

SYSTEMS, METHODS AND APPARATUS
FOR LOCAL PROGRAMMING OF QUANTUM PROCESSOR ELEMENTS

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims benefit under 35 U.S.C. 119(e) to U.S.
5 provisional patent application Serial No. 60/868,654, filed December 5, 2006,
which is incorporated herein by reference in its entirety.

BACKGROUND

Field

The present systems, methods and apparatus relate to scalable
10 quantum computing and the local programming of quantum processor elements.

Description of the Related Art

A Turing machine is a theoretical computing system, described in
1936 by Alan Turing. A Turing machine that can efficiently simulate any other
Turing machine is called a Universal Turing Machine (UTM). The Church-Turing
15 thesis states that any practical computing model has either the equivalent or a
subset of the capabilities of a UTM.

A quantum computer is any physical system that harnesses one or
more quantum effects to perform a computation. A quantum computer that can
efficiently simulate any other quantum computer is called a Universal Quantum
20 Computer (UQC).

In 1981 Richard P. Feynman proposed that quantum computers
could be used to solve certain computational problems more efficiently than a UTM
and therefore invalidate the Church-Turing thesis. See *e.g.*, *Feynman R. P.*,
"Simulating Physics with Computers", *International Journal of Theoretical Physics*,
25 Vol. 21 (1982) pp. 467-488. For example, *Feynman* noted that a quantum

computer could be used to simulate certain other quantum systems, allowing exponentially faster calculation of certain properties of the simulated quantum system than is possible using a UTM.

Approaches to Quantum Computation

5 There are several general approaches to the design and operation of quantum computers. One such approach is the "circuit model" of quantum computation. In this approach, qubits are acted upon by sequences of logical gates that are the compiled representation of an algorithm. Circuit model quantum computers have several serious barriers to practical implementation. In the circuit
10 model, it is required that qubits remain coherent over time periods much longer than the single-gate time. This requirement arises because circuit model quantum computers require operations that are collectively called quantum error correction in order to operate. Quantum error correction cannot be performed without the circuit model quantum computer's qubits being capable of maintaining quantum
15 coherence over time periods on the order of 1,000 times the single-gate time. Much research has been focused on developing qubits with coherence sufficient to form the basic information units of circuit model quantum computers. See *e.g.*, Shor, P. W. "Introduction to Quantum Algorithms", arXiv.org:quant-ph/0005003 (2001), pp. 1-27. The art is still hampered by an inability to increase the
20 coherence of qubits to acceptable levels for designing and operating practical circuit model quantum computers.

 Another approach to quantum computation comprises using the natural physical evolution of a system of coupled quantum systems as a computational system. This approach does not make critical use of quantum gates
25 and circuits. Instead, starting from a known initial Hamiltonian, it relies upon the guided physical evolution of a system of coupled quantum systems wherein the problem to be solved has been encoded in the terms of the system's Hamiltonian, so that the final state of the system of coupled quantum systems contains

information relating to the answer to the problem to be solved. This approach does not require long qubit coherence times. Examples of this type of approach include adiabatic quantum computation, cluster-state quantum computation, one-way quantum computation, quantum annealing and classical annealing, and are
5 described, for example, in *Farhi, E. et al.*, "Quantum Adiabatic Evolution Algorithms versus Simulated Annealing" arXiv.org:quant-ph/0201031 (2002), pp 1-16.

Embodiments of Quantum Computers

A quantum computer is any computing device that makes direct use
10 of quantum mechanical phenomena, such as superposition and entanglement, to solve computational problems. To date, many different systems have been proposed and studied as physical realizations of quantum computers. Examples of such systems include the following devices: ion traps, quantum dots, harmonic oscillators, cavity quantum electrodynamics devices (QED), photons and nonlinear
15 optical media, heteropolymers, cluster-states, anyons, topological systems, systems based on nuclear magnetic resonance (NMR), and systems based on spins in semiconductors. For further background on these systems, see Nielsen and Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, Cambridge (2000), pp. 277-352; Williams and Clearwater,
20 *Explorations in Quantum Computing*, Springer-Verlag, New York, Inc. (1998), pp. 241-265; Nielsen, Micheal A., "Cluster-State Quantum Computation", arXiv.org:quant-ph/0504097v2 (2005), pp 1-15; and Brennen, Gavin K. et al., "Why should anyone care about computing with anyons?", arXiv.org:quant-ph/0704.2241 (2007), pp 1-19.

