From Aristotle to Konrad Zuse

A Very Brief Historical Account of the Theoretical and Technological Breakthroughs That Led to the Digital Computer Revolution

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The Theoretical Foundations

Aristotelian Logic

Aristotle is largely accepted as the original inventor of a universal method of reasoning described in his collective works called the Organon. Logic, as it became known later, is the tool by means of which we can know everything based on what we already know. This method of Aristotle was perceived as a rigorous scientific approach and was based on an axiomatic foundation.

The axioms of Aristotelian logic are:

1. Law of identity: A implies A
2. Law of non-contradiction: A is not not-A
3. Law of the excluded middle: either A or not-A
4. Law of Rational Inference from what is known to what is unknown

Aristotle and his logic made a profound impact on western civilization. His methods were studied and developed further by medieval mathematicians. Although classical logicians (scholars of Aristotelian logic) and modern formal logicians (school of logicism) often challenged each other with conflicting notions and alternate systems of axiomatic logics, it is nowadays admitted by many that modern formal logic has its roots in Aristotle’s theories. To this effect, Kant asserted that Aristotle had discovered the complete system of logic and Prantl drew the conclusion that any logician
who thought he had discovered anything new after Aristotle was, amongst other things, confused.¹

The System of Binary Numbers

Wilhelm Gottfried Von Leibniz (1646 – 1716) is considered one of the greatest scientists in the history of mankind. He is the co-inventor of differential and integral calculus, alongside with Newton. His interests and contributions ranged over a very broad spectrum of subjects, including Physics, Philosophy, Law, Politics and Theology, subjects very similar to the variety Aristotle struggled with. Leibniz studied the Greek language, he was taught Aristotelian logic and it is believed his works were greatly influenced by it.²

One of the most important discoveries and contributions of Leibniz was the relation of mathematics and symbolic logic. As early as in 1666, in his thesis Dissertation on the Combinatorial Art, he proposed a system by means of which all principles of reasoning could be reduced to symbolic logic and constitute the mathematics of thought. That would in turn lead to a universal mathematical logic. Then, in 1701, he published his Essay of a new Science of Numbers, where he described a complete binary number system that he had developed as early as in 1679. We can now understand in retrospect his foresight on how such a binary system could be integrated with a universal symbolic logic to develop computational machines.

Leibniz is probably one of the most fascinating and also controversial figures in the history of science. He ignited one of the most interesting debates in the history of science regarding the ontology of space-time, rebutting fiercely the substantival account of the Newtonian concepts of absolute space and time with his relationalism and the notion of a
living force being the metaphysical foundation of physics. The substantivalism-relationism debate still goes on in nowadays and a final verdict has not been reached yet. During his later years, Leibniz attempted to develop several analog computational machines but he stayed short of developing one based on binary numbers. In the words of Laplace, “Leibniz saw in his binary arithmetic the image of creation. He imagined that Unity represented God, and zero the void; that the Supreme Being drew all beings from the void, just as unity and zero express all numbers in his system of numeration.”

Leibniz, in a sense, can be considered the main link between Aristotle’s logic and the discoveries that followed which led to the development of the digital computer.

**Boolean Algebra**

George Boole (1815 – 1864) was a mathematical genius even though he lacked formal education in mathematics. At the age of 24 he published his first paper *Researches on the Theory of Analytical Transformations*, in the Cambridge Mathematical Journal. He then worked on the theories of Gottfried Leibniz and at the age of 32, in 1847, he published his work, *The Mathematical Analysis of Logic*, where he showed the relation of mathematics and logic.

George Boole continued working on a symbolic mathematical language that had three basic operations, AND, NOT, and OR, and two binary objects, TRUE and FALSE. He detailed his method in his paper published in 1854, *An Investigation of the Laws of Thought on Which Are Founded the Mathematical Theories of Logic and Probabilities.*
Undoubtedly, George Boole is the father of the modern digital computer theory of operation. The foundations, as he laid them, are still unchallenged. The technological discoveries to follow were just limited by the ability and speed of reducing to practice the theory he developed.

