Jacques Jiao
Siwen Wang
AP Computer Science Principles
June 21, 2024

Micro-Scale Logic Gates in Computers

Problem Statement

AND, OR, and NOT are three basic Boolean operations. With these three operations, computers can perform numerical operations in the form of binary. However, how computers perform these actions on the micro-scale is rarely a concern for ordinary people. By making an adder using BJT transistors and researching the evolution of components computers use for logic gates, I aim to understand better how computers work. In the paper, I will first write about the change of micro components of computers from mechanical switches to vacuum tubes to transistors to integrated circuits. Then, using the adder I built, I would elaborate on how computers work on the micro-scale.

Background

Mechanical computing devices have been around for a long time, with digital devices such as abaci and analog devices like slide rulers.

A significant problem can be found in analog computing devices—noises. Noise can affect the correctness of the answer obtained with the device—you won't be able to obtain the same result two times. Thus, although having simpler and more intuitive structures, analog devices are used less for their inaccuracy.

Thus, through the years, digital computing devices have been preferred for their versatility and accuracy in many cases over analog computing devices, but they were decimal-based, just like human mathematics. However, this means the computers would have extremely delicate mechanical structures, resulting in high cost and low speed.

In 1854, English mathematician George Boole FRS published *The Laws of Thought*. In which it includes the thought of Boolean algebra. In short, it includes ideas on how to perform numerical operations on 1s and 0s. The three most basic operations are AND, OR, and NOT.[3]

x	*y*	*x* **AND** *y*	*x* **OR** *y*
0	**0**	0	0
0	**1**	0	1
1	**0**	0	1
1	**1**	1	1

Table showing results of AND and OR operations for possible inputs.

x	**NOT** *x*
0	1
1	0

Table showing results of NOT operations for possible inputs.

[2]

History of Switching Gate Components

Electromagnetic Relays

During his time at the Massachusetts Institute of Technology in 1936, Claude Elwood Shannon connected the principles of Boolean algebra to the switching behavior of electrical components. This connection was further explored in Shannon's 1937 master's thesis, *A Symbolic Analysis of Relay and Switching Circuits*, in which he demonstrated that telegraphic relays could perform all possible Boolean algebra operations. Shannon's groundbreaking theory led to the construction of the Harvard Mark I, one of the earliest general-function electromagnetic computers, which played a crucial role in the Manhattan Project by simulating atomic bomb explosions.

Triodes

The use of electromagnetic relays, while common, is hindered by their lack of durability due to the presence of moving metal parts that are prone to wear and tear. This often leads to frequent breakdowns and the need for costly replacements, in addition to slow switching speeds.

In 1906, Lee De Forest introduced the vacuum tube triode, comprised of a cathode, grid, and plate, which became essential for amplifying analog electrical signals. Initially designed for amplifying radio and telephone signals, triodes not only made transcontinental telephone calls possible but also proved to be a superior alternative to relays due to their faster switching speed and lack of moving parts. Notably, ENIAC, the first programmable, electronic, general-purpose digital computer, completed in 1945, utilized triodes as its main processing components.

Bipolar Junction Transistors

The use of triodes comes with certain limitations. Operating vacuum tubes requires high voltages and a significant amount of energy. Additionally, they are large, costly, and not very durable. To address these issues, the bipolar junction transistor (BJT) was developed in 1947. It performs the same functions as triodes but can operate at lower voltages and is less prone to breakdown. Notably, the University of Manchester's experimental Transistor Computer became operational in November 1953, making it widely considered to be the first transistor computer to come into operation worldwide.

Integrated Circuit and Microprocessors and Field-Effect Transistors

As the demand for computational power continues to grow, more logic gates are necessary. This led to the development of the next generation of computers, which utilize integrated circuit (IC) chips and later microprocessors as the foundation of their logic. Field-effect transistors (FET), although operating in different ways as BJT, have the same function of switching. In essence, ICs consist of numerous transistors integrated into a single small chip, while microprocessors are ICs with an additional component that enables the computer to operate at a faster pace. For instance, the Apple M1 Ultra, one of the most advanced microprocessors available on the market now, includes 114 billion transistors integrated into an 864 square millimeter chip. Despite their high complexity, their fundamental logic gates function in the same manner as bipolar junction transistors. [1]

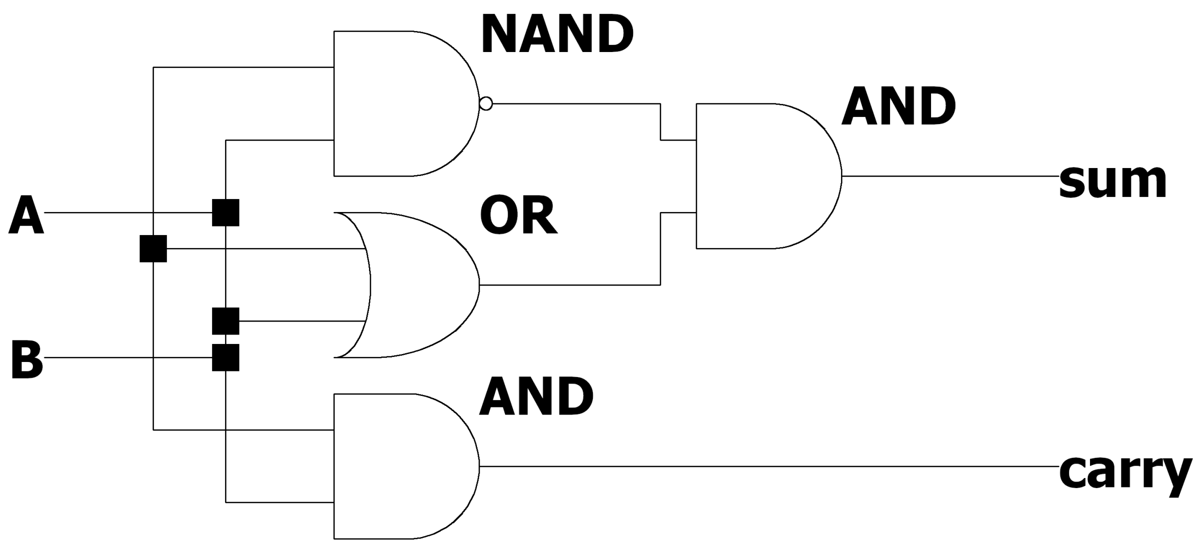
Constitution of BJT Logic Gates

The fundamental unit within a computer's processor is known as an adder. True to its name, its primary function is the addition of two numbers. The simplest iteration of an adder is the half-adder, designed to compute the sum of two individual binary digits.

