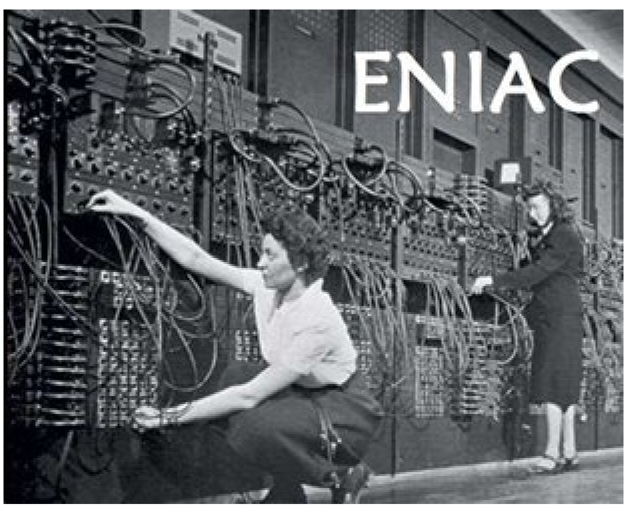
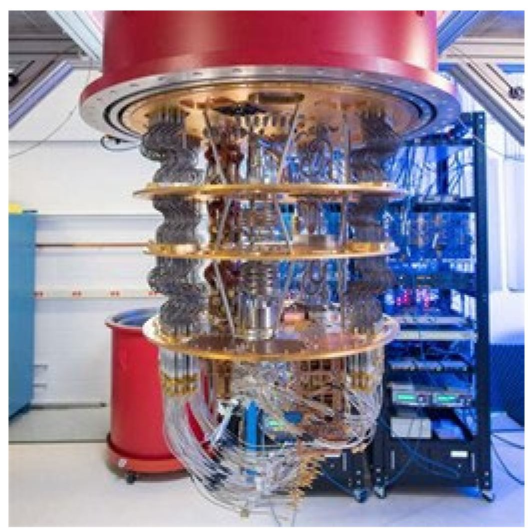
The Quantum Leap
October 25, 2021

What is a Computer? - Analog vs Digital vs Quantum

Before we can get into the inner workings of a Quantum Computer, we should make sure we are in alignment with what a computer actually is. At its core, a computer is a machine that is designed to perform prescribed mathematical and logical operations at high speed and display the results of these operations. Mankind has been using "computers" in the form of the abacus, since circa 2700 BC. Fast forward a few millennia, and we see the first "programmable computer" invented by Charles Babbage in 1833. It then took another 100+ years for the first working "electromechanical programmable digital computer" or the Z3, to be invented by Konrad Zuse in 1941.

During World War II, a flurry of advances occurred, including the usage of vacuum tubes and digital electronic circuits, and the development of the famously depicted Enigma, which was used to break the encryption of German military communications. This was soon followed by Colossus in 1944, which was the first "electronic digital programmable computer" which was also used for military advantage. Enigma and Colossus were built in Bletchley Park in the UK, while ENIAC was the first such device built in the US, and which was used extensively from 1943-1945. It weighed 30 tons and contained over 18,000 vacuum tubes, 1,500 relays, and hundreds of thousands of resistors, capacitors, and inductors, but could add or subtract 5,000 times per second, which was a thousand times faster than any prior device and could handle multiplication, division and square roots. In many ways, the tangle of cables and electronics noted in photos of ENIAC (below left) seem eerily similar to the photos of today's Quantum Computers (below right):



