On Quantum Computing

Quantum Computing with rf SQUIDs
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Computer components have been steadily decreasing in size and increasing in power required, tending to follow Moore's empirical "law," which states that computing power doubles approximately every 18 months. However, extrapolation suggests that within about 10 years the size of a transistor logic gate element will be only a few atoms. Consequently, computer power will soon reach a limit, unless another approach for computing can be developed. Quantum computing is one possible approach.

An ordinary electronic computer uses two-level logic, zero and one. A quantum computer, on the other hand, has states corresponding to zero and one and all linear combinations in a single element called a qubit. A quantum computer would consist of many qubit gates with entangled states. These gates could be addressed in parallel by unitary transformations, which must be carried out reversibly, implying no loss of energy in a gate operation. Quantum computers are "wired" so that they can do many calculations as the same time. This is known as "parallelism" and represents the power of a quantum computer.

The quantum computer would be superior to the classical computer for two important problems: finding the factors of a large number and searching an unstructured database.

Q & A

What is a quantum computer?
Unlike ordinary computers, a quantum computer uses quantum mechanics to do calculations. While ordinary computers use a system of "logic" based on either zeros or ones, quantum computers would use a logical system that is based on zeros, ones or a combination of both. This combination would theoretically allow a quantum computer to do certain calculations, like finding the two factors of a particular product, exponentially faster than the conventional computers of today.

What is an rf SQUID?
A radio frequency superconducting quantum interference device, or an rf SQUID, is a magnetic field measuring device made of a loop of superconducting material with an insulating barrier. The particular rf SQUIDs worked with at UM are made of thin films of aluminum and niobium and are roughly the diameter of a human hair (about 50 microns).

How are quantum computers and rf SQUIDs related?
The research group at Maryland is trying to make the rf SQUID to the quantum computer what a bit is to today's computers. In other words, the rf SQUID is used as a qubit, or a quantum bit, in a quantum computer.
Since it is far easier to find the product of two numbers than to find the factors of such a product (a nearly impossible task for conventional computers), industry and banks use this asymmetry to transmit information securely. In other words, the factors of a particular product are the key to many encrypted security systems, and if one could find the factors of a large number quickly, this security would be lost.

Searching an unstructured database may become crucial as the information on the World Wide Web expands. Here, again, the parallel processing quantum computers would provide an exponential speed-up.

Several systems have been proposed for quantum computing including trapped ions, quantum dots, and Josephson junctions. Although there are advantages and disadvantages to all systems, we believe that Josephson junction arrays have the greatest potential for realizing the entangled qubits of a quantum computer.

![Schematic of a Josephson junction. A thin insulator of aluminum oxide is sandwiched between two superconducting layers of niobium and aluminum.](image)

In 1961, Brian Josephson, a graduate student at Cambridge University, published a Physics Letter with a remarkable conclusion, i.e. coupled electron pairs could tunnel across a narrow insulating barrier between a pair of superconductors without the development of a potential difference across this junction. In addition, if a voltage were applied across the junction, the phase difference of the electron wavefunctions on the two sides of this barrier would be oscillatory with its derivative proportional to the voltage. If this barrier were part of a superconducting loop, an applied voltage would produce an alternating current. These conclusions were confirmed by experiment shortly after Josephson's publication.

Our approach to quantum computing takes advantage of the "Josephson Effect". We plan to use radio frequency (rf) superconducting quantum interference devices (SQUIDs) as qubits. An rf SQUID is a single Josephson junction loop, which can be modeled as an loop inductance $L$ in parallel with the junction and a capacitance $C$ and a resistance $R$. If we ignore the resistance, adjust to an appropriate critical current through the junction, and apply an appropriate small biasing magnetic field through the loop, then we believe that it is possible to treat the rf SQUID as a qubit with flux (magnetic field times area of the loop) as the relevant macroscopic quantum variable. That is, in a simple picture, clockwise current through the loop can be taken as 1 and counter-clockwise current as 0. This can be modeled as a double potential well. Coupling among qubits arises because the magnetic field from one qubits influences the properties of a neighboring qubit.

This project on quantum computing began last summer with support from
Department of Defense. The research is very difficult because the experiments must be carried out at mK temperatures in a special He³-He⁴ dilution refrigerator and the SQUIDs must be well isolated from outside interference in order to have long coherence times. Our approach to the development of a quantum computer is sequential.

First, we must prepare very good junctions, probably from aluminum or niobium. At the same time, we must learn how to isolate our system in the dilution refrigerator from external noise. Next, we must prepare rf SQUIDs and exhibit tunneling from one well to another in the SQUID. This is called macroscopic quantum tunneling or MQT. The quantum mechanical energy levels in the double-well system are separated by energies in the GHz range. The next step will be to look for enhanced absorption of microwaves at frequencies corresponding to the separations of the energy levels. This is called energy level spectroscopy. Then, we must see if there is quantum coherence, that is look for coherent tunneling between the two wells. This is called macroscopic quantum coherence (MQC) and may be the most difficult aspect of the research. Finally, we must prepare arrays of rf SQUIDs and look for interactions among them.

At the present time, four faculty (J. R. Anderson, A. J. Dragt, C. Lobb, and F. C. Wellstood), two post-docs (Roberto Ramos and Phil Johnson), and four students (Mark Gubrud, Mikkel Erjnaes, Jim Farrell and Dan Sullivan) are involved in this research, which is being carried out primarily in our Center for Superconductivity. In addition, Dr. Manheimer is setting up a parallel system with a dilution refrigerator at the Laboratory for Physical Sciences. We have already made very good Al/AlO/Al junctions as demonstrated by their current-voltage characteristics. One of the dilution refrigerators, a 50 µW system, is operating successfully down to 90 mK and the second, a 100 µW system, is being modified and with it we already have reached temperatures below 20 mK. There is a long way to go before successful realization of a quantum computer. A first step will be to demonstrate that quantum mechanics really applies to a system of rf SQUIDs. Experts have predicted that 40 years should be allowed for the development of a working quantum computer.