양자정보 로드맵

고등과학원 계산과학부
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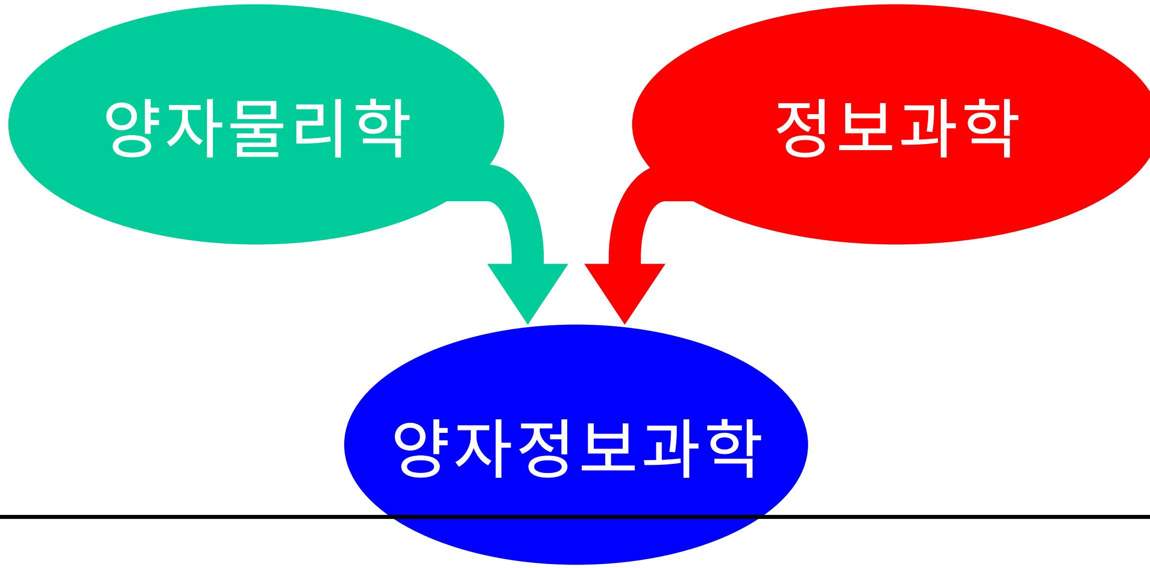


양자병렬성

→ 디지털보다 지수함수적으로 크고 빠른 양자컴퓨터
양자푸리에변환, 양자데이터검색,
나노 시뮬레이션(양자다체문제)

양자복사불가능성, 양자측정의 비가역성

→ 양자암호, 절대적인 디지털보안

양자얽힘의 양자상관성

→ 양자원격전송, 양자압축코딩, 양자암호, 양자이미징

Who would give up
the huge Hilbert Space,
the Nonlocality,
and the novelty of
quantum measurements?

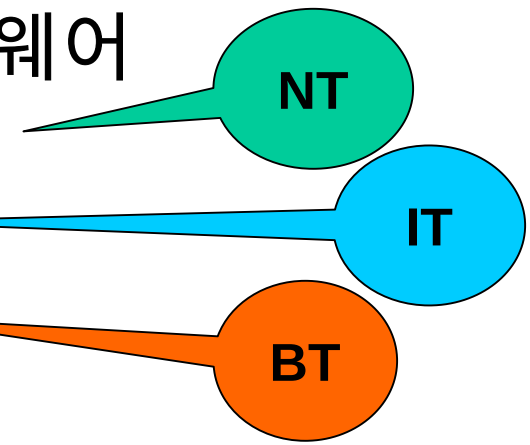
Q Comp

Q Comm
Q Metr
Q Img

Q Crypt

양자 정보 처리

- 양자 컴퓨터
  - 양자 알고리듬: 소프트웨어
    - 양자시스템 시뮬레이션
    - 큰 수 소인수 분해
    - 데이터베이스 검색
  - 실험: 하드웨어
    - **Ion Trap**
    - **NMR**
    - **Cavity QED, etc.**