25 In brief, an example of an ion trap quantum computer is a computer structure that employs ions that are confined in free space using electromagnetic fields. Qubits may be represented by the stable electronic states of each ion. An example of a quantum dot quantum computer is a computer structure that employs

electrons that have been confined to small regions where their energies can be quantized in such a way that each dot may be isolated from the other dots. An example of a harmonic oscillator is computer structure that employs a particle in a parabolic potential well. An example of an optical photon quantum computer is a
5 computer structure in which qubits are represented by individual optical photons which may be manipulated using beam-splitters, polarization filters, phase shifters, and the like. An example of a cavity QED quantum computer is a computer structure that employs single atoms within optical cavities where the single atoms are coupled to a limited number of optical modes. An example of an NMR
10 quantum computer is a computer structure in which qubits are encoded in the spin states of at least one of the nuclei in the atoms comprising a molecular sample. An example of a heteropolymer quantum computer is a computer structure that employs a linear array of atoms as memory cells, where the state of the atoms provides the basis for a binary arithmetic. An example of a quantum computer that
15 uses electron spins in semiconductors is the Kane computer, in which donor atoms are embedded in a crystal lattice of, for example, silicon. An example of a topological quantum computer is a computer structure that employs two-dimensional "quasiparticles" called anyons whose world lines cross to form braids in a three-dimensional spacetime. These braids may then be used as the logic
20 gates that make up the computer structure. Lastly, an example of a cluster-state quantum computer is a computer structure that employs a plurality of qubits that have been entangled into one quantum state, referred to as a cluster-state. "Cluster-state" generally refers to a particular quantum computing method, and those of skill in the art will appreciate that the present systems, methods and
25 apparatus may incorporate all forms of quantum computing, including the various hardware implementations and algorithmic approaches. Those of skill in the art will also appreciate that the descriptions of various embodiments of quantum computers provided herein are intended only as examples of some different physical realizations of quantum computation. The present systems, methods and

apparatus are in no way limited by or to these descriptions. Those of skill in the art will also appreciate that a quantum processor may be embodied in a system other than those described above.

Qubits

5 As mentioned previously, qubits can be used as fundamental units of information for a quantum computer. As with bits in UTMs, qubits can refer to at least two distinct quantities; a qubit can refer to the actual physical device in which information is stored, and it can also refer to the unit of information itself, abstracted away from its physical device.

10 Qubits generalize the concept of a classical digital bit. A classical information storage device can encode two discrete states, typically labeled "0" and "1". Physically these two discrete states are represented by two different and distinguishable physical states of the classical information storage device, such as direction or magnitude of magnetic field, current, or voltage, where the quantity
15 encoding the bit state behaves according to the laws of classical physics. A qubit also contains two discrete physical states, which can also be labeled "0" and "1". Physically these two discrete states are represented by two different and distinguishable physical states of the quantum information storage device, such as direction or magnitude of magnetic field, current, or voltage, where the quantity
20 encoding the bit state behaves according to the laws of quantum physics. If the physical quantity that stores these states behaves quantum mechanically, the device can additionally be placed in a superposition of 0 and 1. That is, the qubit can exist in both a "0" and "1" state at the same time, and so can perform a computation on both states simultaneously. In general, N qubits can be in a
25 superposition of 2^N states. Quantum algorithms make use of the superposition property to speed up some computations.

 In standard notation, the basis states of a qubit are referred to as the $|0\rangle$ and $|1\rangle$ states. During quantum computation, the state of a qubit, in general, is

a superposition of basis states so that the qubit has a nonzero probability of occupying the $|0\rangle$ basis state and a simultaneous nonzero probability of occupying the $|1\rangle$ basis state. Mathematically, a superposition of basis states means that the overall state of the qubit, which is denoted $|\Psi\rangle$, has the form $|\Psi\rangle = a|0\rangle + b|1\rangle$, where
5 a and b are coefficients corresponding to the probabilities $|a|^2$ and $|b|^2$, respectively. The coefficients a and b each have real and imaginary components, which allows the phase of the qubit to be characterized. The quantum nature of a qubit is largely derived from its ability to exist in a coherent superposition of basis states and for the state of the qubit to have a phase. A qubit will retain this ability
10 to exist as a coherent superposition of basis states when the qubit is sufficiently isolated from sources of decoherence.

