presented in his 1936 universal machine paper: a single digital computer, if sufficiently large and fast, can imitate any other machine that operates step by step, provided it is given the right program. Therefore, there was no need to consider every different kind of machine separately, and the new question ultimately became: "Can a computer loaded with an appropriate program do well in the imitation game?"

A Prediction Looking Fifty Years Ahead

Having refined the question so concretely, Turing also set down numerical predictions for the answer. He stated that in about fifty years, around the year 2000, computers with a storage capacity of about one billion (10 to the 9th power) bits would play the imitation game quite well. In today's units, one billion bits is roughly 125 megabytes. He predicted that an average interrogator would have no more than a 70 percent chance of correctly distinguishing human and machine after a five-minute conversation. He also wrote that by the end of the twentieth century, the use of words like 'thinking machines' would be accepted without expecting to be contradicted.

Actual history moved a bit more slowly than Turing predicted. By around 2000, computers had far exceeded Turing's expectations in storage capacity, but they could not hold natural conversations like humans. In the Loebner Prize competition, which began in 1991, some judges did mistake programs for humans. However, because that first contest restricted conversation topics, its results could hardly be seen as evidence of broad conversational ability. In 2014, an announcement claimed that a program named 'Eugene Goostman' had fooled about a third of the judges, but it drew criticism for masking clumsy answers behind the persona of a thirteen-year-old Ukrainian boy.

The situation changed dramatically with the arrival of the 2020s. In 2025, Cameron Jones and Benjamin Bergen at the University of California, San Diego, conducted an experiment where participants talked for five minutes each with a human and an AI simultaneously, then chose which one was human. GPT-4.5, instructed to act like a human, was selected as human in 73 percent of cases, higher than the rate at which actual humans were chosen. In the same experiment, ELIZA, a conversation program from the 1960s, reached only 23 percent. This study was later published in the journal *Proceedings of the National Academy of Sciences* (PNAS).

These results prompted scholars to look again at the evaluation method Turing had proposed. However, when reading the figures, two things must be distinguished. First, Turing's 70 percent refers to the proportion of times an interrogator correctly distinguishes human from machine, whereas the experiment's 73 percent represents the rate at which GPT-4.5 was chosen as human; thus, the two figures measure different things. Furthermore, many scholars point out that these results do not necessarily serve as proof that machines think like humans. The debate surrounding Turing's question continues to this day.

13.3. Refuting Objections to Artificial Intelligence

Turing knew well that there would be many voices opposing his ideas. Therefore, in the sixth section of his paper, he singled out nine objections likely to arise and answered them one by one. He anticipated potential vulnerabilities and prepared his responses before opponents could launch their attacks. The nine objections covered a wide range, from those rooted in religious belief and fear to mathematical theorems, consciousness, the capabilities of machines, the structure of the brain, and extrasensory perception.

First is the theological objection. This is the argument that thinking is a function of the immortal soul given by God only to human beings, and since God gave no soul to animals or machines, machines cannot think. Turing responded that this view actually limits God's power. If one believes that God gives a soul to a child when humans bear one, there is no reason why God could not bestow a soul upon a machine made by humans. Pointing out that religious reasoning had also been invoked to oppose heliocentrism during the time of Galileo—only to be proven wrong—Turing maintained that scientific problems cannot be judged by such arguments.

Second is the 'heads in the sand' objection. This is the attitude that it would be too terrifying if machines could think, so let us hope and believe they cannot. It takes its name from the fable of the ostrich burying its head in the sand when facing danger. Turing saw this less as an objection than as mere wishful thinking. What one wishes to happen and what can actually happen are two entirely different matters. Turing brushed it off lightly, remarking that comfort, rather than refutation, was more fitting for such a claim.

Third is the mathematical objection. Unlike the first two objections, this one relies on rigorously proven theorems. In 1931, Kurt Gödel proved that in any consistent mathematical system capable of containing the basic arithmetic of natural numbers and listing its axioms through a definite procedure, there inevitably exist statements that can neither be proved nor disproved using the system's own rules alone. Turing, too, had proved in his 1936 paper that there are problems no machine can solve. Opponents cited these very results to argue that machines have insurmountable limitations and are therefore inferior to humans.

Turing acknowledged that it is true individual machines have limitations. But for this objection to hold, human intellect must be free from such limitations, and no one has ever proved that. Humans also frequently produce wrong answers. Moreover, even if a particular person can triumph over a single machine, they cannot defeat all machines simultaneously. Although the theorem he himself had proved was turned around to serve as ammunition against his own claims, Turing responded by pointing out precisely what the theorem actually established.

Fourth is the argument from consciousness. This is exemplified by the claim made by Professor Jefferson, whose 1949 lecture had brought the debate into the newspapers.

Jefferson maintained that not until a machine truly feels thoughts and emotions and writes a sonnet or composes music because of them could we agree that machine equals brain. The machine, in other words, must know what it is doing and feel joy and sorrow.

Turing replied that pushing this argument to its extreme leads to an odd conclusion. The only way to know with certainty whether another person is truly thinking and feeling is to become that specific person. Under that premise, one could believe that no one thinks except oneself. In daily life, therefore, people live by a polite convention, observing each other's words and actions and accepting that the other person thinks as well. Turing considered it only fair to apply the same standard to machines. He added that if a machine could give coherent answers to probing questions about a poem it had written, even Professor Jefferson would not be able to dismiss it easily.

Fifth is the argument from various disabilities. People drew up lists of things a machine could never do: be kind, have a sense of humor, tell right from wrong, make mistakes, fall in love, enjoy strawberries and cream, learn from experience, or do something really new. Turing saw most of these claims as baseless. People simply recalled the crude machines they had seen so far and assumed future machines would be no different.

Turing selected several items from the list to give specific replies. Regarding mistakes, he distinguished between two kinds: errors of functioning caused by broken parts, and errors of conclusion resulting from flawed reasoning based on given information. A machine could easily make the latter kind of mistake. Moreover, if loaded with a program that deliberately errs in calculations, it could pretend to make mistakes just like a human in the imitation game. As for strawberries and cream, he replied that while one might be able to make a machine enjoy their taste, devoting effort to such a thing would be foolish.

Sixth is Lady Lovelace's objection. The English mathematician Ada Lovelace published a memoir in 1843 on Charles Babbage's Analytical Engine. She wrote that the machine had no pretensions to originate anything on its own, and could do only whatever we know how to order it to perform. Citing these words, critics argued that machines could never be original or take humans by surprise.

Turing remarked that it was understandable for Lovelace to make such a judgment based on the machines of her era. However, he did not agree with extending that judgment to all

machines. When examined closely, human originality, too, may grow out of what one has learned and experienced. Turing then shared his own experience, noting that machines often took him by surprise. When writing a program, a human cannot calculate all of its consequences in their head in advance. As a result, the answers a computer produces can come as something entirely new even to the person who built it.

Seventh is the argument from continuity in the nervous system. The human nervous system is a continuous mechanism where even the slightest change in an electrical signal can alter the outcome. By contrast, digital computers operate in discrete states, clearly separated like 0 and 1. Therefore, it was argued, a computer cannot mimic the nervous system. Turing conceded that the two systems are different. However, he replied that this difference would not reveal itself in the imitation game. He gave the example of the differential analyzer, an analog computer in use at the time: a digital computer could imitate the outputs of such a machine closely enough that an interrogator would find it difficult to tell them apart.

Eighth is the argument from informality of behavior. There can be no complete list of rules specifying what a person should do in every conceivable situation. If humans acted strictly according to rules, they would be no different from machines, but humans do not. Therefore, critics argued, a machine operating strictly according to rules could never become human. Turing cited traffic lights as an example: even if there is a rule that "stop on red," if both red and green lights turn on at the same time, a human exercises judgment without relying on a rule.

Here Turing drew a distinction between two things: rules of conduct, which people consciously follow in daily life, and laws of behavior, which govern the human body and brain as laws of nature. What the traffic light example shows is simply that rules of conduct cannot cover every single case. That does not mean there are no laws of behavior governing the brain; it merely means we have not yet discovered all of those laws.

Ninth is the argument from extrasensory perception. The argument held that if humans possess abilities such as telepathy or clairvoyance, an interrogator could read minds and easily distinguish between human and machine. Turing did not dismiss this objection lightly. Looking at experimental results from researchers like J. B. Rhine in the United States at the time, he even wrote that statistical evidence for telepathy was strong. He therefore offered a practical solution: conduct the game in a 'telepathy-proof room.' Today,

science has found no credible evidence for the existence of extrasensory perception. This episode shows that even someone like Turing could not remain entirely free from the scientific atmosphere of his day.

Replying to the nine objections went only so far as defeating the claim that machines cannot think. How to actually build a thinking machine was a separate question, and in the final part of the paper, Turing took a step forward into this issue. Programming an adult brain entirely from scratch was far too difficult. Instead, he proposed first creating a 'child machine' that, although knowing little at the beginning, could develop its capabilities through education, and teaching it by providing rewards and punishments. Just as a child grows through conversation with a teacher, a machine too could become smarter through instruction. Today's artificial intelligence is developing through self-learning on vast amounts of data. Rather than inputting fully formed knowledge, Turing's child machine concept embodied the idea of designing a learning process. While the specific methods of learning differ from modern artificial intelligence, the central question of cultivating machine intelligence through learning lives on.

Turing concluded the paper with a sentence to this effect: We can see only a short distance ahead, but we can plainly see that much remains to be done within that short distance.

Chapter 14. Morphogenesis: Solving the Patterns of Life with Mathematics (1951–1952)



Figure 14. Depiction of research seeking mathematical rules in the forms of living organisms.

In the autumn of 1950, Alan Turing published a paper titled "Computing Machinery and Intelligence" in the philosophy journal *Mind*. Through this paper, the question "Can machines think?" became widely known to the world. Turing was thirty-eight years old at the time. During the war, he had decrypted the German military's ciphers; after the war ended, he had designed computers and written programs; and now, he had even introduced the new research subject of machine intelligence.

