The following is an analysis of "Quantum supremacy using a programmable superconducting processor," a peer-reviewed paper published in *Nature* and claiming the first ever confirmed case of quantum supremacy—a major breakthrough on the road to the proliferation and greater utility of quantum computers.

Main (Introduction)

Richard Feynman first posited the usefulness of a quantum computer in the 80s, suggesting they could be useful for the simulation of complex quantum systems, as these take a lot of time and resources with classical computers. The team at Google set out to do this, and in doing so achieved quantum supremacy—according to their claims—on their superconducting qubit processor. This demonstrates that quantum computers can be superior to classical ones for some problems, and opens the door to improved optimization processes, machine learning pathways, and more, though a variety of possible uses are still blocked by a lack of fault-tolerant qubits. The degree of success they've achieved was the product of a variety of innovations: the development of high-fidelity gates for their qubit matrix, cross-entropy benchmarking, and component-level fidelities.

A suitable computational task (Methods)

The experiment chosen for their quantum computer had to be difficult for a classical computer to simulate, so they set out to have their computer simulate the bitstring output of a pseudo-random quantum circuit. Classical computation finds this problem exponentially more difficult as the width and depth of the circuit increases. To test their quantum processor integrity, they used cross entropy benchmarking, which compares the frequency of a bitstring's appearance with its ideal probability. This ideal probability is computed on a classical computer, thus verifying their results. With the integrity of their results verified, they then constructed a scenario with a quantum circuit wide and deep enough for its output's calculation to be unrealistic on a classical computer. The error rate of their quantum processor needed to be lower, however.

Building a high-fidelity processor (Methods)

The quantum processor, Sycamore, is composed of a 2D matrix of 53 (originally 54, but one didn't work) transmon qubits, individually tunable. The hardware involved has a microwave drive for exciting the qubits and magnetic flux control to change their frequency (which can be quickly switched between 0 to 40 MHz). The processor is made using aluminum and is set between two silicon wafers using indium bonds. The chip is attached to a superconducting circuit and cooled below 0.02 Kelvin to keep the ambient energy below the qubit energy. The circuit can be read via frequency multiplexing, with 277 digital-to-analog controllers used to control the processor. For single-qubit gate control, the 25-ns microwave pulses were designed to minimize transitions to higher states and various frequency-dependent errors. The performance of any given qubit was checked using cross-entropy benchmarking to determine the probability of error in any given qubit. This is then compared with the errors occurring as various random gates are applied to each qubit.

The same experiment was then run with all qubits simultaneously. It showed only a small error increase, demonstrating that the system had low microwave crosstalk. Two-qubit gates are more complicated, but they are possible via tuning two neighboring qubits to be on-resonance and then activating 20MHz coupling for 12 ns. They found the error for these gates as well. A benchmark for qubit readout was also measured. The fidelity of a quantum circuit could then be measured as the product of the probabilities of all gates and measurements performing without error. They calculated a fidelity of 0.2 percent for their most complex quantum circuits (53 qubits, 1,113 single-qubit gates, and 430 two-qubit gates), and proceeded to test this calculation experimentally.

Fidelity estimation in the supremacy regime (Methods & Results)

The gate sequence for the supremacy simulation consists of sequences of single- and double-qubit gates constructed such that they maximize the difficulty of the computation for a classical computer, with low circuit depth and thus a highly entangled state. To estimate the mean of the simulated probabilities for the measured bitstrings, they split their circuit into two patch circuits, removed fractions of their two-qubit gates to make elided circuits, and ran verification circuits with the same gate count but simpler pattern than the supremacy circuit. Using these three other circuit types, the supremacy circuit's fidelity can be evaluated. They collected 30 million samples in ten instances of their most complex circuit—which had 53 qubits and 20 cycles. They determined that, with 5σ confidence, the average fidelity of these circuits run on the quantum processor is greater than 0.1 percent.

The classical computational cost (Analysis)

To determine the classical computational cost (as they couldn't just let their simulation run for an indeterminate amount of time) the team at Google used a hybrid Schrödinger-Feynman algorithm, breaking up quantum circuits of 43 qubits or less so they can be simulated by a Schrödinger algorithm, then recombined with an operation similar to Feynman path-integral. In this way, Google data centers compute the amplitudes of each bitstring. The total runtime of the quantum computer's simulation on a classical computer was extrapolated by running a portion of the simulation on the Summit supercomputer (which they claimed to be the most powerful of the time) as well as on Google Cloud servers.

The Summit supercomputer was not even capable of measuring the runtime of this simulation, instead settling for a similar but less difficult one, and found that it would take a full year to get a result of even 1 percent fidelity. The Google Cloud servers could estimate runtimes for the original simulation, finding with 0.1 percent fidelity that the simulation would take 50 trillion core-hours and use one petawatt hour of energy. These results were both drastically more expensive than the 600 second runtime of the quantum processor. It is anticipated that classical computers will get closer to this quantum efficiency, but quantum advancements will continue to outpace them.