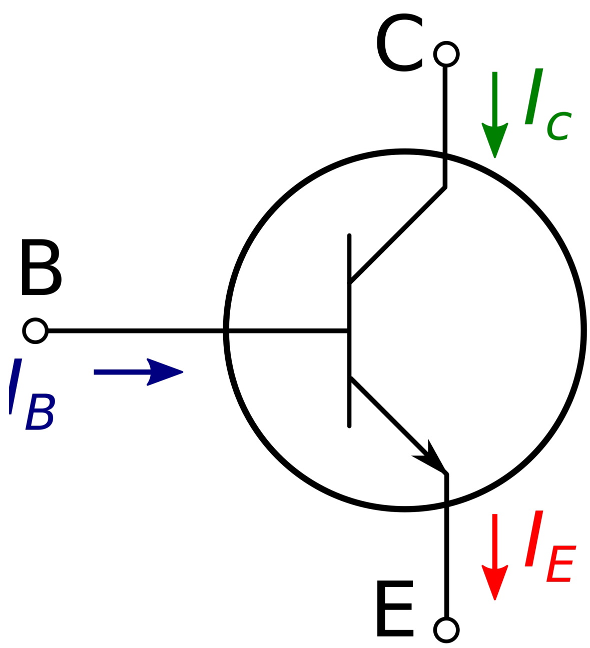
A	B	Carry	Sum
0	0	0	0
1	0	0	1
0	1	0	1

A	B	Carry	Sum
1	1	1	0

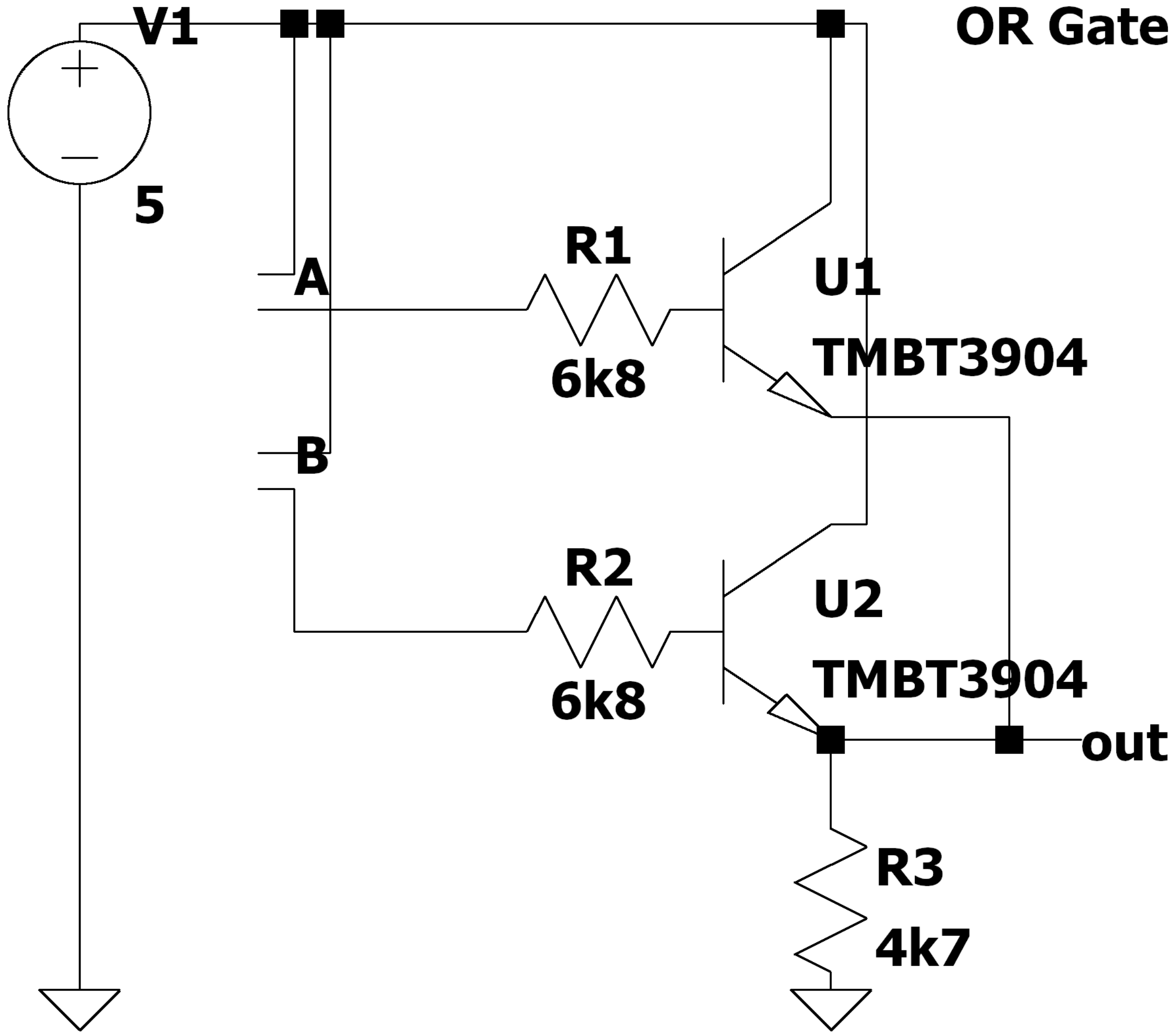
Possible results of the half-adder.

