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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 ~ 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 $E = (n+½)\,hf$.
  - 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 hf.
- 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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