To complete a computation using a qubit, the state of the qubit is measured (*i.e.*, read out). Typically, when a measurement of the qubit is performed, the quantum nature of the qubit is temporarily lost and the
15 superposition of basis states collapses to either the $|0\rangle$ basis state or the $|1\rangle$ basis state and thus regaining its similarity to a conventional bit. The actual state of the qubit after it has collapsed depends on the probabilities $|a|^2$ and $|b|^2$ immediately prior to the readout operation.

Superconducting Qubits

20 One hardware approach to quantum computation uses integrated circuits formed of superconducting materials, such as aluminum or niobium. The technologies and processes involved in designing and fabricating superconducting integrated circuits are similar to those used for conventional integrated circuits.

Superconducting qubits are a type of superconducting device that
25 can be included in a superconducting integrated circuit. Superconducting qubits can be separated into several categories depending on the physical property used to encode information. For example, they may be separated into charge, flux and phase devices, as discussed in, for example Makhlin *et al.*, 2001, *Reviews of*

- Modern Physics* 73, pp. 357–400. Charge devices store and manipulate information in the charge states of the device, where elementary charges consist of pairs of electrons called Cooper pairs. A Cooper pair has a charge of $2e$ and consists of two electrons bound together by, for example, a phonon interaction.
- 5 See e.g., Nielsen and Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, Cambridge (2000), pp. 343-345. Flux devices store information in a variable related to the magnetic flux through some part of the device. Phase devices store information in a variable related to the difference in superconducting phase between two regions of the phase device. Recently,
- 10 hybrid devices using two or more of charge, flux and phase degrees of freedom have been developed. See e.g., US Patent No. 6,838,694 and US Patent Application No. 2005-0082519.

Examples of flux qubits that may be used include rf-SQUIDs, which include a superconducting loop interrupted by one Josephson junction, or a

15 compound junction (where a single Josephson junction is replaced by two parallel Josephson junctions), or persistent current qubits, which include a superconducting loop interrupted by three Josephson junctions, and the like. See e.g., Mooij *et al.*, 1999, *Science* 285, 1036; and Orlando *et al.*, 1999, *Phys. Rev. B* 60, 15398. Other examples of superconducting qubits can be found, for example,

20 in Il'ichev *et al.*, 2003, *Phys. Rev. Lett.* 91, 097906; Blatter *et al.*, 2001, *Phys. Rev. B* 63, 174511, and Friedman *et al.*, 2000, *Nature* 406, 43. In addition, hybrid charge-phase qubits may also be used.

The qubits may include a corresponding local bias device. The local bias devices may include a metal loop in proximity to a superconducting qubit that

25 provides an external flux bias to the qubit. The local bias device may also include a plurality of Josephson junctions. Each superconducting qubit in the quantum processor may have a corresponding local bias device or there may be fewer local bias devices than qubits. In some embodiments, charge-based readout and local bias devices may be used. The readout device(s) may include a plurality of dc-

SQUID magnetometers, each inductively connected to a different qubit within a topology. The readout device may provide a voltage or current. DC-SQUID magnetometers typically include a loop of superconducting material interrupted by at least one Josephson junction.

5 Superconducting Quantum Processor

A computer processor may take the form of an analog processor, for instance a quantum processor such as a superconducting quantum processor. A superconducting quantum processor may include a number of qubits and associated local bias devices, for instance two or more superconducting qubits.

- 10 Further detail and embodiments of exemplary superconducting quantum processors that may be used in conjunction with the present systems, methods, and apparatus are described in US Patent Publication No. 2006-0225165; US Provisional Patent Application Serial No. 60/872,414, filed January 12, 2007, entitled "System, Devices and Methods for Interconnected Processor Topology";
- 15 US Provisional Patent Application Serial No. 60/956,104, filed August 16, 2007, entitled "Systems, Devices, And Methods For Interconnected Processor Topology"; and US Provisional Patent Application Serial No. 60/986,554, filed November 8, 2007 and entitled "Systems, Devices and Methods for Analog Processing."