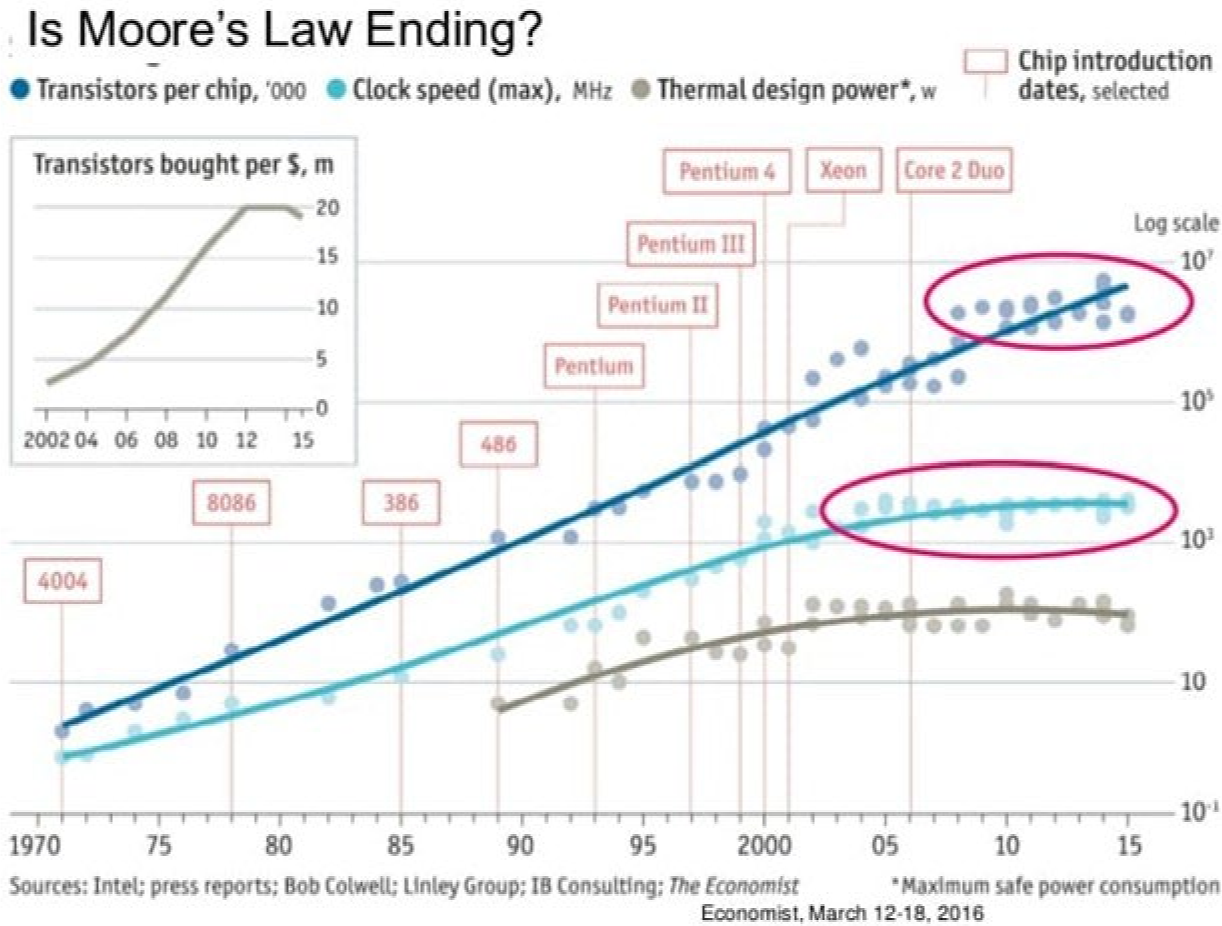


The next big advance in computers came with the invention of the integrated circuit in the 1950's. By 1968 the first silicon-gate semiconductor integrated circuit was developed at Fairchild Semiconductor, generally known as the MOSFET (short for metal oxide semiconductor field effect transistor) and is the core technology underpinning most current "digital computers". The next big advance in computers came with the invention of the integrated circuit in the 1950's. By 1968 the first silicon-gate semiconductor integrated circuit was developed at Fairchild Semiconductor, generally known as the MOSFET (short for metal oxide semiconductor field effect transistor) and is the core technology underpinning most current "digital computers".

Moore's Law

The first MOSFET semiconductors built in 1971 had process nodes that were 10 microns in size, which is a fraction of the width of a human hair (which is about 50-70 microns). Gordon Moore was a co-founder of Fairchild Semiconductor, and in 1975 he postulated that the number of transistors that could fit on an integrated circuit would double every two years, implicitly suggesting that the costs would thereby decrease by a factor of two. This log-linear relationship was estimated, at the time, to continue for ten years but has amazingly been fairly consistent through today, meaning it has held for nearly 50 years. However, for this rule/law to be in effect, the size of the process nodes needed to continue to shrink. In fact, today's generation of MOSFET includes 5 nm nodes ("nm" or nanometer is one-billionth the size of a meter), which is 1/2,000th the size of the first MOSFET nodes. Ironically, as these size scales continue to shrink, they begin to approach "quantum scale" whereby the electrons being used in the processors begin to exhibit quantum behaviors thereby reducing their effectiveness at processing, in traditional digital devices, due to quantum tunneling.

While Moore's Law has been amazingly prescient and consistent for these many decades, there is a theoretical minimum size that can't be breached efficiently utilized for transistors, largely because of these scale/quantum limitations. While the 5nm processor size is the current working minimum for semiconductors, and there are 3nm and even 2nm transistor scales in development, it appears that there is some end likely in sight, likely due to this quantum tunneling challenge at such scales. The graphic below[1] shows the uncanny straight line (dark blue) of transistor scale. However, the light blue and brown lines show some recent plateauing of maximum clock speed and thermal power utilization, indicating the declining efficiency as scale reduces.