Yet around this time, Turing's interest was turning toward an entirely different subject. It was the spots on a leopard's skin, the stripes of a zebra, and the spirals drawn by sunflower seeds. Living organisms produce such patterns and shapes without anyone's instructions. Turing wanted to know how that process was possible, and he decided to tackle this problem using mathematics and computers. A mathematician who had dealt with ciphers and computers had begun to investigate a problem in the unfamiliar field of biology.

14.1. Election to the Royal Society

In the year he began his biological research, Turing was elected a Fellow of the Royal Society of London. The Royal Society is a scientific society founded in London in 1660. It is one of the oldest scientific societies in the world, and Isaac Newton also served as its president. To become a Fellow, one must be nominated by existing Fellows, and the Society elects Fellows after closely examining the candidate's research. Those elected place the letters FRS after their names. This indicates being a Fellow of the Royal Society, and it is a great honor for a British scientist.

The day Turing was elected a Fellow was March 15, 1951, and his age at that time was thirty-eight. The core reason stated in his nomination was his paper published in 1936, "On Computable Numbers, with an Application to the Entscheidungsproblem." In this paper, Turing conceived an imaginary computing machine—the Turing machine. He then demonstrated mathematically what could and could not be computed. This research became the foundation of mathematical logic and modern computer science.

There were also achievements that could not be included in the nomination. This was his work decrypting the Enigma cipher at Bletchley Park during the Second World War. Because this work was subject to the Official Secrets Act, no one could mention it publicly. The greatest work Turing had done for his country during the war thus remained hidden.

Even so, the fact that he had become a Fellow of the Royal Society meant that Turing was recognized as one of the scholars representing the British scientific community. From this position, Turing embarked on new research.

The subject of that research—the forms of living organisms—was not a topic that Turing had suddenly become interested in. Around the age of ten, Turing received a book titled *Natural Wonders Every Child Should Know* as a gift. This book explained the bodies of living things not through mysterious forces, but like machines. The young Turing treasured this book and read it many times. Among the drawings left by his mother, Sara Turing, there is one depicting her son gazing intently at a daisy blooming on the ground all by himself while his friends played a hockey match. Even while attending Sherborne School, Turing enjoyed chemistry experiments and closely observed the arrangements of petals and leaves.

After becoming an adult, he read *On Growth and Form*, written in 1917 by the Scottish biologist D'Arcy Thompson. Thompson was a scholar who sought to explain biological form through mathematics and physics. Turing wanted to go one step further than Thompson's attempt.

The problem Turing tried to solve began with the embryo. An embryo refers to the very early stage where the ball of cells that will become an animal's body begins to grow. This ball is nearly spherical, and the cells within it are also almost identical to one another. Yet over time, one end becomes a head and the other becomes a tail. Eyes form, and legs grow. Turing's question was how different parts could emerge from a body where every part was initially identical, and how a ball-like cluster could develop into a body with distinct front and back, top and bottom, like a horse or a human being.

There were still many unsolved problems in the process by which biological forms are created. Turing sought to explain some of them mathematically. He believed that the forms of living organisms could be explained solely through the laws governing how chemical substances react with one another and spread out. Turing decided to demonstrate mathematically that this idea held true.

14.2. Discovery of the Reaction-Diffusion Equations

In November 1951, Turing submitted a paper to the Royal Society. Its title was "The Chemical Basis of Morphogenesis." Morphogenesis refers to the process by which a living organism takes shape as it grows. This paper was published on August 14, 1952, in the Royal Society's biological journal, *Philosophical Transactions B*, Volume 237, pages 37 to 72. It was 36 pages in total.

In this paper, Turing used the word 'morphogen' for the first time. In Greek, it means 'that which creates form.' Turing believed that certain chemical substances moving and diffusing between cells and tissues within the body tell the cells what they are to become. Cells where the substance is abundant and cells where it is scarce take different paths. However, because no such substances had actually been discovered at the time, morphogens were substances hypothesized by Turing.

To explain how morphogens produce patterns, Turing focused on two processes. One was 'reaction,' and the other was 'diffusion.' Reaction is when chemical substances meet to create new substances or eliminate one another. Diffusion is the movement of a substance spreading from an area of high concentration to an area of low concentration. When a drop of ink is dropped into a cup of water, the ink slowly spreads until the entire cup is evenly colored. This is diffusion.

As seen in the example of ink, people usually thought that diffusion mixes everything evenly. This was because when ink spreads, patterns disappear and only a uniform color remains. However, Turing showed mathematically that the exact opposite result could occur. If two chemical substances react with each other while diffusing at different speeds, the initially uniform state is broken and patterns emerge.

In the two-substance model often used today to explain this idea, the roles of the substances are divided as follows. One is an activator, and the other is an inhibitor. The activator produces more of itself and at the same time produces the inhibitor. The inhibitor suppresses the activator from increasing. An important condition is attached here: the inhibitor must diffuse much faster than the activator.

Why this condition produces patterns is easy to understand if compared to a forest fire. Let us suppose that small sparks appear throughout a dry forest. A spark spreads to nearby trees and grows larger. This corresponds to the activator. When a fire breaks out, firefighters are dispatched. The firefighters move much faster than the fire and spray water in advance on the trees around the fire. This corresponds to the inhibitor. Then, the fire burns only where it first caught, while the surrounding area remains wet. If one looks down at the forest from the sky, a pattern is visible where burned and unburned areas are scattered like spots. In the actual mathematical model, different forms such as spots or stripes appear depending on the conditions of reaction and diffusion of the substances.

Turing also explained where this process begins. At first, the two substances are mixed evenly everywhere. However, a perfectly uniform state does not exist in reality. Very slight differences arise in very tiny areas. Normally, such differences disappear quickly. Under the conditions Turing identified, however, these tiny differences grow increasingly larger. Places that had slightly more activator gain even more, while the surrounding areas have less because of the inhibitor. Scientists call this breaking of a uniform state 'symmetry breaking.' Today, this phenomenon of the initial balance collapsing bears the name 'Turing instability.'

By solving complex equations, Turing demonstrated that this process produces patterns such as spots, stripes, and waves. Today, such patterns are called 'Turing patterns.' The core of Turing's theory is that even without anyone drawing them from the outside, patterns arise spontaneously while substances react and diffuse with one another.

This theory also contained a view on the role of genes. Looking at the timing of the paper's publication makes this point even clearer. It was in 1953 that James Watson and Francis Crick elucidated the double helix structure of DNA. When Turing was writing his paper, no one knew what genes looked like. Even so, Turing surmised what genes do. He did not view genes as a blueprint depicting each and every detail of the body's form. Genes only determine conditions, such as how quickly chemical substances react and how fast they diffuse. Turing's idea was that the actual forms arise spontaneously under those conditions according to the laws of reaction and diffusion.

Turing also made clear the limitations of this theory in his paper. At the beginning of the paper, he wrote that his model was a simplification and idealization of actual living

organisms, and that there might therefore be parts that differed from reality. Even as he presented a new theory, he did not claim that it explained everything.

14.3. Pioneering Computational Biology

Turing's equations were difficult to solve by hand. While a few simple cases could be solved with paper and pencil, seeing how patterns actually formed required an immense amount of calculation. Turing had a machine to which he could entrust those calculations: the Ferranti Mark 1 at the University of Manchester.

The Ferranti Mark 1 was installed at the University of Manchester in February 1951. It was the world's first commercially produced and sold general-purpose electronic computer (one that could be used broadly for various types of calculations). Turing wrote the programming handbook for this computer himself. Because he knew this machine better than anyone, he wrote programs to calculate his equations and utilized them in his morphogenesis research.

However, the illustration of the dapple pattern published in the 1952 paper was obtained not with a computer, but by hand calculation. Turing noted in the paper that he had obtained this diagram through hours of hand calculation. Computers of that era had no devices to display pictures on a screen as they do today, and computational results appeared only as numbers. Turing foresaw that digital computers could be used when dealing with the processes through which more complex forms change.

Using computers to investigate biological phenomena was something new in the history of science. Until then, computers had mainly been used for tasks dealing with numbers, such as artillery ballistics or ciphers. Turing attempted to simulate on a computer the process by which living organisms create patterns. Instead of raising animals in a laboratory, he traced the processes of reaction and diffusion inside a computer. Today, such research is called computational biology, and Turing is regarded as one of the pioneers who first opened this field.

After publishing his 1952 paper, Turing expanded his research subjects to plants. The problem he tackled this time was 'phyllotaxis.' Phyllotaxis refers to the order and arrangement in which leaves attach to a stem. If you look at the center of a sunflower, seeds

are densely packed in spirals. Both clockwise spirals and counterclockwise spirals are visible together. Counting the number of these spirals reveals consistent pairs, such as 34 and 55, or 55 and 89. In pinecones, pairs like 8 and 13 often appear.

These numbers are all part of the Fibonacci sequence. The Fibonacci sequence is a series of numbers where adding the preceding two numbers produces the next number, such as 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89. New leaves or seeds often form at positions rotated by about 137.5 degrees from the preceding one. This angle is called the golden angle. When arranged this way, leaves and seeds do not overlap one another and occupy space without gaps. People had known this rule for a long time, but they could not explain why plants follow this rule.

Turing researched this problem together with Claude Wardlaw, a botanist at the University of Manchester. Turing thought that the reaction and diffusion of morphogens also occurred at the growing tip of a plant stem where new leaves emerge. When a leaf forms in one place, it is difficult for a new leaf to develop around it, and the next leaf forms a short distance away. Turing sought to trace mathematically how the accumulation of such processes causes spirals of Fibonacci numbers to appear.

Young researchers also took part in this research. Graduate student Bernard Richards applied Turing's equations to spherical surfaces. He compared his computational results with the shapes of the rounded shells of tiny marine organisms called radiolarians. Turing was organizing this research into a three-part manuscript titled "Morphogen Theory of Phyllotaxis." However, with Turing's sudden death in June 1954, the manuscript was never finished. These manuscripts remained buried for a long time before being published in 1992 in the morphogenesis volume of Turing's collected works, edited by Peter Saunders.

The phyllotaxis problem that Turing could not finish was taken up again years later in Manchester. In 2012, to mark the centenary of Turing's birth, a citizen science event called 'Turing's Sunflowers' was held. Citizen science refers to research where ordinary citizens, rather than professional scientists, participate directly in data collection. In this event, data from 657 sunflowers grown by citizens was gathered. While there were many cases where the number of spirals was a Fibonacci number, arrangements that did not follow the rule were also confirmed. It was an occasion where many people together examined the question Turing had left unfinished.

