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5.1. The Origin of Modern Computing Architectures

When tracing the ancestry of modern computing architecture, it is tempting to consider that modern computers are part of a linear chain of successive transmutations, with each machine simply an improvement of the one that previously existed. While this view of inherited improvements in computer design may hold true for certain classes of architecture (consider the iterative improvements of the iPhone X from the original iPhone), the root of the architectural tree is much less defined.

From the 1700s until the early 1900s, mathematicians served as the first *human* computers for calculations related to applications of science and engineering[1]. The word "computer" originally referred to "one who computes". Women mathematicians often served in the role of computer. In fact, the use of women as human computers was so pervasive that computational complexity was measured in "kilo-girls", or the amount of work a thousand human computers could complete in one hour[2]. Women were widely considered to be better at doing mathematical calculations than men, as they tended to be more methodical. Women were not allowed to hold the position of engineer. As such, they were relegated to more "menial" work, such as computing complex calculations.

The first general-purpose digital computer, the *Analytical Engine*, was designed by British mathematician Charles Babbage, who is credited by some as the father of the computer. The Analytical Engine was an extension of his original invention, the Difference Engine, a mechanical calculator that was capable of calculating polynomial functions. Ada Lovelace, who perhaps should be known as the mother of computing, was the very first person to develop a computer program and the first to publish an algorithm that could be computed using Charles Babbage's Analytical Engine. In her notes is included her recognition of the general-purpose nature of the Analytical Engine: "[t]he Analytical Engine has no pretensions whatever to originate anything. It can do whatever we know how to order it to perform.[3]" However, unlike modern computers, the Analytical Engine was a mechanical device and was only partially built. Most of the designers of what became the direct forerunners to the modern computer were unaware of the work of Babbage and Lovelace when they developed their own machines.

Thus, it is perhaps more accurate to think about modern computer architecture rising out of a primordial soup of ideas and innovations that arose in the 1930s and 1940s. For example, in 1937, Claude Shannon, a student at MIT, wrote what would go on to be perhaps the most influential masters thesis of all time. Drawing upon the work of George Boole (the mathematician who developed Boolean algebra), Shannon showed that Boolean logic could be applied to circuits and could be used to develop electrical switches. This would lead to the development of the binary computing system, and much of future digital circuit design. While men would design many early electronic computers, women (who were not allowed to be engineers) became programming pioneers, leading the design and development of many early software innovations, such as programming languages, compilers, algorithms, and operating systems.

A comprehensive discussion of the rise of computer architecture is not possible in this book (see *Turing's Cathedral*[4] by George Dyson and *The Innovators*[6] by Walter Isaacson for more detailed coverage); however, we briefly enumerate several significant innovations that occurred in the 1930s and 1940s that were instrumental in the rise of modern computer architecture.

5.1.1. The Turing Machine

In 1937, British mathematician Alan Turing proposed[7] the "Logical Computing Machine", a theoretical computer. Turing used this machine to prove that there exists no solution to the decision problem (in German, the *Entscheidungsproblem*), posed by the mathematicians David Hilbert and Wilhelm Ackermann in 1928. The decision problem is an algorithm that takes a statement as input and determines whether the statement is universally valid. Turing proved that no such algorithm exists by showing that the *halting problem* (will machine *X* halt on input *y*?) was undecidable for Turing's machine. As part of this proof, Turing described a universal machine that is capable of performing the tasks of any other computing machine. Alonzo Church, Turing's dissertation advisor at Princeton University, was the first to refer to the *logical computing machine* as the *Turing machine*, and its universal form as the *universal Turing machine*.

Turing later returned to England and served his country as part of the code breaking unit in Bletchley Park during World War II. He was instrumental in the design and construction of the *Bombe*, an electromechanical device that helped break the cipher produced by the Enigma machine, which was commonly used by Nazi Germany to protect sensitive communication during World War II.

After the war, Turing designed the *automatic computing engine* (ACE). The ACE was a stored-program computer, meaning that both the program instructions and its data are loaded into the computer memory and run by the general-purpose computer. His paper, published in 1946, is perhaps the most detailed description of such a computer[8].

5.1.2. Early Electronic Computers

World War II accelerated much of the development of early computers. However, due to the classified nature of military operations in World War II, many of the details of innovations that occurred as a result of the frenetic activity during the war was not publicly acknowledged until years later. A good example of this is Colossus, a machine designed by British engineer Tommy Flowers to help break the Lorenz cipher, which was used by Nazi Germany to encode high-level intelligence communication. Some of Alan Turing's work aided in its design. Built in 1943, Colossus is arguably the first programmable, digital, and fully electronic computer. However, it was a special-purpose computer, designed specifically for code breaking. The Women's Royal Naval Service (WRNS, known as the "Wrens") served as operators of Colossus. In spite of the *General Report of the Tunny*[14] noting that several of the Wrens showed ability in cryptographic work, none of them were given the position of cryptographer, and instead were delegated more menial Colossus operation tasks[5,15].

On the other side of the Atlantic, American scientists and engineers were hard at work creating computers of their own. Harvard professor Howard Aiken (who was also a Naval Commander in the U.S. Navy Reserves) designed the Mark I, an electromechanical, general-purpose programmable computer. Built in 1944, it aided in the design of the atomic bomb. Aiken built his computer largely unaware of Turing's work and was motivated by the goal of bringing Charles Babbage's analytical engine to life[6]. A key feature of the Mark I was that it was fully automatic and able to run for days without human intervention[6]. This would be a foundational feature in future computer design.

