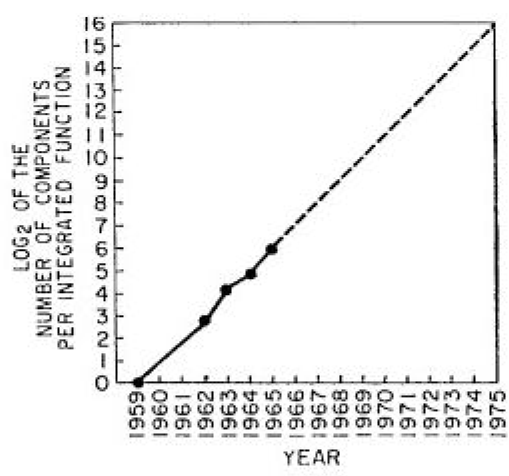
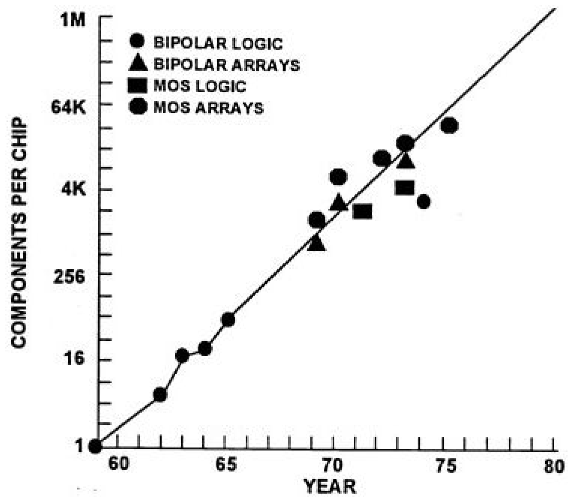
Future of Moore's Law

One of the fundamental concepts of computer chip engineering is the well-known principle of Moore's Law. This deals with the evolution of chips and transistors over time, and how constantly-improving technology inevitably impacts the size and structure of computer chips. Coined around 1970, Moore's Law stated that "processor speeds, or overall processing power for computers will double every two years" (*Moore's Law*). More specifically, this law is usually interpreted as saying that the number of transistors on a standard CPU chip is the parameter that doubles every two years. This postulate was based upon historical trends and statistical data, and held for many years since it was introduced. However, many people today believe that due to constraints of physics, this trend may no longer continue to be valid. It is important to realize, however, that though the physical attributes of chips will at some point prevent the number of transistors doubling, there may be other computing options that can still allow our chip speeds to grow at this exponential rate spelled out in Moore's Law. Whether this will be achievable forever, it is tough to say. One can never predict exactly what technological opportunities will be available years from now; otherwise, innovation would have no meaning.

In order to predict the future of Moore's Law, one must first seek to understand its past. Gordon Moore, the creator of this law, was the co-founder and chairman emeritus of Intel Corporation. He first introduced the idea to the public in an interview with Electronics Magazine in 1965, where he discussed the evolution of integrated circuits over their lifetime. He observed that many different approaches were used to "include increasingly complex electronic functions in limited space with minimum weight," and that the combination of these approaches was the "way of the future"("Cramming Components" 1). The goal, of course, is to optimize the chip by seeking maximum performance at the minimum cost for consumers. According to Moore, the biggest barrier for early digital systems was that the "thermodynamic equilibrium considerations that often limit yields in chemical reactions," meaning the problem stems from how much heat per square inch is generated in components ("Cramming Components" 2). Moore's argument for bringing integrated circuits into circulation was that the two-dimensional, flat structure was able to stay cool even when the chip was shrunk ("Cramming Components" 3). This is where the law originated: with the ability to add more transistors without risk of heat damage, more components could be added to the same sized integrated circuit as technology advanced. Moore based his predictions of exponential growth upon the advancement of the chip from the years 1959-65, as shown in his figure below ("Cramming Components" 3):



Moore predicted this trend of transistors doubling every year would continue at least until 1975. So, in 1995, he evaluated his previous predictions and made even more. The figure below is the same graph as above, but filled in with data from later years. Unsurprisingly, the data points fall very close to the linear regression line drawn from the data used in his first prediction ("Lithography" 5):



