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A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Report of the Quantum Information Science and Technology Experts Panel

"… it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds sway."
Richard P. Feynman (1985)

Disclaimer:
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List of Acronyms and Abbreviations

(**Note:** Definitions of acronyms and technical terms for the whole roadmap are contained in Appendix A.)

ARDA	Advanced Research and Development Activity
ARO	Army Research Office
CMOS	complementary metal oxide semiconductor
DFS	decoherence-free subspace
GHZ	Greenberger, Horne, and Zeilinger
KLM	Knill, Laflamme, and Milburn
NMR	nuclear magnetic resonance
NRO	National Reconnaissance Office
NSA	National Security Agency
QC	quantum computation/computing
QCPR	Quantum Computing Program Review
QED	quantum electrodynamics
QIP	quantum information processing
QIS	quantum information science
QIST	quantum information science and technology
rf	radio frequency
RSFQ	rapid single flux quantum
SET	single electron transistor
TEP	technology experts panel

QUANTUM COMPUTATION ROADMAP VERSION 2.0 RELEASE NOTES

April 2004

The quantum computation (QC) roadmap was released in Version 1.0 form in December 2002 as a living document. This new, Version 2.0, release, while retaining the majority of the Version 1.0 content, provides an opportunity to

- incorporate advances in the field that have occurred during the intervening 14 months;
- make minor modifications to the roadmap structure to better capture the challenges involved in transitioning from a single qubit to two;
- add major sections on topics that could not be covered in Version 1.0; and
- reflect on the purpose, impact, and scope of the roadmap, as well as its future role.

Some of the most significant changes in this Version 2.0 of the QC roadmap have been to incorporate the major advances that have occurred since the release of Version 1.0. These include

- realization of probabilistic controlled-NOT quantum logic gates in linear optics,
- the controlled-NOT quantum logic gates demonstrated in two-ion traps,
- the achievement of near single-shot sensitivity for single electron spins in quantum dots, and
- the excellent coherence times observed in Josephson qubits

which, together with the other multiple advances noted in the roadmap, are indicative of the continued healthy rate of development of this challenging field toward the roadmap desired goals.

In meetings of the roadmap experts panel members at the August 2003 Quantum Computing Program Review in Nashville, Tennessee, it was decided to increase the number of "two qubit" development status metrics in the mid-level roadmap view to more accurately reflect the distinct, challenging scientific steps encountered within each QC approach in moving from one qubit to two. It was also decided to relegate coverage of the DiVincenzo "promise criteria" and development status metrics for "unique qubits" from the mid-level view roadmap tables to the appropriate summary section. With these changes and additions, Version 2.0 of the QC roadmap provides a more precise and up-to-date account of the status of the field and its rate of development toward the roadmap 2007 desired goal, as of March 2004.

Perhaps the most unsatisfactory aspect of Version 1.0 of the QC roadmap was that with its almost exclusive focus on experimental implementations, only a limited coverage of the important role of theory in reaching the roadmap desired goals was possible. One of the major additions in Version 2.0 is the expansion of the theory summary section to adequately represent the pivotal roles of theory, with sections on: quantum algorithms and quantum computational complexity, quantum information theory, quantum computer architectures, and the theory of decoherence. A second major addition in Version 2.0 is a full summary section on cavity-QED approaches to QC. Another significant change in Version 2.0 is in the coverage of solid-state

QC, where the summary section has been streamlined, and in the roadmap's mid-level view the great diversity of SSQC approaches has been captured into just two categories: "charge or excitonic qubits" and "spin qubits." With these major additions and changes, Version 2.0 of the QC roadmap provides a significantly more comprehensive view of the entire field and the role of each element in working toward the roadmap high-level desired goals.

With the benefit of just over one year of experience with the impact of and community response to the first version of the QC roadmap, this Version 2.0 release provides an opportunity to reflect on its structure, scope, and future role. One of the most useful features of the roadmap is that by proposing specific desired development targets and an associated timeline it has focused attention and inspired debate, which are essential for effectively moving forward. The roadmap experts panel members have received considerable input regarding the roadmap's chosen desired high-level goals; the majority of comments characterize these goals as falling into the "ambitious yet attainable" category. Nevertheless, in the light of the recent progress noted in this roadmap update, it is worth asking whether an even more aggressive time line could be envisioned leading to a significantly more advanced development destination for QC (beyond the roadmap's desired quantum computation testbed era) within the 2012 time horizon. This question can be best considered by comparing the QC roadmap with generally accepted principles of science and technology roadmaps [1,2]. The research degree of difficulty involved in reaching the 2007 desired high-level goal is unquestionably very high, but the risk associated with the fundamental scientific challenges involved is mitigated by pursuing the multiple paths described in the roadmap. Achieving the high-level goals along one or more of these paths will require a sustained and coordinated effort; the uncertainties remain too high today to pick out a more focused development path. An attempt to do so at this time could potentially divert resources away from ultimately more promising research directions. This would increase the risk that QC could fail to reach the quantum computational testbed era by 2012, beyond the considerable but acceptable levels of the path defined in this roadmap. However, this issue should be reassessed once the field moves closer to the 2007 desired goal. The roadmap experts panel members believe that the QC roadmap's desired high-level goals and timeline, while remaining consistent with accepted norms of risk within advanced, fundamental science and technology research programs, are sufficiently challenging to effectively stimulate progress. They intend to revisit these important issues in future updates.

