Some Computer Prehistory and Early History

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ABSTRACT

This talk will superficially breeze through a few thousand years of computing and calculating history, discuss some ideas and technologies that played key roles in early computing, and describe some features of a few early computing devices. Special emphasis will be given to the ENIAC and some issues in decimal arithmetic.

The latest version of this handout can be found at http://www.sonoma.edu/users/l/luvisi/somehist/

1. Decimal (base ten) Subtraction via Complements

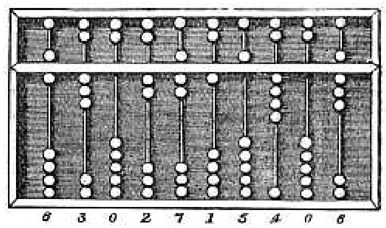
Most of the devices discussed in this talk work in base ten. When a device only tracks a finite number of digits (as any real device must), a phenomenon known as rollover occurs at the top of the device's range. For example, if a device can only work with two decimal digits, then when 01 is added to 99, the result is 00. When 2 is added to 99, the result is 01.

With only two digits, it turns out that adding 99 is equivalent to subtracting one, adding 98 is equivalent to subtracting 2, and so on. For example, 54 + 98 = (1)52. I place the "1" in parenthesis to indicate that it is forgotten by a two digit device. In general, adding 100-n is equivalent to subtracting n. In this case, 100-n is known as the ten's complement of n, meaning that number which, when added to n, produces a power of ten (100 in the two digit case)[28].

But how do we produce 100-n on a device that can't subtract? It turns out that 100-n is just one higher than 99-n, and 99-n is extremely easy to calculate. Each digit of n is simply subtracted from nine. Depending on how the device in question works and represents numbers, this can be done through using a lookup table, counting methods, creative routing of wires, or logical operations on binary representations. 99-n is known as the nines' complement of n (note the apostrophe is after the "s"), meaning that number which, when added to n, produces a series of nines.

2. Some Incomplete Ancient History

2.1. The Abacus



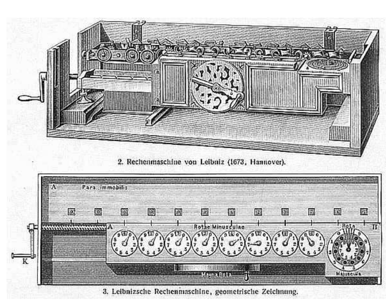
The Abacus[13] is a decimal device, operating in base ten. Each column of beads represents a single decimal digit. The two beads at the top of a column each represent a count of five, while the five beads at the bottom each represent one.

The Abacus tracks intermediate results, and makes it easy for the operator to modify the values represented. During a calculation, working out the new value to place in each position, and tracking carries and borrows, is performed by the operator.

2.2. The Pascaline

Blaise Pascal’s Pascaline[40] could add numbers mechanically, including tracking carries between digits. Numbers were added by inserting a stylus into a hole in a wheel, and rotating the wheel.

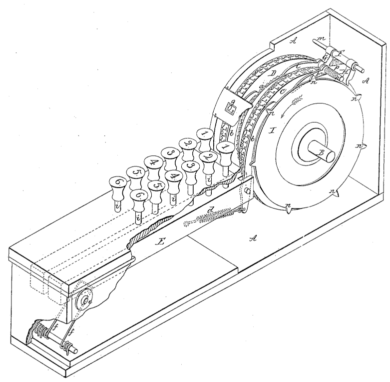
2.3. The Leibniz Calculator



The Leibniz Calculator[41] could perform repeated addition, and addition at an adjustable digit offset, corresponding to multiplication by a power of ten. General multiplication could be achieved by repeating the addition of the multiplicand an appropriate number of times at each offset, as prescribed by the multiplier.

During addition, all digits were transmitted simultaneously with each digit being sent through its own gear, the value of each digit being encoded by the amount of rotation that occurred.

2.4. Adding Machines



Key punch operated adding machines[23] allowed numbers to be added into a running total merely by pressing the appropriate keys. Mathematical functions could be looked up in a book of function tables, or computed using appropriate algorithms[1].