The Technological Foundations

Alongside the theoretical developments in mathematics, logic and physics, there were many efforts throughout history to develop computational machines of different kinds. Most developments were constraint by the technological limitations of their times. Despite these limitations, some very remarkable computational machines were developed. Counting machines, such as the Abacus developed by the Babylonians in the 4th century BC, the mechanical calculator of the German Wilhelm Schickard in 1623 and the Pascaline by the French Blaise Pascal in 1642, were special purpose devices but still far from general purpose computing machines. Such devices were just calculators and possessed no memory capacity but contributed highly to the advancement of science and to the development of general purpose computing machines. Furthermore, some specific problem-solving analog machines, such as those developed for use in gunships during World War I and II for the purpose of solving ballistics equations may be considered as special purpose programmable analog computers. It is true that specific purpose analog computers contributed highly towards the development of electronic analog computers and to a better understanding of the concept of analog computation.
The Analog Computer: The Predecessor or an Alternative?

The concept of analog computing is either unknown or misunderstood by many modern scientists and computer engineers. In nowadays, little or nothing is mentioned about analog computers in general curriculum science programs, although some universities do basic research on the subject. There is now a perception that computing is synonymous to digital machines based on the binary number system. While this is partially true, there were many attempts in history to develop computers that operated on principles other than Boolean algebra and the binary system of numbers. In fact, specific purpose analog computers were developed and used since the early 19th century for both military and civilian purposes. Due to the lack of a rigorous mathematical foundation for analog computation and the fast progress in digital technology, analog computers were totally displaced by digital. However, analog computers were always a viable alternative to digital, at least as a concept. Some developments of the distant past present us with a striking and even puzzling aspect of our scientific history and evolution.

The Antikythera Computer

In 1901, sponge divers working off the cost of the Greek island of Antikythera discovered parts of a mechanical device in a ship wreck, dated as back as in 65 BC. The device included a very complex assembly of gears, several graduated dials and accompanying mechanisms and casing. This is a discovery that caused many archaeologists and historians of science to wonder whether there are some aspects of ancient Greek civilization, and consequently of
human history, that have remained in the dark or lost in time.

A careful study of the device by a great number of archaeologists and engineers has contributed to the conclusion of it being an analog computer for calculating and predicting the motion of some planets in our solar system with great accuracy.

The three main fragments of the Antikythera computer exhibited at the National Archeological Museum of Athens, Greece

Professor Sir Christopher Zeeman, during one of his lectures at Trinity University, described the theory of operation of the Antikythera analog computer and made several important comments regarding its historical implications and the evolution of computational machines. One of his most interesting statements was that laymen were forced during the dark ages to accept the model of the sun going around the earth in order to reinforce the idea of man being the center of the universe, for almost 1000 years to follow. However, after the discovery and analysis of the Antikythera computer it became clear that there was a very accurate analog model of planetary motions since at least the first century BC.
What happened to the body of knowledge and technology used by ancient Greeks to develop the Antikythera analog computer? This is an important question that has not been answered by historians and archeologists.

The Difference and Analytical Engines

Although never built, the Analytical Engine and the Difference Engine of Charles Babbage (1791 – 1871) were the first known modern attempts to develop analog computational machines. Babbage was an English mathematics professor involved in the checking of calculations made for the Royal Astronomical Society. At some point he realized that human errors could be minimized or eliminated completely, if the calculations could be performed automatically, “like a steam”. In 1822, he proposed the construction of the Difference Engine, a steam powered machine having the ability of storing numbers and executing a program. After 10 years of unsuccessful prototyping and redesigns his government funding dried up and the project was cancelled. Babbage then conceived of a more advanced design, the Analytical Engine, a steam-powered general-purpose computer made of several thousand parts with a input-output device, a memory and a processing unit. The input-output mechanism was similar to that used for controlling patterns to be woven. Babbage was the first to think of punch cards to control the sequence of instruction send to a computer, a concept that remained in use until the late 1970’s.

Babbage was unable to complete the construction of the Analytical Engine due to the technological limitations of his time. His Difference Engine drawings were bought by a Swedish entrepreneur, who later built a modified version.
We can only guess the path computer technology would have taken should Charles Babbage have managed to build the Analytical Engine. It is certain that a large industry around analog computing would have developed much earlier than the industry for digital computers. The same may be true for theoretical computing science. Although some could claim that analog computers would have a fate similar to that of telegraph machines after the telephone was invented, we cannot know the path technology could have taken in this area, since we can only speculate on its growth and the theoretical advancements to follow. In nowadays, most scientist can only think in “digital terms”, which is the prevailing state-of-the-art, and any objective comparisons with alternative but non-developed approaches are severely limited in that sense.