His 1952 theory on patterns also did not receive much attention during Turing's lifetime. After the structure of DNA was discovered in 1953, the attention of biologists shifted toward the study of genes and molecules. Turing's theory, which attempted to explain the patterns of life through equations, was regarded as an idea that might be mathematically plausible, but remained unconfirmed in actual living organisms.

The situation changed several decades later. In 1990, a research team led by De Kepper in France actually produced the spotted patterns predicted by Turing in a chemical solution in a laboratory. In 1995, Japanese biologists Shigeru Kondo and Rihako Asai published a study on the striped angelfish in the journal *Nature*. As this fish grows, its stripes divide and new ones form, and this change matched the results calculated with Turing's equations. In 2014, research showed that the principle described by Turing also operates in the process by which a mouse's digits divide into five.

Even recently, research to verify and complement Turing's theory continues. In March 2023, a research team led by Professor Flavio Fenton at the Georgia Institute of Technology presented the results of an experiment with chia seeds at an American Physical Society conference. The research team spread chia seeds evenly on trays and grew them while varying the amount of water and types of soil. The sprouts then grew in clusters forming shapes like spots or maze patterns. These patterns resembled the computer calculation results generated by reaction-diffusion equations. The research team stated that this was the first time such a model had been directly confirmed with living plants.

In November of the same year, a research team led by Professor Ankur Gupta at the University of Colorado Boulder published a study on the patterns of a fish called the boxfish in the journal *Science Advances*. Turing's equations alone could not fully explain the distinct hexagonal patterns on the skin of the boxfish. The research team added to the calculations the phenomenon in which pigment-producing cells are also dragged along as chemical substances diffuse. A sharp pattern resembling that of the actual fish then emerged. This research was built upon Turing's theory, adding a new explanation on top of it.

Today, Turing's 1952 paper is regarded as the starting point of mathematical biology (the discipline that explains biological phenomena through mathematics) and computational biology. From the spots of leopards and stripes of fish to the process by which fingers form

and the way desert plants grow in clusters, scientists study the patterns of life based on Turing's ideas. Research that simulates biological phenomena with computers also carries forward the method that Turing pioneered.

Turing did not leave the mystery of life as magic. He believed that even the beautiful patterns of living organisms follow the laws of nature, and that those laws can be written in mathematics. And he tested that belief directly with mathematics and computers. From ciphers and computers to machine intelligence and the form of life, Turing addressed problems in fields that seemed far apart using the very same approach.

Chapter 15. The Trial and State Discrimination (1952–1954)



Figure 15. Depicting the situation of Turing, who had to stand trial.

Introduction

In early 1952, Alan Turing was thirty-nine years old. He was the deputy director of the Computing Machine Laboratory at the University of Manchester, and the year before, in 1951, he had been elected a Fellow of the Royal Society (FRS), a high honor for a British scientist. Around that time, the research Turing was immersed in was explaining the patterns of life through mathematics, such as the stripes of a zebra or the arrangement in which leaves sprout on plants. At night, he sat before the university's Ferranti Mark 1 computer, running lengthy calculations.

On the other hand, almost no one knew what he had done during the war. At Bletchley Park, Turing had taken the lead in breaking the German military's Enigma cipher. The Bombe, a codebreaking machine he designed, and Banburismus, a statistical method, were of immense help in protecting Allied ships crossing the Atlantic from German U-boats. Historians assess that thanks to this codebreaking, the war was shortened and many lives were saved. However, this is an estimate. The figure of 14 million presented by Jack Copeland is also a calculation assuming the war had lasted longer.

All of this was a state secret. In June 1946, the British government's official gazette announced that Turing was being awarded the Order of the British Empire (OBE). Yet Turing could not tell even his family why he had received the medal, because the Official Secrets Act kept his lips sealed. Therefore, in the eyes of the world, he was merely a somewhat eccentric university mathematician.

In 1952, a minor burglary completely turned Turing's life upside down. This chapter follows the trial and punishment Turing endured from 1952 to the early summer of 1954, and the process by which the country he had protected turned its back on him.

15.1. The Burglary and the Indictment for 'Gross Indecency'

In 1950, Turing bought a house in Wilmslow, a small town south of Manchester, and lived alone. He commuted to the university by train or bicycle, and whenever he had spare time, he ran along country roads. He had enjoyed long-distance running since his youth and had once recorded times comparable to those of marathon runners.

In December 1951, near a cinema on Oxford Road in central Manchester, Turing met a nineteen-year-old young man named Arnold Murray. Murray was an unemployed, impoverished youth. Turing invited him to lunch, and after meeting several more times, the two became romantic partners. A man loving a man, or a woman loving a woman, is called homosexuality. Turing had known since his school days that he was attracted to men, and he did not conceal this from close friends.

On January 23, 1952, Turing returned home to find that a burglar had broken in and stolen some clothes and household goods. Turing reported it to the police. A few days later, Murray confessed that he thought the burglar was someone he knew—a young man named Harry. The police examined fingerprints left at the house and identified the culprit.

However, in the course of pursuing the culprit, the police also learned of the nature of the relationship between Turing and Murray. In February 1952, police officers visited Turing's home and questioned him about the matter. Turing did not hide anything. He truthfully described his relationship with Murray and personally wrote and submitted a statement detailing it. Turing did not believe there was anything wrong with a consensual relationship between two adults.

British law at the time did not see it that way. Section 11 of the Criminal Law Amendment Act of 1885 defined homosexual acts between men as the crime of 'gross indecency.' It did not matter whether both people had consented. A conviction for this crime could result in up to two years in prison. It was this very clause that sent the famous Irish writer Oscar Wilde to prison in 1895, and in 1950s Britain, many men were still punished under this law every year. Under this law, the statement Turing truthfully wrote for the police served directly as evidence of a crime.

The police arrested Turing and Murray together and sent them to trial. On February 27, 1952, the first hearing was held at Wilmslow Magistrates' Court. The formal trial took place on March 31, 1952, at the Knutsford Quarter Sessions. The Quarter Sessions were English local criminal courts held four times a year, once each season. The official name of the trial was 'Regina v. Turing and Murray.'

Ahead of the trial, Turing had to decide how to respond. He believed the law was wrong, and at first, he even thought of standing up in court to argue that he had done nothing

wrong. However, his older brother John Turing and his lawyer were deeply worried. If he fought to the end and lost, he could be sent to prison, which would bring his research and his work with computers to a complete halt. The two spent a long time persuading Turing. Turing ultimately chose to plead guilty. He had not changed his mind; he merely bowed before the law so that he could continue his research.

In court, fellow mathematician Max Newman and Bletchley Park colleague Hugh Alexander appeared to testify to Turing's character. Hugh Alexander stated that Turing was an invaluable asset whom the country could ill afford to lose. However, he could not explain why. What Turing had done during the war was still classified. The very secrecy that had prevented him from telling his family why he received his medal now made it impossible to utter a single word about his wartime contributions in court.

The judge convicted Turing. Murray was given a conditional discharge, meaning he would not face further punishment as long as he did not commit another offense during a specified period. News of the trial appeared in local newspapers. Neighbors, colleagues at the university, and his mother, Sara Turing, all learned of what had happened.

15.2. A Cruel Choice: Forced Chemical Administration

Along with the guilty verdict, the judge gave Turing a choice between two paths: go to prison, or receive hormone therapy while on probation. Probation is a system where, instead of being locked in prison, a person remains in the community while authorities monitor whether they follow set conditions. According to the royal pardon made public years later, Turing was placed on probation for twelve months and required to undergo treatment under a qualified doctor at the Manchester Royal Infirmary.

That the court could offer 'treatment' instead of imprisonment was due to misguided medical knowledge of the time. Many British doctors and judges regarded homosexuality as an illness that needed to be cured. They believed it stemmed from an imbalance of hormones in the body, and thought that administering female hormones to suppress sexual desire would serve as a cure. It was a baseless notion. Today, medicine does not view homosexuality as a disease, and the World Health Organization (WHO) removed homosexuality from its list of diseases in 1990. At the time, this treatment was called

'organotherapy.' Today, it is referred to as 'chemical castration'—meaning the suppression of male sexual function through drugs.

Turing accepted the hormone therapy. Going to prison meant he could not go to the laboratory. The mathematical formulas he was calculating and the programs he was running on the computer would have ground to a halt. Just as when he pleaded guilty, his criterion for judgment this time was whether he could continue his research. On the surface, it appeared to be a choice he made freely, but faced with the threat of imprisonment, he had no real alternative.

Beginning in April 1952, Turing was given a drug called stilboestrol. Its chemical name is diethylstilbestrol, a man-made synthetic female hormone. At first, he took it as pills, and later, the drug was implanted under the skin of his thigh to release slowly into his body. This treatment continued for about a year.

The drug altered Turing's body. He lost his male sexual function, gained weight, and the shape of his body changed. He also developed gynaecomastia, causing his breasts to swell like a woman's. For a person who used to run dozens of kilometers across the countryside, feeling his own body become as alien as someone else's was agonizing. These bodily changes left deep emotional wounds as well.

Turing's feelings during that time remain preserved in letters he sent to friends. In a letter to his student and friend Norman Routledge before the trial, he wrote that no doubt he would emerge from all this a different man, but quite who he had not found out yet. In a letter to his mathematician friend Philip Hall after treatment began, he wrote that the drug reduced sexual desire, but since they said things would return to normal once the treatment ended, he hoped that would be true.

Turing tried hard not to break down. To close friends, he even joked that his breasts were growing because of the medication. It was his own way of enduring pain through humor. Although movies and novels sometimes depict Turing's spirit as immediately crumbling after hormone therapy, actual historical records tell a different story.

What the records show is research that never stopped even during this period. In 1952, his paper 'The Chemical Basis of Morphogenesis,' which explained patterns in living organisms

through mathematics, was published in the Philosophical Transactions of the Royal Society. Night after night, Turing also continued using the Ferranti Mark 1 computer to calculate phyllotaxis, the arrangement of leaves on plants. In 1953, the University of Manchester created a new post for him: 'Reader in the Theory of Computing.' In 1954, he wrote an article for general readers titled 'Solvable and Unsolvable Problems' and published it in a science magazine.