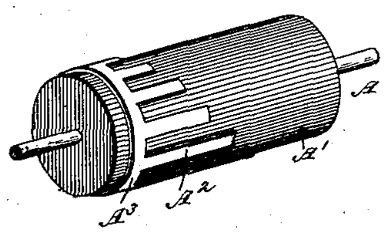
Buttons from multiple columns could be pushed simultaneously to quickly add a multi-digit number in to a running total. By lining up ones fingers and pushing multiple times, a number could be added in multiple times. By repeating this process while shifting ones fingers to the left, multiplication by arbitrary values could be achieved.

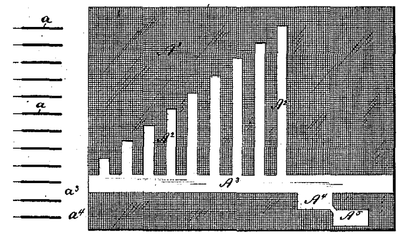
During an addition that used multiple buttons simultaneously, all digits were transmitted simultaneously with each digit being sent through its own gear, the value of each digit being encoded by the amount of rotation that occurred.

2.5. Hollerith and Punched Cards

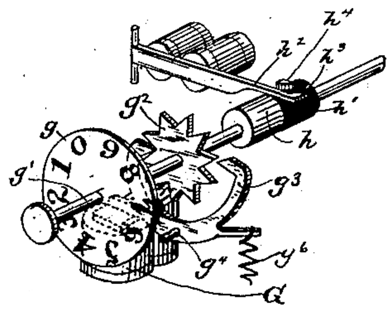
In order to process the 1890 census data more efficiently, Hollerith invented a tabulator for punched cards[25]. It sensed all of the digits in a number simultaneously. By activating the appropriate brush that passed over a turning cylinder with strips of varying length, the appropriate number of pulses was generated for each digit.

All digits were transmitted simultaneously with each digit being sent through its own wire, the value of each digit being encoded by the number of pulses that occurred.

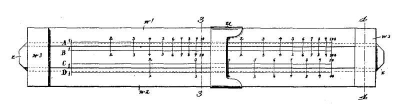




Each pulse turned a counting wheel one position. Carries were tracked by moving a bar on top of part of the counting wheel, and added in at the end of an addition.



2.6. Slide Rules and Books of Tables



While analog devices are not my focus, the slide rule[11, 7, 8] was so widely used that it deserves mention. Most slide rules can multiply and divide with around three digits of accuracy, and more advanced models can calculate logarithms, exponents, squares, cubes, square roots, cube roots, and some trigonometric and inverse trigonometric functions.

For problems requiring more precision, books tabulating the values of commonly used functions were available, often produced manually by teams of people using adding machines.

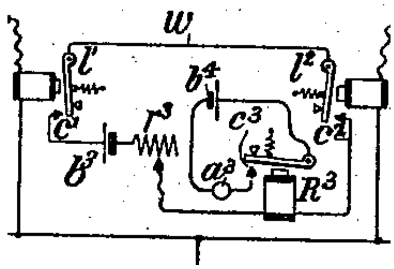
2.7. The Difference Engine and the Analytical Engine

In the early nineteenth century, Charles Babbage designed two mechanical devices capable of calculation. Though not completed during his life-time, the Difference Engine[9] would have been capable of calculating tables of polynomial functions and the Analytical Engine[10] would have been a general purpose computer programmed with punched cards.

2.8. Logic Gates and Flip-Flops

The Relay, invented in the 1830's[24, 36], and its later use by Tesla in logic gates[42] paved the way for the electromechanical calculators that would follow.

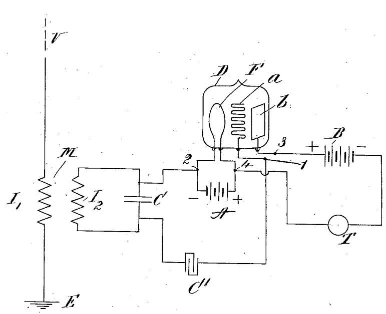
Logic gate for Tesla's remote controlled boat



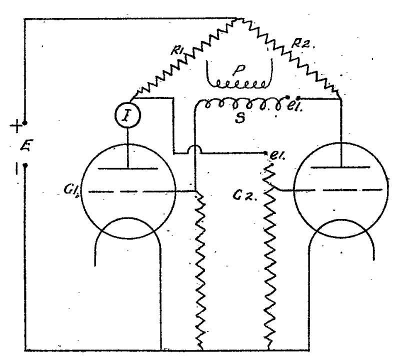
Edison discovered that electrical current could flow from a plate to a heated filament in a vacuum[18], Fleming realized that the one-way nature of this flow could be used to turn alternating current into pulsating direct current[19], and De Forest had the idea of adding a control grid between the filament and the plate[20]. Changes in the voltage between the control grid and the filament change the amount of current that can flow between the plate and the filament. This energized the entire field of electronics and opened the door for many new and improved electronic devices, including amplifiers, oscillators, radio, and RADAR.