The Differential Analyzer

In 1927, Vannevar Bush (1890 – 1974), a professor at MIT, designed an analog computer that could solve simple mathematical equations. Bush developed his concepts further and in 1930 designed a more complex device called the Differential Analyzer. The devise weight was over 100 tons and included several thousands of vacuum tubes, electromechanical relays, hundreds of motors and other mechanical parts, such as shafts, gears and drive belts. Vannevar Bush described his computer in an article published in the Journal of the Franklin Institute in 1931.8

The Differential Analyzer could solve complex differential equations. A later version built in 1935 incorporated a paper tape reader for improved programmability. Besides his computer developments, Bush was a pioneer in concepts like the “vocoder”, a typewriter that understands speech. During
World War 2, he proposed of a device that would act as the programmable storehouse of knowledge and a project was started named the Rockefeller Differential Analyzer, only to be cancelled in 1950, considered as an outdated concept after digital computers emerged.  

From a historical perspective, Vannevar Bush made Charles Babbage’s dream of the Analytical Engine a reality, after more than a century. As Babbage was ahead of his time, it seems that Bush was a bit late in enforcing an alternative level of thinking regarding computational machines. Boolean algebra was already finding its proper place in digital circuit design and advancements in mathematical logic contributed to the development of the software technology needed for programming the new machines, while converting everything we know in binary numbers. The era of analog thinking was coming to an end fast.

Claude Shannon (1916 – 2001) was a graduate student of Vannevar Bush and developed a mathematical model for the Differential Analyzer called the GPAC (General Purpose Analog Computer). Since then, some efforts have been made in improving that model. It is interesting to know that Shannon is also credited for converting the concepts of Boolean Algebra into actual circuit designs and thus setting the stage for digital computer development with his 1938 paper “A Symbolic Analysis of Relay and Switching Circuits”. Shannon’s main motivation was in reducing the complexity of the Differential Analyzer by utilizing the binary number system and Boolean algebra.

Electronic analog computers

The development of analog computers continued though the 60’s by replacing the bulky electromechanical components
with electronic ones. The Operational Amplifier, known as the OP AMP, became the key component and the computational power of an analog computer was measured in terms of the number of amplifiers it contained. A large industry developing analog computers flourished around the world and applications ranged from aircraft design and space flight simulation and control to simple measuring devices. But with the advent of the digital computer and its widespread acceptance and use, the analog computer lost its appeal. Lately there are some efforts to revive the concept of a GPAC (General Purpose Analog Computer) by showing that some fundamental digital functions can be carried out by analog means.¹¹

Recent theoretical and technological developments in MEMS (MicroElectroMechanical Systems) and nanorobotics may form the technical ground for reviving analog computers and provide a technology for constructing an alternative to digital technology for problem solving that will rival it in both speed and size. Much effort and funding are required for such developments to materialize and take the concepts of Babbage and Bush towards the next stage.
The credit for the development of the first truly digital computer based on the binary number system seems to be a subject of controversy and even lengthy legal battles. The first patent for a digital computer was awarded in the US for the ENIAC of Mauchly and Eckert, but it was declared invalid by a US Federal Judge in late 1973, naming John Vincent Atanasoff as the inventor of the digital computer, called the ABC or the Atanasoff-Berry computer. Both developments took place during the Second World War. At the same time however, both the British and the Germans were making significant progress in developing digital computers. By that time, the concept of using Boolean logic
circuitry to solve mathematical problems had matured, due on the achievements, both theoretical and technological, of a countless number of scientists and engineers.

There is now evidence to support claims that the German Civil Engineer Konrad Zuse was the developer of the first digital computer based on the binary system. However, developments in the British side, and specifically the efforts and contributions of Alan Turing in the Development of the COLOSSUS computer were kept secret due to its employment in breaking German communication codes. Therefore, it is safe for our purposes in this book to note that development of the first programmable digital computer started just before the Second World War and continued through it. Actually, it seems that the needs of war accelerated the efforts in this area.