[1] Kostoff R.N. and R.R. Schaller, "Science and technology roadmaps," *IEEE Transactions on Engineering Management* **48**, 132–143 (2001).

[2] Mankins, J.C., "Approaches to strategic research and technology (R&T) analysis and road mapping," *Acta Astronautica* **51**, 3–21 (2002).

EXECUTIVE SUMMARY

Quantum computation (QC) holds out tremendous promise for efficiently solving some of the most difficult problems in computational science, such as integer factorization, discrete logarithms, and quantum simulation and modeling that are intractable on any present or future conventional computer. New concepts for QC implementations, algorithms, and advances in the theoretical understanding of the physics requirements for QC appear almost weekly in the scientific literature. This rapidly evolving field is one of the most active research areas of modern science, attracting substantial funding that supports research groups at internationally leading academic institutions, national laboratories, and major industrial-research centers. Well-organized programs are underway in the United States, the European Union and its member nations, Australia, and in other major industrial nations. Start-up quantum-information companies are already in operation. A diverse range of experimental approaches from a variety of scientific disciplines are pursuing different routes to meet the fundamental quantum-mechanical challenges involved. Yet experimental achievements in QC, although of unprecedented complexity in basic quantum physics, are only at the proof-of-principle stage in terms of their abilities to perform QC tasks. It will be necessary to develop significantly more complex quantum-information processing (QIP) capabilities before quantum computer-science issues can begin to be experimentally studied. To realize this potential will require the engineering and control of quantum-mechanical systems on a scale far beyond anything yet achieved in any physics laboratory. This required control runs counter to the tendency of the essential quantum properties of quantum systems to degrade with time (“decoherence”). Yet, it is known that it should be possible to reach the “quantum computer-science test-bed regime”—if challenging requirements for the precision of elementary quantum operations and physical scalability can be met. Although a considerable gap exists between these requirements and any of the experimental implementations today, this gap continues to close.

To facilitate the progress of QC research towards the quantum computer-science era, a two-day “Quantum Information Science and Technology Experts Panel Meeting” (membership is listed on the inside cover of this document) was held in La Jolla, California, USA, in late January 2002 with the objective of formulating a QC roadmap. The panel’s members decided that a desired future objective for QC should be

- to develop by 2012 a suite of viable emerging-QC technologies of sufficient complexity to function as quantum computer-science test-beds in which architectural and algorithmic issues can be explored.

The panel’s members emphasize that although this is a desired outcome, not a prediction, they believe that it is attainable if the momentum in this field is maintained with focus on this objective. The intent of this roadmap is to set a path leading to the desired QC test-bed era by 2012 by providing some direction for the field with specific five- and ten-year technical goals. While remaining within the “basic science” regime, the five-year (2007) goal would project QC far enough in terms of the precision of elementary quantum operations and correction of quantum errors that the potential for further scalability could be reliably assessed. The ten-year (2012) goal would extend QC into the “architectural/algorithmic” regime, involving a quantum system of such complexity that it is beyond the capability of classical computers to simulate. These high-level goals are ambitious but attainable as a collective effort with cooperative interactions between different experimental approaches and theory.

Within these overall goals, different scientific approaches to QC will play a variety of roles: it is expected that one or more approaches will emerge that will actually attain these goals. Other approaches may not—but will instead play other vitally important roles, such as offering better scalability potential in the post-2012 era or exploring different ways to implement quantum logic, that will be essential to the desired development of the field as a whole. It was the unanimous opinion of the Technology Experts Panel (TEP) that it is too soon to attempt to identify a smaller number of potential "winners;" the ultimate technology may not have even been invented yet. Considerable evolution of and hybridization between approaches has already taken place and should be expected to continue in the future, with existing approaches being superseded by even more promising ones.

A second function of the roadmap is to allow informed decisions about future directions to be made by tracking progress and elucidating interrelationships between approaches, which will assist researchers to develop synergistic solutions to obstacles within any one approach. To this end, the roadmap presents a "mid-level view" that segments the field into the different scientific approaches and provides a simple graphical representation using a common set of criteria and metrics to capture the promise and characterize progress towards the high-level goals within each approach. A "detailed-level view" incorporates summaries of the state-of-play within each approach, provides a timeline for likely progress, and attempts to capture its role in the overall development of the field. A summary provides some recommendations for moving toward the desired goals. The panel members developed the first version of the QC roadmap from the La Jolla meeting and five follow-up meetings held in conjunction with the annual ARO/ARDA/NSA/NRO Quantum Computing Program Review (QCPR) in Nashville, Tennessee, USA, in August 2002. The present (version 2.0) update was developed out of a further four meetings at the August 2003 QCPR; the roadmap will continue to be updated annually.