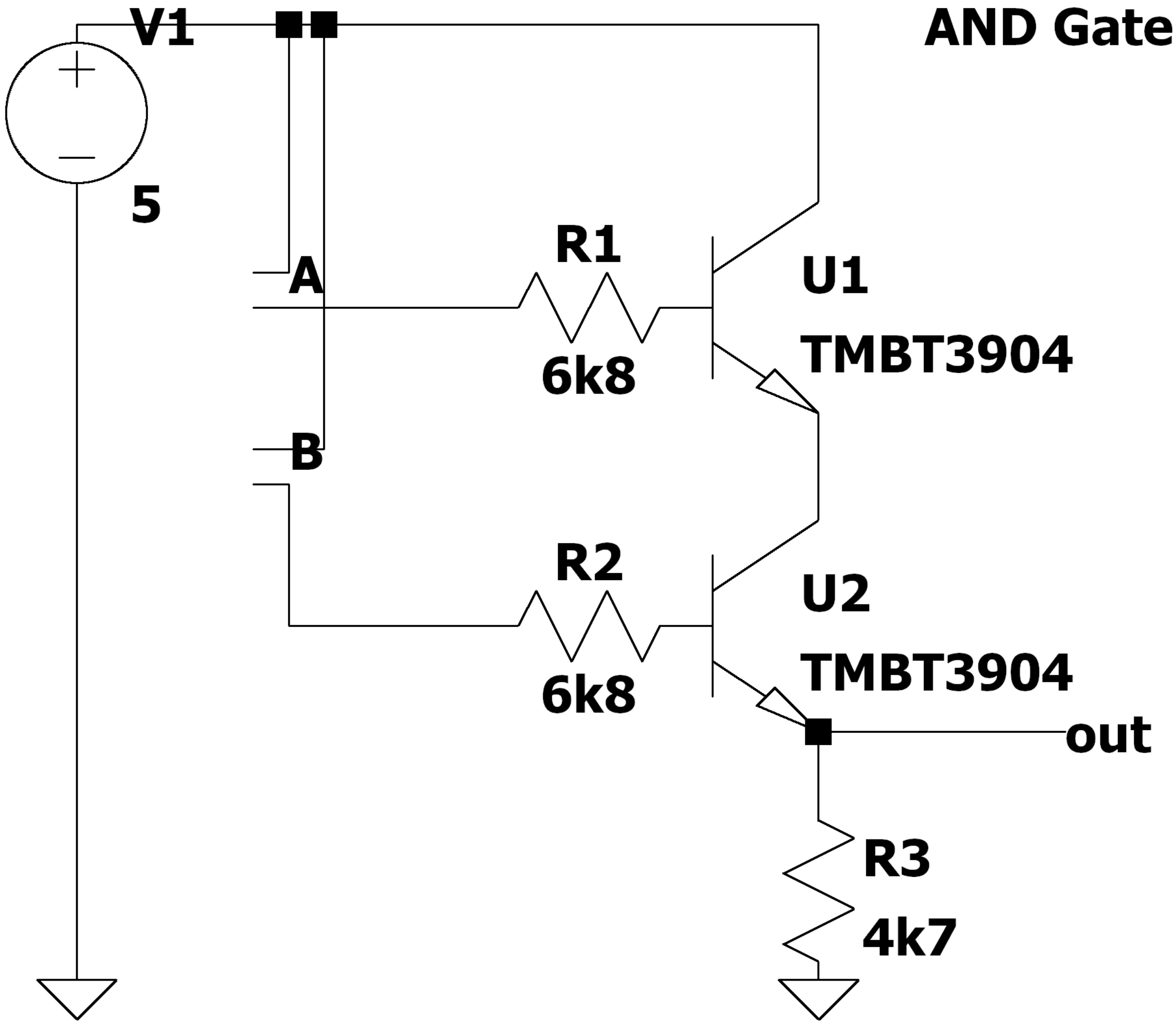


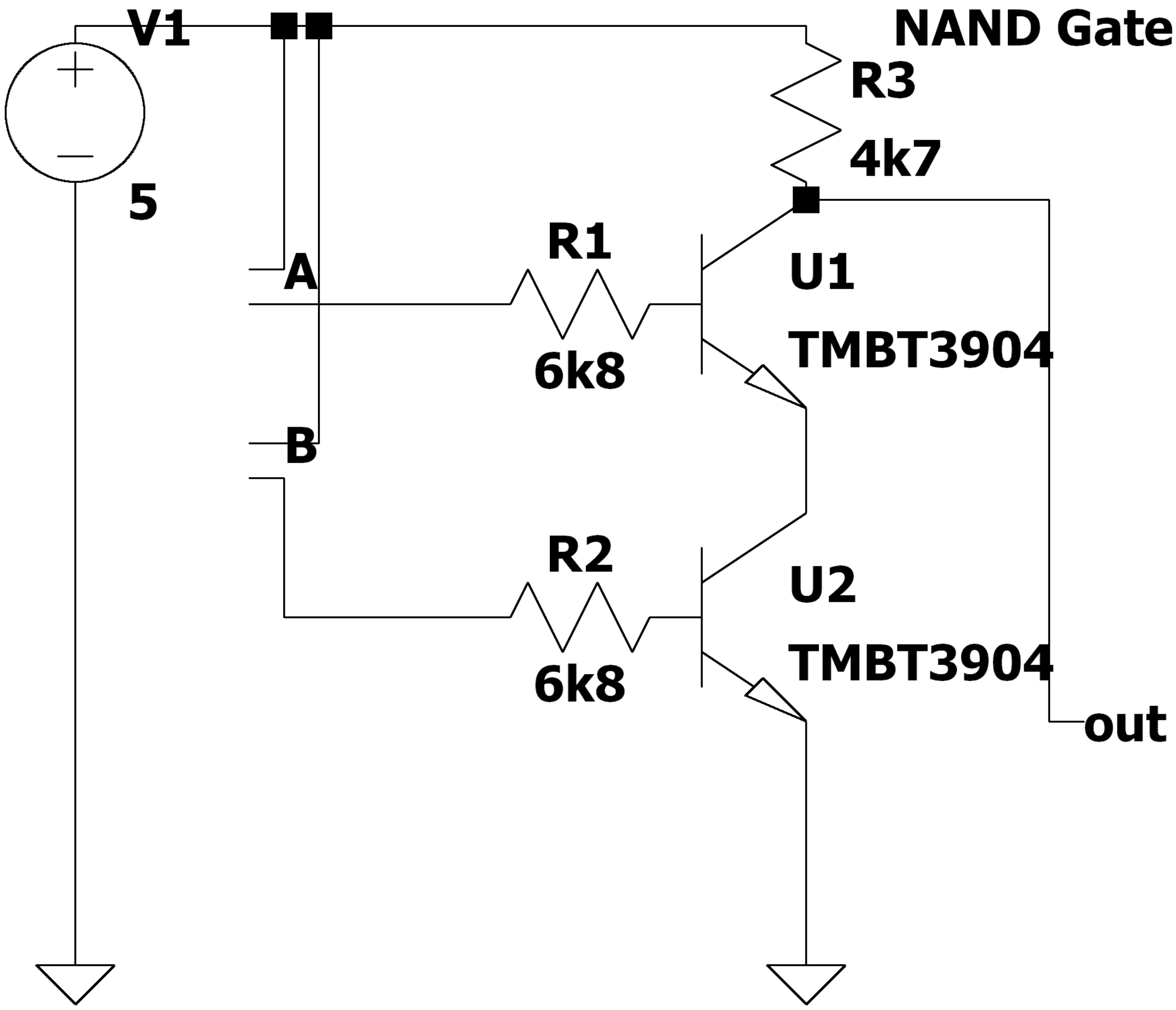
This is the logic gate schematics of a half-adder. With simple Boolean logic gates, we can successfully add two binary digits together. The following are the circuit schematics for the logic gates used in the half-adder.