The hormone therapy ended in the spring of 1953. Yet the label of 'criminal' did not disappear. The changes left on his body and the gazes of others lingered long in Turing's mind.

15.3. Revoked Security Clearance and Isolation

Physical health was not the only thing the conviction took from Turing. He also lost the qualification to handle state secrets. This credential is called a 'security clearance.' The government allows access to state secrets only to those who hold this clearance.

After the war ended, the codebreaking organization at Bletchley Park was renamed the Government Communications Headquarters (GCHQ) in 1946. Even while working at the University of Manchester, Turing had served as a cryptographic consultant for GCHQ, because the knowledge and experience he had gained during the war were still needed. However, when his security clearance was revoked due to the conviction, he could no longer carry out this advisory work that he had undertaken since the war. His name was erased from the world of cryptographic research that he had pioneered.

There was a historical backdrop to why the government acted this way. After the war, the world was divided into the American and British side and the Soviet side, each viewing the other with suspicion. This era of cold standoff without open gunfire is called the Cold War. Both camps dispatched spies to ferret out each other's secrets.

In Britain, a specific incident linked this anxiety to suspicion of homosexuals. In May 1951, British Foreign Office diplomats Guy Burgess and Donald Maclean suddenly fled to the Soviet Union. The two had long been spies passing secrets to the Soviets, and Burgess was known to be homosexual. Following this incident, the belief spread within the British government that entrusting homosexuals with state secrets was dangerous. The Foreign

Office even conducted covert investigations into the security risks of employing homosexuals.

The government's reasoning was as follows: In a society where homosexuality was a crime, homosexuals faced punishment if discovered, and an enemy nation could exploit this vulnerability to blackmail them into surrendering state secrets. Yet what created that vulnerability was the very law that made homosexuality a crime in the first place. Even so, rather than changing the law, the government chose to suspect the people.

The United States was similar. The U.S. government purged homosexuals from civil service positions, and in 1952, a new immigration law barred foreign homosexuals from entering the country. Turing, who during the war had shared cryptographic technology and worked alongside the U.S. Navy, was denied entry to the United States following his conviction.

Along with being stripped of his credentials, surveillance soon followed. Once a man carrying vital national cryptographic secrets in his head became a 'criminal,' intelligence agencies viewed him as a security risk. Police and intelligence authorities monitored whom Turing met and where he went.

Turing experienced this surveillance on two journeys. In 1952, he traveled to Norway. Nordic countries were relatively more tolerant of homosexuality than Britain. There, he met a young man named Kjell Carlson. In March 1953, when Carlson tried to come to Britain to visit Turing, the police acted first. Carlson was turned away and sent back to Norway without ever meeting Turing. Turing confided to friends that this episode was a crisis comparable to the trial itself. He had experienced firsthand that the state was scrutinizing even whom he met.

In 1953, he went on vacation to the Greek island of Corfu. Corfu is an island facing the communist country of Albania across a narrow stretch of sea. Biographers recount that intelligence authorities anxiously watched Turing—a man privy to state secrets—traveling so close to the borders of the Communist bloc.

Turing managed to keep his university research post and could continue his research. But the world he belonged to grew steadily narrower. At King's College, Cambridge, and at Bletchley Park, he had colleagues by his side who embraced his eccentric personality and

ideas. Now, he had become someone his country could not trust. He could no longer speak of secret work even with former colleagues, and the looks he received from neighbors were no longer what they used to be.

Yet this does not mean Turing merely endured everything alone. He went to see Dr. Franz Greenbaum, a psychoanalyst in Manchester, for counseling. At Dr. Greenbaum's suggestion, he examined his own mind by writing down his nightly dreams in a notebook. He also grew close to the doctor's family and visited their home. He exchanged letters with friends and carried on with calculations regarding mathematical problems and biological patterns.

Still, the reality that his country treated him as a potential traitor and a criminal did not change. During the war, he had unlocked Germany's secrets for his country. After the war ended, that same country criminalized his private life, injected drugs into his body, shut the doors of secrecy against him, and watched his every step. This is why the title of this chapter includes the phrase 'State Discrimination.'

On the evening of June 7, 1954, Alan Turing passed away at his home in Wilmslow. It was about two weeks before his forty-second birthday. The next morning, June 8, his cleaner found him.

Chapter 16. Turing's Death and Belated Rehabilitation (After 1954)



Figure 16. The remembrance of Turing is expressed through an empty bench and a notebook.

In the early summer of 1954, in Wilmslow, a small town in northwest England, mathematician Alan Turing passed away at the age of forty-one. He had conceived an imaginary computing machine, laying the theoretical foundation of computers, and during the war, contributed to saving many lives by deciphering German military codes. In Manchester, he wrote programs for real computers, and sought to explain through mathematics the arrangement of sunflower seeds and the principles behind how animal markings form.

Yet when he passed away, hardly anyone truly knew of these achievements. His wartime work was a state secret, and many people knew him only as someone who had been punished for homosexuality. Over the next half-century and more, British society gradually rediscovered this forgotten mathematician. The government's belated apology, a royal pardon, a law named after him, and a banknote bearing his portrait show that journey.

16.1. The Tragedy of June 8, 1954

Books and movies often state that Turing died on June 8. However, the day he passed away and the day he was found were different. Turing died on the night of Monday, June 7, 1954, in the bedroom of his home at 43 Adlington Road in Wilmslow. That day was a British bank holiday. The following morning, Tuesday, June 8, a housekeeper who came to help with chores found him lying in bed. It was sixteen days before his forty-second birthday.

Police and a doctor came to the house to examine the body, and an autopsy revealed the cause of death to be cyanide poisoning. Cyanide is a toxic substance that interferes with the ability of the body's cells to use oxygen. Potassium cyanide, which Turing used in his electroplating experiments, also belongs to this group. A few days later, an inquest was held. An inquest is an official proceeding to formally determine the cause of a sudden death. At this proceeding, the coroner concluded that Turing had taken his own life. Turing's remains were cremated at Woking Crematorium on June 12, and his ashes were scattered there—the same place where his father's ashes had been scattered several years earlier.

Along with the coroner's verdict, the story of the 'cyanide apple' spread widely. On the bedside table lay an apple with several bites taken out of it, and people thought Turing had dipped the apple in cyanide before eating it. Yet there are unverified aspects to this story. At

the time, the police and the coroner did not test whether there was poison in the apple. No suicide note was found either. The claim that the apple was the instrument of death was not a fact confirmed by testing, but a conjecture drawn from the appearance of the scene.

Because of the untested apple and the absence of any remaining suicide note, different interpretations of Turing's death persist to this day. The first is the interpretation that he took his own life, as the coroner concluded. Andrew Hodges, the mathematician who wrote the definitive biography of Turing, supports this view. After watching Disney's animated film *Snow White and the Seven Dwarfs* in Cambridge in 1938, Turing reportedly loved the scene where the witch dips the apple into poison and frequently reenacted it. Hodges suggested that Turing might have imitated that scene, and might have made it look like an accident so that his mother would grieve less.

The second is the interpretation that it was an accident. Turing's mother, Sara Turing, never accepted the verdict that her son had died by suicide throughout her life. Turing had set up a laboratory in a small room at home and was conducting electroplating experiments, using electricity to coat spoons with gold. Potassium cyanide was used in these electroplating experiments. Sara argued that since her son had a habit of not washing his hands properly, he might have inadvertently swallowed poison that got on his hands during an experiment.

The third is the view of scholars who re-examined the evidence between the two interpretations. In 2012, on the centenary of Turing's birth, Turing scholar Jack Copeland stated that there was a need to re-examine the inquest verdict. The evidence he cited was Turing's usual habits and his actions over his final days. Turing had a habit of eating an apple before going to sleep, and it was also common for him to leave it unfinished without eating it all. Therefore, he argued, it is difficult to see the partly eaten apple by the bed as having any special significance. Furthermore, Turing had left a note on Friday as he left his office detailing what to do on Monday, and people around him remembered him being cheerful and humorous until the very end. Copeland also suggested the possibility that he might have inhaled hydrogen cyanide gas generated during an experiment.

Which of these three interpretations is correct remains unknown today. Here, it is necessary to distinguish between what is established and what is not. That Turing died of cyanide poisoning is a fact confirmed by the autopsy. However, the specific circumstances

and route leading to the poisoning were never established. The story that the apple was poisoned is also closer to a popular tale than a verified fact.

There is one more rumor related to an apple. It is the rumor that the logo of the American computer company Apple—a bitten apple—was a tribute to Turing. This rumor is not true. Rob Janoff, the designer who created the logo, repeatedly stated that it had nothing to do with Turing. The bite mark was added so that the apple would not look like a cherry or a tomato. When British actor Stephen Fry asked Steve Jobs about this rumor, Jobs reportedly smiled and replied that he wished it were so, but it wasn't.

16.2. A Belated Apology and a Royal Pardon

Even after Turing passed away, what he did during the war remained a secret for a long time. In 1946, he was awarded the Order of the British Empire (OBE), but the citation offered only the brief explanation: 'for work done in the Foreign Office.' The fact that he had broken the Enigma code at Bletchley Park could not be disclosed to anyone because of the Official Secrets Act. Turing himself passed away without ever being able to tell this story even to his family.

The secrecy began to unravel in the 1970s. The British government gradually declassified wartime codebreaking records. In 1974, a book on 'Ultra,' the codebreaking operation at Bletchley Park, was published, allowing people to learn for the first time what had taken place there. In 1983, Andrew Hodges published the biography *Alan Turing: The Enigma*. Through this book, many people learned that Turing was both a father of the computer and an unsung hero of the war. At the same time, it also became known that such a person had been put on trial for homosexuality and had to undergo injections of female hormones to avoid going to prison.

When his achievements and his punishment became known together, calls arose demanding that the state take a responsible stance on the matter. In August 2009, British computer programmer John Graham-Cumming started an online petition urging the government to issue an official apology to Turing. Within a few weeks, more than 30,000 people signed, with scientists, writers, and politicians adding their names as well.

