Future and Emerging Technologies

DG Information Society and Media

European Commission

Quantum Information Processing and Communication Proactive Initiative

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Quantum Information Processing and Communication Proactive initiative in FET

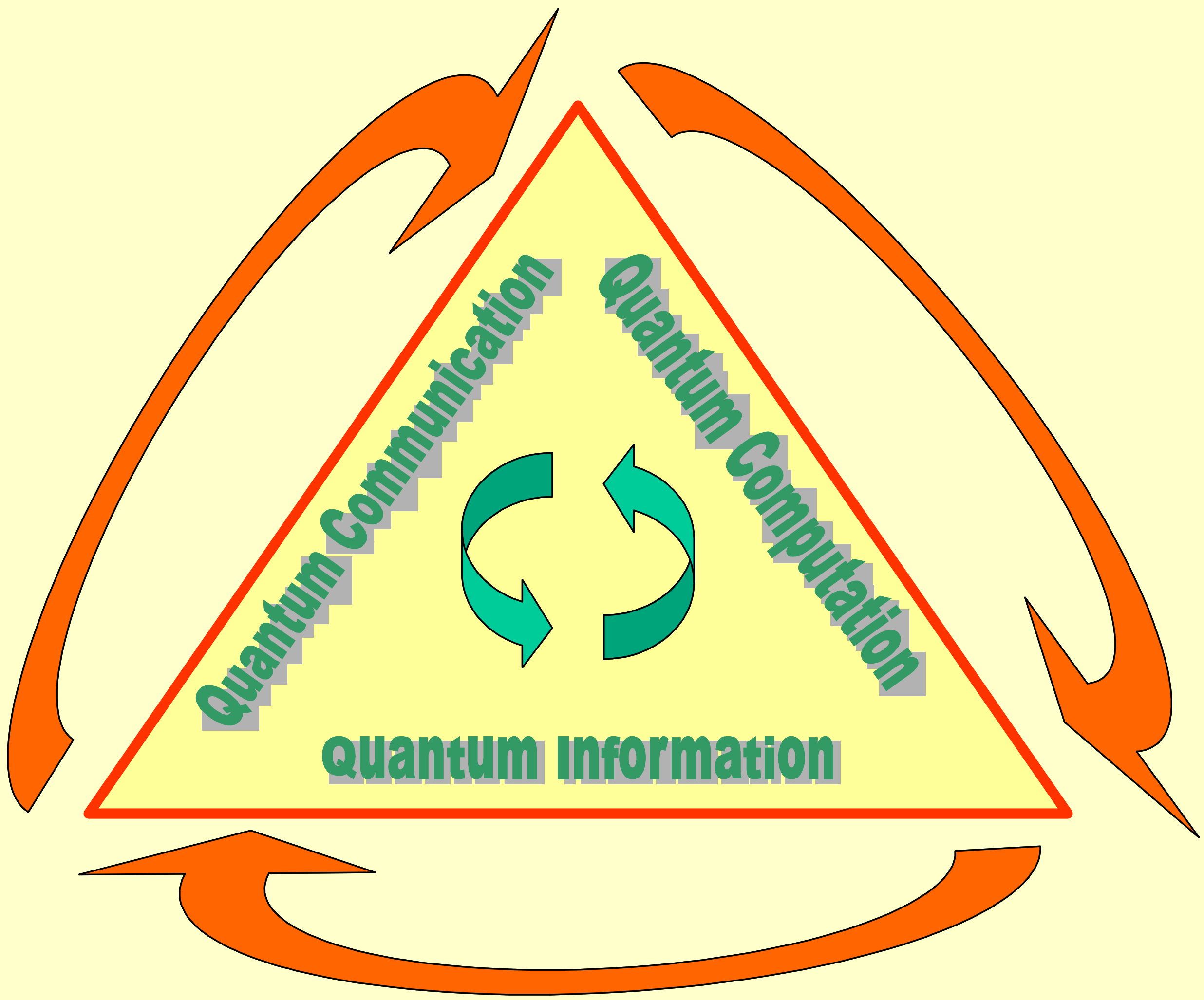
Fundamental multidisciplinary research with numerous, strategic and very striking practical applications

Long-term investment with new results both in applications and fundamental quantum physics coming continuously and new avenues opening up