양자 정보 처리

- 양자 통신
  - 양자 암호 기술

    IT

    - 완벽한 보안 보장
    - 양자암호키의 생성 및 전송
      - 광섬유 **100 km (Toshiba UK, 2003)**
      - 대기 중 **23.4 km** → 위성 암호통신
  - 양자 원격 전송
    - 광자
    - 원자, 분자

(from Michael Brooks)

Quantum Information Processing

Roadmap (1987-1998)

Research Goals

Basic Research

- Quantum interference
- Ion traps
- Cavity QED
- Quantum dots
- NMR schemes
- Si:P
- Shor's algorithm
- Quantum cryptography
- Grover's algorithm
- Single photon detector
- Error correction

Applications

Now

- Photon counters
- Precision range finding
- Optical time-domain reflectometry
- Metrology
- Secure optical communications

(from Michael Brooks)

Quantum Information Processing

Roadmap (1998-2003)

Research Goals

Near Term Goals

- NMR to do 8 qubit QC
- 3-5 photon entanglement
- 3-5 qubit ion trap
- Quantum dot gate
- Silicon-based gate
- Few qubit applications
- New algorithms
- Fault tolerant QC
- Novel QC
- Quantum repeaters
- Quantum amplifiers
- Detectors
- Sources

Applications

Near Future

- Quantum cryptography demonstrators
- General quantum communications
- Random number generators
- 2-photon metrology
- DNA sequencing
- Single molecule sensors
- Simulation of quantum systems
- Quantum gyroscopes

(from Michael Brooks)

Quantum Information Processing
Roadmap (2003-2015)

Research Goals

Mid Term Goals

- 10 - 20 qubit computation
- Demonstrator systems
- Novel algorithms
- Macroscopic superposition
- Bose condensate connections
- Quasi-classical few particle gates and bits

Applications

Far Future

- Quantum repeaters
- Quantum amplifiers
- Quantum computers
  - factoring
  - non-structured information retrieval
- Molecular simulation

LA-UR-02-6900

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:
The opinions expressed in this document are those of the Technology Experts Panel members and are subject to change. They should not to be taken to indicate in any way an official position of U.S. Government sponsors of this research.

December 1, 2002
Version 1.0

This document is available electronically at: http://qist.lanl.gov

2002.12.1
http://qist.lanl.gov
Richard Hughes *et al.*

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 Optical approaches to quantum-information processing and quantum computing	Gerard Milburn and Paul Kwiat
6.5 Solid state approaches to quantum-information processing and quantum computing	David Awschalom, Robert Clark, David DiVincenzo, P. Chris Hammel and, Birgitta Whaley
6.6 Superconducting approaches to quantum-information processing and quantum computing	Terry Orlando
6.7 "Unique" qubit approaches to quantum-information processing and quantum computing	P. Chris Hammel and Seth Lloyd
6.8 Theory component of the quantum computing roadmap	Gary Doolen and Brigitta Whaley