- A superconducting quantum processor may include a number of
- 20 coupling devices operable to selectively couple respective pairs of qubits. Examples of superconducting coupling devices include rf-SQUIDs and dc-SQUIDs, which couple qubits together by flux. SQUIDs include a superconducting loop interrupted by one Josephson junction (an rf-SQUID) or two Josephson junctions (a dc-SQUID). The coupling devices may be capable of both ferromagnetic and
- 25 anti-ferromagnetic coupling, depending on how the coupling device is being utilized within the interconnected topology. In the case of flux coupling, ferromagnetic coupling implies that parallel fluxes are energetically favorable and anti-ferromagnetic coupling implies that anti-parallel fluxes are energetically

favorable. Alternatively, charge-based coupling devices may also be used. Other coupling devices can be found, for example, in U.S. Patent Publication Number 2006-0147154 and US Provisional Patent Application Serial No. 60/886,253 filed January 23, 2007 and entitled "Systems, Devices, and Methods for Controllably
5 Coupling Qubits". Respective coupling strengths of the coupling devices may be tuned between zero and a maximum value, for example, to provide ferromagnetic or anti-ferromagnetic coupling between qubits.

Regardless of the specific hardware being implemented, managing a single qubit may require control over a number of parameters. Conventionally, this
10 requirement has necessitated outside communication (that is, communication from outside of the quantum processor architecture) with each individual qubit. However, the overall processing power of the quantum computer increases with the number of qubits in the system. Therefore, high capacity quantum computers that exceed the abilities of conventional supercomputers must manage a large
15 number of qubits and thus the conventional approach of employing outside control over multiple parameters on each individual qubit requires a complicated system for programming qubit parameters.

Thus, the scalability of quantum processors is limited by the complexity of the qubit parameter control system and there remains a need in the
20 art for a scalable qubit parameter control system.

BRIEF SUMMARY

At least one embodiment may be summarized as a quantum processor including a plurality of programmable devices, wherein each programmable device is connected to at least one communication conduit; and a
25 memory administration system, wherein the memory administration system is linked to at least one programmable device via at least one of the communication conduits.

At least one embodiment may be summarized as a method of programming a quantum processor comprising at least one programmable device, the method including locally programming at least one information storage device with a data signal embodying at least one programmable device control parameter;
5 converting the data signal to an analog signal; and administering the analog signal to the programmable device.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not
10 necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn, are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of
15 recognition in the drawings.

Figure 1A is a schematic diagram of one embodiment of the local programming of quantum processor elements according to the present systems, methods and apparatus.

Figure 1B is a schematic diagram of another embodiment of the local
20 programming of quantum processor elements.

Figures 2A and 2B are flow diagrams of embodiments of methods for respectively programming and reading quantum processor elements.

Figure 3 is a schematic diagram of an embodiment of local programming of a quantum processor through a demultiplexer circuit.

25 DETAILED DESCRIPTION

In the following description, some specific details are included to provide a thorough understanding of various disclosed embodiments. One skilled

in the relevant art, however, will recognize that embodiments may be practiced without one or more of these specific details, or with other methods, components, materials, etc. In other instances, well-known structures associated with quantum processors, such as quantum devices, coupling devices and control systems, including microprocessors and drive circuitry, have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments of the present systems, methods and apparatus. Throughout this specification, the words "element" and "elements" are used to encompass, but are not limited to, all such structures, systems and devices associated with quantum processors, as well as their related programmable parameters.

Unless the context requires otherwise, throughout the specification and claims which follow, the word "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is, as "including, but not limited to."

Reference throughout this specification to "one embodiment," "an embodiment" or "another embodiment" means that a particular referent feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrases "in one embodiment," "in an embodiment" or "another embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

It should be noted that, as used in this specification and the appended claims, the singular forms "a," "an" and "the" include plural referents unless the content clearly dictates otherwise. Thus, for example, reference to "a quantum processor" includes a single quantum processor or two or more quantum processors. It should also be noted that the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise.

Furthermore, it should be noted that while a portion of this specification and the appended claims describes the application of this disclosure in a quantum processor comprising superconducting flux qubits, those of skill in the art will appreciate that the methods described herein may easily be adapted to
5 apply to other forms of quantum processors.

The headings provided herein are for convenience only and do not interpret the scope or meaning of the embodiments.