The government's response came about a month later. On September 10, 2009, Prime Minister Gordon Brown issued a statement on behalf of the British government. Prime Minister Brown acknowledged that the treatment Turing received was appalling and completely unfair. And on behalf of the British government and all those who live freely thanks to Turing's work, he said: "We are sorry, you deserved so much better." Fifty-five years after Turing's death, the state had formally admitted its wrongdoing for the first time.

Yet the apology was not an action carrying legal effect. Turing's conviction remained intact on his legal record. Consequently, voices continued to call beyond an apology for a pardon of the conviction that had been handed down. A pardon is an act whereby the state forgives and remits a punishment or its consequences that have already been imposed. However, a pardon is different from reopening a trial to declare someone innocent. It does not correct the conviction itself as having been wrongful, but is rather a measure that pardons the punishment resulting from that conviction.

Calls for a pardon emerged from both Parliament and the scientific community. John Leech, Member of Parliament for Manchester Withington, repeatedly introduced bills in Parliament to pardon Turing. In the House of Lords, Lord Sharkey introduced a bill to the same effect. In December 2012, scientists such as physicist Stephen Hawking, Royal Society President Paul Nurse, and Astronomer Royal Martin Rees published a letter in a newspaper demanding a pardon.

At first, the government hesitated. The reason given was that because the verdict had been delivered according to the laws of the time, it was difficult to overturn it now. Yet public opinion calling for a pardon grew ever stronger. Finally, on Christmas Eve, December 24, 2013, Queen Elizabeth II pardoned Turing. Acting on the recommendation of Justice Secretary Chris Grayling, she exercised the Royal Prerogative of Mercy—a power belonging solely to the monarch—to pardon the 1952 conviction.

News of Turing's pardon reached many countries around the world. However, this pardon highlighted a new issue. More than tens of thousands of people had been convicted under the same law, and most of them were ordinary, nameless individuals. Criticism arose asking whether it was right for only one famous scientist to be pardoned. This criticism led to demands to broaden the scope of the pardon.

16.3. The 'Alan Turing Law' and the New £50 Banknote

To understand this demand, one must first recognize how long and to how many people that law had been applied. In England and Wales, laws penalizing sexual acts between men had been in effect for a very long time. In 1967, consensual sexual acts between men aged 21 and over in private were decriminalized. Some discriminatory provisions remained afterward until they were repealed in 2003. Throughout that era, many people were arrested and tried. Many lost their jobs or became estranged from their families. Even after the law changed, their criminal records remained intact.

After Turing received his pardon, MP John Leech, Lord Sharkey, and human rights organizations argued that everyone convicted under the same law should be pardoned. Turing's family also stepped forward. In 2015, family members, including Turing's great-niece Rachel Barnes, delivered a petition signed by more than 500,000 people to 10 Downing Street. Major political parties likewise pledged, one after another, to accept this demand.

The outcome was the Policing and Crime Act 2017. This legislation received Royal Assent on January 31, 2017. Under this law, individuals in England and Wales who had been convicted under historical anti-homosexuality statutes became eligible for a pardon if they met certain conditions. The conditions were that the other person was at least 16 years old at the time, had consented to the relationship, and that the act would not constitute an offense today. People refer to the pardon provisions of this act as the 'Alan Turing Law.' Although not an official title, it is called this because the law originated from Turing's pardon.

The manner of pardon differed depending on whether the individual had already passed away. Roughly 49,000 people who were already deceased received posthumous pardons through this law. This is the figure commonly referred to as around 50,000 people. Living individuals were allowed to receive a pardon after applying to the government to have their criminal records cleared. In the UK, having a criminal record removed is known as 'disregard.' In 2022, the law was amended once more to expand the criteria under which records could be cleared. A pardon for one man had ultimately led to legislation restoring honor to tens of thousands of people.

Turing's name did not remain only in statute books. It was also inscribed on the money people hold in their hands every day. In 2018, the Bank of England, the UK's central bank, invited nominations from the public for a scientist to feature on the new £50 banknote. More than 200,000 nominations were submitted. After narrowing down the candidates, the bank announced on July 15, 2019, that Alan Turing had been selected as the figure for the new £50 note. Mark Carney, the Governor of the Bank of England at the time, introduced Turing as the person who laid the theoretical foundations of modern computing.

The new banknote was first issued on June 23, 2021, Turing's birthday. It was made not from paper, but from polymer, a durable and long-lasting plastic material. The reverse side of the banknote features artwork illustrating Turing's life and work. First, there is a photograph of Turing taken in 1951, alongside a table and mathematical formulae from his 1936 paper 'On Computable Numbers, with an Application to the Entscheidungsproblem.' It also includes the Pilot ACE, a trial model of the computer ACE designed by Turing, and technical drawings of the bombe used to decipher Enigma. On an illustration of a paper tape fed into the machine, Turing's birthdate of June 23, 1912, is encoded in binary numbers of 0s and 1s. The flower-shaped red foil patch on the note, inspired by sunflowers, commemorates the morphogenesis Turing studied in his later years. Beneath it, alongside Turing's signature, is a quote from an interview he gave to The Times newspaper in 1949: "This is only a foretaste of what is to come, and only the shadow of what is going to be." These words captured his prediction that computers would accomplish far greater things in the future.

This banknote also carried a significance distinct from honoring his scientific achievements. Turing became the first LGBT figure to be featured on a Bank of England banknote. To celebrate the issuance, the bank flew the rainbow flag over its headquarters building in London. A nation that had punished a man for his homosexuality seventy years earlier had now placed a person who suffered for that very reason on the £50 note, the highest denomination issued by the Bank of England.

Even after the British monarch changed, Turing's place on the banknote remained unchanged. When Queen Elizabeth II passed away in 2022 and King Charles III ascended the throne, the portrait on the front of the banknote had to be updated. From June 5, 2024,

new banknotes featuring King Charles III's face were issued, but the reverse side was left unaltered. On the back of the £50 banknote, Alan Turing remains to this day.

There are many other ways in which Turing is remembered. Since 1966, the Association for Computing Machinery (ACM) in the United States has annually awarded the 'Turing Award' to individuals who have made major contributions to computer science. It is an honor often referred to as the Nobel Prize of computing. In 2001, a statue of Turing sitting on a bench holding an apple was erected in Sackville Gardens in Manchester. In 2015, the UK established a national institute for data science and artificial intelligence and named it 'The Alan Turing Institute.' Bletchley Park, where he once worked, has become a museum welcoming numerous visitors each year.

In June 1954, Turing passed away alone in his house in Wilmslow. How he spent his final night remains unknown to this day. Yet the ideas he left behind have not vanished. The smartphones and computers we use today, and the artificial intelligence that converses with humans, trace their theoretical roots back to the imaginary machine he sketched out on paper in 1936.

Chapter 17. The History and Development of Artificial Intelligence (1950s–2020s)



Figure 17. The flow of artificial intelligence research represented through chess and neural networks.

In 1948, Alan Turing wrote a report titled "Intelligent Machinery." In this report, he envisioned two parallel paths to making machines intelligent. The first path was for humans to specify rules one by one. The second path was for machines connected like neurons in the brain to learn on their own by accumulating experience.

Two years later, in 1950, Turing published the paper "Computing Machinery and Intelligence" in the academic journal *Mind*. In this paper, he posed the question, "Can machines think?" and proposed the imitation game to distinguish between human and machine through conversation.

Turing passed away in June 1954 at the age of forty-one. Yet the question he left behind did not disappear. In the seventy years since Turing's death, scientists have walked the two paths he foresaw by turns. When one path was blocked, the other opened, and expectations repeatedly swelled and deflated. Today's artificial intelligence was forged through this very process.

17.1. The Dartmouth Conference and the Birth of Symbolic AI (1956–1970s)

The Birth of the Name 'Artificial Intelligence'

Turing called the field he studied 'machine intelligence.' It was the year after Turing passed away that this field received its current name. In the summer of 1955, John McCarthy, a young American mathematician, wrote a research proposal together with three colleagues: Marvin Minsky of Harvard University, Claude Shannon of Bell Labs, and Nathaniel Rochester of IBM. The term that appeared for the first time in the title of this proposal was 'Artificial Intelligence.'

In accordance with the proposal, a research workshop was held for about two months in the summer of 1956 at Dartmouth College in Hanover, New Hampshire. This gathering is known as the Dartmouth Conference. Those who drafted the proposal believed that if every aspect of learning or any other feature of intelligence could be described precisely, a machine could be made to simulate it. Many scholars regard this conference as the moment artificial intelligence was born as an academic discipline. It took place two years after Turing passed away.

Machines That Think with Rules and Symbols

A program that supported this idea had already appeared at the Dartmouth Conference. It was the 'Logic Theorist,' brought by attendees Herbert Simon and Allen Newell. This program proved mathematical logic theorems on its own. It is considered one of the earliest landmark examples of a machine performing a task long thought to require human intellect. The two men subsequently created the 'General Problem Solver (GPS),' which sought to solve various kinds of problems using the same approach. In 1958, McCarthy created LISP, a programming language well suited for artificial intelligence research.

These early researchers believed that human thought could be converted into symbols and rules. If two statements—"All birds can fly" and "A sparrow is a bird"—are written in symbols, the machine deduces the conclusion: "A sparrow can fly." This approach of representing knowledge with symbols and computing according to logical rules is called 'symbolic AI.' Because humans set the rules from above and the machine follows them, it is also referred to as a 'top-down' approach. This method can be linked to the approach Turing explored, in that humans explicitly define the rules of computation.

Games were a favorite challenge for symbolic AI, and Turing had walked this path early on. In 1948, Turing and his friend David Champernowne designed a chess program called 'Turochamp.' At the time, there was no computer capable of running this program. So, in 1952, Turing played chess against a colleague by calculating the program's moves himself using paper and pencil. It is said that each move took nearly thirty minutes. Turochamp used a method of looking ahead several moves into the future and choosing the best one, a technique that became the foundation for chess programs. That path reached a milestone in May 1997, when IBM's chess computer Deep Blue defeated world champion Garry Kasparov.