As relays and triodes, the functionality of the logic gates relies on the amplification function of BJTs. BJT can amplify the signal applied to B. There are NPN-type and PNP-type BJTs. Take the NPN type as an example: the signal on B (I_B) would control the passage of electrons, alternating the current from C to E (I_E). [4] Thus, the BJT can be used for electrical switching. [5]

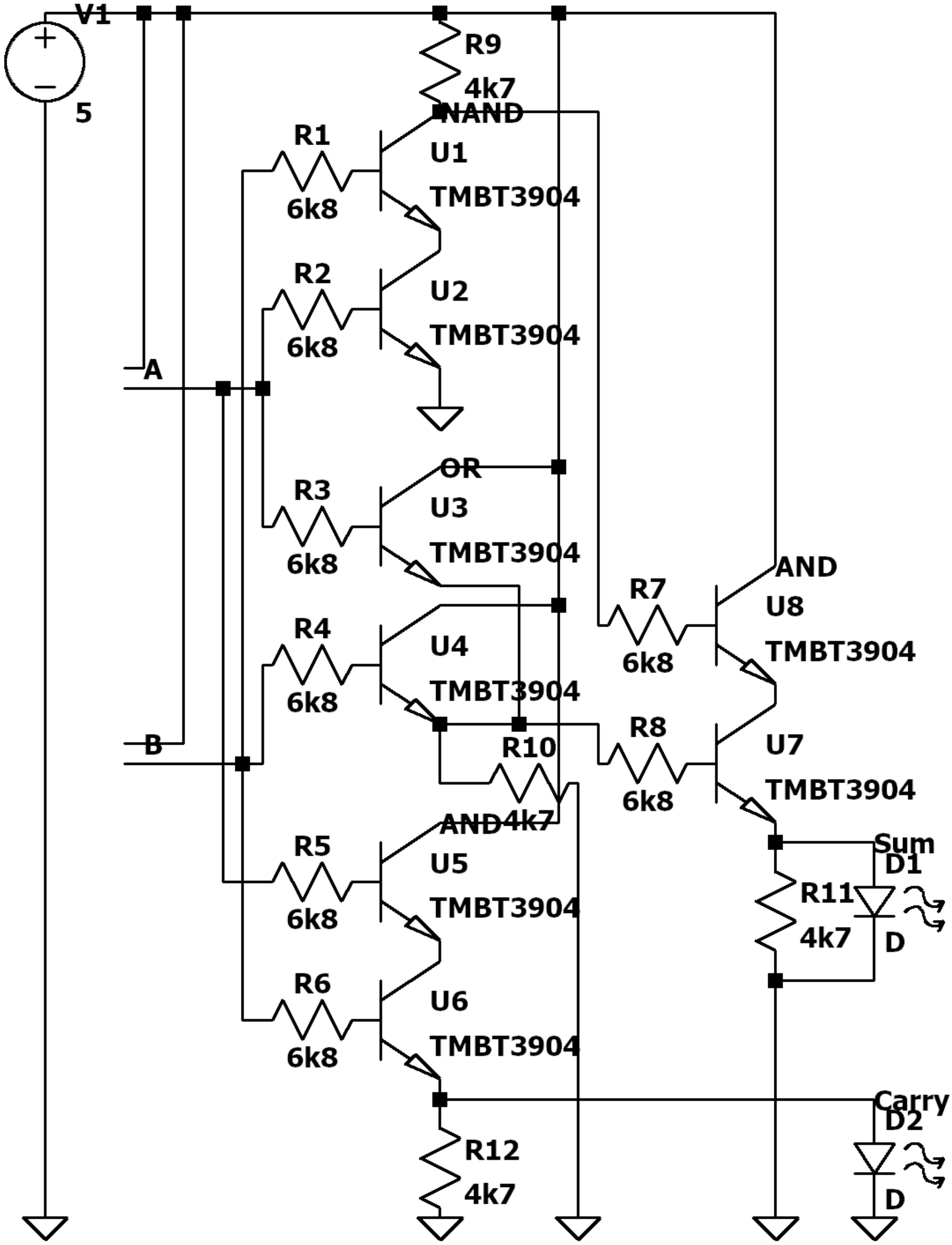



V1
AND Gate
5
R1
A
U1
6k8
TMBT3904
B
R2
U2
6k8
TMBT3904
out
R3
4k7


V1
5
NAND Gate
R3
4k7
R1
6k8
A
B
U1
TMBT3904
R2
6k8
U2
TMBT3904
out

Half-adder

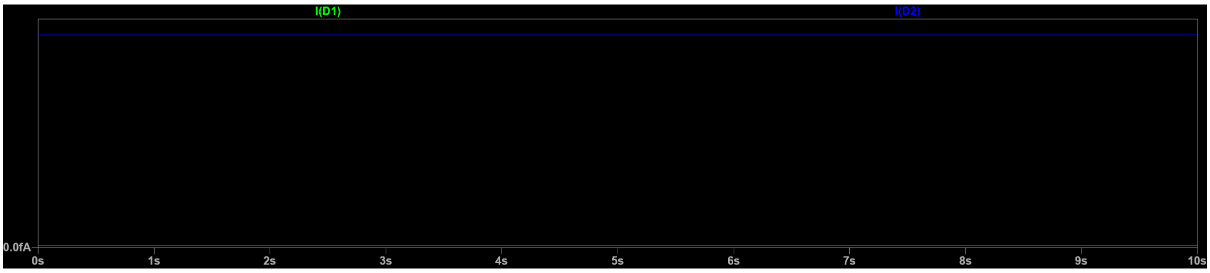
The following is the full half-adder circuit schematics. [6]



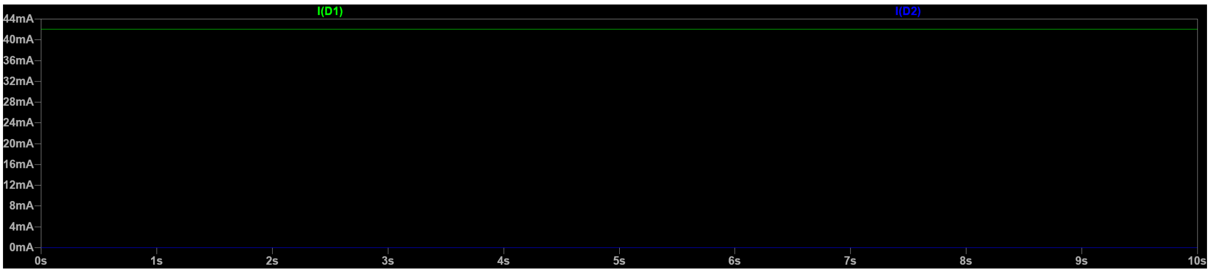
Software Analysis with LTspice

D1 (green) is the Sum. D2 (blue) is the Carry.