The list of computer developments to follow does not necessarily coincide with the actual order in which they occurred, nor it’s an indication of a claim of the originality or ownership of the idea of a programmable digital computer. Furthermore, there were several interim developments, such as the Aiken’s Harvard Mark I sequential calculator, which may or may not qualify as a programmable digital computer depending on the perspective taken. There are certainly conflicting views on this subject and all are respected considering its broader scope.

The Atanasoff-Berry Computer

John Atanasoff (1903-1995), a theoretical physicist and lecturer at Iowa State College, was familiar with the work of Vannevar Bush on the Differential Analyzer and was researching ways of reducing its size, speed and efficiency. He and his graduate student Berry decided to use the binary
system for performing computations, although they were initially skeptical of its effectiveness in replacing the familiar decimal number system. The first computer built in 1939 incorporated several innovations such as the use of disk memory and a central processing unit. In 1942, they built a machine capable of solving simultaneous linear algebraic equations, as well as differential equations, which was named the ABC.\textsuperscript{12}

Atanasoff and Berry had to solve a multitude of technical problems relating to the construction of their computer. Undoubtedly, some of their concepts formed the basis for the evolution of modern digital computers. John Atanasoff received the US National Medal of Technology in 1990 in recognition for his contributions.

**The Z family of computers**

The story of Konrad Zuse (1910-1995) is one of the most amazing technology stories of the twentieth century. Zuse, a German Civil Engineer, not only involved in the development of the first digital computer, if not the first, but also pioneered applications in process control, proposed multi-processor architectures and even designed an original high-level programming language. More amazing is the fact that Zuse claimed to have no prior knowledge of Boolean algebra, Babbage’s work and the Differential Analyzer of Vannevar Bush! What is even much more amazing is that he had no official backing for his efforts and started his developments in his family’s house living room, as far back as in 1936.\textsuperscript{13}

Zuse’s motivation was to build a machine to perform repetitive engineering calculations in a mechanical fashion. It is remarkable that Zuse defined computing as “the
formations of new data from input, according to a given set of rules”. This definition of a process for making inferences from premises is exactly what Aristotle proposed as a method for going for what is known to what is unknown using logic as the vehicle. In turn, Zuse proposed the use of what he called “the yes/no principle” as the basis for the operation of his machine, a concept naturally compatible with logic. His conclusion was that computer operations could be represented as a series of yes/no operations, and the most suitable devices to use were telephone system relays.

According to Zuse’s claims, he was not familiar with Boolean algebra but he devised his own method for manipulating the bits of information that closely approximated the principles of propositional calculus of mathematical logic.

If Zuse’s claims are true, and there is no reason to believe otherwise, we can see how he reduced to practice all of Aristotle’s logic and related theories. One question remaining to this end is whether Zuse was aware of the works of the German Gottfried Wilhelm Leibniz, one of the greatest philosophers and mathematicians of all times, if not the greatest. If Zuse was aware of Leibniz’s work on the subject, and that’s highly possible due to the fact that German Polytechnic Schools included a highly theoretical curriculum at that time, then he was probably able to construct the basic principles of Boolean algebra directly from his works. Nevertheless, that’s a minor point as compared to his overall achievement.

By 1938, Zuse had built his Z1 computer, which was an assembly of mechanical plates and pins, worked with binary numbers and could store 16 24-bit numbers. Paper was very
expensive at that time in Germany, so he used 35mm movie film to punch holes on and use it for inputting the data. The output was displayed on a board of light bulbs. However, the all-mechanical nature of its parts made it unreliable in actual operation.

The Z2 was a prototype for the next step, the Z3. In the Z2, the mechanical relays were replaced with electro-magnetic relays but the mechanical memory was retained from Z1. It also operated with 16 bit floating-point arithmetic.

By 1939, Zuse started working on the Z3, but its construction was delayed with the outbreak of war and a call to military service. He made extraordinary efforts and continued to work on it in his spare time and managed to complete it by 1941. The Z3 had a 64-word capacity memory and was also based on electro-magnetic relays and included over 2,400 of them, 1,800 in the memory and the remaining in the calculating and programming sections.

The Z3 was used by the German Aircraft Research Institute for performing the complex mathematical computations needed for the design of airplane wings. It was later destroyed in an air raid but a replica was made 20 years later and is exhibited in a museum in Germany.