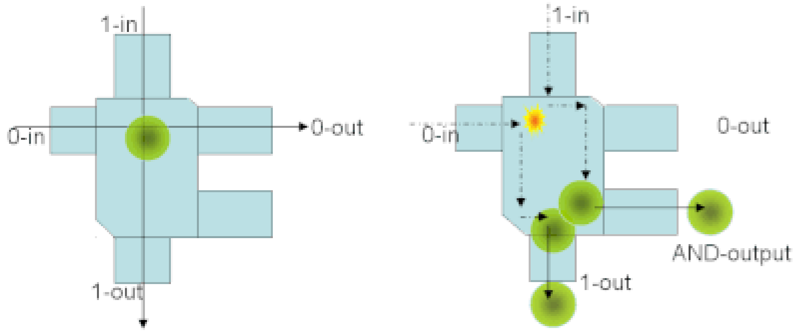


Analogue vs Digital vs. Quantum

Readers that lived through the 90's are likely familiar with the transition from "analogue" to "digital". This manifested most notably in the music industry, with the replacement of analogue phonograph records to digital discs and streamed digitized music. I won't get into the audiophile arguments about which sound was purer but highlight this item to emphasize the "digitization" of things during our lifetime.

In the prior blog post I noted that computers used digital gates to process logic (i.e., AND, NOT and OR gates). However, each of these gates can be performed by analogue methods and can be simulated using billiard balls, which was proposed in 1982 by Edward Fredkin and Tommaso Toffoli. While this is a highly theoretical construct that assumes no friction and perfect elasticity between balls, I point it out because it shows that although current digital computation is amazing, efficient, and powerful, it is just a sophisticated extension of basic analog (i.e., particle) movements. Let me briefly walk you through one example to emphasize this point.
Picture two billiard balls entering a specially constructed wooden box. When a single billiard ball arrives at the gate through an input (0-in or 1-in), it passes through the device unobstructed and exits via 0-out or 1-out. However, if a 0-in billiard ball arrives simultaneously as a 1-in billiard ball, they collide with each other in the upper-left-hand corner of the device and redirect each other to collide again in the lower-right-hand corner of the device forcing one ball to exit via 1-out and the other ball to exit via the lower AND-output. Thus, the presence of a ball

being emitted from the AND-output is logically consistent with the output of an AND gate that takes the presence of a ball at 0-in and 1-in as inputs.[2]



Similar physical gates and billiard balls could be constructed to replicate the OR and NOT gates. As you may recall from the prior blog, all Boolean logic operators can be created using combinations of these three gates, so a theoretical computer constructed entirely of wood and billiard balls, could replicate the results of any existing computer.

Admittedly, this is a theoretical construct, but I cite it to point out that while our current digital computers are amazingly powerful and fast and have led to countless advances and improvements in our daily lives, today's digital computers, at their essence, are somewhat simplistic. The "digitization" vastly improves speed and the ability to stack gates for interoperability and thereby tackling increasingly complex processes, but there are certain limits to their capabilities (I will cover some specifics on speed-up and complexity in subsequent posts).

Quantum Computers, and the gates possible using qubits, are a very different animal. The underlying mechanics and processes cannot be replicated using standard analogue materials because they operate using different laws of physics. Therefore, it is not appropriate to compare the performance of a Quantum Computer with that of a digital computer, to suggest the quantum version is more powerful or faster – it is an "apples to oranges" comparison. Stated another way, it would be like saying a light-emitting diode (LED) is a more powerful candle. It is, in fact, an entirely different form of creating light and comparisons between the two are therefore not useful.

In summary, mankind has been using different forms of "computing devices" for thousands of years and Quantum Computers are in some ways a natural extension of computing progress. However, different laws of physics are involved and therefore Quantum Computers are in a new category of computing devices that have the potential to create new approaches to problems and novel new solutions.

In the next few posts I will dig in on where this new computing approach will provide the most benefit, and how "Superposition" and "Entanglement" are used to massively increase the computing power of Quantum Computers.

References

[1] The Economist Technology Quarterly, published March 12, 2016
[2] Wikipedia contributors. (2021, May 4). Billiard-ball computer. In *Wikipedia, The Free Encyclopedia*. Retrieved 15:51, October 25, 2021, from https://en.wikipedia.org/w/index.php?title=Billiard-ball_computer&oldid=1021387675

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