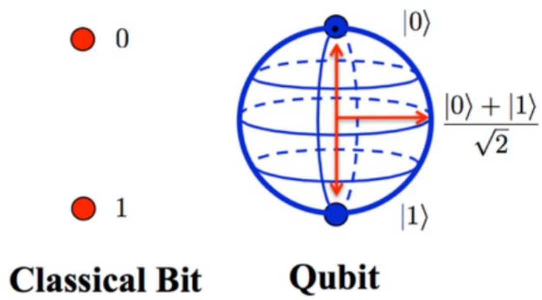
The advancements achieved in this picture were possible through two main reasons. Firstly, the die size has increased, because as "defect densities decreased we could work with larger areas while still maintaining acceptable yields" ("Lithography" 5). Another improvement was that as engineering of production improved, chip etching "evolved to finer and finer dimensions," meaning that the chips could once again be sized down ("Lithography" 6). Lastly, Moore claimed that there was one more influence: "circuit and device cleverness," that is, innovation in the structure of integrated circuits ("Lithography" 7).

However, upon looking to the future from the vantage of 1995, Moore himself assumed that his predicted trend would die at some point in the near future. He claimed that chips were physically so small that "there was no more room to be clever," and that regarding etching, "this is a really difficult trend to stay on...I have no faith that simple extrapolation beyond [the 0.18 micron generation] relates to reality" ("Lithography" 14). Die areas could only become so big—there were limits approaching for all of the factors that had previously brought Moore's Law into reality. One might ask then, why is Moore's Law still in question, if it would be most certainly dead within a number of years?

The answer may not be as clear cut as one would assume. According to Joel Hruska, "the text of Gordon Moore's 1965 prediction hasn't changed, the ways people have *understood* it very much have" (Hruska ¶ 2). Regarding the original trend of transistors doubling within a given time frame, this concept is very much dead. Hruska claims that "the classic definition factually no longer works," naturally due to the physical restraints mentioned previously (Hruska ¶ 5). However, field experts have begun interpreting Moore's Law as the simple notion that the cost to performance ratio of a standard chip doubles within a predictable amount of time. Clearly, Moore's Law has been greatly broadened, but in a way that still supports the spirit behind Moore's original proposal. At face value, Moore's Law is truly just the simple statement that humans will never stop innovating and finding ways to improve performance, by whatever means possible. And in that light, it is clear to see that Moore's Law is very much alive.

In the early days, the way these improvements were achieved through adding more transistors. But there was a finite limit on how far this could go, so new ways of achieving higher speeds were chased. New and creative innovations— like 3D NAND stacking, packaging techniques, and usage of new materials— have all been able to increase the yield of CPU chips (Hruska ¶ 4). But even then, the time interval required for the chip performance to double keeps increasing over time, as the classical computer draws ever closer to its physical capacity. In the near future, the innovation that needs to occur may be in the entire design of the CPU. One such idea, still in its early, uncertain stages, is the revolutionary concept of quantum computing.

What makes quantum computing so revolutionary is the way it represents information. Classical computers store data in binary bits, so they can only contain two states, requiring a lot of bits to represent the numbers necessary. However, quantum computers store information in qubits, which can represent multiple states at the same time. Rather than simply just 0's and 1's, quantum qubits can represent "0, 1, blend of 2, a number lying between 0 and 1 in the qubit state or an amalgamation of various numbers at a time" (Faroukh 7). This seemingly abstract concept can be visualized in the figure below (Faroukh 7):

