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McClean, J. Exploiting locality in quantum computation for quantum chemistry. Reiher, M. Elucidating reaction mechanisms on quantum computers. Peruzzo, A. A variational eigenvalue solver on a photonic quantum processor. Scalable quantum simulation of molecular energies. X 6 , This paper is a good example of the emerging importance of classical-quantum co-processing. Valiron, B. Programming the quantum future.

ACM 58 , 52—61 This paper offers another perspective on quantum programming language design issues. Metodi, T. A quantum logic array microarchitecture scalable quantum data movement and computation. Thaker, D. Quantum memory hierarchies: efficient designs to match available parallelism in quantum computing. Balensiefer, S. An evaluation framework and instruction set architecture for ion-trap based quantum microarchitectures.


This paper describes the use of a software toolchain to explore architectural designs and optimizations. Devitt, S. Performing quantum computing experiments in the cloud.


This paper describes a software toolchain that improves the efficiency fold in their quantum chemistry application. Omer, B. Green, A. Quipper: A scalable quantum programming language.


The most significant is Shor's algorithm for factoring the product of two large primes in polynomial time [Shor94]. Additional algorithms include Grover’s fast database search; adiabatic solution of optimization; precise clock synchronization; quantum key distribution; and recently, Gauss sums and Pell’s equation [Grover96, Childs, Chuangb, BB84, vandam02a, Hallgren02a2]. The tremendous computational potential of quantum computers is closer than we may think.

Despite significant practical difficulties, small quantum devices of 5 to 7 bits have been built in the laboratory [Vandersypen00, Laflamme99]. No matter the choice, any technology used to implement a quantum information processor must adhere to four main requirements [DiVincenzo00]:

1. It must allow the initialization of an arbitrary N-qubit quantum system to a known state.
2. The quantum system will interact with its environment and lose state, a process called decoherence. Finally, there is the difficulty of transmitting quantum data between computational units without losing state.
3. The state of quantum computation. This kind of scale is very hard to achieve.
4. The probability of error of each operation on a quantum computer is less than some constant estimated to be as high as 10^-4 , scalable quantum computers can be built using faulty components [Kraus98, Preskill98, Aharonov97].

The recent intense interest in quantum computers has focused on Shor’s algorithm for prime factorization of large numbers. The security of many modern cryptosystems relies on the seeming intractability of factoring the product of two large primes. In particular, it is easy to show that an efficient algorithm for factoring implies that the widely-used RSA public-key system becomes efficiently breakable.

While the best-known factoring algorithms for a classical computer run in exponential time, Shor’s algorithm can factor an n-bit integer in O(n^3 log n log log n) with error correction. A bit product RSA would take approximately 1. Unfortunately, practical quantum architectures needed to achieve such gains have not been well-examined, and the overhead of quantum error correction is very significant.

Most of the quantum literature assumes fixed quantum circuit models that only work for one algorithm and one data size. Elementary architectural concepts needed to make quantum computers an engineering reality are still lacking: how do we provide quantum storage, data paths, classical control circuits, parallelism, and system integration? We try to answer these questions in the text that follows while providing some introduction to the state of quantum computation. This kind of scale is very hard to achieve.

Quantum data is inherently very unstable, which leads to a lack of reliable operations that can be performed on it. Also if left idle, this quantum data will interact with its environment and lose state, a process called decoherence. Finally, there is the difficulty of transmitting quantum data between computational units without losing state.

This implies that the greatest challenge towards a large, practically useful quantum computer, is designing an architecture that incorporates the required amount of fault-tolerance while minimizing overhead.

Previous work in large-scale quantum architecture [Oskin02, Oskin03, Copsey03] has led to the consideration of several main scalability issues that must be taken into account: reliable and realistic implementation technology; robust error correction and fault-tolerant structures; efficient quantum resource distribution.

Reliable and realistic implementation technology. There are multiple approaches from very diverse fields of science for the realization of a full-scale quantum information processor. Solid state technologies, trapped ions, and superconducting quantum computation are just a small number of many physical implementations currently being studied.

No matter the choice, any technology used to implement a quantum information processor must adhere to four main requirements [DiVincenzo00]:

1. It must allow the initialization of an arbitrary N-qubit quantum system to a known state.

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Valiron and the other anonymous reviewer s for their contribution to the peer review of this work. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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Buy or subscribe. Change institution. Rent or Buy article Get time limited or full article access on ReadCube. Figure 1: Design tool flows and abstraction stacks. References 1 Moore, G. Design Methods — Springer. 2 Shor, P. Acknowledgements We thank the many collaborators who have helped shape our thinking over the years: K. Chong View author publications.

View author publications. Ethics declarations Competing interests The authors declare no competing financial interests. Additional information Reviewer Information Nature thanks B.