Based on quantum mechanical physical systems: manipulation and control of individual quantum degrees of freedom and their coherent quantum superpositions

Information is physical

QIPC


Quantum Communication
Quantum Computation
Quantum Information

Qubits

Bit = a physical system which can be prepared in one of two different states

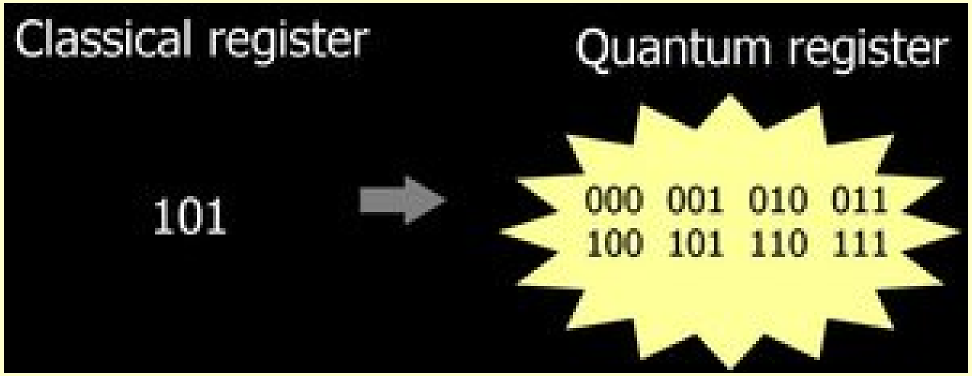
Qubit = quantum mechanical two-state system

Examples: spin of electron or any other elementary particle, two electron levels in atom or ion, etc.

QM superpositions a qubit is in both states ‘0’ and ‘1’

The following 6 slides are after
http://cam.qubit.org/wiki/index.php/What_is_Quantum_Computation%3F

Quantum register

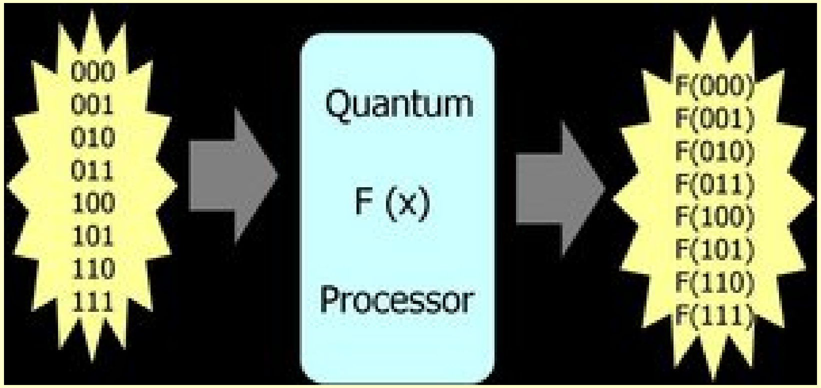


Classical register: can store one out of 8 given numbers

Quantum register: at any given moment can store all eight numbers in a quantum superposition