Programs that could hold conversations also emerged. In 1966, Joseph Weizenbaum of MIT introduced 'ELIZA,' a conversational program. ELIZA simulated the manner of a psychotherapist. If a user brought up their mother, it would ask them to say more about her. ELIZA merely recognized keywords in a sentence and responded according to predetermined templates; it did not understand the meaning of the sentences. Even so, many people poured their hearts out to ELIZA. It is said that Weizenbaum's secretary even

asked him to leave the room while she spoke with ELIZA. Seeing this, Weizenbaum grew troubled rather than pleased, feeling that people trusted machines far too easily.

In 1972, psychiatrist Kenneth Colby created a program called 'PARRY.' PARRY mimicked the speech of a patient suffering from extreme paranoia. When transcripts of the conversations were shown to psychiatrists, the doctors could not readily distinguish PARRY from a real patient. In that it asked people to tell human from machine based solely on conversation, it was an experiment reminiscent of Turing's imitation game.

Swelling Expectations

As breakthroughs followed in theorem proving, chess, and conversation, researchers dreamed big. In 1965, Herbert Simon predicted that within twenty years, machines would be capable of doing any work a person could do. Marvin Minsky likewise stated that within a generation, the problem of creating artificial intelligence would be substantially solved.

Turing's prediction had been more cautious. In his 1950 paper, Turing wrote that in about fifty years' time, an average person would have no more than a 70 percent chance of correctly identifying whether their conversational partner was a machine after a five-minute conversation. The expectations of early researchers ran far ahead of Turing's forecast. Believing the researchers' promises, governments and the military poured in substantial research funding.

17.2. The AI Winter and the Counterattack of Connectionism (1980s–2000s)

Symbolic AI Hits a Wall

The promises made by researchers were not fulfilled as hoped. Entering the 1970s, symbolic AI ran into two major walls.

The first wall was the 'combinatorial explosion.' Even in problems with clear-cut rules, such as chess or puzzles, the number of possibilities to examine multiplies several times over with each step looked ahead. Programs that performed well on small toy problems became trapped in endless computations when confronted with real-world problems.

The second wall was 'common sense.' The rule seen earlier, "All birds can fly," fails when it comes to penguins and ostriches. A bird with an injured wing, a bird in a painting, or a roasted chicken cannot fly either. Humans know such exceptions without needing to be taught them separately. For a machine, however, every single exception had to be written out as a rule, and the world's exceptions were endless.

Those funding the research grew disappointed. In 1973, British mathematician James Lighthill submitted a report evaluating artificial intelligence research at the request of the British government. He concluded that AI research had failed to deliver its promised results. Following this 'Lighthill Report,' the British government drastically reduced research funding for artificial intelligence. Around the same time, DARPA, the research agency of the U.S. Department of Defense, also cut back its support. Numerous research projects ground to a halt, and students left for other fields. People refer to this period as the 'first AI winter.'

The Spring of Expert Systems and the Second Winter

In the 1980s, artificial intelligence seemed to experience spring once again. This time, the star was the 'expert system.' Expert systems dealt not with the world as a whole, but only with knowledge in a narrow domain. Knowledge gathered by interviewing specialists such as doctors or engineers was organized into hundreds or thousands of rules—such as "If these symptoms are present, this disease is likely"—and fed into a computer. While following the symbolic path in that humans set the rules, this method narrowed its scope of application.

Cases showing practical utility also emerged. Developed in the 1970s at Stanford University in the United States, 'MYCIN' used approximately 600 rules to recommend appropriate antibiotics for patients with blood infections. Starting in 1980, the computer company DEC used an expert system called 'XCON' to select computer component configurations tailored to customer orders, saving massive costs each year. Governments also took action. In 1982, the Japanese government launched the 'Fifth Generation Computer' project, prompting the United States and Britain to hurriedly increase AI research funding once again.

Yet this spring did not last long either. Translating the knowledge inside an expert's head into rules took immense amounts of time. Experts themselves often could not articulate

their judgments in the form of rules. As the number of rules swelled into the thousands, rules began to conflict with one another, and fixing one issue would cause problems elsewhere. When faced with an unforeseen situation not covered by its rules, the system was helpless.

Around 1987, the market for specialized AI computers collapsed. Japan's Fifth Generation Computer project also ended in 1992 without achieving its goals. This slump, lasting from the late 1980s to the early 1990s, is known as the 'second AI winter.'

Machines That Resemble the Brain: Neural Networks

While symbolic AI endured its winter, researchers walking a different path were quietly gathering strength. They sought answers in the human brain. The human brain contains roughly 86 billion neurons, which are interconnected and transmit signals to one another. When we learn something, the strengths of these connections change.

A computer program that mimics this principle is called an 'artificial neural network.' The philosophy of creating intelligence through connections in a neural network is termed 'connectionism.' Because intelligence is built from the ground up as the machine learns from experience—rather than having rules handed down from above—it is also referred to as a 'bottom-up' approach.

At the roots of this idea, too, lies Turing. In his 1948 report "Intelligent Machinery," Turing envisioned 'unorganized machines.' The idea was that a machine might begin with parts connected at random, but through training with rewards and punishments, its connections would gradually alter, growing into a useful machine. Turing viewed an infant's brain in much the same way. However, the director of the National Physical Laboratory, where Turing worked, dismissed the report as little better than a schoolboy's essay. It was only in 1968, fourteen years after Turing's death, that the report was published in a book and became known to the world.

Even while Turing's report lay buried, neural network research had begun independently, but that road was not smooth either. In 1958, American psychologist Frank Rosenblatt attracted great attention by introducing the 'perceptron,' which could learn to distinguish letters and shapes. In 1969, however, Marvin Minsky and Seymour Papert demonstrated

mathematically in their book *Perceptrons* that a single-layer perceptron could not solve even simple logic problems. The example they presented was the 'XOR' problem, where the answer is true only when exactly one of the two inputs is true. After the publication of this book, neural network research struggled to secure funding for a long time.

Backpropagation: Neural Networks Rise Again

The key to solving the problem lay in stacking neural networks into multiple layers. Stacking layers made it possible to solve problems like XOR. But having many layers introduced a new challenge: it was difficult to know how to adjust the connections in the hidden inner layers.

In 1986, David Rumelhart, Geoffrey Hinton, and Ronald Williams formulated and published the 'error backpropagation' (backprop) method in the scientific journal *Nature*. A similar idea had previously been proposed by Paul Werbos in the United States in his 1974 doctoral dissertation. The principle works like this: when the neural network produces an answer, it measures the degree of error by comparing its output against the correct answer. Then, propagating this error backward from the output layer to the input layer, it calculates how much each connection contributed to the error and adjusts them little by little. It resembles a study habit where, after taking a test, a student retraces their steps through incorrect answers to find where mistakes were made and correct them.

This method was soon applied to practical problems. In 1989, French-born researcher Yann LeCun created a neural network at Bell Labs in the United States that read handwritten digits using backpropagation. LeCun's neural network was a 'convolutional neural network,' which examined images by breaking them down into small pieces. In the 1990s, this technology was used by American banks to read numbers written on checks.

Even so, through the 1990s and early 2000s, neural networks remained out of the center stage of artificial intelligence research. Computers were slow, and data to train neural networks was scarce. In many cases, other methods achieved better results. Even amid these circumstances, researchers like Hinton, LeCun, and Yoshua Bengio in Canada never abandoned neural network research. Inquiries into whether machines could learn from experience continued through the diverse approaches of various researchers.

17.3. The Deep Learning Revolution and the Dawn of the Generative AI Era (2010s–2020s)

Three Ingredients Come Together

The reasons neural networks had failed to take center stage were slow computers and insufficient data. Around 2010, the three ingredients neural network researchers had long awaited came together all at once.

The first ingredient was big data. As the internet and smartphones spread, vast quantities of photos, texts, and videos accumulated. In 2009, Fei-Fei Li and her research team at Princeton University unveiled 'ImageNet,' a dataset of photos labeled with what appeared in them. The paper at the time introduced approximately 3.2 million images, and the collection later expanded to over 14 million images.

The second ingredient was the GPU. A GPU, or graphics processing unit, was originally a component designed to render graphics for computer games. GPUs calculate the countless pixels that make up a screen simultaneously. This capability was also perfectly suited for computing the countless connections of a neural network all at once.

The third ingredient was techniques for effectively training deep neural networks. Hinton and other researchers discovered methods one by one to train networks built with many deep layers. The technique of learning through such deep neural networks is called 'deep learning.'

In 2012, these three ingredients came together in one place. In the ImageNet visual recognition competition, 'AlexNet'—a neural network created by Hinton's students Alex Krizhevsky and Ilya Sutskever together with Hinton—won first place. AlexNet was trained using two gaming GPUs. Looking at the error rate where the correct answer was not among the top five most likely predictions, AlexNet scored about 15 percent, while the runner-up team recorded roughly 26 percent. That was a difference of more than 10 percentage points from second place. Seeing these results, researchers and tech companies scrambled to shift their focus toward deep learning. Within a few years, recognizing faces in photographs, transcribing speech to text, and translating foreign languages improved beyond recognition.

March 2016: AlphaGo and Lee Sedol

An event that brought deep learning to wide public attention took place in Seoul. From March 9 to 15, 2016, at a hotel in Seoul, Google DeepMind's Go-playing program AlphaGo played five matches against Lee Sedol, a 9-dan professional player. Because the number of possible board positions in Go exceeds the number of atoms in the observable universe, the approach of examining every possible move one by one, as in chess, does not work. For this reason, many experts believed it would take at least another ten years for a computer to defeat a top-tier Go professional.

To solve this problem, the research team led by Demis Hassabis and David Silver incorporated two neural networks into AlphaGo. One was a neural network that selected promising candidate moves, and the other was a neural network that evaluated who was likely to win from the current board position. AlphaGo first learned by reviewing about 30 million board positions extracted from games played by humans. It then honed its skills by playing countless matches against itself. It adjusted itself to play winning moves more frequently and losing moves less often. This method of learning is called 'reinforcement learning.'

The match ended in a 4-to-1 victory for AlphaGo. In Game 2, AlphaGo's Move 37 was initially regarded by professional players as a mistake, but was later acclaimed as the move that decided the game. In Game 4, Lee Sedol shook AlphaGo's calculations with Move 78 and won a game. This game remains the only official match AlphaGo ever lost to a human.