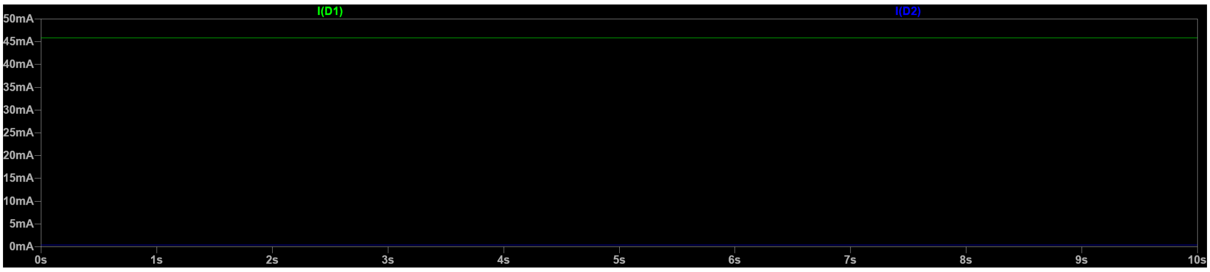
Both A and B are disconnected.



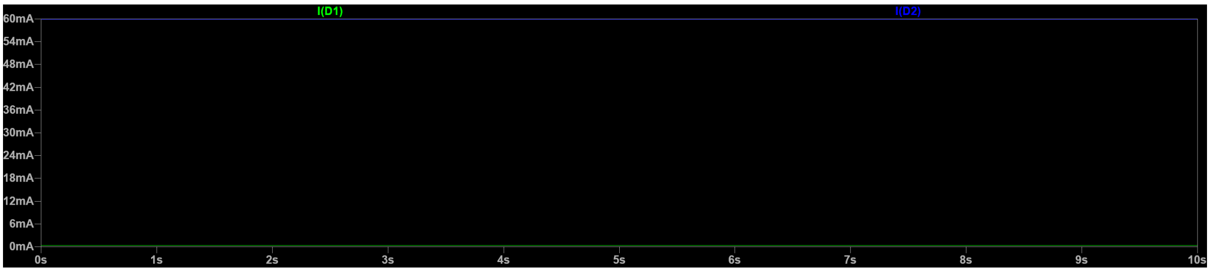
Only A is connected.



Only B is connected.



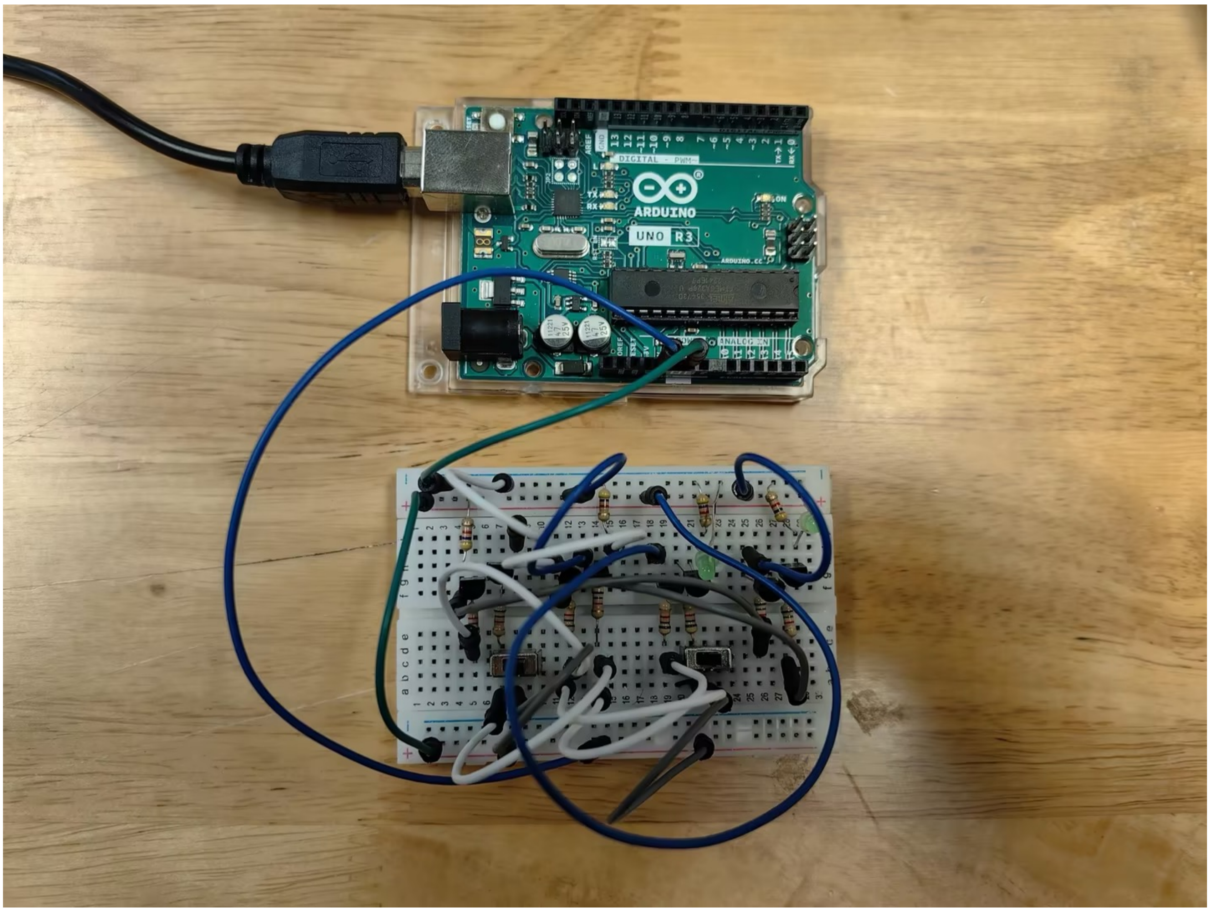
Both A and B are connected.