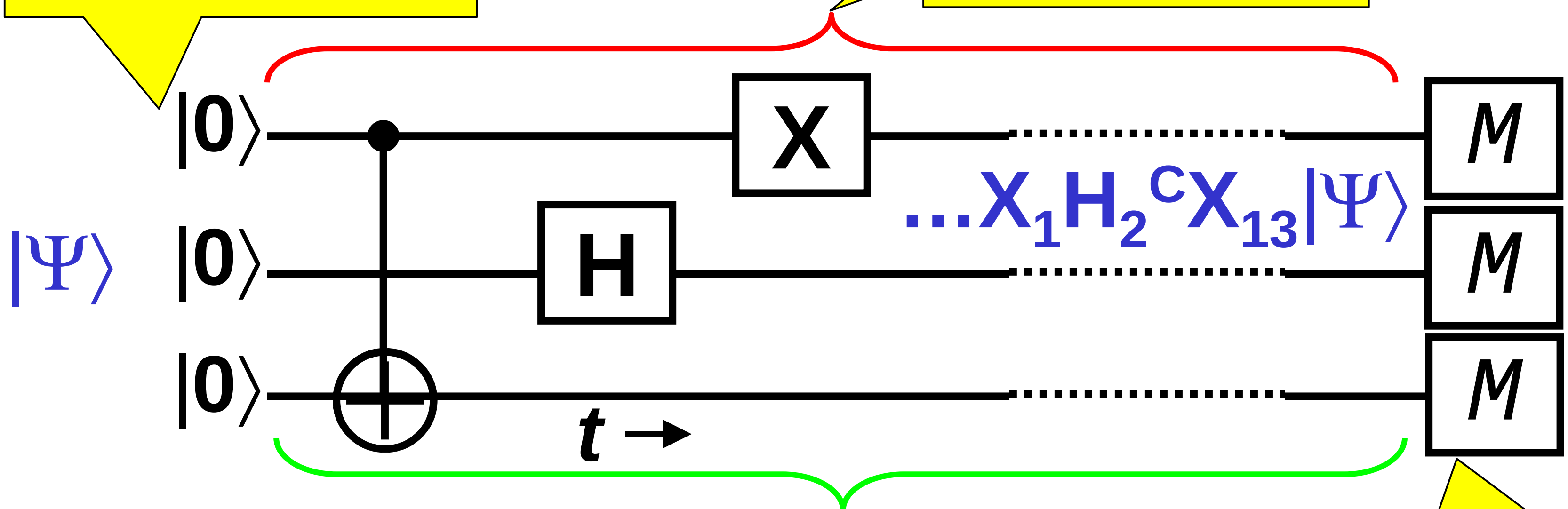
Quantum Circuit

DiVincenzo, Qu-Ph/0002077

1. Scalable Qubits

2. 초기상태 준비

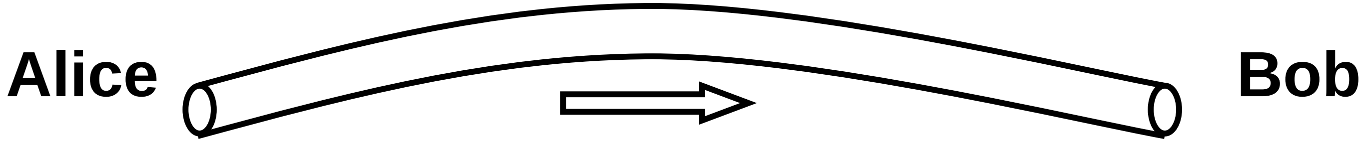
3. Cohere, Not Decohere



4. Universal Gates
유니터리 동역학
: 결정론적
: 가역적

5. 양자측정
: 확률적
: 비가역적 변화

Quantum Networking



6. Interconvertibility between stationary and flying qubits.

7. Faithful transmission of flying qubits.

DiVincenzo, Qu-Ph/0002077

양자암호키전송√ **[BB84,B92]**	**Single-Qubit Gates**	~ 3
양자텔레포테이션√ 양자암호키전송**[E91]**√ 양자중계기	**Single-** **& Two-Qubit Gates**	~ 3
양자오류수정 양자컴퓨터 **7-Qubit QC**√	**Single-** **& Two-Qubit Gates**	$\geq$ 40 $\geq$ 100

High-Level Goals of the Road Map for QC

By 2012, QC science test-beds with sufficient complexity to explore architectural and algorithmic issues

- By 2007:
  - Encode a single qubit into a state of logical qubit
  - Perform a repetitive error correction of the logical qubit
  - Transfer the state of the logical into the state of another set of physical qubits with high fidelity
- By 2012:
  - Implement a concatenated quantum error-correcting code

- Fault-tolerant scalability
  - Creating deterministic, on-demand quantum entanglement
  - Encoding quantum information into a logical qubit
  - Extending the lifetime of quantum information
  - Communicating quantum information coherently from one part of a QC to another
- ~ 50 physical qubits
  - multiple logical qubits through the full range of operations required for F-T QC in order to perform a simple instance of a relevant quantum algorithm
  - a natural experimental QC benchmark that a digital computer cannot simulate

The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria: Quantum Computation #1	#2	#3	#4	#5	QC Networkability #6	#7
NMR	red	orange	orange	green	orange	red	red
Trapped Ion	orange	green	orange	green	green	orange	orange
Neutral Atom	orange	green	orange	orange	orange	orange	orange
Optical	green	orange	green	orange	orange	orange	green
Solid State	orange	orange	orange	orange	orange	red	red
Superconducting	orange	green	orange	orange	orange	red	red
Unique Qubits							
e-Helium	orange	green	orange	orange	orange	red	red
Spectral Hole Burning	orange	green	orange	orange	green	orange	orange

Legend: (green) = a potentially viable approach has achieved sufficient proof of principle

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

(red) = 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.