It also paved the way for Eccles and Jordan to invent the Flip-Flop[14, 15]. A Flip-Flop stores information in the state of a vacuum tube circuit, and can change states much faster than a relay can open or close. Because Flip-Flops only have two stable states, they are inherently digital circuits.

De Forest Audion Tube



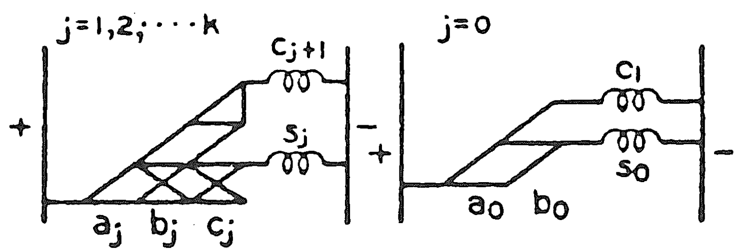
Eccles-Jordan Flip-Flop



2.9. Boolean Logic with Relays, and Abstract Machines

In 1938 Claude Shannon applied Boolean Logic[4] to networks of relays, including the development of a binary full adder[37].

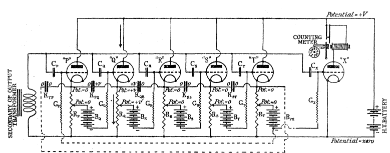
Shannon Adder



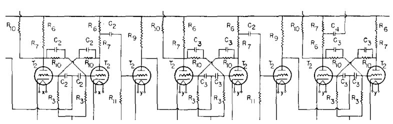
In 1939, Turing published his paper on the Halting Problem[43], which described abstract computing machines now referred to as "Turing Machines."

2.10. Digital Logic at Electronic Speeds

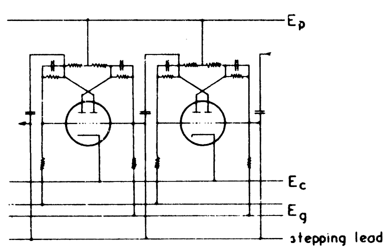
During the 1930s and early 1940s electronic counters using vacuum tubes and thyratrons (gas tubes) were developed for counting cosmic rays and pulses from radiation detectors. These included Thyratron Ring Counters[47],



thyratron binary ripple counters[48, 49], vacuum tube binary ripple counters[38, 32, 33, 34, 35],



and vacuum tube ring counters[12],



among others[31].

When used in these ways, one of the flip-flop’s two states is considered to be "on" and the other to be "off." In a binary counter, the flip-flops turn on and off in the familiar binary counting sequence. In a ring counter, only one flip-flop in the ring is on at any given time, and each incoming pulse causes the current flip-flop to turn off and the next one to turn on.

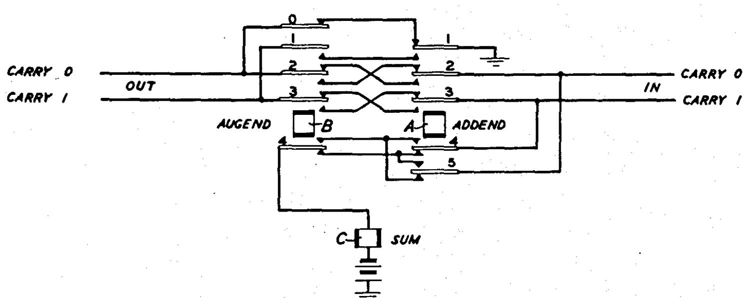
By storing and processing information using only electronic circuits with no mechanical components, these counters were able to operate much faster than mechanical wheels or electro-mechanical relays.

3. Electro-Mechanical Calculating Devices

3.1. Bell Labs

In the late 1930s and early 1940s, a Bell Labs engineer named George Stibitz developed relay based binary adders and a series of relay based calculators[5, 39, 2, 27]. His adder had the interesting property that the time required to add two numbers of one bit in length was the same as the time required to add two numbers of any length. To understand the diagram, you must understand that a binary "1" is represented by a connection to ground, and a binary "0" is represented by no connection. Carries are transmitted between adders on two lines, one that is connected to ground if there is a carry, and one that is connected to ground if there is no carry.