The quantum computer-science test-bed destination that we envision in this roadmap will open up fascinating, powerful new computational capabilities: for evaluating quantum-algorithm performance; allowing quantum simulations to be performed; and for investigating alternative architectures, such as networked quantum subprocessors. The journey to this destination will lead to many new scientific and technological developments with potential societal and economic benefits. Quantum systems of unprecedented complexity will be created and controlled, potentially leading to greater fundamental understanding of how classical physics emerges from a quantum world, which is as perplexing and as important a question today as it was when quantum mechanics was invented. We can foresee that these QC capabilities will lead into an era of "quantum machines" such as atomic clocks with increased precision with benefits to navigation, and "quantum enhanced" sensors. Quantum light sources will be developed that will be enabling technologies for other applications such as secure communications, and single-atom doping techniques will be developed that will open up important applications in the semiconductor industry. We anticipate that there will be considerable synergy with nanotechnology and spintronics. The journey ahead will be challenging but it is one that will lead to unprecedented advances in both fundamental scientific understanding and practical new technologies.

1.0 BACKGROUND: QUANTUM COMPUTATION

The representation of information by classical physical quantities such as the voltage levels in a microprocessor is familiar to everyone. But quantum information science (QIS) has been developed to describe binary information in the form of two-state quantum systems, such as: two distinct polarization states of a photon; two energy levels of an atomic electron; or the two spin directions of an electron or atomic nucleus in a magnetic field. A single bit of information in this form has come to be known as a "qubit." With two or more qubits, it becomes possible to consider quantum logical-"gate" operations in which a controlled interaction between qubits produces a (coherent) change in the state of one qubit that is contingent upon the state of another. These gate operations are the building blocks of a quantum computer. (See Appendix A for a glossary of quantum computation [QC] terms.) In principle, a quantum computer is a very much more powerful device than any existing or future classical computer because the superposition principle allows an extraordinarily large number of computations to be performed simultaneously. For certain problems, such as integer factorization and the discrete-logarithm problem, which are believed to be intractable on any present-day or future conventional computer, this "quantum parallelism" would permit their efficient solution. These are important problems as they form the foundation of nearly all publicly used encryption techniques. Another example of great potential impact, as first described by Feynman, is quantum modeling and simulation (e.g., for designing future nanoscale electronic components)—exact calculations of such systems can only be performed using a quantum computer. This simulation capability has the potential for discovering new phenomenology in mesoscopic/nanoscopic physics, which in turn could lead to new devices and technologies. (It is not known if quantum computers will offer computational advantages over conventional computers for general-purpose computation.) To realize this potential will require the engineering and control of quantum-mechanical systems on a scale far beyond anything yet achieved in any physics laboratory. Many approaches to QC from diverse branches of science are being pursued. Needless to say, these present-day QC technologies are some orders of magnitude away in both numbers of qubits and numbers of quantum logic operations that can be performed from the sizes that would be required for solving interesting problems. A few experimental approaches are now capable of performing small numbers of quantum operations on small numbers of qubits, with realistic assessments of the challenges for scale-up, while the bulk of the field is at the single-qubit stage with optimistic ideas for producing large-scale systems. There are both fundamental and technical challenges to bridging this gap.

A serious obstacle to practical QC is the propensity for qubit superpositions of 0 and 1 to "decohere" into either 0 or 1. (This phenomenon of decoherence is invoked to explain why macroscopic objects are not observed in quantum superposition states.) However, theoretical breakthroughs have been made in generalizing conventional error-correction concepts to correct decoherence in a quantum computer. A single logical bit would be encoded as the state of several physical qubits and quantum logic operations used to correct decoherence errors. These quantum error-correction ideas have been shown to allow robust, or fault-tolerant QC with the encoded logical qubits, at the expense of introducing considerable overhead in the numbers of physical qubits and elementary quantum logic operations on them. (For example, one logical qubit may be encoded as a state of five physical qubits in one scheme, although the number of physical qubits constituting a logical qubit could well be different for different physical QC implementations.) It has been established, under certain assumptions, that if a threshold precision per gate operation could be achieved, quantum error correction would allow a quantum computer to compute indefinitely.

An essential ingredient of quantum error-correction techniques and QC in general, is the capability to create entangled states of multiple qubits on demand. In these peculiarly quantum-mechanical states the joint properties of several qubits are uniquely defined, even though the individual qubits have no definite state. The strength of the correlations between qubits in entangled states is the most prominent feature distinguishing quantum physics from the familiar world of classical physics. The unusual properties of these states, which do not readily exist in nature, underlie the potential new capabilities of QC and other quantum technologies. Although present-day QC experiments are making rapid progress, demonstrations of on-demand entanglement are few and the precision of gate operations is quite far from the fault-tolerant thresholds. However, experimental capabilities will progress and the fault-tolerant requirements are likely to be relaxed once the underlying assumptions are adapted to specific approaches. The overall purpose of this roadmap is to help achieve these thresholds and to facilitate the progress of QC research towards the quantum computer-science era.

2.0 INTRODUCTION: PURPOSE AND METHODOLOGY OF THE ROADMAP

This roadmap has been formulated and written by the members of a Technology Experts Panel (TEP or the "panel"), whose membership of internationally recognized researchers (see list on inside cover) in quantum information science and technology (QIST) held a kick-off meeting in La Jolla, California, USA, in late January 2002 to develop the underlying roadmap methodology. The TEP held a further five meetings in conjunction with the annual ARO/ARDA/NSA/NRO Quantum Computation Program Review (QCPR) meeting in Nashville, Tennessee, USA, in August 2002. The sheer diversity and rate of evolution of this field, which are two of its significant strengths, made this a particularly challenging exercise. To accommodate the rapid rate of new developments in this field, the roadmap will be a living document that will be updated annually, and at other times on an *ad hoc* basis if merited by significant developments. Certain topics will be revisited in future versions of the roadmap and additional ones added; it is expected that there will be significant changes in both content and structure. At the La Jolla meeting, TEP members decided that the overall purpose of the roadmap should be to set as a desired future objective for QC

- to develop by 2012 a suite of viable emerging-QC technologies of sufficient complexity to function as quantum computer-science test-beds in which architectural and algorithmic issues can be explored.