2003~2007

Development Status Metric

QC Approach	1	1.1	2	2.1	2.2	2.3	3	3.1	3.2	3.3	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8
NMR		green		green	green	green		green	orange	orange		orange	orange	green	green	orange	green	green	orange
Trapped Ion		green		green	green	green		orange	orange	orange		red	orange	orange	orange	red	red	orange	red
Neutral Atom		orange		green	orange	red		red	red	red		red	red	orange	red	red	red	red	red
Optical		orange		green	green	green		red	orange	orange		orange	red	red	red	orange	red	orange	red
Solid State																			
Gated qubits		orange		orange	orange	red		red	red	red		red	red	red	red	red	red	red	red
Optically measured QD qubits		green		green	green	red		orange	red	red		red	red	orange	red	red	red	red	red
Doped or "Spin" qubits		orange		red	red	red		red	red	red		red	red	red	red	red	red	red	red
Superconducting		green		green	green	red		red	red	red		red	red	red	red	red	red	red	red

(green) = sufficient experimental demonstration

(orange) = preliminary experimental demonstration, but further experimental work is required

(red) = no experimental demonstration

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 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.

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 and more physical qubits.

4.3 Quantum state and process tomography.

4.4 Demonstrate decoherence-free subspaces (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.

2008~2012

Development Status Metric

QC Approach	5	5.1	5.2	6	6.1	6.2	6.3	7	7.1	7.2	7.3	7.4	7.5
NMR		red	orange		orange	orange	red		red	red	red	orange	red
Trapped Ion		red	red		red	red	red		red	orange	red	red	red
Neutral Atom		red	red		red	red	red		red	red	red	red	red
Optical		red	red		red	red	red		red	red	red	red	red
Solid State													
Gated qubits		red	red		red	red	red		red	red	red	red	red
Optically measured QD qubits		red	red		red	red	red		red	red	red	red	red
Doped or "Spin" qubits		red	red		red	red	red		red	red	red	red	red
Superconducting		red	red		red	red	red		red	red	red	red	red

green = sufficient experimental demonstration

orange = preliminary experimental demonstration, but further experimental work is required

red = no experimental demonstration

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 and 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.