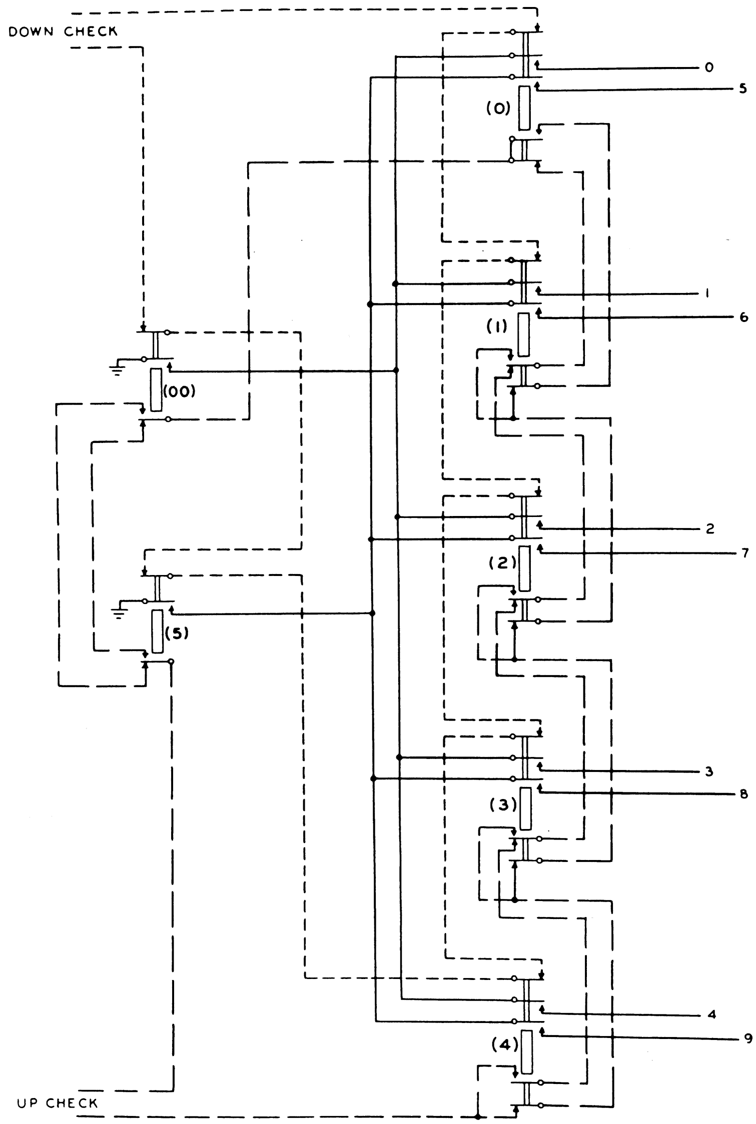
Stibitz Adder



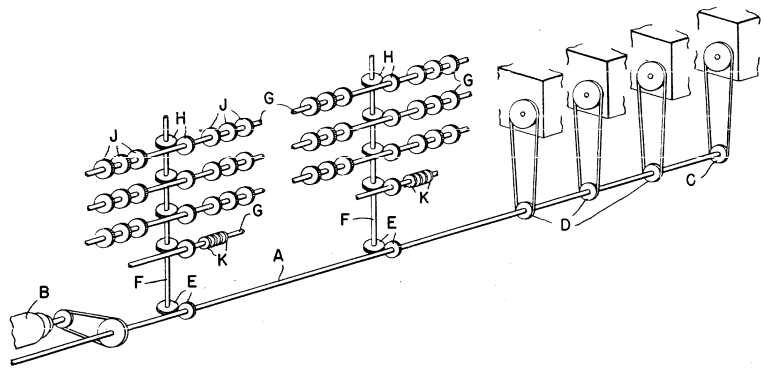
The first Bell Labs machine, called the "Complex Computer" used an excess-3 number system, where each decimal digit was represented by four binary digits, but the binary number used was three greater than the decimal digit being represented. For example, the decimal digit "0" was represented by the binary number "0011 (3)," "1" by "0100 (4)," and so on up to "9" being represented by "1100 (12)." This had the advantages that addition generated a carry exactly when the addition of the corresponding decimal digits would have generated a carry, and taking the ones' complement of a number (inverting each bit) would generate the nines' complement of the number (replacing each digit d with 9-d).