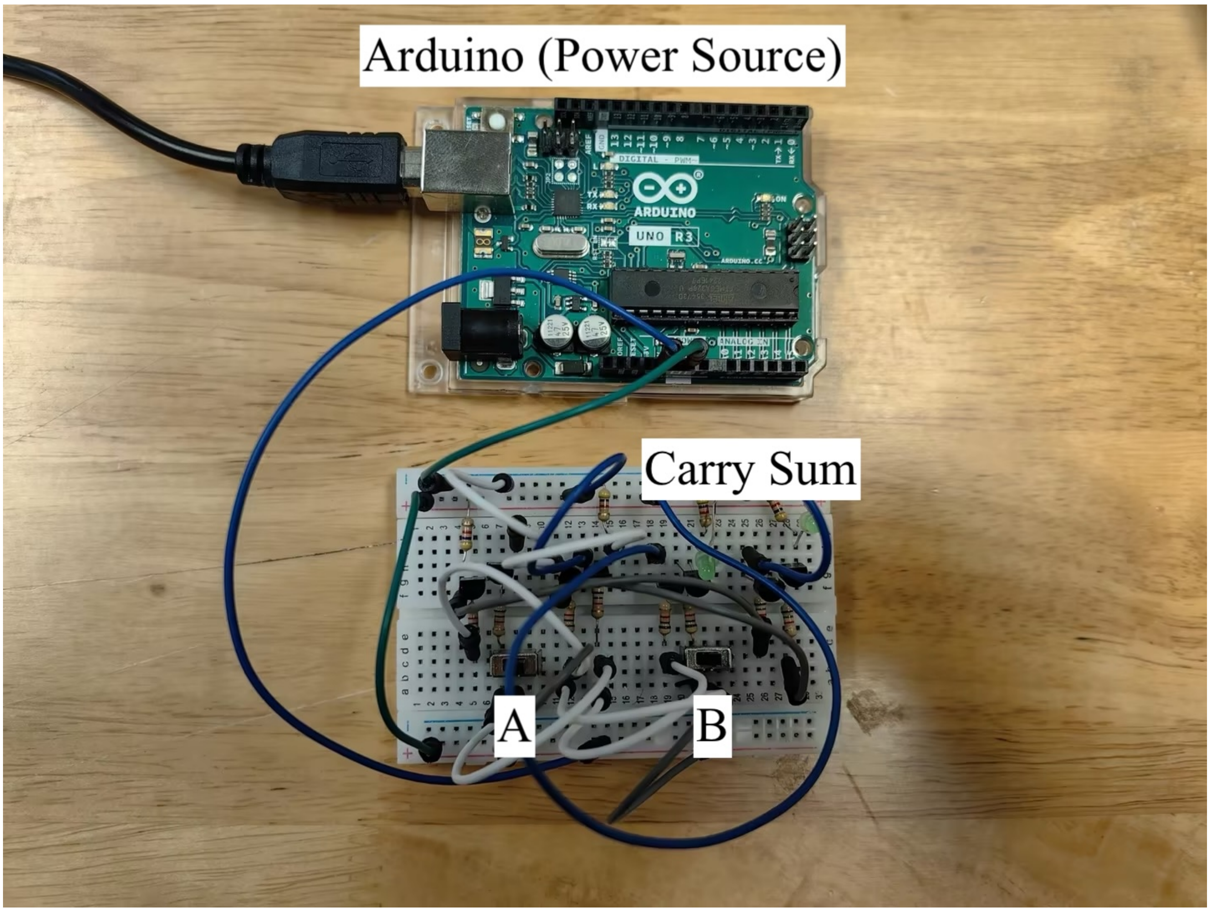
From the simulation results, we find that the circuit is correct as it follows the input and output of a half-adder.

Real Implementation

The circuits are implemented by using 2N3904 NPN transistors on a breadboard circuit with an Arduino board providing a 5-volt voltage. The following are the pictures of the actual circuit.

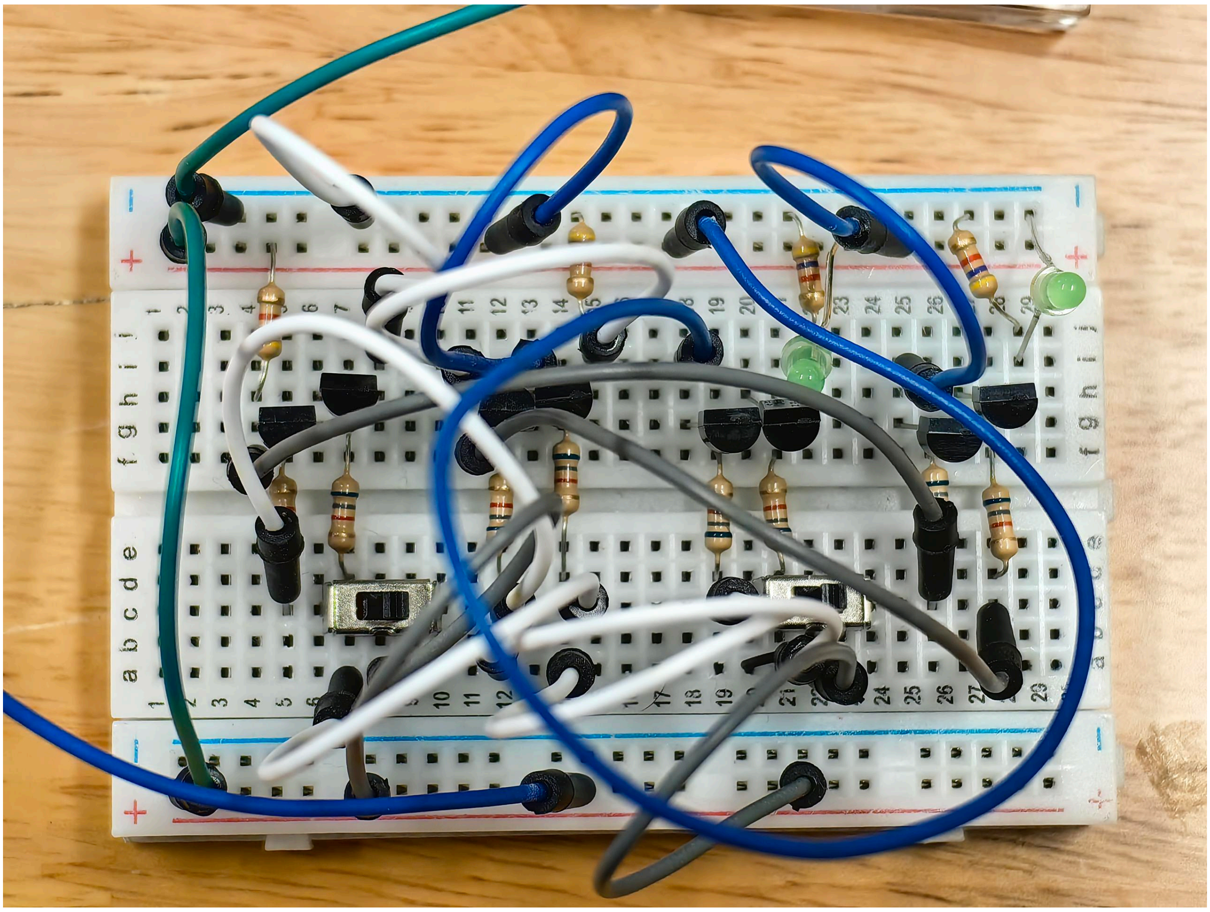


Overview.