'N' qubit register: 2^N numbers

Quantum computation

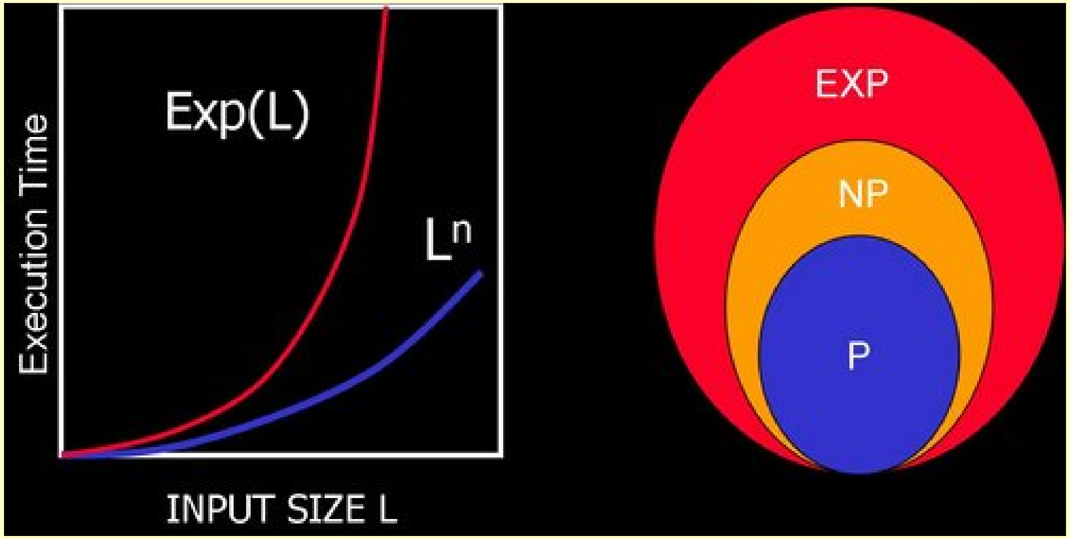


‘N’ qubits can perform 2N calculations in parallel

Exponential decrease in the execution time

Determines the efficiency of the algorithm the efficiency of the algorithm

How powerful are quantum computers?



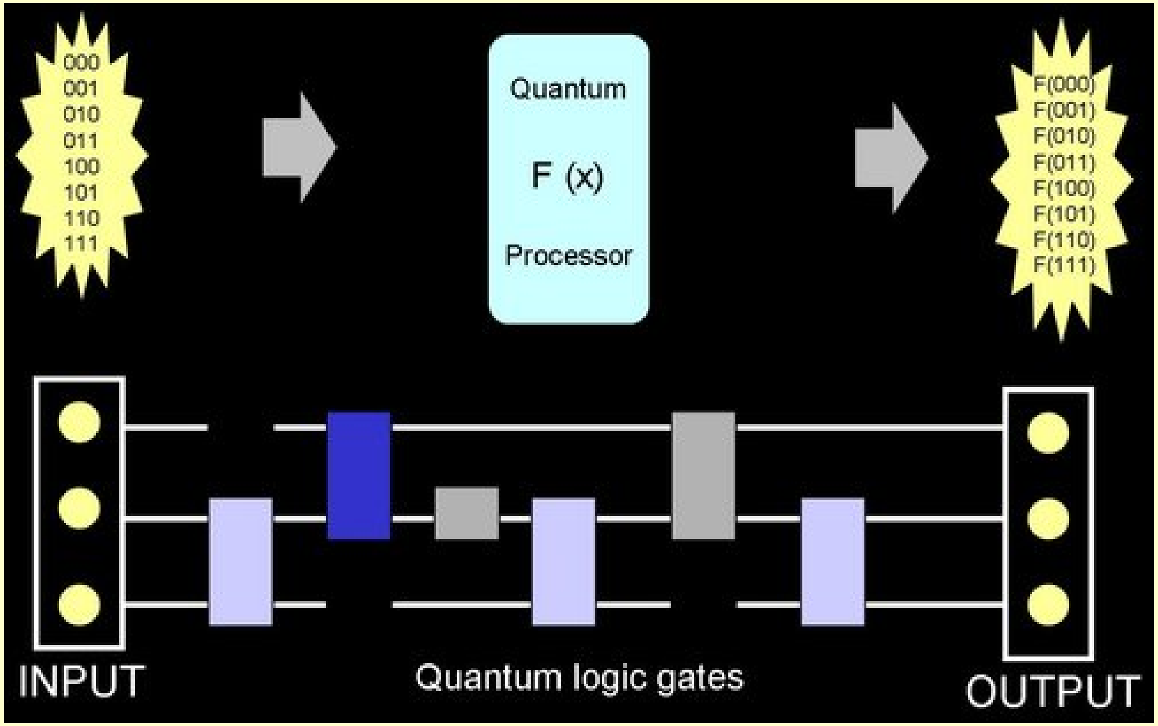
L = Input size = total # of bits needed to specify the input of a problem; T = execution time

T ~ L^N polynomial => problem class P (ex. Multiplication)

Hard problems: outside class P, intractable (ex. Factorization)

Some quantum algorithms can turn ‘hard’ problems into ‘P’ problems

Quantum processor



Q logic gates: simple q computing device that performs one elementary q operation on ‘n’ qubits at the same time. Usually n = 2. => perform operations on q superpositions

Why is it difficult to build an elementary quantum processor?