Zuse continued with his Z4 model in 1942, an improved version of the Z3 with a 32-bit word length, 1024 word memory capacity, several input devices and increased programmability using the concepts of conditional jumping and address translation. By the end of the war, as the Ally force were closing in Berlin he moved the Z4 to a small village and later transported it to Zurich in 1950 and install it at the Federal Polytechnic School. There it stayed until 1955
and then moved to the French Aerodynamics Research Institute where it stayed operational until 1960.

In 1949, Zuse founded the company ZUSE KG and continued developing and selling computers, having for some time a monopoly in central Europe. He was a pioneer in applying his computers in process control. However, his company was faced with stiffed competition from emerging larger firms and eventually was bought by Siemens AG, Munich.

**The British COLOSSUS**

Built during the Second World War, the British designed and built the COLOSSUS computer for the hard task of breaking the code of secret German communications. It was completed by 1943 and reported to contain in the order of 2,000 vacuum tubes. The detail design of the British computer was kept a secret, all records were destroyed after the war and very little is known about it – even a replication in nowadays seems to be very difficult. Some machines were kept operational until around 1960. Even these days, getting any information on COLOSSUS operational details is extremely difficult. Due to the secrecy surrounding its development, the COLOSSUS had very little influence in on later computer developments and technology.\(^\text{14}\)

One of the major contributors to the design of COLOSSUS was the English mathematician Alan Turing, generally accepted as a scientific genius. Turing was able to develop theories about the operation of computers before any hardware was actually developed. One of the problems he was investigating was whether a set of instructions given to a computer actually solves the problem they are supposed to, something that apparently was taken for granted by other
computer developers of his time. In this respect, Turing was well ahead on the computer software side, a fact that supports the assertion that the COLOSSUS was an advanced programmable machine, even at its early stages.

The ENIAC

A joint project of the American government and the University of Pennsylvania, the ENIAC (Electronic Numerical Integrator and Computer) was also designed and built during the Second World War. It was a general-purpose computer and included tens of thousands of vacuum tubes, resistors and capacitors, while weighing over 30 tons. It required a power of about 160 Kilowatts and had a high downtime due to vacuum tube high failure rate.

The ENIAC was developed by John William Mauchly and J. Presper Eckert Jr., who later, with the help of John Von Neumann, conceived the idea of a stored program memory, in addition to the memory for data. The new design was called the EDVAC (Electronic Discrete Variable Automatic Computer) but it was not completed until 1952. By that time, the first commercially available fully programmable computers, such as the UNIVAC I (Universal Automatic Computer), built by Remington Rand Corporation, appeared in the market.

From Mainframes to Personal Computers

I still recall the time when, as an undergraduate student at the State University of New York at Buffalo, I had to use the punching card machine to write code in FORTRAN programming language and then submit the deck to the mainframe computer operator for processing by the card reader. That was during the late 1970s. By the time I enrolled...
in a graduate program, in the early 80’s, card punching was replaced by CRT terminal input via the use of line editors. What a relief that was in making changes to long computer programs, such as for instance, the dynamic simulation of airplane flight or robotic manipulator motion analysis and control.

Mainframe computing was replaced by distributed computing in mid 80’s. The IBM PC was introduced in 1981 and changed computing forever. The emphasis was placed on developing smaller but faster and affordable machines. The application focus of computers was rapidly shifting from the traditional scientific and engineering computation area to a wide host of applications covering almost every aspect of information processing and communications, such as record keeping, financial transactions, process and quality control, appliance control and security surveillance, to name a few. Networking enabled the sharing of databases and other hardware resources, such as memory and even CPU power. Subsequent developments allowed computers to invade other more traditional domains of everyday life, such as personal communications and entertainment. Networks started connecting to one another using telephone lines and that eventually led to the realization of the World Wide Web, known as the Internet.

The evolution in the development and use of digital technology in the last 30 years has been explosive. But it really took almost 2,500 years for the human race to reach this point. From Aristotle and his logic, to Leibniz and his binary system, to George Boole and his algebra, to the first digital computers of the 40’s, to the mainframes of the 60’s and 70’s, and last, but not least, to the personal computers of the 80’s.
References