In accordance with the present systems, methods and apparatus, a scalable technique for quantum computing involving local programming of
10 quantum processor elements is described. Throughout this specification and the appended claims, the term "quantum processor" is used to describe a system that comprises at least two qubits and at least one device, such as a qubit coupler, for communicating information between at least two qubits. Some embodiments of a quantum processor may include tens, hundreds, thousands, or even millions of
15 qubits and qubit couplers. In some embodiments, the components of a quantum processor may be entirely contained within a single structure, such as a superconducting quantum processor chip. In other embodiments, the components of a quantum processor may be distributed over a plurality of structures with a means for communicating information therebetween.

20 Figure 1A shows an exemplary quantum processor 100 which includes memory administration system 101 and three programmable devices 121, 122, 123. Throughout this specification and the appended claims, the terms "programmable device" and "programmable devices" are used to describe any of a variety of components in a quantum processor for which programming is desired.
25 Examples of programmable devices include qubits, qubit couplers, specific components of qubits and qubit couplers, and the like. For example, a superconducting flux qubit may include two components: a closed superconducting current path and a compound Josephson junction, and separate data signals may be programmed into both of these components individually.

Those of skill in the art will appreciate that quantum processor 100 may be scaled to include any number of devices by simply scaling the devices shown in Figure 1A accordingly. Furthermore, although Figure 1A shows quantum processor 100 as one physical structure, the components of quantum processor 100 may be divided into a plurality of separate physical units that are communicably connected by a system of communication conduits. For example, quantum processor 100 may include a plurality of distinct processor chips, or a multi-chip module, wherein spatially separated components may be communicably connected by a system of communication conduits. Reference throughout this specification and the appended claims to a "communication conduit" or a plurality of "communication conduits" encompasses all means of signal transfer, including but not limited to electrical wires, conductive traces, magnetic (inductive) coupling, capacitive coupling, fiber-optics, and the like.

In Figure 1A, memory administration system 101 comprises a string of memory registers 111, 112, 113 which are used to administer signals representative of data, such as N-bit digital signals, to each programmable device 121-123 in quantum processor 100. Those of skill in the art will appreciate that the terms "administer", "administering", "administration" and the like are used herein to encompass, but are not limited to, all manner of generating, managing, storing, operating upon and transferring the data signals. The N-bit signals may be programmed to represent various parameters that influence the behavior of programmable devices 121-123. For illustration, 8-bit signals and serially connected 8-bit memory registers 111-113 are shown in Figure 1A, but those of skill in the art will appreciate that signals of any bit length or resolution may be employed and that memory registers 111-113 may be connected in another manner or may not be connected at all, *i.e.*, they may be connected in parallel, in an X-Y addressable array, through a demultiplexer circuit, in a network including at least one packet router, or they may each be independently controlled and each have their own individual communication lines A, B, C, D.

As shown in Figure 1A, the data signals administered by memory registers 111-113 are digital signals, however those of skill in the art will appreciate that data signals of other forms may be employed. Before being applied to programmable devices 121-123, the digital signals may be converted into analog signals by digital-to-analog converters (DACs) 131, 132, 133. Each respective DAC 131-133 may receive the digital bits of an N-bit signal and use this N-bit digital signal to produce at least one analog signal which may then be administered to at least one of programmable devices 121-123. In some embodiments, such as that shown in Figure 1A, this administration is accomplished via intermediate coupling devices 141, 142, 143. The intermediate coupling devices 141-143 may each be connected to a coupler activation line and be activated/deactivated by the coupler activation line. In some embodiments, intermediate coupling devices 141-143 may be connected in series to a single coupler activation line as illustrated in Figure 1A. Thus, in such embodiments, a signal is only administered or applied from a DAC 131-133 to a programmable device 121-123 when a corresponding intermediate coupling device 141-143 is activated by the coupler activation line. For example, a signal may be administered from DAC 131 to programmable device 121 when intermediate coupling device 141 is activated by the coupler activation line. In some embodiments, a coupler activation line may be analog variable such that intermediate coupling devices 141-143 may provide controllable levels of partial coupling between DACs 131-133 and programmable devices 121-123. In some embodiments, a coupler activation line may only be ON/OFF controllable, such that intermediate coupling devices 141-143 may provide only controllable ON/OFF coupling between DACs 131-133 and programmable devices 121-123. Other embodiments of the present systems, methods and apparatus may omit the intermediate coupling devices 141-143 and instead signals may be coupled directly from DACs 131-133 to programmable devices 121-123.