The roadmap is intended to function in several ways to aid this development. It has a prescriptive role by identifying what scientific, technology, skills, organizational, investment, and infrastructure developments will be necessary to achieve the desired goal, while providing options for how to get there. It also performs a descriptive function by capturing the status and likely progress of the field while elucidating the role that each aspect of the field is expected to play toward achieving the desired goal. The roadmap can identify gaps and opportunities, and places where strategic investments would be beneficial. It will provide a framework for coordinating research activities and a venue for experts to provide advice. The roadmap will therefore allow informed decisions about future directions to be made, while tracking progress, and elucidating interrelationships between approaches to assist researchers to develop synergistic solutions to obstacles within any one approach. The roadmap is intended to be an aid to researchers and to those managing or observing the field.

Underlying the overall objective for the QC roadmap, the panel members decided on a four-level structure with a division into "high level goals," "mid-level descriptions," "detailed level summaries," and a summary that includes the panel's recommendations for optimizing the way forward.

The panel members decided on specific ambitious, but attainable five- and ten-year high level technical goals for QC. These technical goals set a path for the field to follow that will lead to the desired QC test-bed era in 2012.

The mid-level roadmap view captures the breadth of approaches to QC on the international scale and uses a graphical format to describe in general terms how the different research approaches are progressing towards these technical goals relative to common sets of criteria and metrics. The panel decided to first segment the field into a few broad categories, with multiple projects grouped together in each category according to their underlying similarities. The panel decided that two types of measures were necessary to adequately represent the status of each category: a set of criteria characterizes the "promise" of a class of approaches as a candidate QC technology; whereas a set of metrics captures the "status" of the approach in terms of technical advances along the way to achieving the high-level goals.

The "detailed summaries" provide more information on the essential concept of each approach, the breadth of projects involved, the advantages and challenges of the class of approaches, and a timeline for likely progress according to a common format. These summaries, written by subgroups of the panel members after soliciting input from their respective scientific communities, are intended to provide a brief, readable account that represents the status and potential of the entire approach from a world-wide perspective. The panel has endeavored to provide a complete, balanced, and inclusive picture of each research approach, but with the caveat that it is expected that additional content will need to be added to each summary in future versions of the roadmap, after further input from the scientific community. The panel members decided that it was not appropriate for the roadmap to attempt to describe the relative status of different individual projects within each approach.

The panel members found it especially challenging to adequately represent the status and role of theory in the roadmap. Clearly, theory has been pivotal in the development of QC to its present state, providing often unanticipated advances that have stimulated experimental investigations. At the same time, it is difficult to schedule or define meaningful "metrics" for such future breakthroughs. For Version 1.0 of the roadmap the panel decided that the primary focus would be on experimental approaches to QC and limited the description of theory to its historical role. In the present Version 2.0 release all sections have been updated to reflect advances in the 14 months since release of Version 1.0. In addition new sections on cavity-QED approaches to QC and a full theory section, with coverage of decoherence theory, quantum information theory, quantum algorithms and QC complexity, and quantum computer architectures, have been added. In addition, each detailed summary for the different experimental areas provides an overview of the specific areas in which additional theory work is needed.

3.0 QUANTUM COMPUTATION ROADMAP 2007 AND 2012 HIGH-LEVEL GOALS

Although QC is a basic-science endeavor today, it is realistic to predict that within a decade fault-tolerant QC could be achieved on a small scale. The overall objective of the roadmap can be accomplished by facilitating the development of QC to reach a point from which scalability into the fault-tolerant regime can be reliably inferred. It is essential to appreciate that "scalability" has two aspects: the ability to create registers of sufficiently many physical qubits to support logical encoding *and* the ability to perform qubit operations within the fault-tolerant precision thresholds. The desired 2007 and 2012 high-level goals of the roadmap for QC are therefore,

- by the year 2007, to
  - encode a single qubit into the state of a logical qubit formed from several physical qubits,
  - perform repetitive error correction of the logical qubit, and
  - transfer the state of the logical qubit into the state of another set of physical qubits with high fidelity, and
- by the year 2012, to
  - implement a concatenated quantum error-correcting code.

Meeting these goals will require both experimental and theoretical advances. While remaining within the basic-science regime, the 2007 high-level goal requires the achievement of four ingredients that are necessary for fault-tolerant scalability:

- creating deterministic, on-demand quantum entanglement;
- encoding quantum information into a logical qubit;
- extending the lifetime of quantum information; and
- communicating quantum information coherently from one part of a quantum computer to another.

This is a challenging 2007 goal—requiring something on the order of ten physical qubits and multiple logic operations between them, yet it is within reach of some present-day QC approaches and new approaches that may emerge from synergistic interactions between present approaches.