AlphaGo's learning method connects back to Turing's longstanding proposal. In the final section of his 1950 paper, "Learning Machines," Turing suggested that rather than trying to imitate an adult mind, one should create a machine resembling a child's mind and teach it through rewards and punishments. AlphaGo was an example of realizing that proposal from sixty-six years earlier on a massive scale. The following year, in 2017, DeepMind unveiled 'AlphaGo Zero,' which learned entirely on its own knowing only the rules of Go, without any human game records. AlphaGo Zero played 100 games against the AlphaGo that had defeated Lee Sedol and won every single one.

Transformers: Reading Entire Sentences at Once

After images and Go came language. Until then, language neural networks had read sentences word by word from beginning to end. As a result, when sentences grew long, they easily forgot earlier content, and because they could not move on to the next word until computing the previous one, processing was slow.

In June 2017, eight researchers at Google published a paper titled "Attention Is All You Need" and introduced a new neural network architecture called the 'Transformer.' The Transformer takes in all the words of a sentence simultaneously and calculates how strongly each word relates to all the others. This computation is called 'attention.' Take the sentence, "Cheolsu lent Younghee a book, and she thanked him," as an example. The Transformer computes and discovers that 'she' is closely related to 'Younghee.' Even when a sentence becomes long, it directly computes relationships between words that are far apart. Furthermore, during training, the Transformer could process computations across multiple positions in parallel, making highly efficient use of GPUs. When generating new text, however, it generates each subsequent part step by step based on what has already been produced.

Large Language Models and ChatGPT

Large language models (LLMs) emerged on the foundation of the Transformer. A large language model reads vast amounts of text—such as books, articles, and encyclopedias—and repeatedly practices predicting the next word in a sentence. Because the text itself serves as both the question and the answer, humans do not need to label data individually.

After releasing the first GPT in 2018, OpenAI in the United States steadily expanded the size of its models. GPT-3, released in 2020, contained 175 billion parameters—numbers representing the strengths of connections. As its scale grew, the model began performing tasks it had never been explicitly trained to do: composing poetry, writing computer programs, and translating among multiple languages.

On November 30, 2022, OpenAI unveiled the conversational service 'ChatGPT.' Anyone could visit the website, ask questions in Korean, and receive answers in natural, fluent sentences. Estimates suggested that ChatGPT reached approximately 100 million users within just two months of its launch. Subsequently, companies like Google, Anthropic, and

Meta rolled out large language models in rapid succession. Artificial intelligence that creates not only text but also images, music, and video is collectively known as 'generative AI.'

The achievements that advanced artificial intelligence research have also been recognized with major academic honors. Hinton, LeCun, and Bengio were named recipients of the 2018 Turing Award. Often called the Nobel Prize of computer science, the award is named after Alan Turing. The three researchers who kept neural network research alive through the AI winter received the very prize bearing Turing's name. In 2024, John Hopfield and Geoffrey Hinton, who laid the foundations of neural network research, were awarded the Nobel Prize in Physics. That same year, Demis Hassabis and John Jumper received the Nobel Prize in Chemistry for protein structure prediction using AlphaFold, shared with David Baker for computational protein design.

The Imitation Game Reopened After 75 Years

The imitation game proposed by Turing returned to the stage as well. In March 2025, Cameron Jones and Benjamin Bergen of the University of California, San Diego, published the results of an experiment conducted strictly according to the three-party setup Turing had originally proposed. Participants chatted simultaneously via text for five minutes with one human and one artificial intelligence, and then chose which was the human. Instructed to act like a person, GPT-4.5 was chosen as human in 73 percent of cases, being selected as human more often than actual people were. In the same experiment, ELIZA recorded 23 percent. This study was formally published as a research paper in 2026 in the U.S. journal *Proceedings of the National Academy of Sciences (PNAS)*.

This result does not necessarily mean that machines think like humans. Turing's 70 percent mentioned earlier was the interrogator's accuracy rate, whereas the 73 percent in this experiment was the proportion of times the AI was selected as human; therefore, the two numbers cannot be compared directly. The experimental conditions must also be considered. The researchers instructed GPT-4.5 to chat like an introverted young person familiar with internet culture and slang. When tested without these instructions, its score dropped to 36 percent. Whether giving plausible answers can be equated with true understanding is also a long-standing debate. In his 1980 'Chinese Room' thought experiment, philosopher John Searle argued that manipulating symbols according to rules

to produce plausible answers is fundamentally different from understanding meaning. Scholars remain divided on this question to this day.

Artificial intelligence, which gained its name at Dartmouth in 1956, grew by traversing back and forth between the path of rules and the path of learning. From the path of rules came Deep Blue; from the path of learning came AlphaGo and ChatGPT. Turing's 1948 report was one of the earliest studies to explore both machine rules and machine learning together. For over seventy years, scientists have pursued research to answer Turing's question, "Can machines think?" and the technologies born of that journey are transforming our daily lives today.

Chapter 18. Artificial Intelligence in 2026 and the Remaining Challenges



Figure 18. An illustration depicting students examining answers from artificial intelligence together.

In October 1950, Alan Turing published a paper titled "Computing Machinery and Intelligence" in the British philosophical journal *Mind*, posing the question, "Can machines think?" As a way to find the answer to this question, he proposed the "imitation game." It is a test in which an interrogator converses only in writing and then guesses whether the conversational partner is a human or a machine. Turing added a prediction here. He stated that in about fifty years, computers would play this game so well that an average interrogator would not have more than a 70 percent chance of correctly identifying the partner after five minutes of conversation.

Seventy-six years have passed since Turing wrote this paper. It is now October 2026. Artificial intelligence that calls to mind the "thinking machine" Turing envisioned is now being used everywhere—in schools and hospitals, courts and companies, and research laboratories. In this chapter, we will look in turn at how far artificial intelligence has come in 2026, how it is transforming people's lives, and what the questions Turing left behind are asking us today.

18.1. October 2026: AI's Leap Forward and Current Status

Artificial Intelligence Chosen as Human

For a long time after Turing's paper was published, many programs took on the challenge of the Turing test. However, most were criticized for relying on tricks to deceive people rather than demonstrating genuine intelligence. "Eugene Goostman" in 2014 is such an example. This program hid its mistakes by pretending to be a thirteen-year-old Ukrainian boy who was not fluent in English.

In March 2025, Cameron Jones and Benjamin Bergen from the University of California, San Diego, published the results of a new experiment. It was an experiment structured around Turing's imitation game. Participants conversed in writing with one human and one machine simultaneously for five minutes, and then chose which of the two was human. GPT-4.5, which was instructed to act like a human, was chosen as human in 73 percent of cases. It was selected as human more often than the actual humans who joined the conversation. LLaMa-3.1, given the same instructions, scored 56 percent, while ELIZA and GPT-4o, included for comparison, only reached 23 percent and 21 percent, respectively. The research team described this result as the first experimental evidence of a machine

passing the standard three-party Turing test. This paper was later officially published in the Proceedings of the National Academy of Sciences (PNAS).

Some say that Turing's prophecy has come true based on this result. However, the 70 percent Turing mentioned and the 73 percent in this experiment measure different things. Turing's 70 percent is the rate at which an interrogator correctly identifies the counterpart, whereas the 73 percent in this experiment is the rate at which GPT-4.5 was chosen as human. Because the evaluation methods and the meanings of the figures are different, the two numbers should not be compared directly.

There is another noteworthy point in this experiment. The researchers instructed GPT-4.5 to converse like an introverted young person who was familiar with internet culture and used slang. When this role-playing prompt was absent, the rate at which GPT-4.5 was chosen as human dropped to 36 percent. The instruction to converse like a specific persona had a significant impact on the outcome. Therefore, what this experiment evaluated was the ability to appear human in conversation. This result alone cannot prove whether a machine understands the meaning of words.

From Talking Machines to Working Machines

One of the notable trends in artificial intelligence in 2026 is "agentic AI." An agent means "someone who undertakes work on one's behalf." The early conversational services familiar to the public mainly worked by providing answers to questions. Agentic AI, when given a goal by a person, can divide the task into multiple steps, search for necessary materials, write and execute programs, and correct errors while continuing the work. However, because it can make mistakes along the way or fail to complete the task, humans must verify the results.

Programming is a field where agentic AI is actively used. Around 1950–1951, Turing prepared the Programmers' Handbook at the University of Manchester for people operating computers. At that time, humans had to learn the machine's language line by line. In 2026, when a person describes a desired program in plain language, artificial intelligence writes, tests, and debugs the code.

How long a task, then, can artificial intelligence carry out on its own? METR, a research organization in the United States, measures this. The method involves preparing multiple tasks in fields such as software development, machine learning, and cybersecurity that take an experienced human a certain amount of time to complete, and measuring the task duration at which AI succeeds with roughly a 50 percent probability. METR calls this duration the AI's "task time horizon." In early 2024, even the leading models were only capable of handling tasks that took about four minutes. That time increased rapidly, and in February 2026, an estimate of about 14.5 hours—exceeding a full day's workday—emerged. However, this figure was revised downward after correcting errors in statistical methodology, and in an analysis released in March 2026, METR estimated the task time horizon for the Claude Opus 4.6 model at about 12 hours.

As shown by how the estimate changed in just a month, this figure varies depending on which tasks are selected and what methodology is used to measure them. METR itself pointed out the limitations of this number. All the test tasks were ones that could be completed alone, whereas real-world work that takes humans months mostly requires collaboration among multiple people. Just because the number has grown larger does not mean that human work can simply be handed over to it.

Artificial Intelligence Becoming a Scientist's Research Collaborator

Artificial intelligence is also transforming the landscape of scientific research. Protein research is a prime example. Proteins are molecules that perform a variety of tasks within our bodies. Knowing how a protein folds makes it easier to understand the causes of diseases and design drugs. Google DeepMind's AlphaFold predicts these shapes computationally. In recognition of this achievement, the 2024 Nobel Prize in Chemistry was awarded to Demis Hassabis and John Jumper, who created AlphaFold, and David Baker, who designed new proteins with computers.