By employing the present systems, methods and apparatus, at least a portion of the control communication may be contained within quantum processor 100 while external input includes the programming of the N-bit signals via communication lines A-D, and, in some embodiments, the control of
5 intermediate coupling devices 141-143 via at least one coupler activation line. As such, the number of communication lines required to connect quantum processor 100 to an external system is greatly reduced and becomes essentially independent of the number of programmable devices in quantum processor 100.

One skilled in the art will recognize that a DAC may be applied to
10 convert digital signals to analog, analog signals to digital, or to perform both operations simultaneously or interchangeably, depending on the signal direction. As such, the system described in Figure 1A may also be operated in reverse, whereby signals from programmable devices 121-123 are coupled to DACs 131-133 via intermediate coupling devices 141-143. The signals may then be
15 converted into digital representations which may be administered or applied to memory registers 111-113 and transmitted to an external reading system.

The present systems, methods and apparatus are not linked to a particular type of quantum processor and its associated programmable devices. Rather, the present systems, methods and apparatus may be applied to any form
20 of quantum processor. In some embodiments, quantum processor 100 may be a superconducting quantum processor comprising a plurality of superconducting flux qubits coupled by a plurality of programmable qubit couplers, such as those described in US Patent Publication Nos. 2006-0225165 and 2006-0147154, and in *Harris, R.. et al.*, "Sign and Magnitude Tunable Coupler for Superconducting Flux
25 Qubits", arXiv.org:cond-mat/0608253 (2006), pp 1-5. Since such qubits and their associated couplers are designed to manage flux signals, the N-bit signals from memory registers 111-113 may be administered in the form of discrete magnetic flux quanta. Memory registers 111-113 may then take the form of superconducting shift registers, such as single flux quantum (SFQ) shift registers or the flux-based

superconducting shift registers described in US Provisional Patent Application Serial No. 60/913,980, filed April 25, 2007, and entitled "Adiabatic Superconducting Qubit Logic Devices And Methods." In some embodiments, the superconducting shift registers may be serially linked as illustrated in Figure 1A, or they may be connected in parallel, or they may be connected in an X-Y addressable array, or they may be connected to a routing system. The N-bit signal loaded into each register may be represented digitally by discrete magnetic flux quanta within the superconducting shift registers. Each of the superconducting shift registers 111-113 may be inductively or galvanically coupled to a respective superconducting DAC 131-133, where the digital magnetic flux quanta may be used to produce at least one analog supercurrent. Thus, in some embodiments a memory register, such as memory register 111 and a DAC, such as DAC 131, may be realized within the same physical structure. Examples of superconducting DACs are described in US Provisional Patent Application Serial No. 60/917,884, filed May 14, 2007, entitled "Scalable Superconducting Flux Digital-To-Analog Conversion Using A Superconducting Inductor Ladder Circuit"; US Provisional Patent Application Serial No. 60/917,891, filed May 14, 2007, entitled "Systems, Methods, And Apparatus For A Scalable Superconducting Flux Digital-To-Analog Converter"; and US Provisional Patent Application Serial No. 60/975,487, filed September 26, 2007, and entitled "Systems, Methods and Apparatus for a Differential Superconducting Flux Digital-to-Analog Converter."

In some embodiments, the at least one analog supercurrent that is output by a DAC may be inductively coupled to at least one programmable device 121-123 via at least one intermediate coupling device 141-143 by activating the coupler activation line. In other embodiments, the at least one analog supercurrent may be inductively coupled directly to at least one of programmable devices 121-123. As previously described, in some embodiments the system may also be operated in reverse to produce digital output from the SFQ shift registers based on analog input from one or more programmable devices 121-123.

In some embodiments of the present systems, methods and apparatus, a plurality of DACs may be coupled to a single programmable device. Figure 1B is a schematic diagram of such an embodiment for the local programming of quantum processor elements. The embodiment illustrated in

5 Figure 1B is similar to that illustrated in Figure 1A, except that in Figure 1B two DACs 132 and 133 are coupled to a single programmable device 124, while DACs 132 and 133 are also each coupled to a respective memory register 112 and 113. This coupling scheme can provide control over the rate at which programmable device 124 is programmed from an initial state X to a programmed state Y,

10 effectively realizing an arbitrary waveform generator. In the embodiment shown in Figure 1A, each programmable device 121-123 is coupled to a single DAC (131-133, respectively) and therefore each programmable device 121-123 is programmed at the same time and at the same rate. However, in the embodiment shown in Figure 1B, programmable device 124 is coupled to two DACs 132 and

15 133 and this allows a degree of control over the time and rate at which programmable device 124 is programmed. Those of skill in the art will appreciate that while only one programmable device 124 is shown as being coupled to two DACs 132 and 133 in Figure 1B, all or any number of the programmable devices in a quantum processor may be coupled to two or any number of DACs.