The 2012 high-level goal, which requires on the order of 50 physical qubits,

- exercises multiple logical qubits through the full range of operations required for fault-tolerant QC in order to perform a simple instance of a relevant quantum algorithm, and
- approaches a natural experimental QC benchmark: the limits of full-scale simulation of a quantum computer by a conventional computer.

The 2012 goal would be within reach of approaches that attain the 2007 goal. It would extend QC into the quantum computer test-bed regime, in which architectural and algorithmic issues could be explored experimentally. Quantum computers of this size would also open up the possibilities of quantum simulation as originally envisioned by Feynman. New ways of using the computational capabilities of these small quantum computers could be explored, such as distributed QC and classically networked arrays ("type II" quantum computers), which recent work suggests may be advantageous for partial differential equation simulations, even though in contrast to other potential QC applications no exponential or polynomial speed-up would be possible.

Within these overall goals, different scientific approaches will play a variety of roles; it is expected that one or more approaches will emerge that will actually attain these goals, while others will not, but will instead play vitally important supporting roles (by exploring different ways to implement quantum logic, for instance) that will be essential to the desired development of the field as a whole. It was the unanimous opinion of the TEP that it is too soon to attempt to identify a smaller number of potential "winners;" the ultimate technology may not have even been invented yet. Considerable evolution of and hybridization between the various approaches has already taken place and should be expected to continue in the future, with some existing approaches being superseded by even more promising ones.

4.0 QUANTUM COMPUTATION ROADMAP MID-LEVEL VIEW

The mid-level roadmap view is intended to describe in general terms how the entire field of QC is progressing towards the high-level goals and provides a simple graphical tool to characterize the promise and development status according to common sets of criteria and metrics, respectively. The requirements for quantum computer hardware capable of achieving the high-level goals are simply stated but are very demanding in practice.

1. A quantum register of multiple qubits must be prepared in an addressable form and isolated from environmental influences, which cause the delicate quantum states to decohere.
2. Although weakly coupled to the outside world, the qubits must nevertheless be strongly coupled together to perform logic-gate operations.
3. There must be a readout method to determine the state of each qubit at the end of the computation.

Many different routes from diverse fields of science to realizing these requirements are being pursued. Consequently, in order to adequately represent progress, the TEP decided to segment the field into several broad classes, based on their underlying experimental physics subfields. These subfields are

- nuclear magnetic resonance (NMR) quantum computation,
- ion trap quantum computation,
- neutral atom quantum computation,
- cavity quantum electro-dynamic (QED) computation
- optical quantum computation,
- solid state (spin-based and quantum-dot-based) quantum computation,
- superconducting quantum computation, and
- "unique" qubits (e.g., electrons on liquid helium, spectral hole burning, etc.) quantum computation.
- the theory subfield, including quantum information theory, architectures, and decoherence challenges.

Each of the different experimental approaches has its own particular strengths as a candidate QC technology. For example, atomic, optical, and NMR approaches build on well-developed experimental capabilities to create and control the quantum properties necessary for QC, whereas the solid-state and superconducting approaches can draw on existing large investments in fabrication technologies and materials studies. However, the different approaches are at different stages of development. Insights from the more developed approaches can be usefully incorporated into other, less advanced approaches, which may hold out greater potential for leading to larger-scale quantum computers. The panel decided that to adequately represent this diversity required a set of criteria for the 'promise' of each approach, and a set of metrics for its 'status' (state of progress towards the high-level goals).

To represent the promise of each approach the panel decided to adopt the "DiVincenzo criteria." Necessary conditions for any viable QC technology can be simply stated as:

1. a scalable physical system of well-characterized qubits;
2. the ability to initialize the state of the qubits to a simple fiducial state;
3. long (relative) decoherence times, much longer than the gate-operation time;
4. a universal set of quantum gates; and
5. a qubit-specific measurement capability.

Two additional criteria, which are necessary conditions for quantum computer networkability are

6. the ability to interconvert stationary and flying qubits and
7. the ability to faithfully transmit flying qubits between specified locations.

The physical properties, such as decoherence rates of the two-level quantum systems (qubits) used to represent quantum information must be well understood. The physical resource requirements must scale linearly in the number of qubits, not exponentially, if the approach is to be a candidate for a large-scale QC technology. It must be possible to initialize a register of qubits to some state from which QC can be performed. The time to perform a quantum logic operation must be much smaller than the time-scales over which the system's quantum information decoheres. There must be a procedure identified for implementing at least one set of universal quantum logic operations. In order to read out the result of a quantum computation there must be a mechanism for measuring the final state of individual qubits in a quantum register. The two networking criteria are necessary if it is desired to transfer quantum information from one location to another, (e.g., between different registers or between different processors in a distributed computing situation).

Many different QC architectures are possible within the DiVincenzo framework. For example, architectures based on "clocked" or "ballistic" quantum logic implementations are being pursued. Some approaches are intrinsically limited to quantum logic gates between nearest-neighbor qubits, which would allow parallel operations within a QC, whereas other approaches are capable of performing logic gates between widely-separated qubits but are limited to serial operations.

To visually represent the DiVincenzo "promise criteria" of each QC approach, the panel decided to use a simple three-color scheme as shown below (Table 4.0-1).

