Classical Circuit Simulations for Superconducting Quantum Circuits

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Abstract

• Classical superconducting circuit simulators are powerful and available.
  • Include Josephson junction as basic element.
  • Provide efficient time-domain simulations of complex circuits.
  • May show effects otherwise attributed to quantum circuits.
• Circuits of coupled superconducting qubits are being developed for quantum computing (QC).
  • Entangled quantum theory incompatible with classical simulators.
  • Quantum model difficult to simulate on conventional computers for complex circuits already being tested.
  • Classical circuit simulations should provide the baseline to compare with quantum effects, but this is seldom done.
  • Coupled oscillators are delocalized even in classical limit.
Superconducting Circuit Simulators

- Based on standard semiconductor circuit simulation tool “SPICE” with Josephson junction (JJ) added as standard element.
  - Available on a variety of computer platforms, with some in public domain [1].
- Widely used to simulate operation of classical superconducting digital and analog circuits.
  - Provide currents and voltages on ps time-scale.
  - Simulators can also include effects of noise and thermal fluctuations.
JJs in Classical and Quantum Circuits

• A JJ is a tunable inductor in parallel with a nonlinear resistor and a capacitor.
  • The maximum current through the lossless inductor is the critical current $I_C$.
  • For larger currents, the JJ is resistive.
  • The JJ is also an LC resonator, with frequency $\sim 10$ GHz, which is low-loss (high-Q) only for very low T.
  • Classical circuits generally switch between lossless and lossy states.
  • Quantum circuits (qubits) generally function using high-Q resonators at very low T.
Circuit Model vs. Quantum State Model

- A classical circuit has a definite $I(t)$ and $V(t)$, with random thermal noise contributions.
- A quantum-modified circuit may have a quantum noise contribution at low $T$, but is otherwise described by a classical circuit model.
- A circuit with quantum superposition does NOT have a definite $I(t)$ and $V(t)$, and cannot be described by a classical circuit model.
  - This is believed to require a quantum state model, leading to entanglement if two or more states are coupled.
Entanglement and the Promise of Quantum Computing

- In an N-bit classical computing system, there are $2^N$ possible states, but only one at a time.
- In an N-qubit QC system with entanglement, $2^N$ quantum states may be processed in parallel.
  - When $N = 300$, $2^N$ is greater than the number of atoms in the known universe.
  - This massive parallelism could enable QC to solve problems impossible by any classical computer.
  - This theoretical parallelism also explains why this cannot be simulated efficiently on a classical computer.
Why use classical simulator for quantum problem?

• Because these are circuits with classical inputs and outputs, and the baseline performance should be that predicted by the classical circuit model.

• Researchers may identify effects as “quantum” that actually follow from a classical model.

• Re-analysis of “quantum” experiments in JJs using classical circuit simulators has reproduced “quantum” results [2-4].
  – However, this analysis has been ignored by the QC community.

• QC is the first technology promising revolutionary performance based on quantum entanglement.
  – We should be skeptical until we have clear proof [5].
Thermal and Quantum Switching of JJ

- A JJ just below $I_C$ can switch to the normal state if driven by noise or fluctuations.
- Experiments as far back as the 1980s [6] showed that the thermal fluctuation current decreased as the JJ was cooled to very low $T$, but then this decrease saturated.
- These results were accepted as proving “macroscopic quantum tunneling” (MQT) associated with quantum fluctuations.
  - This MQT in JJs provided the basis for later suggestions to use JJs for qubits.
- However, more recent reconsideration of the same data showed that this could be simulated using fully classical circuit simulations [3], suggesting that MQT may not be needed.
Ising Model for Optimization Problems

• One type of special-purpose computer is based on the Ising Model, which minimizes the energy of a 2D array of magnets.
  – One can obtain “simulated annealing” of this model by gradually cooling the arrays of magnets.
  – This classical model maps onto general optimization problems in computer science.
• In addition to solving this on a general-purpose digital computer, this has also been implemented in several classical physical systems at room temperature.
  – CMOS chips and Photonic oscillator arrays [7,8].
Is “Quantum Annealer” a Quantum Computer?

• Another implementation of Ising model is a 2D array of Josephson junctions in coupled inductive loops
  – This superconducting analog computer is being sold by D-Wave Systems as a “Quantum Annealer” [9].
  – This superconducting chip operates at 20 mK in a dilution refrigerator, and solves optimization problems.
  – This operates as a *classical* superconducting circuit using thermal fluctuations, but D-Wave claims that this is quantum-enhanced by quantum fluctuations and MQT (but *not* an entanglement-based quantum computer).
  – Circuits should be modeled with classical circuit simulators, and operation compared to classical Ising computers.
Quantum Entanglement of Supercond. Qubits

• Other superconducting QC programs (Google, IBM) use entangled superconducting qubits to form quantum logic gates (such as CNOT).
  – Qubits such as transmons are superconducting resonators with tunable frequencies, each 2 quantum states – no classical limit.
  – Resonators are weakly coupled to each other or to a common transmission line -- necessary to enable quantum entanglement.

• Designed to solve complex quantum algorithms for fully entangled circuit of ~100 logical qubit gates, but not soon.
  – Noisy environment destroys quantum coherence, creating errors.
  – In principle, quantum error correction could use extra qubits to correct errors in logical qubits, but not clear how.
Noisy Intermed.-Scale Quantum (NISQ) Systems

• Accepted by QC researchers that near-term systems of ~ 50-100 superconducting qubits are NISQ circuits without full quantum coherence [10-12].
  – Massive parallel performance not possible with NISQ.
  – Several practical algorithms have been suggested for similar NISQ circuits, such as quantum chemistry [13].

• “Quantum Supremacy” over classical computers has been claimed for some NISQ superconducting circuits.
  – This means that the fully entangled quantum model cannot be simulated on a classical computer, because of the $2^N$ parallelism required.
  – It does NOT mean that this NISQ circuit is solving a useful computationally difficult problem.
Coupled Superconducting Oscillators

• Classical circuit simulations can provide baseline performance of NISQ superconducting circuits, even relatively large ones.
  – This is seldom done, but it should be.

• Note that these coupled qubits are coupled oscillators, which are well known in classical and quantum physics.
  – A linear array of coupled identical classical oscillators forms a band of delocalized collective modes, analogous to energy bands in crystals.

• Ref. [14] examined a chain of 9 coupled qubit oscillators.
  – With all tuned to the same resonant frequency, an excitation coupled at one end propagated to the other end.
  – With the middle resonator detuned, the two ends were decoupled.
  – This was interpreted in terms of entangled qubits, but it also follows from classical coupled modes.
  – *So does this really validate entangled quantum theory?*
Quantized Classical Oscillators?

- Experimental evidence for quantized energy levels in superconducting oscillators.
  - Cannot be obtained from classical circuit model.

- Consider model for classical oscillators with quantized energies $E = (n+\frac{1}{2}) \hbar f$.
  - These have currents and voltages $I(t)$ and $V(t)$, but only amplitudes with these total energies permitted.
  - This allows zero-point oscillation in ground state at $T=0$, and excited states coupled by photons with $\hbar f$.

- Such a semi-classical model would slightly modify the classical circuit model, without any superposition or entanglement.
  - This might provide an alternative simple model to compare with experiments.
Conclusions

• Superconducting circuit simulators including Josephson junctions can describe the classical dynamics of complex classical circuits.

• These simulators do not include the quantum state model or entanglement, but should still provide a first approximation for superconducting quantum annealing and quantum gate circuits.

• To the extent that classical simulators reproduce the essential properties of prototype superconducting quantum circuits, those circuits are unlikely to provide a significant quantum advantage.
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