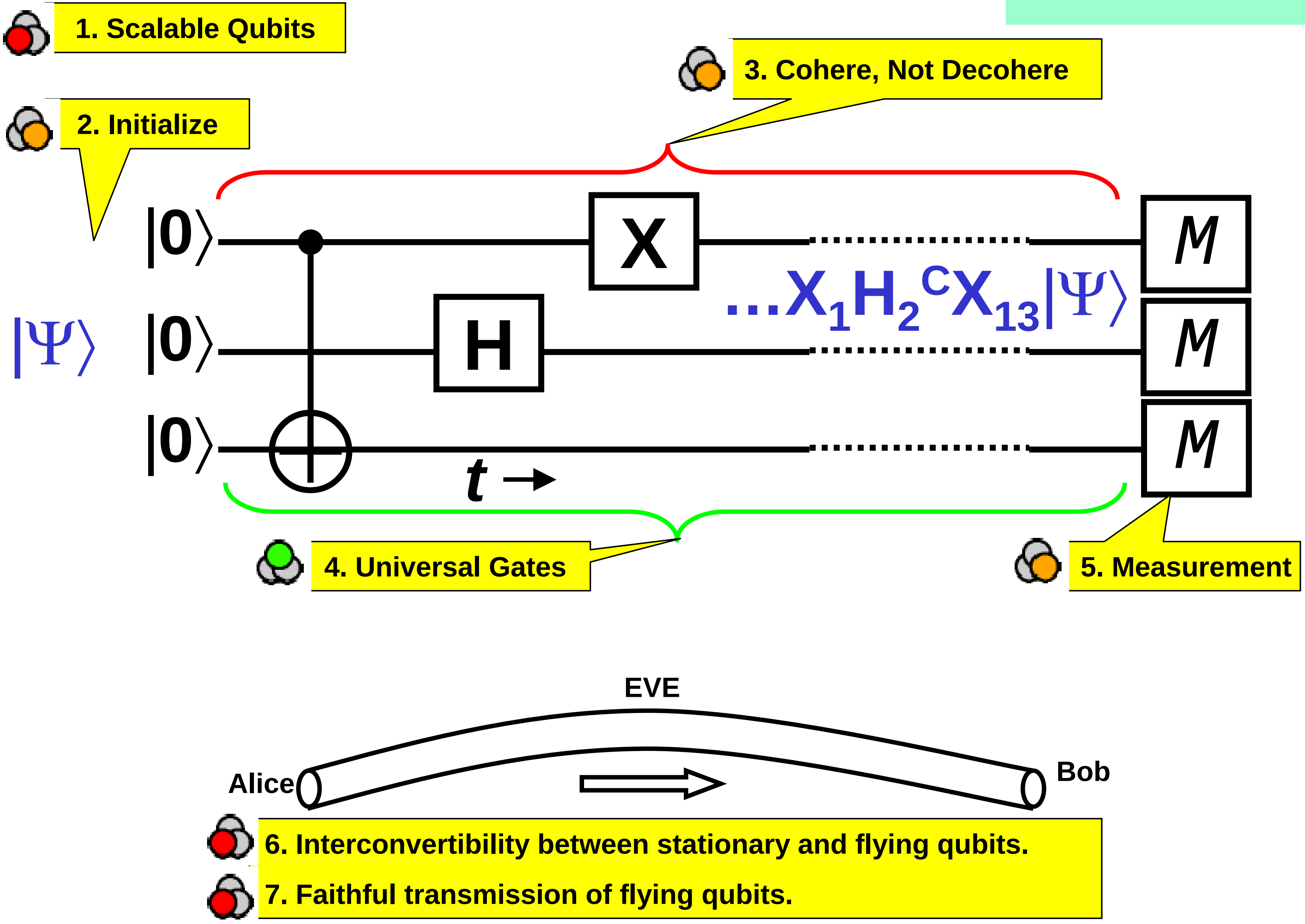
7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

NMR

Nuclear Magnetic Resonance QC Research

Research Leader(s)	Research Location
Cory & Havel	MIT Nuclear Engineering
Gershenfeld & Chuang	MIT Media Lab
Glaser	Munich
Jones	Oxford
Lee	Korea
Kumar	Bangalore, India
Knill	Los Alamos
Laflamme	Waterloo
Zeng	China

NMR



1. Scalable Qubits
2. Initialize
3. Cohere, Not Decohere
|0⟩
|0⟩
|0⟩
|Ψ⟩
X
H
…X₁H₂ᶜX₁₃|Ψ⟩
M
M
M
t
4. Universal Gates
5. Measurement
EVE
Alice
Bob
6. Interconvertibility between stationary and flying qubits.
7. Faithful transmission of flying qubits.

NMR

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 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.

NMR

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 and more physical qubits.

4.3 Quantum state and process tomography.

4.4 Demonstrate decoherence-free subspaces (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.

NMR

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.

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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 and 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.

