QUANTUM COMPUTING WITH SUPERCONDUCTORS I: ARCHITECTURES

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Abstract: Josephson junctions have demonstrated enormous potential as qubits for scalable quantum computing architectures. Here we discuss the current approaches for making multi-qubit circuits and performing quantum information processing with them.

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1 Introduction

Macroscopic quantum behavior in a Josephson junction (JJ) was first demonstrated in the mid-1980s by John Clarke's group at UC Berkeley (Devoret et al., 1985; Martinis et al., 1985, 1987; Clarke et al., 1988). These experiments used a superconducting device referred to as a large area, current-biased JJ, which would later become the phase qubit. Beginning in the mid-1990s the group of James Lukens at SUNY Stony Brook (Rouse et al., 1995; Friedman et al., 2000) and a collaboration between the Delft University group of Hans Mooij and the MIT group of Terry Orlando (Mooij et al., 1999; van der Wal et al., 2000) demonstrated macroscopic quantum behavior in superconducting loops interrupted by one or more JJs (called superconducting quantum interference devices, or SQUIDS), what would later become flux qubits. And in the late 1990s the group of Yasunobu Nakamura at NEC in Tsukuba (Nakamura et al., 1997, 1999) developed the first

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Cooper-pair box or charge qubit. Many of the earlier experiments were motivated by seminal theoretical work of Caldeira and Leggett (1981, 1983).

The modern era of superconducting quantum computation began in 2002. That year, the group of Siyuan Han at the University of Kansas and the group of John Martinis, then at NIST Boulder and currently at UC Santa Barbara, independently showed that long-lived quantum states in a current-biased JJ can be controllably prepared, manipulated, and subsequently measured (Martinis et al., 2002; Yu et al., 2002). This same year, the group of Michel Devoret, then at the CEA in Saclay and currently at Yale University, demonstrated similar quantum control using a Cooper-pair box (Vion et al., 2002). These experiments suggest that JJ-based qubits can be used as the building blocks of a solid-state quantum computer, creating a tremendous interest in this intrinsically scalable approach. An impressive list of additional experimental achievements soon followed, including the demonstration of two-qubit quantum logic (Yamamoto et al., 2003).

In this chapter we will review the current approaches for making multi-qubit systems. For a more detailed discussion of single qubits we refer to the excellent review by Makhlin et al., (2001). Also, a recent introductory account of the field has been given by You and Nori (2005). The approach we follow here is to construct circuit models for the basic qubits and coupled-qubit architectures. Many designs have been proposed, but only the simplest have been implemented experimentally to date.

After reviewing in section 2 the basic phase, flux, and charge qubits, we discuss three broad classes of coupling schemes. The simplest class uses fixed linear coupling elements, such as capacitors or inductors, and is discussed in section 3. The principal effect of fixed, weak couplings is to lift degeneracies of the uncoupled qubit pair. However, because such interactions are always present (always turned on), the uncoupled qubit states, which are often used as computational basis states, are not stationary. A variety of approaches have been proposed to overcome this shortcoming. In section 4 we discuss tunable couplings that allow the interactions of section 3 to be tuned, ideally between "on" and "off" values. A related class of *dynamic* couplings is discussed in section 5, which make use of coupling elements that themselves have active internal degrees of freedom. They act like tunable coupling elements, but also have additional functionality coming from the ability to excite the internal degrees of freedom. Examples of this are resonator-based couplings, which we discuss in some detail.

2 The Basic Qubits: Phase, Flux, and Charge

The primitive building block for all the qubits is the JJ shown in Figure 1. The low-energy dynamics of this system is governed by the phase difference φ between the condensate wave functions or order parameters on the two sides of the insulating