Table 4.0-1
The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria							
	Quantum Computation						QC Networkability	
	#1	#2	#3	#4	#5		#6	#7
NMR	🔴	🟡	🟡	🟢	🟡		🔴	🔴
Trapped Ion	🟡	🟢	🟡	🟢	🟢		🟡	🟡
Neutral Atom	🟡	🟢	🟡	🟡	🟡		🟡	🟡
Cavity QED	🟡	🟢	🟡	🟡	🟢		🟡	🟡
Optical	🟡	🟡	🟢	🟡	🟡		🟡	🟢
Solid State	🟡	🟡	🟡	🟡	🟡		🔴	🔴
Superconducting	🟡	🟢	🟡	🟡	🟡		🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.							

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟡 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

The values assigned to these criteria constitute a snapshot in time of the panel's opinions on the potential of each approach as a candidate QC technology. Future developments within an approach will lead to these values being updated.

To represent the present status of each approach the panel developed a set of metrics that represent relevant steps on the way to the 2007- and 2012-year goals. The panel decided to use a similar color coding to indicate the status of each approach (Table 4.0-2). The "development status metrics", which have been augmented somewhat for this version 2.0, are given on the page facing Table 4.0-2.

The development status metrics 1 through 4 correspond to steps on the way to achieving the high-level goals for 2007, while development status metrics 5 through 7 correspond to steps leading up to the high-level goal for 2012. For each QC approach the TEP members have assigned a status code for each of these metrics. These codes will be updated in future versions of the roadmap to reflect significant developments within each approach.

Table 4.0-2
The Mid-Level QC Roadmap—Development Status Metrics

QC Approach	1	1.1	2	2.1	2.2	2.3	3	3.1	3.2	3.3	3.4	3.5	3.6	4	4.1	4.2	4.3	4.4
NMR		G		G	G	G		G	Y	Y	G	G	G		Y	Y	G	G
Trapped Ion		G		G	G	G		G*	G*	Y	Y*	Y	Y*		R	Y	R	R
Neutral Atom		Y		G	Y	R		R	R	R	Y	R	R		R	R	R	R
Cavity QED		Y		G	G	Y		Y	Y	Y	R	R	R		Y	R	R	R
Optical		Y		G	G	G		Y*	Y	Y	G	G	G		Y	R	R	R
Solid State:																		
Charged or exitonic qubits		G		G	G	R		Y*	Y*	Y*	R	R	R		R	R	R	R
Spin qubits		G		Y	Y	R		R	R	R	R	R	R		R	R	R	R
Superconducting		G		G	G	Y*		Y*	R	Y*	R	R	R		R	R	R	R

QC Approach	4	4.5	4.6	4.7	4.8	5	5.1	5.2	6	6.1	6.2	6.3	7	7.1	7.2	7.3	7.4	7.5
NMR		G*	G	G	Y		R	Y		G*	Y	R		R	R	R	Y	R
Trapped Ion		R	R	R	R		R	R		R	R	R		R	R	R	R	R
Neutral Atom		R	R	R	R		R	R		R	R	R		R	R	R	R	R
Cavity QED		R	R	R	R		R	R		R	R	R		R	R	R	R	R
Optical		Y	R	Y	R		R	Y*		R	R	R		R	R	R	Y*	R
Solid State:																		
Charged or exitonic qubits		R	R	R	R		R	R		R	R	R		R	R	R	R	R
Spin qubits		R	R	R	R		R	R		R	R	R		R	R	R	R	R
Superconducting		R	R	R	R		R	R		R	R	R		R	R	R	R	R

Legend: G = sufficient experimental demonstration
Y = preliminary experimental demonstration, but further experimental work is required
R = no experimental demonstration and * = a change in the development status between Versions 1.0 and. 2.0

1. Creation of a qubit
   - 1.1 Demonstrate preparation and readout of both qubit states.

2. Single-qubit operations
   - 2.1 Demonstrate Rabi flops of a qubit.
   - 2.2 Demonstrate decoherence times much longer than the Rabi oscillation period.
   - 2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.

3. Two-qubit operations
   - 3.1 Implement coherent two-qubit quantum logic operations.
   - 3.2 Produce and characterize the Bell entangled states.
   - 3.3 Demonstrate decoherence times much longer than two-qubit gate times.
   - 3.4 Demonstrate quantum state and process tomography for two qubits.
   - 3.5 Demonstrate a two-qubit decoherence-free subspace (DFS).
   - 3.6 Demonstrate a two-qubit quantum algorithm.

4. Operations on 3–10 physical qubits
   - 4.1 Produce a Greenberger, Horne, and Zeilinger (GHZ) entangled state of three physical qubits.
   - 4.2 Produce maximally-entangled states of four or more physical qubits.
   - 4.3 Quantum state and process tomography.
   - 4.4 Demonstrate DFSs.
   - 4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations etc.) between physical qubits.
   - 4.6 Demonstrate quantum error-correcting codes.
   - 4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza).
   - 4.8 Demonstrate quantum logic operations with fault-tolerant precision.

5. Operations on one logical qubit
   - 5.1 Create a single logical qubit and “keep it alive” using repetitive error correction.
   - 5.2 Demonstrate fault-tolerant quantum control of a single logical qubit.

6. Operations on two logical qubits
   - 6.1 Implement two-logical-qubit operations.
   - 6.2 Produce two-logical-qubit Bell states.
   - 6.3 Demonstrate fault-tolerant two-logical-qubit operations.