NMR


Nuclear Magnetic Resonance
ROAD MAP
TIME LINES
Task
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Characterize qubits
characterize the noise generators (and their sources)
measure the spectral density of noise generators
measure the fidelity of qubit state preparation (solid state)
Single qubit operations
Two-qubit operations
process tomography (liquids)
demonstrate state and process tomography (solids)
measure the fidelity of coherent two qubit logic operations (solids)
measure the fidelity and correlation for preparing Bell states (solids)
measure the relaxation superoperator for 2 qubits (liquids)
measure the correlations of noise generators for multiple qubit (liquids and solids)
demonstrate decoherence-free subspace (solids)
Operations on 3 to 10 physical qubits
evaluate the scaling of the fidelity of qubit state preparation (solids)
measure the fidelity and correlation of producing a GHZ & W states (solids)
measure the fidelity of producing cat-states for four or more qubits
demonstrate noiseless subsystem (solids)
measure the fidelity of entanglement swapping
demonstate quantum error correction (solids)
measuring the scaling of decoherence rates with increasing size of cat states (solids)
Operations on one logical qubit
measure the fidelity of logical qubit state preparation (solids)
information storage with two levels of quantum error correction
measure the fidelity of single logical qubit operations
quantum information storage beyond the natural decay time
Operations on two logical qubits
measure the fidelity of two logical qubit operations
measure the fidelity and correlation for preparing Bell states of two logical qubits
Operations on 3 to 10 logical qubits
measure the fidelity and correlation for preparing a GHZ state of three logical qubits
measure the fidelity for preparing the cat state for 4 or more logical qubits
measure the fidelity of entanglement swapping between logical qubits
demonstrate Deutsch-Jozsa with logical qubits
Instrumentation and General Methods
precise coherent control with incoherence in the internal or external Hamiltonian
improved statistical measures for tomography
improved linearity of RF modulators and system
optics for control of hyperfine interaction