20 Figure 2A is a flow diagram of a method 200 for programming the elements of a quantum processor (such as, for example, quantum processor 100 of Figure 1A) according to an embodiment of the present systems, methods and apparatus. Those of skill in the art will appreciate that while Figure 2A refers to all devices in singular form, method 200 may be applied over a plurality of devices. In

25 act 201 of method 200, a binary signal is programmed or written to a memory register (such as one or more of memory registers 111-113 from Figure 1A). In act 202, the binary signal is converted into a analog signal. In act 203, the analog signal is administered or applied to one or more programmable devices of the quantum processor, such as programmable devices 121-123 from Figure 1A.

Thus, acts 201 through 203 may all be completed within the dimensions of the quantum processor, thus reducing the need for communication with external programming systems.

Figure 2B is a flow diagram of a method 250 for reading information
5 from readable devices by essentially operating method 200 in reverse. Those of skill in the art will appreciate that while Figure 2B refers to all devices in singular form, method 250 may be applied over a plurality of devices. In act 251, a signal is output by or read from the readable device and converted into a digital representation. In act 252, the digital representation of the signal is output to or
10 read-out by another system. Again, acts 251 to 252 may be completed within the dimensions of the quantum processor, thus reducing the need for communication with external programming systems.

As previously discussed, a variety of coupling schemes may be implemented to program data storage devices, such as memory registers 111-113.
15 For instance, memory registers 111-113 may be serially coupled to communication lines A-D as illustrated in Figures 1A and 1B. In other embodiments, memory registers 111-113 may be coupled in parallel to similar communication lines. In some embodiments of the present systems, methods and apparatus, the data storage devices may be programmed through a routing system; an example of
20 such a routing system is a demultiplexer circuit.

Figure 3 is a schematic diagram of an embodiment of local programming of a quantum processor 300 through a demultiplexer circuit 350. As illustrated in Figure 3, quantum processor 300 includes memory administration system 301, which is similar to memory administration system 101 from Figure 1A
25 except that it includes a demultiplexer circuit 350 that may be used to rout signals to data storage devices 311-313. In operation, demultiplexer 350 may receive a signal through at least one of communication lines A and B and, through a sequence of internal routing procedures, direct the signal towards a specific output channel. The specific output channel may correspond to at least one of data

storage devices 311-313. The general operation of a demultiplexer is understood in the art; as such, those of skill in the art will appreciate that demultiplexer 350 may include additional signal input lines. In some embodiments, demultiplexer 350 may include a plurality of routing devices arranged in logical rows to form a logical binary tree. Demultiplexer 350 may include additional signal input lines (not shown) such that each logical row of routing devices is controlled by a respective signal input line.

The above description of illustrated embodiments is not intended to be exhaustive or to limit the embodiments to the precise forms disclosed.

Although specific embodiments of and examples are described herein for illustrative purposes, various equivalent modifications can be made without departing from the spirit and scope of the disclosure, as will be recognized by those skilled in the relevant art. The teachings provided herein of the various embodiments can be applied to other quantum computing systems, methods and apparatus, not necessarily the exemplary quantum computing systems, methods and apparatus generally described above.

For instance, the foregoing detailed description has set forth various embodiments of the systems, methods and apparatus via the use of block diagrams, schematics, and examples. Insofar as such block diagrams, schematics, and examples contain one or more functions and/or operations, it will be understood by those skilled in the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof.

The various embodiments described above can be combined to provide further embodiments.