PowerPoint slides. PowerPoint slide for Fig. Rights and permissions Reprints and Permissions. The exponential speedup offered by quantum computing, based on the ability to process quantum information through gate manipulation [Deutsch85] , has led to several quantum algorithms with substantial advantages over known algorithms with traditional computation.

The most significant is Shor's algorithm for factoring the product of two large primes in polynomial time [Shor94] . Additional algorithms include Grover's fast database search; adiabatic solution of optimization; precise clock synchronization; quantum key distribution; and recently, Gauss sums and Pell's equation [Grover96, Childs, Chuangb, BB84, vandam02a, Hallgren02a2].

The tremendous computational potential of quantum computers is closer than we may think. Despite significant practical difficulties, small quantum devices of 5 to 7 bits have been built in the laboratory [Vandersypen00, Laflamme99].

More importantly, improvements in quantum error correction codes have made possible the Threshold Theorem, according to which, as long as the probability of error of each operation on a quantum computer is less than some constant estimated to be as high as 10 −4 , scalable quantum computers can be built using faulty components [Knill98, Preskill98, Aharonov97].

The recent intense interest in quantum computers has focused on Shor's algorithm for prime factorization of large numbers. The security of many modern cryptosystems relies on the seeming intractability of factoring the product of two large primes.

In particular, it is easy to show that an efficient algorithm for factoring implies that the widely-used RSA public-key system becomes efficiently breakable. While the best-known factoring algorithms for a classical computer run in exponential time, Shor's algorithm can factor an n-bit integer in O n 3 time O n 3 log n log 5 with error correction.

A bit product RSA would take approximately 1. Unfortunately, practical quantum architectures needed to achieve such gains have not been well-examined, and the overhead of quantum error correction is very significant. Most of the quantum literature assumes fixed quantum circuit models that only work for one algorithm and one data size.

Elementary architectural concepts needed to make quantum computers an engineering reality are still lacking: how do we provide quantum storage, data paths, classical control circuits, parallelism, and system integration? We try to answer these questions in the text that follows while providing some introduction to the state of quantum computation. This kind of scale is very hard to achieve. Quantum data is inherently very unstable, which leads to a lack of reliable operations that can be performed on it.

Also if left idle, this quantum data will interact with its environment and lose state, a process called decoherence. Finally, there is the difficulty of transmitting quantum data between computational units without losing state.
This implies that the greatest challenge towards a large, practically useful quantum computer, is designing an architecture that incorporates the required amount of fault-tolerance while minimizing overhead. Previous work in large-scale quantum architecture [Oskin02, Oskin03, Copsey03] has led to the consideration of several main scalability issues that must be taken into account: reliable and realistic implementation technology, robust error correction and fault-tolerant structures; efficient quantum resource distribution.

Reliable and realistic implementation technology: There are multiple approaches from very diverse fields of science for the realization of a full-scale quantum information processor.

Solid state technologies, trapped ions, and superconducting quantum computation are just a small number of many physical implementations currently being studied. No matter the choice, any technology used to implement a quantum information processor must adhere to four main requirements [DiVincenzo00]:

1. It must allow the initialization of an arbitrary N-qubit quantum system to a known state.
2. The second requirement encompasses multi-qubit operations; thus, it implies that a quantum architecture must also allow for sufficient and reliable communication between physical qubits.

### About Quantum Computing For Computer Architects

While existing technologies for building quantum computers are in their infancy, it is not too early to consider their scalability and reliability in the context of the design of large-scale quantum computers.

To architect such systems, one must understand what it takes to design and model a balanced, fault-tolerant quantum computer architecture. The goal of this lecture is to provide architectural abstractions for the design of a quantum computer and to explore the systems-level challenges in achieving scalable, fault-tolerant quantum computation.

In this lecture, we provide an engineering-oriented introduction to quantum computation with an overview of the theory behind key quantum algorithms. Next, we look at architectural case studies based upon experimental data and future projections for quantum computation implemented using trapped ions. While we focus here on architectures targeted for realization using trapped ions, the techniques for quantum computer architecture design, quantum fault-tolerance, and compilation described in this lecture are applicable to many other physical technologies that may be viable candidates for building a large-scale quantum computing system.

We also discuss general issues involved with programming a quantum computer as well as a discussion of work on quantum architectures based on quantum teleportation. Finally, we consider some of the open issues remaining in the design of quantum computers. Article :

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Nature, — Wineland, D. Experimental primer on the trapped ion quantum computer. Amy, M. Computer Aided Verification: 29th Int. Download references. We thank the many collaborators who have helped shape our thinking over the years: K. Brown, I. Chung, E. Chi, A. Faruque, A. Harrow, J. Heckey, A. Javadi-Abhari, J. Kubiatowicz, D. Kudrow, T. Metodi, M. Oskin, S. Patil, J. Reppy, D. Schuster, M.
Quantum computing sits at an important inflection point.

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Figure 1: Design tool flows and abstraction stacks.

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