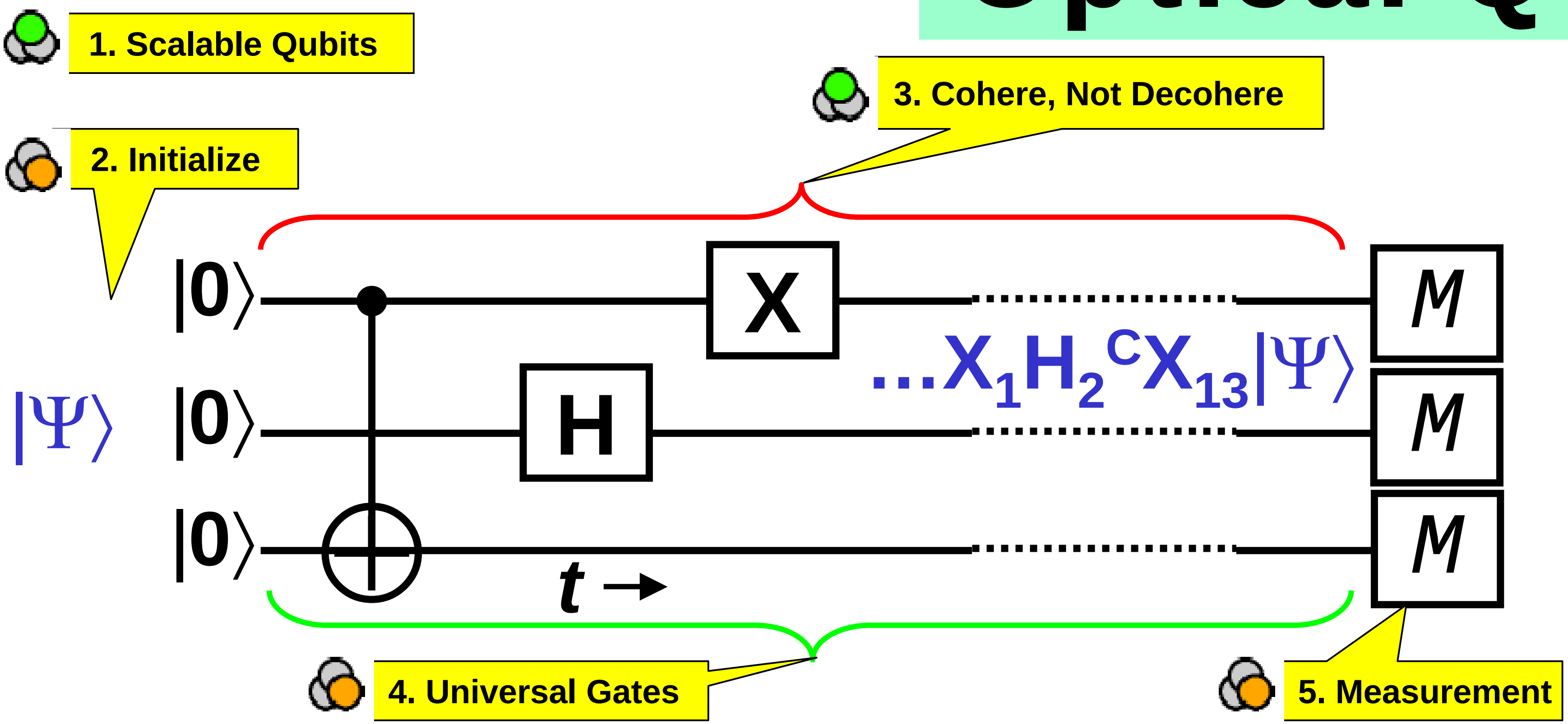
Optical QC

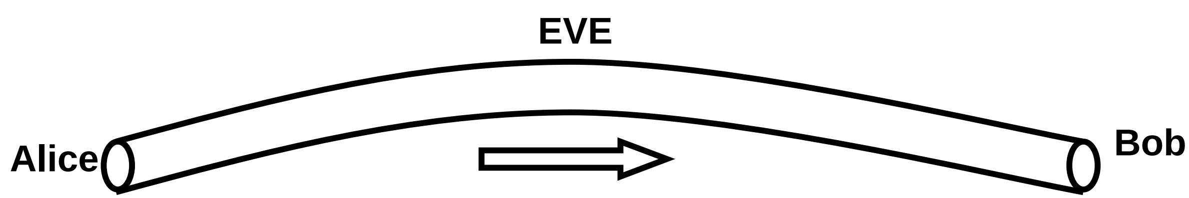
Optical QC Research

Research Leader(s)	Research Location
Bouwmeester, D.	U. of California, Santa Barbara, USA
DeMartini, F.	Rome U., Italy
Dowling, J.	JPL, California, USA
Franson, J. D.	John Hopkins, Maryland, USA
Gisin, N.	U. of Geneva, Switzerland
Howell, J. C.	U. of Rochester, New York, USA
Imamoglu, A.	U. of California, Santa Barbara, USA
Kwiat, P. G.	U. of Illinois, Urbana-Champaign, USA
Milburn, G. J. and Ralph, T. C.	U. of Queensland, Australia
Nakamura, J.	NEC, Tskuba, Japan
Rarity, J.	U. of Bristol, UK
Sergienko, A. V.	Boston U., Massachusetts, USA
Shih, Y. H.	UMBC, Maryland, USA
Steinberg, A.	U. of Toronto, Canada
Takeuchi, S.	Hokkaido U., Japan
Walmsley, I.	U. of Oxford, UK
Weinfurter, H.	U. of Munich, Germany
White, A. G.	U. of Queensland, Brisbane Australia
Yamamoto, Y.	Stanford U., California, USA
Zeilinger, A.	U. of Vienna, Austria
A European collaboration (RAMBOQ)*	John Rarity (coordinator), U. of Bristol

* This collaboration has been funded in the current round of the FET QIPC scheme of the European Commission.