All of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification including, but not limited to: US Patent

No. 6,838,694; US Patent Publication No. 2005-0082519; US Patent Publication No. 2006-0225165; US Provisional Patent Application Serial No. 60/872,414, filed January 12, 2007, entitled "System, Devices and Methods for Interconnected Processor Topology"; US Provisional Patent Application Serial No. 60/956,104, 5 filed August 16, 2007, entitled "Systems, Devices, And Methods For Interconnected Processor Topology"; US Provisional Patent Application Serial No. 60/986,554, filed November 8, 2007, entitled "Systems, Devices and Methods for Analog Processing"; US Patent Publication No. 2006-0225165; US Patent Publication No. 2006-0147154; US Provisional Patent Application Serial No. 10 60/913,980, filed April 25, 2007, and entitled "Adiabatic Superconducting Qubit Logic Devices And Methods"; US Provisional Patent Application Serial No. 60/917,884, filed May 14, 2007, entitled "Scalable Superconducting Flux Digital-To-Analog Conversion Using A Superconducting Inductor Ladder Circuit"; US Provisional Patent Application Serial No. 60/917,891, filed May 14, 2007, entitled 15 "Systems, Methods, And Apparatus For A Scalable Superconducting Flux Digital-To-Analog Converter"; and US Provisional Patent Application Serial No. 60/975,487, filed September 26, 2007, entitled "Systems, Methods and Apparatus for a Differential Superconducting Flux Digital-to-Analog Converter" are incorporated herein by reference, in their entirety and for all purposes. Aspects of 20 the embodiments can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments.

These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms 25 used should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the scope of the invention shall only be construed and defined by the scope of the appended claims.

CLAIMS

1. A quantum computing system comprising:
an external programming system;
a quantum processor; and
a number of communication lines providing communication between the external programming system and the quantum processor, wherein the quantum processor further comprises:
a number of programmable devices; and
a memory administration system including a plurality of communication conduits, wherein the memory administration system provides communication between the communication lines and at least some of the communication conduits to administer data signals from the external programming system to the programmable devices, and wherein the number of programmable devices is greater than the number of communication lines.
2. The quantum computing system of claim 1 wherein the quantum processor includes at least one programmable device that is formed of a material that is superconducting below a critical temperature.
3. The quantum computing system of claim 1 wherein at least one of the communication conduits of the memory administration system is formed of a material that is superconducting below a critical temperature.
4. The quantum computing system of claim 1 wherein the quantum processor includes at least one programmable device that is selected from the group consisting of: a closed superconducting current path, a compound Josephson junction, a superconducting flux qubit, a superconducting charge qubit, a superconducting phase qubit, a superconducting hybrid qubit, a qubit coupler, a superconducting qubit coupler, a quantum dot, a trapped ion, a trapped neutral atom, an impurity, a nuclear spin qubit, an electronic spin qubit, and a photonic qubit.

5. The quantum computing system of claim 1 wherein the memory administration system includes at least one digital-to-analog converter (DAC).

6. The quantum computing system of claim 5 wherein the DAC includes a superconducting DAC, and wherein digital signals are represented by discrete magnetic flux quanta.

7. The quantum computing system of claim 1 wherein the memory administration system includes an X-Y addressable array.

8. The quantum computing system of claim 1 wherein the memory administration system includes a demultiplexer circuit.

9. A method of programming a quantum processor, wherein the quantum processor includes a number of programmable devices and a memory administration system, the method comprising:

defining a plurality of programmable parameters corresponding to the number of programmable devices by an external programming system;

transmitting a plurality of signals embodying the plurality of programmable parameters from the external programming system to the memory administration system via a number of communication lines that is less than the number of programmable devices; and

administering the plurality of signals embodying the plurality of programmable parameters to the number of programmable devices by the memory administration system.

10. The method of claim 9 wherein the memory administration system includes at least one digital-to-analog converter (DAC) and the plurality of signals embodying the plurality of programmable parameters are digital signals, and further comprising:

converting the plurality of signals embodying the plurality of programmable parameters from digital signals to analog signals by the at least one DAC before administering

the plurality of signals embodying the plurality of programmable parameters to the number of programmable devices.

11. The method of claim 9 wherein administering the plurality of signals embodying the plurality of programmable parameters to the number of programmable devices by the memory administration system includes routing the plurality of signals embodying the plurality of programmable parameters to the number of programmable devices via an X-Y addressable array.

12. The method of claim 9 wherein administering the plurality of signals embodying the plurality of programmable parameters to the number of programmable devices by the memory administration system includes routing the plurality of signals embodying the plurality of programmable parameters to the number of programmable devices via a demultiplexer circuit.