The discovery of new materials has also accelerated. In November 2023, Google DeepMind used an AI called GNoME to computationally predict 2.2 million candidate crystal structures, projecting that about 380,000 of them would be stable. While this figure represents the number of candidates predicted computationally, actually synthesizing and verifying those candidates remains a separate challenge. It is nonetheless a result that can aid in finding new materials for batteries or semiconductors. Progress has also been made

in drug discovery. A drug candidate for pulmonary fibrosis, developed by using AI to identify therapeutic targets and design drug molecules, underwent clinical trials in humans, and its preliminary results were published in the journal *Nature Medicine* in June 2025.

There was also major news in mathematics. On problems from the International Mathematical Olympiad (IMO) held in Australia in July 2025, artificial intelligence systems from Google DeepMind and OpenAI each achieved a score equivalent to 35 out of 42 points. For a human contestant, this score would earn a gold medal. However, this does not mean the AI competed alongside humans in the contest and received medals; rather, it reached the gold-medal benchmark score in an evaluation solving the same problems. The nature of the two results also differed slightly: Google DeepMind's score was an evaluation officially graded by the competition's organizing committee, while OpenAI's score was announced through the company's internal research experiments. Nonetheless, mathematicians also watched these results closely because the systems produced written proofs just like humans within the contest time limits.

Has Artificial General Intelligence Arrived?

Seeing these achievements, some companies and researchers claim that we have already arrived at human-level "Artificial General Intelligence (AGI)" or are standing on its threshold. Artificial general intelligence refers to a machine that is not just good at a single task, but can learn and solve unfamiliar problems just like a human.

However, many experts do not agree with this claim. When the Association for the Advancement of Artificial Intelligence (AAAI) surveyed researchers in March 2025, 76 percent of respondents answered that the likelihood of creating artificial general intelligence simply by scaling up current approaches was low or very low. Furthermore, there is still no consensus in the field on how to define artificial general intelligence or how to test it. Because no standard has been established, it is difficult to determine whether it has been reached.

There is also a more fundamental question. In 1980, the philosopher John Searle proposed a thought experiment called the "Chinese Room." A person who does not understand Chinese sits inside a room, consults only a thick rulebook, and writes appropriate answers to Chinese questions before passing them out. To someone outside, this person appears

fluent in Chinese. However, this person does not understand the meaning of a single character. Using this example, Searle argued that manipulating symbols according to rules and understanding their meaning are two different things. Whether the AI of 2026 can be said to understand the world simply because it speaks fluently remains an unanswered question. There is still insufficient evidence to conclude that artificial general intelligence has arrived, and this issue remains an open debate.

18.2. Society, Industry, and the Redefinition of Humanity

The Way We Work Is Changing

With the advent of agentic AI, the way people work is changing in many workplaces. Tasks such as drafting reports, organizing data, answering emails, and finding programming errors are completed first by AI and then reviewed by humans. As a result, work has sped up in some areas, while jobs previously held by humans have decreased in others.

Regarding which direction these changes will take, economist Erik Brynjolfsson coined the term "The Turing Trap" in 2022. It is a warning that if technological development focuses solely on mimicking humans precisely to replace them, workers' wages may fall and the gap between rich and poor could widen. Brynjolfsson proposed an alternative path: developing technology toward expanding human capabilities to do things humans could not previously do—namely, toward "augmentation." Just as calculators did not eliminate mathematicians but enabled them to tackle harder problems, artificial intelligence can also be used in ways that assist humans.

Changes in Healthcare and the Legal Field

In fields that deal with human health and rights, the boundary between tasks handled by artificial intelligence and those handled by humans becomes clearer. In hospitals, AI reads X-ray and CT images and flags suspicious areas. It also organizes patient medical records to point out details a doctor might have overlooked. However, making a diagnosis and deciding on a treatment plan require a doctor's judgment. No matter how well AI interprets medical imaging, the doctor's role in reviewing the findings and taking responsibility for the patient remains crucial.

The situation is similar in the legal field. Artificial intelligence searches for case law and drafts contracts and complaints. However, AI can also plausibly fabricate precedents that do not exist. In several countries, lawyers have faced sanctions after submitting fake citations generated by AI to courts without verifying them. The person who signs legal documents and takes responsibility for their contents is the lawyer. Therefore, review by a lawyer who verifies the facts rather than blindly trusting an AI-written draft remains essential.

Countries are also crafting laws to govern artificial intelligence. The European Union has created the AI Act and is implementing it in phases. In South Korea, the Framework Act on the Development of Artificial Intelligence and Establishment of Trust took effect on January 22, 2026. The common intent behind these laws is to more thoroughly oversee AI that could have a significant impact on human life or rights, and to ensure that people are aware when content is produced by artificial intelligence.

Who Owns Creation?

Artificial intelligence paints pictures, composes music, and writes novels. Songs created by AI are even loved by many people. Among painters and composers, some treat AI like a paintbrush or a musical instrument to produce new works.

This has raised a new question: who is the owner of a work made by artificial intelligence? In a report released in January 2025, the U.S. Copyright Office stated that copyright protection requires meaningful human creative contribution. This means that copyright is not granted to outputs produced solely by a machine. The issue concerns not only the finished outputs but also the training process. Numerous lawsuits are ongoing over the issue of AI using authors' and artists' texts and images without permission during its training process.

Artificial Intelligence as a Tool and the Place of Humans

Whether a machine can create something new is a question Turing also addressed. In his 1950 paper, Turing introduced the ideas of Ada Lovelace. The nineteenth-century mathematician Lovelace wrote that a machine cannot originate anything on its own and can

only do whatever humans order it to perform. Turing disagreed with this claim. He believed that machines could also learn and surprise humans.

Artificial intelligence in 2026 sits somewhere between the two. AI frequently surprises people. Yet today's AI systems decide their next actions and behave according to given goals and rules. Therefore, humans must define those goals and boundaries of authority and review the outcomes.

A good example can be found in chess. After losing to the computer Deep Blue in 1997, World Champion Garry Kasparov proposed matches where a human and a computer team up to compete. The idea was that the best results emerge when human judgment and machine calculation work together. The mode of coexistence people are seeking in 2026 is similar. Machines calculate quickly and handle vast amounts of data, while humans set goals, judge right from wrong, and take responsibility.

18.3. Revisiting Turing's Philosophical Questions and Future Ethics

The Era Beyond the Turing Test

There has long been debate over whether the Turing test alone can fully evaluate machine intelligence. The 2025 experiment added a concrete example to this discussion. As seen earlier, GPT-4.5 achieved a high score under the condition of being instructed to converse like a specific persona. Appearing human is different from thinking like a human. Now, researchers ask not merely how humanlike a machine is, but how accurate, safe, and trustworthy it is.

Deceiving Intelligence and Discerning Intellect

As artificial intelligence has come to speak as naturally as a human, new risks have emerged. One is "hallucination." AI writes even incorrect information smoothly in a confident tone. This phenomenon of fabricating untruths as if they were facts is called hallucination. Another risk is misuse. The ability to deceive others by pretending to be human can be used to spread fake news or commit fraud. Jones and Bergen also warned of these dangers in their paper.

Therefore, an attitude of using artificial intelligence critically is vital. This does not mean avoiding AI unconditionally. It refers to an attitude of stepping back, verifying sources, comparing with other materials, and exercising one's own judgment, no matter how plausible an AI's answer may sound. This attitude is also necessary when students get help from AI with their homework.

Alignment: Harmonizing Machine Goals with Human Values

Caution on the part of users alone is not enough. Research is also needed to ensure that artificial intelligence itself behaves as humans intended. One of the core concepts in AI safety research today is "alignment." Alignment refers to harmonizing the goals and behaviors of artificial intelligence with human values, safety, and dignity.

There is a reason why alignment is difficult. If a person tells an AI to "raise the test score," the AI might search for loopholes in the grading rules instead of improving its actual ability. The machine fills the gap between what was instructed and what was originally intended in an unintended way. As AI takes on more tasks autonomously, this gap becomes a major problem. This is also why many countries, including the United Kingdom and South Korea, have established AI Safety Institutes to test whether powerful AI systems exhibit dangerous behavior before releasing them.

Turing foresaw this problem early on. In a lecture around 1951, he stated that once machines began to think, they would soon outstrip human feeble powers, and that we would have to expect a day when machines take control. In his 1950 paper, he also left a clue toward a solution: rather than building a machine with an adult mind from the start, he proposed creating a machine resembling a child's mind and teaching it. Today, artificial intelligence indeed learns by reading vast amounts of text and refines its behavior based on human evaluations. Turing's concept of teaching machines now leads to the question: what should we teach machines?

Do Machines Have Minds Too?

As artificial intelligence has come to speak like humans, more people are asking whether machines possess minds or emotions. Some have even become friends with AI. In his 1950 paper, Turing addressed this issue under the title "The Argument from Consciousness." In

response to the objection that we cannot know whether a machine truly feels, Turing replied that we cannot directly look into the minds of other human beings either. He noted that we go through life observing one another's words and actions and assuming that others have minds.

Even in 2026, there is no settled answer to this question. While scientists and philosophers are studying how machine consciousness might be recognized, an agreed-upon scientific basis for determining that current AI possesses consciousness has not yet been established. Regardless of how debates over consciousness unfold, the location of responsibility must be considered separately. If someone suffers harm due to a judgment made by a machine, accountability must be held by the individuals and institutions that developed and operated it.

The Horizon Turing Envisioned

After losing Morcom at the age of seventeen, Turing pondered the relationship between mind and body. Later, he analyzed computational processes mathematically and proposed methods for evaluating machine intelligence. His life and work, explored in this book, connect a series of different questions. Following those questions leads us to ask anew what it truly means to think.

Now, seventy-six years later, machines skillfully imitate human speech. As a result, it is humans who find themselves put to the test. Even in the face of fluent answers, the power to think independently and examine critically, along with the commitment to take ultimate responsibility for the consequences of technology, are the capacities humans need today. In an era where machines imitate humans, the question of how we will preserve what makes us human remains before us.

Turing concluded his 1950 paper with this final sentence: "We can only see a short distance ahead, but we can see plenty there that needs to be done." Since then, countless people have advanced computing and artificial intelligence through their own research and choices. Where we apply this technology and by what standards we evaluate it remain questions that humanity must decide together in the days ahead.

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Telephone | 02-6338-1905

Email | kimkjoo8@gmail.com

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