Later models took instructions from paper tape and used the biquinary system, where two wires were used to signal the values 0 or 5, and five other wires were used to signal the values 0, 1, 2, 3, or 4. This provided error checking, because one and only one of the "0 or 5" wires should be grounded, and one and only one of the "0-4" wires should be grounded.

Biquinary Number Representation[2]



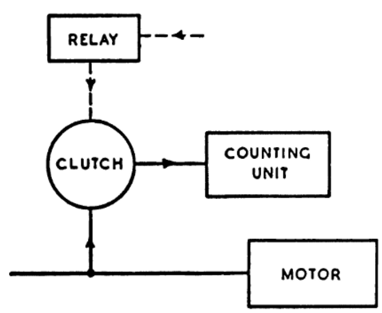
3.2. The Harvard Mark I



The Harvard Mark I[17, 21, 2, 45, 26, 3, 29] was a relay computer that took instructions from a paper tape and used the position of wheels to store numbers. During transfers or additions, pulses operated clutches that momentarily linked the wheels to continuously turning drive shafts. When advancing from nine to zero, a cam operated a relay that tracked the presence of an outstanding carry.

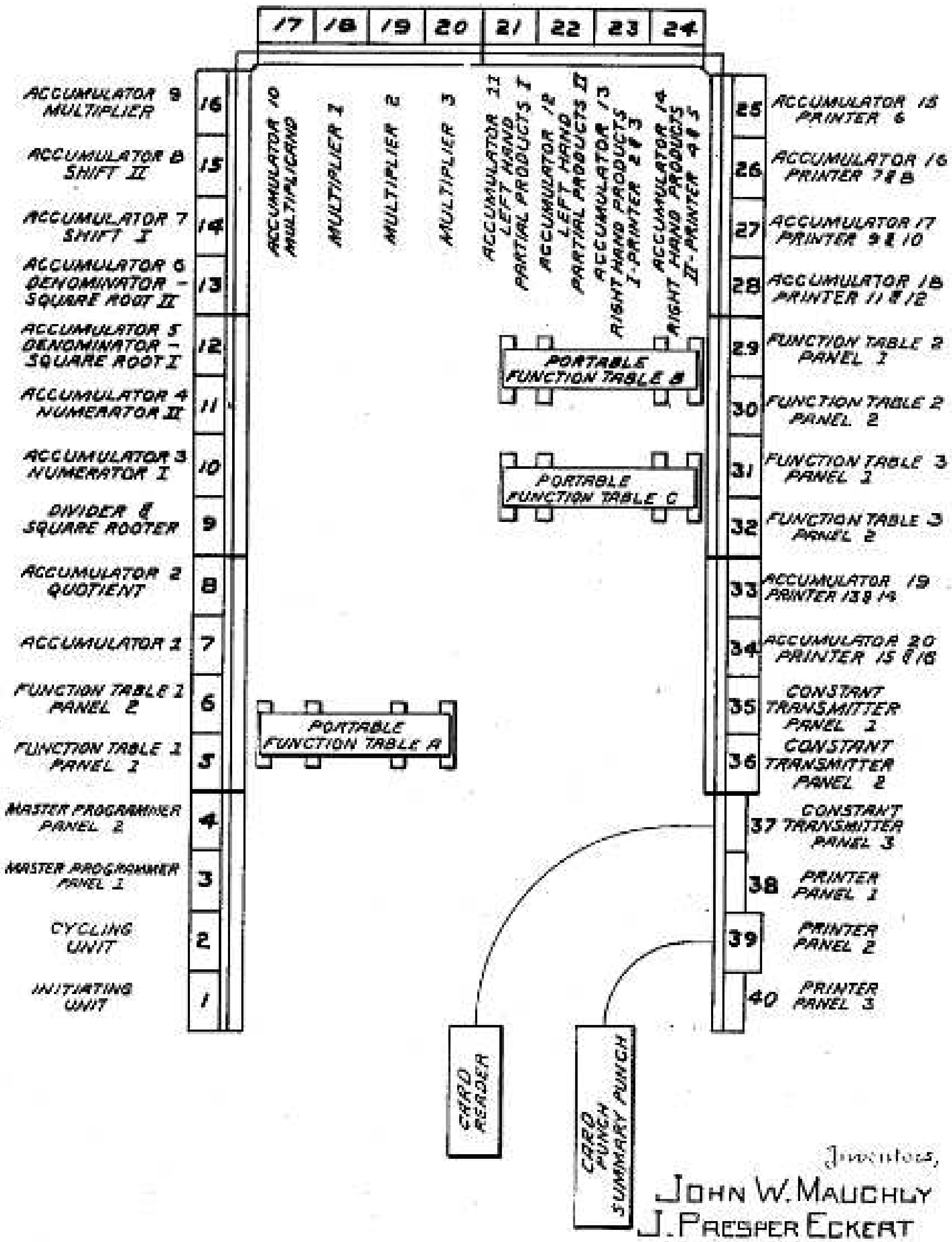
During addition, all digits were transmitted simultaneously with each digit being sent through as a series of pulses, the value of each digit being encoded by the number of pulses.