Optical QC





6. Interconvertibility between stationary and flying qubits.

7. Faithful transmission of flying qubits.

Optical QC

1. Creation of a qubit

1.1 Demonstrate preparation and readout of both qubit states.

2. Single-qubit operations

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Optical QC

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Optical QC

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- 7.2 Produce maximally-entangled states of four and more logical qubits.
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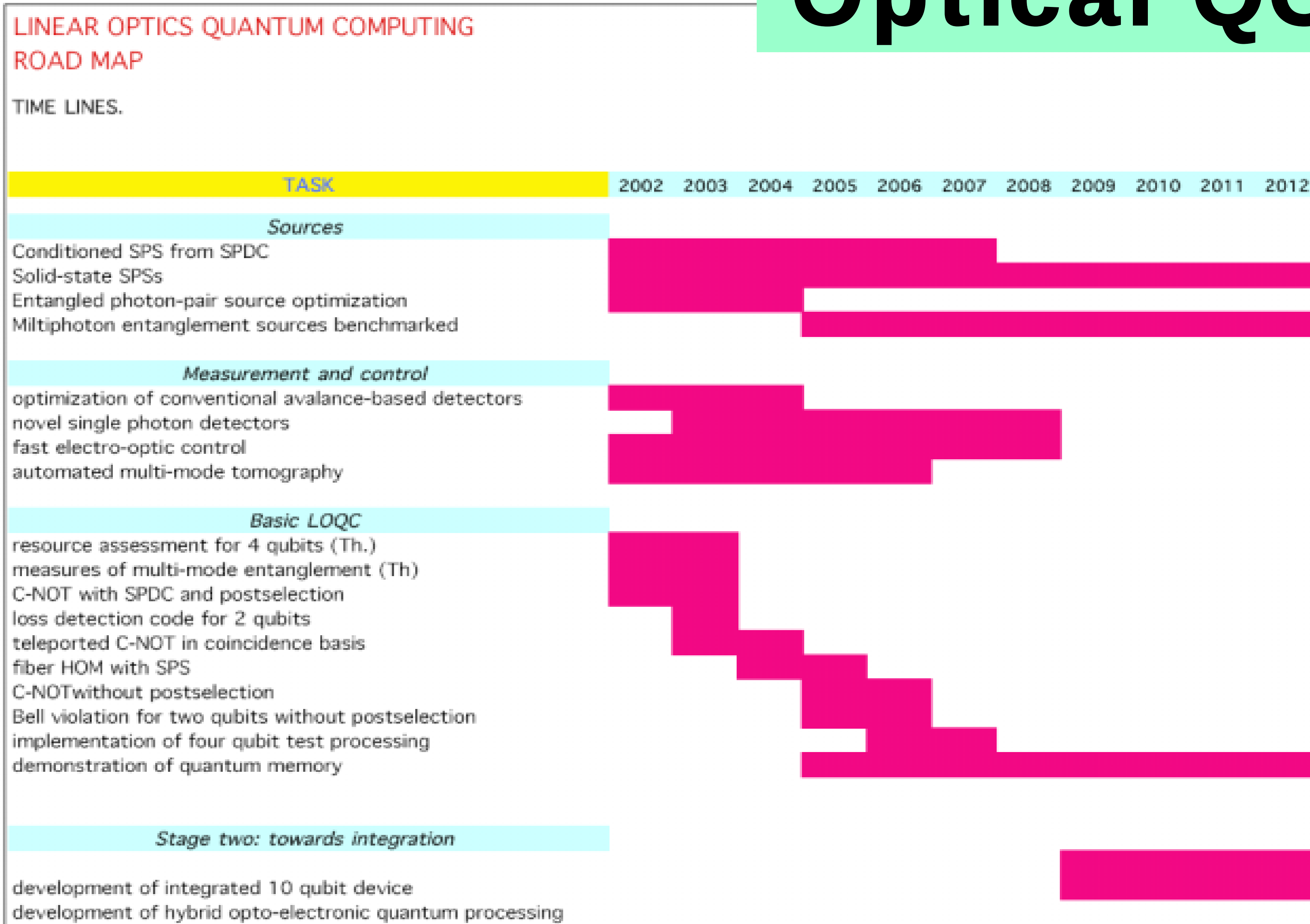
- 7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

Optical QC


LINEAR OPTICS QUANTUM COMPUTING
ROAD MAP
TIME LINES.
TASK
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Sources
Conditioned SPS from SPDC
Solid-state SPSs
Entangled photon-pair source optimization
Miltiphoton entanglement sources benchmarked
Measurement and control
optimization of conventional avalance-based detectors
novel single photon detectors
fast electro-optic control
automated multi-mode tomography
Basic LOQC
resource assessment for 4 qubits (Th.)
measures of multi-mode entanglement (Th)
C-NOT with SPDC and postselection
loss detection code for 2 qubits
teleported C-NOT in coincidence basis
fiber HOM with SPS
C-NOTwithout postselection
Bell violation for two qubits without postselection
implementation of four qubit test processing
demonstration of quantum memory
Stage two: towards integration
development of integrated 10 qubit device
development of hybrid opto-electronic quantum processing

Quantum Cryptography:

A to B

- 100 km using fiber (Toshiba UK, 2003) √
- 23.4 km on air √ → Satellite comm?

A ← E → B

A to R1 to R2 to … to B

A, B, C, D, … on the network

Quantum Imaging

Quantum Metrology

And whatelse?

Who would give up

the huge Hilbert Space,

the Nonlocality,

and the novelty of

quantum measurements?