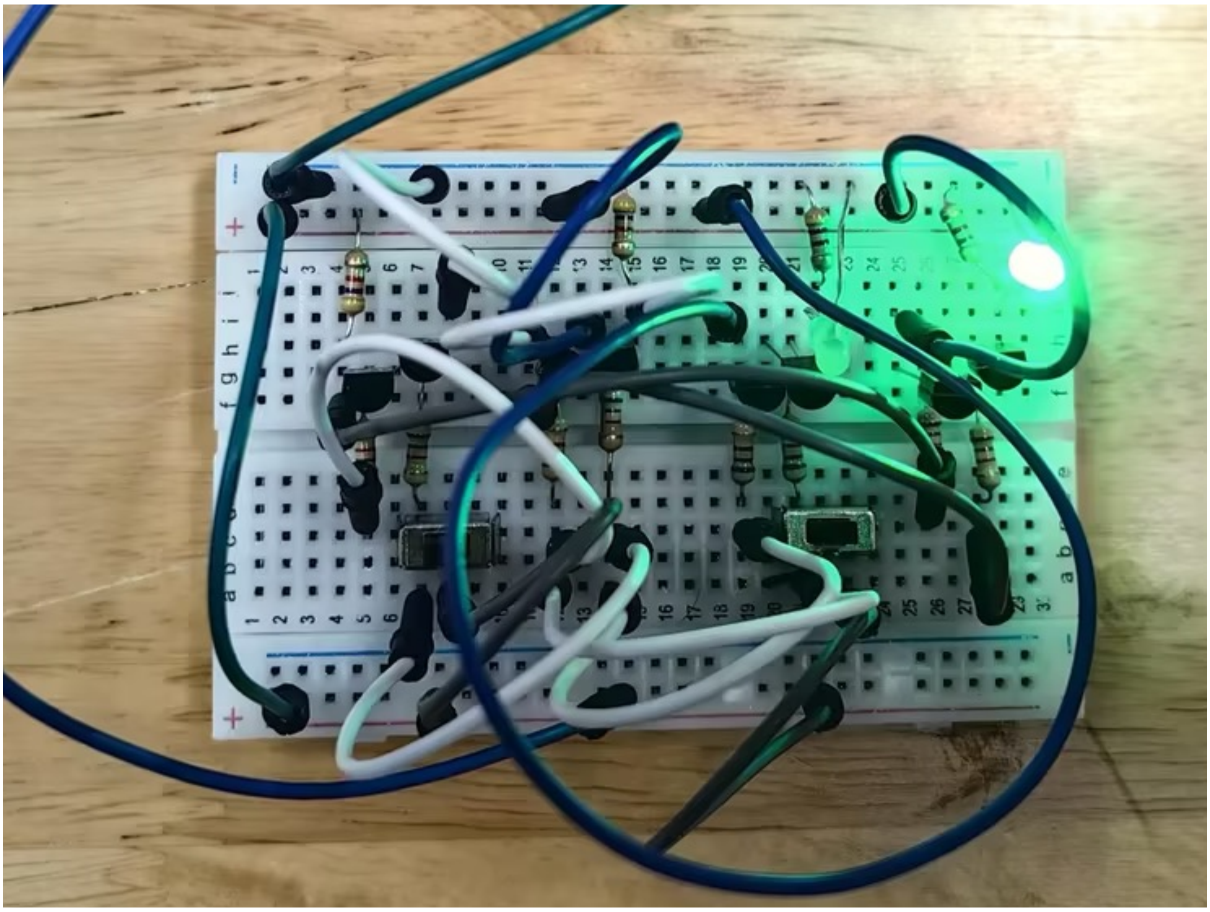


Labeled Overview, showing the Arduino board, switches A and B, and LED for carry and sum.

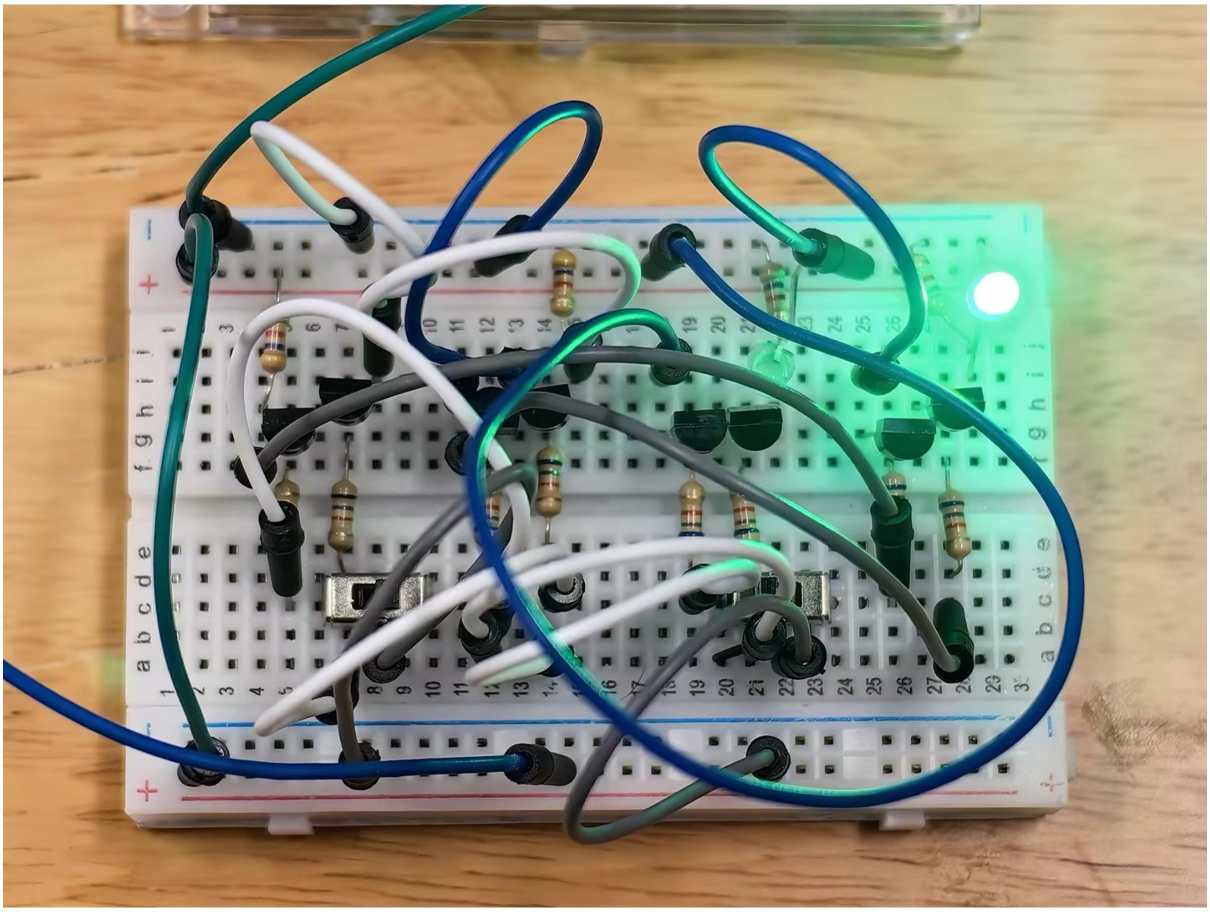
The following pictures show the circuit operating under all possible circumstances.