Mark I counting circuit for a single decimal digit[21]



4. The ENIAC

ENIAC Top View

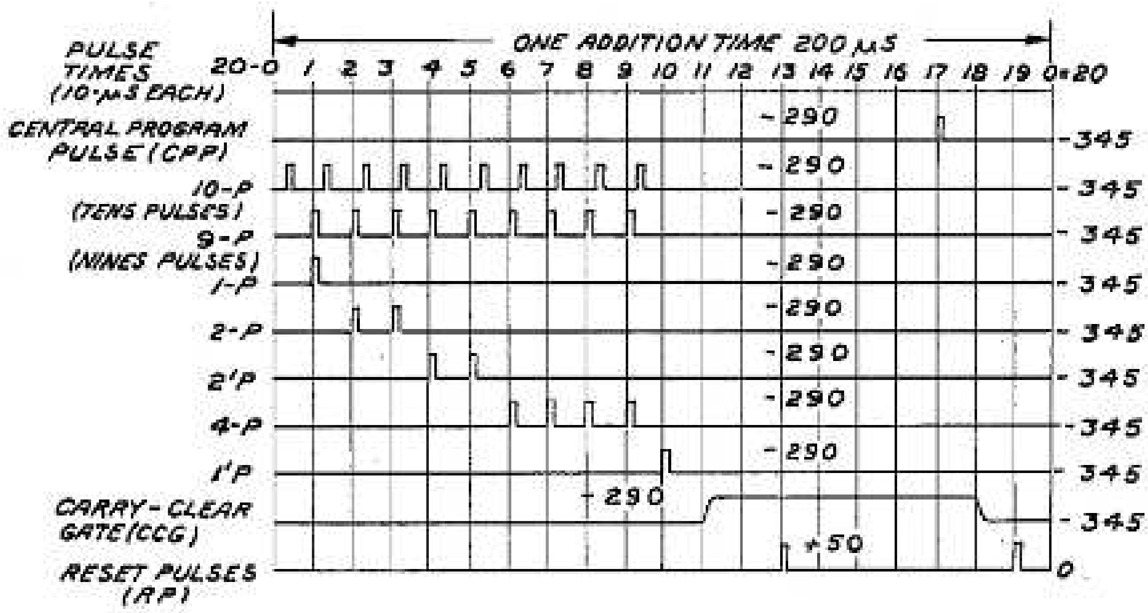


The ENIAC[17, 22, 21, 2, 45, 26, 3, 16, 6, 46, 44] was built for speed. It used about 18,000 vacuum tubes, cost over $500,000 1946 dollars to build, consumed 174KW, occupied 1800 square feed, and weighed more than

60,000 pounds.

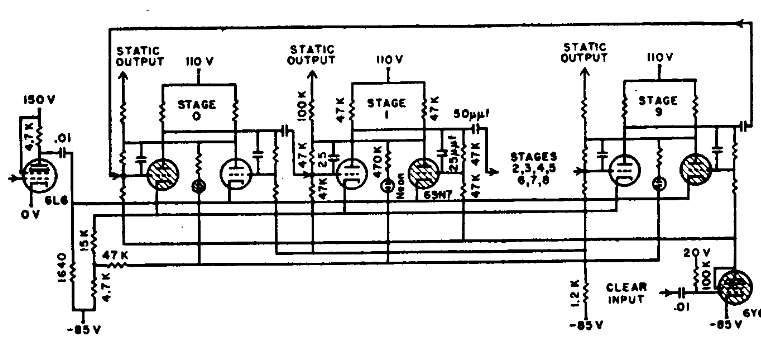
The ENIAC could perform 5,000 additions per second. Each addition time was divided into 20 smaller time periods, during which different timing signals were sent throughout the machine by the central cycling unit.