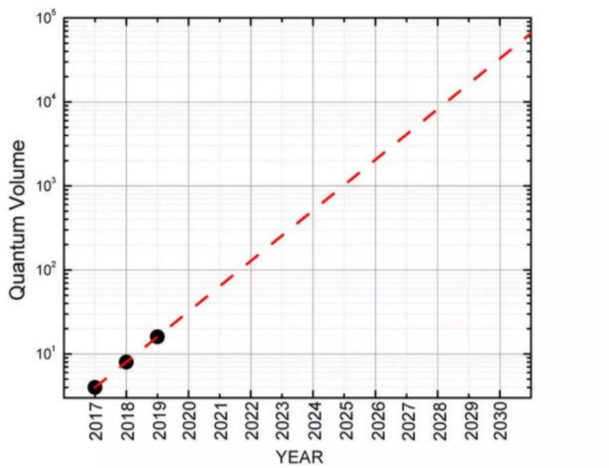


This new way of representing information would change the entire game plan of how CPUs are built, impacting both the computation and storage of memory. With only 500 qubits, "2^{500} states can be attained… every state is further equal to 500 0s and 1s," meaning that the number of distinct values that can be stored is four to the power of the number of qubits present (Faroukh 13). Compared to the way binary data is stored, that is an exponential increase in a computer's ability to store information. Technology would see an insane speedup in computation; problems that would take classical computers hundreds of years to solve could theoretically be completed by a quantum computer in a matter of days. Not only that, quantum computers could, in theory, solve problems that classical computers are not even capable of solving, regardless of time. Physicist Tien D. Kieu claimed that if a quantum computer was given a certain "infinite search" problem, "the speed-up can actually turn an infinite time into a finite time" by solving the problem using parallel computing (Hodges 2). With this field of such remarkable possibilities, it seems this might be the next innovation to keep Moore's Law alive. However, there is still a long way to go before quantum computing can be refined and mass produced, and until then it cannot begin to compete with a standardized classical computer.

Quantum computing, in theory, is amazing and all powerful, and would definitely cause a surge in Moore's Law; in fact, adding a single qubit would theoretically double the speed of a quantum computer (Faroukh 13). But that is just the problem with the quantum computer ideal: it is still very theoretical. It is questionable whether society will ever have the necessary understanding of quantum physics to truly harness the power of this type of computing. Developing this technology is so difficult, in fact, that the concept has actually been around for upward of thirty years, but has yet to make any impact on the general public.

There are a number of reasons why quantum has not already taken over the computing world. Firstly, quantum computers are insanely sensitive to their environment due to their nature, so much that they must operate close to absolute zero temperature. As a result of this sensitivity, it is “extremely difficult to isolate a quantum system… without it getting entangled with the environment” (Ponnath 2). Another disadvantage with quantum is that the uncertainty— a common theme in quantum mechanics— of the qubits’ initial states can invalidate certain matrix operations and other algorithms (Ponnath 2-3). Furthermore, one of the biggest problems is that, in contrast to the classical computer, “small errors cannot be eliminated in quantum computing” (Ponnath 3). Since the single job of any computer is to perform calculations at near perfect accuracy, this is a major deal breaker with the idea of switching to quantum computing. Above all else— performance, speed, or otherwise— accuracy must be valued at top priority in computing, because institutions rely on this aspect for precision and safety. In this light, it may be awhile before the field of quantum computing can overcome these obstacles and drive Moore’s Law forward again.

Though society is quite far off from quantum becoming mainstream, this is not to say there have not been significant improvements within the field in recent years. IBM even claims that quantum computers have already begun showing a trend similar to Moore’s Law, and they predict that years to come will continue to reflect this trend (Shankland ¶ 4). The figure below depicts this familiar prediction (Shankland):



So maybe quantum computers aren’t ready for the market yet, and will not be overtaking classical computers anytime soon. But it is clear to see that the exponential progress over a predictable period is happening now, and it is beginning to fall in line with the spirit of Moore’s Law. It is impossible to predict just how far quantum computing or any other innovations will go, but Moore’s Law says simply that society will not stop innovating. Perhaps one hundred years from now, classical computers will no longer be relevant, and Moore’s Law will evolve to mean the number of qubits in a quantum system will double every year. Perhaps quantum computing will fall through, and technology will see a new innovation for computing rise to the surface. Whatever it may be, it is simply a fact of human nature that we will never stop improving, innovating, and creating the way for a better quality of life. Gordon Moore may not have been able to see further ahead than simple transistors on a classical computer chip, but he knew that the bounds of human creativity are limitless. As for the literal sense of Moore’s Law— the infinite doubling of transistors on chips— this is most certainly dead. But as for the real vision behind it, the desire for exponential progress in the field of technology, this will undoubtedly remain alive for ages to come.

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