Comparison between Quantum Computing and Classical Computing

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Two kinds of physics describe nature: classical mechanics, which defines the macroworld, and quantum mechanics, which defines the microworld (Manin, 1999). For much of computing history, computers have been only relying on classical mechanics (Rieffel & Polak, 2000). However, Yuri Manin (1999), credited with proposing the quantum computer, predicts we will approach the limits of how efficient we can make classical computers because of quantum phenomena. But can we take advantage of these problematic effects? Quantum computing uses quantum mechanics for a new avenue of computing. Emanuel Knill, a researcher from the Physics University of Colorado, and Michael Nielsen, a notable quantum computing scientist, (2000) believe that quantum computation shows promise for a new revolution in efficiency. For example, Stephen Jordan (n.d.), principal researcher at Microsoft's Quantum Systems group, lists that quantum computing has a super polynomial speedup in factoring, a notoriously time-consuming problem for classical computers. While classical computing and quantum computing use similar computational structures, their stark difference in efficiency arises from the implementations of the fundamental physics that they use. Moreover, various implementations of quantum mechanics can lead to quantum computers with differing properties.

Bits and Qubits

Classical mechanics is deterministic. In a classical computer, a bit, the "fundamental unit of information," is strictly defined as either a 1 or a 0 (Matuschak & Nielsen, n.d.). These bits, when combined, can express more complex objects, such as an image. The quantum equivalent of a bit is more ambiguous. When we zoom into the realm of particles, we can only work with probabilities of states. Amit Hagar and Michael Cuffaro (2019), historians of science, account that upon realizing the quantum world was built on probabilities, physicists described particles and their properties as superpositions, a combination of probable states. Take spin, a fundamental property of elections that has up and down states. When an electron is by itself, its spin is 50% up and 50% down. However, when the same electron interacts with a photon, its spin chooses to be either up or down—the superposition collapses to one state. Qubits, a short form of quantum bit, exploit superposition to encode information in the probabilities. Since qubits can store more information, quantum computers can express exponentially more states than a classical computer. Rieffel Ph.D., a senior research scientist at NASA's ARC, and Wolfgang Polak Ph.D., a quantum computing consultant, (2000) note that this effect is commonly known as quantum parallelism. From an information theory standpoint, bits and qubits are similar in structure, but qubits' quantum nature allows information to be encoded in probabilities, leading to greater computational power.

Implementing Qubits in Quantum Computers

It is usually unimportant how classical computers store their bits, but quantum computers' properties heavily depend on how their qubits are stored. Qubits are extremely sensitive, so it is necessary to have special architectures to prevent the superposition from collapsing. The two foremost architectures for maintaining superposition are superconducting loops and trapped ions. Kjaergaard et al. (2019), a group of researchers at MIT, believe that superconducting qubits are currently the frontrunner. In the journal Nature, senior physics reporter Elizabeth Gibney (2020) comments that superconducting qubit technology is more familiar to the current industry; Google used superconducting qubits to "[achieve] quantum advantage." From the industry's perspective, superconducting qubits are easier to work with because they build on classical technology, which companies like Google, IBM, and Intel are used to (Gibney, 2020). However, superconducting qubits are not technologically the best. The

MIT researchers concede that superconducting quantum computers will require redundancy for larger computers because error rates are too high (Kjaergaard et al., 2019). In response, trapped ion qubit technology has lower error rates and even longer-lasting qubits (Gibney, 2020). IonQ, the leading trapped ion company, boasts that they achieved the lowest error rates yet (Atoms make better quantum computers, n.d.). Although IonQ may be inclined to report low error rates, trapped ion qubits are intrinsically less error prone (Gibney, 2020). A long-term standpoint would recommend trapped ion computers because their low error rates allow for constructing more effective computers with more qubits in the future. But they are currently much slower than superconducting qubits and less developed (Gibney, 2020). Although there is no clear consensus over which technique is better, quantum computers will be greatly affected by future computer scientists' choice of architecture, unlike classical computers.

Classical and Quantum Gates

Back to classical computing, we can expand on bits further and create gates. These gates transform bits using circuitry based on transistors, tiny electrical switches. The NOT gate takes an input and reverses it: a 1 becomes a 0, and a 0 becomes a 1 (Matuschak & Nielsen, n.d.). Likewise, the Pauli-X quantum gate switches the probabilities of states (Roell, 2018). The probability of a 1 swaps with the probability of a 0. Andy Matuschak, a software engineer and independent researcher, and Michael Nielsen, who coauthored one of the classic quantum computing papers, (n.d.) instruct that although many quantum logic gates are derived from classical gates, some of the minor differences in the two sets allow for advantages in quantum computing. One significant difference between quantum and classical gates is reversibility. Jason Roell (2018), a software engineer who reports on quantum computing, emphasizes this difference because it means that quantum computers do not lose information. Given an output, it is possible to reconstruct the input. Conversely, some classical gates, such as the AND gate, take two inputs and return one output, losing information in the process and rendering it impossible to retrieve the inputs with just the output. Both classical gates and quantum gates manipulate information, but some of their differing properties, such as reversibility, give quantum computers clear benefits.

Conclusion

Although this report focuses on the fundamental building blocks of computing, the distinctions between classical and quantum computing at the basic levels translate to the differences at the higher levels. While much of the computational theory is analogous between the two, their differing fundamental physics leads to their disparities. Bits and qubits are both fundamental units of information, but qubits can store information using superposition. How quantum computers store qubits also leads to differences concerning the feasibility of larger machines and their speed. Furthermore, the differences in quantum and classical gates, such as reversibility, can be utilized by quantum algorithms. Quantum computing is currently in its infancy, and to invent more efficient solutions to solve classically challenging problems, it is necessary to understand the differences between quantum and classical computing.

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