7. Operations on 3–10 logical qubits
   - 7.1 Produce a GHZ-state of three logical qubits.
   - 7.2 Produce maximally-entangled states of four or more logical qubits.
   - 7.3 Demonstrate the transfer of quantum information between logical qubits.
   - 7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.
   - 7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

When interpreting this mid-level graphical part of the roadmap, it is important to appreciate that both the "promise criteria" and "development status metrics" need to be considered. For example, the "promise criterion" for NMR QC (in the liquid state) indicates that it does not have good scalability potential, but the "development status" metric shows that multiple steps have already been achieved in this approach. Although not likely in its current form to be a candidate for a large-scale QC technology, the opportunity to learn how to perform QIP tasks within this approach is of tremendous value to the field in general. Conversely, some approaches are much less far along in their development status metrics, but an inspection of their promise criteria reveals that they offer significantly greater potential for achieving a large-scale QC technology. Intermediate between these two extremes a few approaches have the essential ingredients for QC under sufficient control that they have started to make the first steps towards developing a scalable architecture. The detailed-level view of the roadmap provides the means to more fully understand these subtleties of interpretation.

5.0 QUANTUM COMPUTATION ROADMAP DETAILED-LEVEL VIEW

The purpose of the detailed-level roadmap summaries is to provide a short description of each of the experimental approaches, along with explanations of the graphical representation of the metrics in the mid-level view and descriptions of the likely developments over the next decade. A common set of points is addressed in each summary:

- who is working on this approach,
- the location and the size of the group,
- a brief description of the essential idea of the approach and how far it is developed,
- a summary of how this approach meets the DiVincenzo criteria and their status,
- a list of what has been accomplished, when it was accomplished, and by whom, for the development status metrics 1–7,
- the "special strengths" of this approach,
- the unknowns and weaknesses of this approach,
- the 5-year goals for this approach,
- the 10-year goals for this approach,
- the necessary achievements to make the 5- and 10-year goals for the approach possible,
- scientific "trophies" that could be produced (these are defined to be breakthrough-quality results)
- what developments in other areas of QIST or other areas of science will be useful or necessary in this approach,
- how will developments within this approach have benefits to others areas of QIST or other areas of science in general,
- the role of theory in this approach, and
- a timeline that shows the necessary achievements and makes connection to the mid-level development status metrics.

Note: The TEP decided that assessments of individual projects within an approach would not be made a part of the roadmap because this is a program-management function.

In addition to the theory component of the detailed-level summary for each approach, there is a separate summary for fundamental theory. This summary provides historical background on significant theory contributions to the development of QC and also spells out general areas of theoretical work that will be needed on the way to achieving the 2007 and 2012-year high-level goals.

6.0 DETAILED QUANTUM COMPUTATION SUMMARIES

The summaries of the different research approaches to QC are listed in the table below (Table 6.0-1). Each of the summaries listed below is linked to a file on this web site (click on the summary title below to view/download that document).

Table 6.0-1
Detailed Summaries of Quantum Computation Approaches

Quantum Computation Approach Summary	Compiled by
6.1 Nuclear magnetic resonance approaches to quantum-information processing and quantum computing	David Cory
6.2 Ion trap approaches to quantum-information processing and quantum computing	David Wineland
6.3 Neutral atom approaches to quantum-information processing and quantum computing	Carlton Caves
6.4 Cavity QED approaches to quantum-information processing and quantum computing	Michael Chapman
6.5 Optical approaches to quantum-information processing and quantum computing	Paul Kwiat and Gerard Milburn
6.6 Solid state approaches to quantum-information processing and quantum computing	David Awschalom, Robert Clark, David DiVincenzo, P. Chris Hammel, Duncan Steel and, Birgitta Whaley
6.7 Superconducting approaches to quantum-information processing and quantum computing	Terry Orlando
6.8 "Unique" qubit approaches to quantum-information processing and quantum computing	P. Chris Hammel and Seth Lloyd
6.9 Theory component of the quantum computing roadmap	David DiVincenzo, Gary Doolen, Seth Lloyd, Umesh Vazirani, Brigitta Whaley

7.0 QUANTUM COMPUTATION ROADMAP SUMMARY: THE WAY FORWARD

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."
—Richard P. Feynman (1986)

When taking on a basic scientific challenge of the complexity and magnitude of QC, diversity of approaches, persistence, and patience are essential. Major strengths of QC research are the breadth of concepts being pursued, the high level of experimental and theoretical innovations, and the quality of the researchers involved. The rate of progress and level of achievements are very encouraging, but breakthroughs in basic science cannot be expected to happen to a schedule. Nevertheless, the desired 2012 QC destination and the high-level goals that are set out in this roadmap, although ambitious, are within reach if experimenters and theorists work together, appropriate strategic basic research is pursued, and relevant technological developments from closely related fields, such as nanotechnology and spintronics, are incorporated. In developing this document the TEP members have noted several areas where additional attention, effort, or resources would be advantageous.