Meanwhile, American engineers John Mauchly and Presper Eckert of the University of Pennsylvania designed and built the *Electronic Numerical Integrator and Computer* (ENIAC) in 1945. ENIAC is arguably the forerunner of modern computers. It was digital (though it used decimal rather than binary), fully electronic, programmable, and general purpose. While the original version of ENIAC did not have stored-program capabilities, this feature was built into it before the end of the decade. ENIAC was financed and built for the U.S. Army's Ballistic Research Laboratory and was designed primarily to calculate ballistic trajectories. Later, it would be used to aid in the design of the hydrogen bomb.

As men were drafted into the armed forces during World War II, women were hired to help in the war effort as human computers. With the arrival of the first electronic computers, women became the first programmers, as programming was considered secretarial work. It should come as no surprise that many of the early innovations in programming, such as the first compiler, the notion of modularizing programs, debugging, and assembly language, are credited to women inventors. Grace Hopper, for example, developed the first high-level and machine-independent programming language (COBOL) and its compiler. Hopper was also a programmer for the Mark I and wrote the book that described its operation.

The ENIAC programmers were six women: Jean Jennings Bartik, Betty Snyder Holberton, Kay McNulty Mauchly, Frances Bilas Spence, Marlyn Wescoff Meltzer, and Ruth Lichterman Teitelbaum. Unlike the Wrens, the ENIAC women were given a great deal of autonomy in their task; given just the wiring diagrams of ENIAC, they were told to figure out how it worked and how to program it. In addition to their innovation in solving how to program (and debug) one of the world's first electronic general-purpose computers, the ENIAC programmers also developed the idea of algorithmic flow charts, and developed important programming concepts such as subroutines and nesting. Like Grace Hopper, Jean Jennings Bartik and Betty Snyder Holberton would go on to have long careers in computing, and are some of the early computing pioneers. Unfortunately, the full extent of women's contributions in early computing is not known. Unable to advance, many women left the field after World War II. To learn more about early women programmers, we encourage readers to check out *Recoding Gender* [11] by Janet Abbate, *Top Secret Rosies*, a PBS documentary[12] directed by LeAnn Erickson, and *"The Computers"* by Kathy Kleiman[13].

The British and the Americans were not the only ones interested in the potential of computers. In Germany, Konrad Zuse developed the first electromechanical general-purpose digital programmable computer, the Z3, which was completed in 1941. Zuse came up with his design independently of the work of Turing and others. Notably, Zuse's design used binary (rather than decimal), the first computer of its kind to use the binary system. However, the Z3 was destroyed during aerial bombing of Berlin, and Zuse was unable to continue his work until 1950. His work largely went unrecognized until years later. He is widely considered the father of computing in Germany.

5.1.3. So What Did von Neumann Know?

From our discussion of the origin of modern computer architecture, it is apparent that in the 1930s and 1940s there were several innovations that led to the rise of the computer as we know it today. In 1945, John von Neumann published a paper, "First draft of a report on the EDVAC"[9], which describes an architecture on which modern computers are based. EDVAC was the successor of ENIAC. It differed from ENIAC in that it was a binary computer instead of decimal, and it was a stored-program computer. Today, this description of EDVAC's architectural design is known as the *von Neumann architecture*.

The **von Neumann architecture** describes a general-purpose computer, one that is designed to run any program. It also uses a stored-program model, meaning that program instructions and data are both loaded onto the computer to run. In the von Neumann model there is no distinction between instructions and data; both are loaded into the computer's internal memory, and program instructions are fetched from memory and executed by the computer's functional units that execute program instructions on program data.

John von Neumann's contributions weave in and out of several of the previous stories in computing. A Hungarian mathematician, he was a professor at both the Institute of Advanced Study and Princeton University, and he served as an early mentor to Alan Turing. Later, von Neumann became a research scientist on the Manhattan Project, which led him to Howard Aiken and the Mark I; he would later serve as a consultant on the ENIAC project, and correspond regularly with Eckert and Mauchly. His famous paper describing EDVAC came from his work on the Electronic Discrete Variable Automatic Computer (EDVAC), proposed to the U.S. Army by Eckert and Mauchly, and built at the University of Pennsylvania. EDVAC included several architectural design innovations that form the foundation of almost all modern computers: it was general purpose, used the binary numeric system, had internal memory, and was fully electric. In large part because von Neumann was the sole author of the paper[9], the architectural design the paper describes is primarily credited to von Neumann and has become known as the von Neumann architecture. It should be noted that Turing described in great detail the design of a similar machine in 1946. However, since von Neumann's paper was published before Turing's, von Neumann received the chief credit for these innovations.

Regardless of who "really" invented the von Neumann architecture, von Neumann's own contributions should not be diminished. He was a brilliant mathematician and scientist. His contributions to mathematics range from set theory to quantum mechanics and game theory. In computing, he is also regarded as the inventor of the *merge sort* algorithm. Walter Isaacson, in his book *The Innovators*, argued that one of von Neumann's greatest strengths lay in his ability to collaborate widely and to intuitively see the importance of novel concepts[6]. A lot of the early designers of the computer worked in isolation from one another. Isaacson argues that by witnessing the slowness of the Mark I computer, von Neumann was able to intuitively realize the value of a truly electronic computer, and the need to store and modify programs in memory. It could therefore be argued that von Neumann, even more than Eckert and Mauchly, grasped and fully appreciated the power of a fully electronic stored-program computer[6].

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