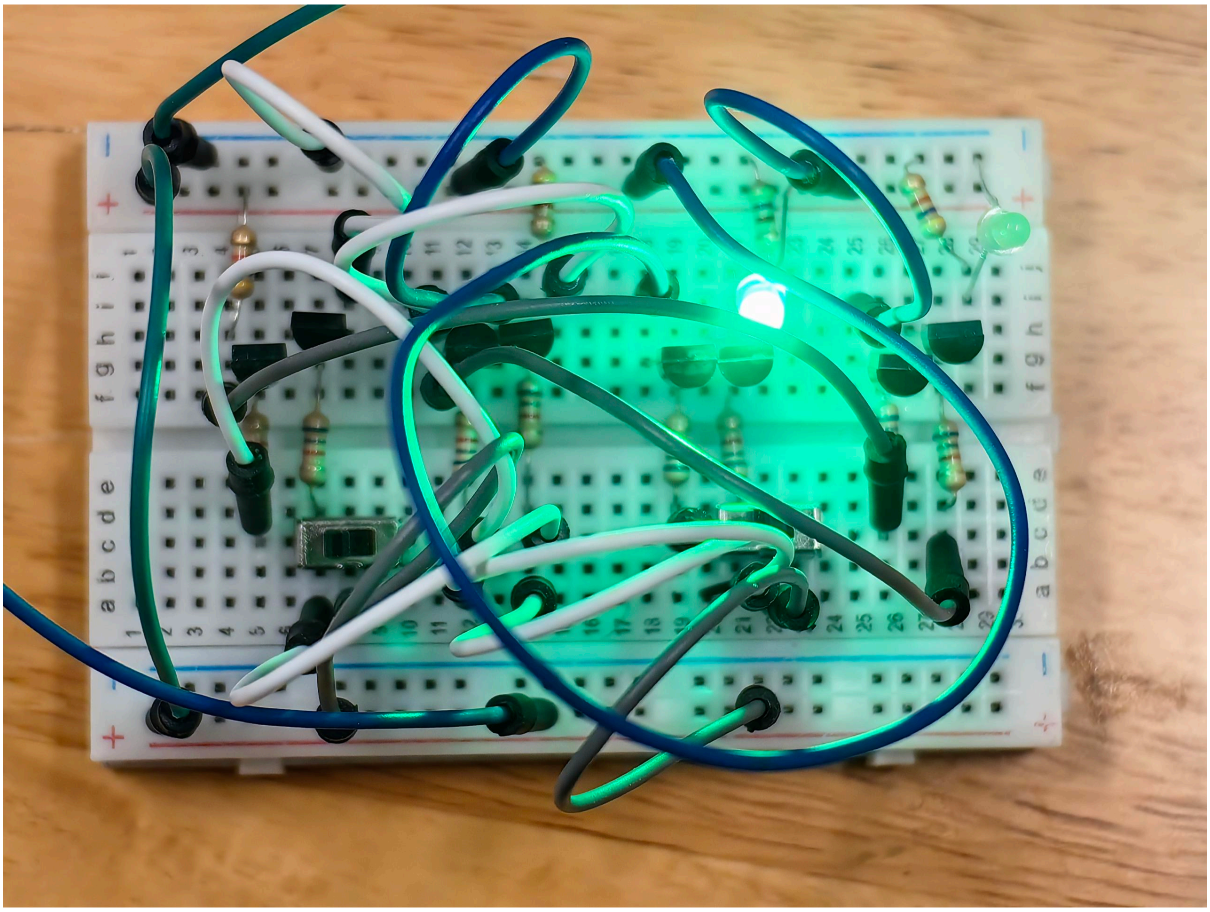
Both switches open. Neither LED lighted.



A closed. B open. Only LED for sum lighted.



A open, B closed. Only LED for sum lighted.



Both A and B closed. Only LED for carry lighted.

The pictures indicate that the circuit works as intended.

Beyond the Half-Adder

Although BJTs are forgone in the development of computing devices, the underlying logic for logic gates remains the same. The same circuit can be implemented by using relays, triodes, BJT, or FET by only changing the voltage and resistance. By combining half-adders, one can add large binary numbers together. By learning about BJTs and the most simple half-adder, we can learn about the most fundamental logic for computers' operation, whether complex or simple, whether electromechanical or nanometer-scale. [1]

Bibliography

[1] Wikipedia contributors. "History of computing hardware." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 13 May. 2024. Web. 11 Jun. 2024.

[2] Wikipedia contributors. "Boolean algebra." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 10 Jun. 2024. Web. 11 Jun. 2024.

[3] Boole, George. An Investigation of the Laws of Thought on Which Are Founded the Mathematical Theories of Logic and Probabilities. 1854.

[4] Wikipedia contributors. "Bipolar junction transistor." *Wikipedia, The Free Encyclopedia*. Wikipedia, The Free Encyclopedia, 28 Apr. 2024. Web. 14 Jun. 2024.

[5] SwellFox. “How to Use a Bipolar Junction Transistor (BJT) as a Switch?” *CircuitBread*, 11 Jan. 2024, www.circuitbread.com/tutorials/how-to-use-a-bipolar-junction-transistor-bjt-as-a-switch.

[6] HackSpace magazine. “Building a Half Adder.” *Raspberry Pi Foundation*, 1 Jan. 2018, projects.raspberrypi.org/en/projects/halfadder. Accessed 18 June 2024.