Verifying the digital error model (Analysis)

The experiment done by the team at Google showed that the errors of its system were both discrete and probabilistic with digitized, localized quantum state errors, as predicted by the theory of quantum error correction. The fidelity of their system was just the fidelity of each gate multiplied together. Their experiment also achieved a low number of correlated errors via their choice of circuits, allowing them to make a system where quantum phenomena like entanglement have a measure of stability.

The future (Discussion)

The computation performed in this experiment is the first that can be performed only on a quantum processor, thus quantum supremacy has been achieved. The classical computations equivalent to the quantum experiment done increase exponentially with computational volume, and hardware improvements should thus be able to increase quantum computational volume at a double-exponential rate every few years. If this happens, we could run quantum processes like the Shor and Grover algorithms, but such a rate requires advancement in the field of quantum error correction to be made possible. If these advancements are pursued, we will be capable of new types and methods of computation outside of the classical scope, and near-term applications could be coming soon.

Article Analysis

Is the topic of the paper somewhat original?

The topic of the paper is original—this marks the first credible claim of quantum supremacy in history.

Do the authors have a solid track record?

John M. Martinis, a physicist and professor at UCSB, has been pursuing this subject matter since his PhD thesis in 1985, and they are backed by Google, a well-known and successful tech company. This speaks to a good track record.

Is one of the authors a statistician, or is a statistician's contribution acknowledged?

There are 77 authors attributed, but none of them are specifically listed as statisticians.

Who sponsored the study?

Google sponsored the study, hiring Martinis' team in 2014 to build them the Sycamore quantum computer.

What was the aim of the study? What hypothesis did the researchers test? Are the conclusions reached (assuming they are valid) important to you and others (explain)?

The researchers aimed to prove that their Sycamore quantum processor could complete a computation that a classical computer could not finish in a reasonable time scale. They found that they could simulate such a scenario—taking one million samples of an instance of a quantum circuit—in 200 seconds, compared to an estimated 10,000 years by a classical supercomputer. This could be important to the entire world. If quantum computing becomes scalable, it could revolutionize runtimes for operations in most industries.

If human subjects were used, was consent to participate in the study obtained from the subjects? Was the study approved by an institutional review board? Was the assignment of patients to study groups truly random?

NA

Were enough data obtained to reach valid conclusions?

Yes, the quantum circuit was sampled 3 million times, with

Were the outcome measures (end points) appropriate?

The endpoint of the measurement was designed such that a classical computer's simulation of the same phenomenon the quantum processor simulated would take an unreasonable amount of time for the classical machine.

Was the statistical analysis (if used) appropriate for the study?

The use of a confidence interval and estimations for a comparable classical computing runtime were appropriate, as some of the data required to quantify just how impressive the Sycamore processor's achievements were would be impossible to experimentally measure (we couldn't wait 10,000 years for a classical computer to complete its quantum circuit simulation, for example).

Do the Results section and the Methods section match?

The sections discussing results followed from the methods of experimentation discussed.

How are outliers handled in the data?

Outliers were not prevalent in the data. This is because the entire purpose of this study is to acknowledge and account for error in the qubits, so most of these errors were well documented.

Were changes made in the study protocol after the trial began, to save time or money or because of untoward events?

The qubit count was reduced from 54 to 53 because of a defective qubit, we may have gotten an even more drastic quantum supremacy announcement, otherwise. The computational state space would have doubled (from 2^{53} to 2^{54}).

Are both P values and confidence intervals reported?

P values are not discussed, though a variety of other techniques are used to prove that the simulations by the quantum processor are predictable. The confidence interval is reported, with They determined that, with 5σ confidence, the average fidelity of quantum circuits running on the quantum processor determined to be greater than 0.1 percent.

Are the results plausible?

The results are plausible. Quantum supremacy has long been a possibility theorized, but incredibly difficult to achieve without crippling error frequency. The work of Martinis' team at Google should pave the way for even further advancements toward a useful quantum computer.

Are the results consistent with those of other studies?

This study was the first of its kind, though IBM did release an article shortly after claiming that they had a supercomputer that could compute the same calculations as the Sycamore processor in a reasonable amount of time, albeit much slower than the 600 seconds it took Sycamore to sample the supremacy circuit 3 million times. This would reduce the quantum supremacy Google claimed to a quantum advantage.

Have the authors discussed possible limitations of the study?

Yes, until further advancements are made in the fields of error correction (or the advent of a creative application) this announcement means nothing for practical computing tasks.

Do the study's findings have practical importance, regardless of whether they have statistical significance?

They have theoretical practical importance—quantum computing could open doors to powerful optimization, simulation, and more, if the problems concerning error correction are solvable.