ENIAC Timing Diagram



The ENIAC used vacuum tube ring counters with ten flip-flops to represent each digit in a number.

ENIAC ring counter for a single decimal digit

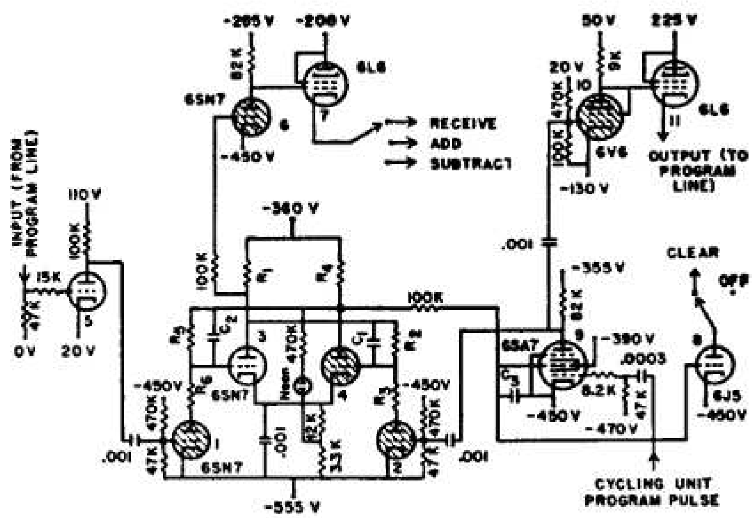


Accumulators each held ten digits and a sign. Addition was performed by having one accumulator transmit the value it held into another accumulator. The receiving accumulator would add the value received to the value it already contained.

During addition, all digits were transmitted simultaneously with each digit being sent through as a series of pulses, the value of each digit being encoded by the number of pulses. Carries were tracked with separate flip-flops and propagated all at once at the end of the addition.

The ENIAC was programmed by manually connecting control circuits on the accumulators and other units to each other via cables and control busses that ran by all of the units of the machine. The connections between the various control circuits resembled a flow chart, with different control circuits performing different actions when activated by receiving a control pulse, and sending a control pulse to other control circuits when finished with their assignment.

ENIAC Accumulator Control Circuit



Data and control pulses used the same voltages so that data pulses could be routed to control circuits, allowing the behavior of the machine to be conditional on the value of a number. Loops could be programmed by simply connecting a set of control circuits up in a loop. Advanced conditionals and loops, including nested loops, were programmed using the Master Programmer, a unit of the machine that had counters and steppers specifically designed for controlling loops.

5. Decimal Multiplication

5.1. Bell Labs Machines

The Complex Computer performed multiplication via shifting and repeated addition[39]. Later Bell Labs machines would perform repeated subtractions when the multiplier digit was over five, adjusting the number of additions or subtractions to perform for the next digit appropriately[2].

5.2. Mark I

The Mark I began a multiplication by creating a table of the first nine multiples of the multiplicand. It then processed two digits of the multiplier at a time, looking up the partial products for each one, and adding them into two partial product accumulators at the same time. At the end, the two partial product accumulators were added together.

5.3. ENIAC

The ENIAC was able to multiply one digit of the multiplier by the entire multiplicand at once through the use of lookup tables and two accumulators[6, 30].

Using pencil and paper to multiply a number by a single digit, one might work it out like this.

```
      456
x       9
     ----
       54
      45
+    36
     ----
     4104
```

At first, it looks like we need to perform an addition for all but one of the digits in the multiplicand. However, by noticing that each multiplication of two digits results in a number that is, at most, two digits long, we can collect the left hand digits into one number and the right hand digits into another number, thereby performing only one addition.

```
      456
x       9
     ----
     345
+     654
     ----
     4104
```

The ENIAC went further, by keeping the left and right parts separate until the very end of the calculation. During the processing of each digit of the multiplier, the left hand parts were all looked up at once and added into a left hand part accumulator, and the right hand parts were all looked up at once and added into a right hand part accumulator. At the very end of the calculation, the left hand accumulator and the right hand accumulator were added together to produce the final product.

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