- The emphasis of the quantum computing roadmap out to 2007 is on the experimental development of error-corrected logical qubits. Without this critical building block, plans for further scale-up would be premature; they would not have a firm foundation. Nevertheless, it is important to begin investigations aimed at evaluating key factors associated with scaled architectures at an exploratory design level, for the various implementation approaches. Such pathway studies, carried out in parallel with the qubit demonstration programs, will require expertise outside of the quantum information science framework. By examining the feasibility of the qubit schemes from a systems perspective, this exercise would define sensible metrics for scale-up, and initiate a closing of the gap between conventional computer systems protocols and quantum information science requirements. It would also encourage a dialogue between quantum information scientists and engineers that will become increasingly important as the field moves toward the logical qubit milestones.
- As one looks to the future development of QC one should anticipate the need for an increasing industrial involvement as the first steps into the realm of scalability are made. For example, much could be learned by trying to develop a few qubit "quantum subprocessor" that incorporates the quantum ingredients and the classical control and readout in a single device. But this will involve a level of applied-science expertise and capability that is unlikely to be found in a university environment. University-industry partnerships would offer an effective route forward. The first steps in this direction are already taking place (e.g., the Australian Centre for Quantum Computing Technology) and the panel recommends that further interactions of this type need to be encouraged and facilitated.
- While the intrinsic scalability of qubits is a central issue, it is also important to think in parallel about the more conventional scalability of experimental infrastructure and techniques required to control and readout the qubits, in order to meet the roadmap timeline. At present, single and few-qubit implementations often involve a substantial array of complex, expensive, and highly specialized equipment items. The step-up from few-qubit experiments to the 2007 high-level goal of encoding quantum information into a logical qubit formed by several physical qubits and the demonstration of fault-tolerant control via repetitive error correction goes beyond replicating qubit cells and will place stringent demands on the overall experimental configuration. In the case of all-electronic solid-state qubits for example, the development of a fast (classical) control chip interfaced to a qubit chip is being pursued to address this issue (where it is instructive to consider the electronics and procedures required to operate a single rf-SET readout element). The control chip in this case may well involve a mix of technologies operating at different temperature levels, such as RSFQ and rf-CMOS, requiring collaboration across traditional boundaries. The drive towards fault-tolerant logical qubit operations separately raises many engineering, as opposed to

physics, issues and the early involvement of industry will be important. These issues will be brought into sharp focus by the 2012 objectives requiring some 50 physical qubits.

- Another area in which the TEP members foresee a future need for increased industrial involvement is in the general area of "supporting technology." Efforts have already been made to ensure that certain critical capabilities are available to researchers in the superconducting QC community, and analogous needs in other areas of QC research should be anticipated. Examples of relevant areas include: materials and device fabrication, electro-optics, and single-photon detectors. The panel intends to amplify on the role of industry in future versions of this roadmap.

- Theory is an area in which the panel believes that some refocusing or expansion of effort would benefit the development of QC towards the roadmap objectives. Continued research efforts on high-quality, fundamental QC theory remain essential, but additional emphasis on theory and modeling that is directed at specific experimental QC approaches is required if this field is to move forward effectively. For example, further study of the fault-tolerant requirements in the context of the physics of specific approaches to QC is necessary. Closer involvement of theorists with their experimental colleagues is encouraged.

- The panel also recommends that additional effort be directed at QC architectural issues. For example, what architectures are suitable for a scalable system, and how may the most demanding requirements for scalable QC be traded-off against each other? Also, quantum logic units need to be integrated with data storage, data transmission, and schedulers, some or all of which can benefit from quantum implementation.

- Additional efforts within the mathematics and theoretical computer-science communities to better define the classes of problems that are amenable to speed-up on a QC should be encouraged, as should the more mundane but very important analysis of how abstract quantum algorithms can be mapped onto physical implementations of QC.

- The desired developments set out in this roadmap cannot happen without an adequate number of highly skilled and trained people to carry them out. The panel notes that graduate-student demand for research opportunities in QC is outstripping resources in many university departments. The panel believes that additional measures should be adopted to ensure that an adequate number of the best physics, mathematics, and computer-science graduate students can find opportunities to enter this field, and to provide a career path for these future researchers. Additional graduate-student fellowships and postdoctoral positions are essential, especially in experimental areas, and there is a need for additional faculty appointments, and the associated start-up investments, in quantum information science.

The quantum computer-science test-bed destination that we envision in this roadmap will open up fascinating, powerful new computational capabilities: for evaluating quantum algorithm performance, allowing quantum simulations to be performed, and for investigating alternative architectures, such as networked quantum subprocessors. The journey to this destination will lead to many new scientific and technological developments with myriad potential societal and economic benefits. A quantum computer provides the capability to create arbitrary quantum states of its qubits and so could be used as a tool for fundamental science and as an ingredient of quantum technologies that will open up new capabilities utilizing the uniquely quantum-mechanical property of entanglement. It will be possible to create and control quantum systems of unprecedented complexity, potentially leading to greater fundamental understanding of how classical physics emerges from a quantum world, which is as perplexing and as important a question today as it was when quantum mechanics was invented. The development of small-scale QC capabilities will lead into an era of "quantum machines" such as atomic clocks with increased precision with benefits to navigation, and "quantum enhanced" sensors. Quantum light sources will be developed that will be enabling technologies for other applications such as secure communications, and single-atom doping techniques will be developed that will open up important capabilities in the semiconductor industry. The journey ahead will be challenging but it is one that will lead to unprecedented advances in both fundamental scientific understanding and practical new technologies.