- Engineer the physical state that represents the qubit and control it
- Engineer the interaction between qubits (q gates) and control it
- Prepare with precision the input = initial q state of the qubit
- Measure = read-out of the sinal state
- Decoherence = interaction with the environment destroys the q state and its superpositions
- To build a q computer from elementary q processor(s) we need also a q netwrok => q communication

Entanglement

- |0>|0>, |0>|1>, |1>|0>, |1>|1>
- Any superposition of the four states
- Bell states: max entangled

  |0>|0> + |1>|1> |0>|0> - |1>|1>

  |0>|1> + |1>|0> |0>|1> - |1>|0>

- Entanglement describes correlations between quantum systems that are much stronger than any classical correlations
- The total amount of information that can be encoded onto the two qubits is still two bits. But now the information is encoded in such a way that neither of the two qubits carries any well defined information on its own: all of the information is encoded in their joint properties.

The following 4 slides are after the article: “Fundamentals of quantum information” by Anton Zeilinger in Physics World, March 1998

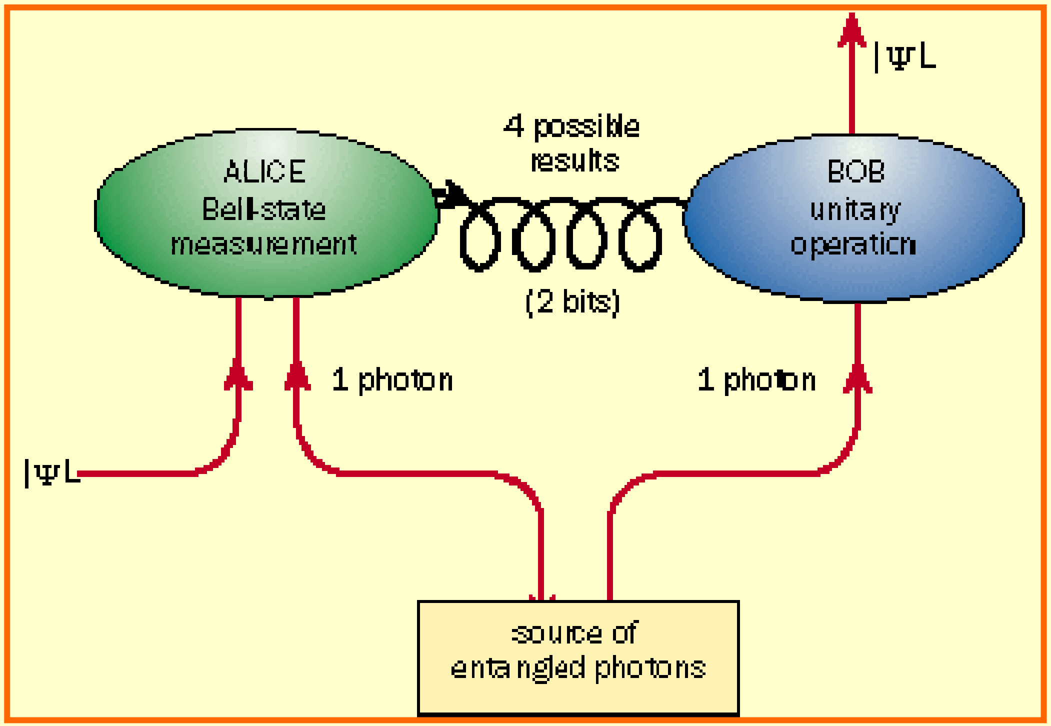
Quantum teleportation

- Alice has an object that she wants to give to Bob.
- Alternative approaches:

  - Alice can send the object itself

  - Alice can scan all of the information contained in the object and transmit that information to Bob who, with suitable technology, could then reconstitute the object. Unfortunately, such a strategy is not possible because quantum mechanics prohibits complete knowledge of the state of any object.

- What we have to do is to guarantee that Bob's object has the same properties as Alice's original. And most importantly, we do not need to know the properties of the original.



•|Ψ> : unknown state Alice wants to transfer to Bob

•ancillary pair: an entangled pair of ph.

•Alice performs a joint Bell-state measurement on |Ψ> and anc. ph.1 => randomly obtains one of the four possible Bell states.

•This measurement projects the other ancillary photon into a quantum state uniquely related to the original.

•Alice transmits the result of her measurement to Bob **classically**

•Bob performs one of the four unitary operations to obtain the original state and complete the teleportation.

The laws of Special Relativity remain valid

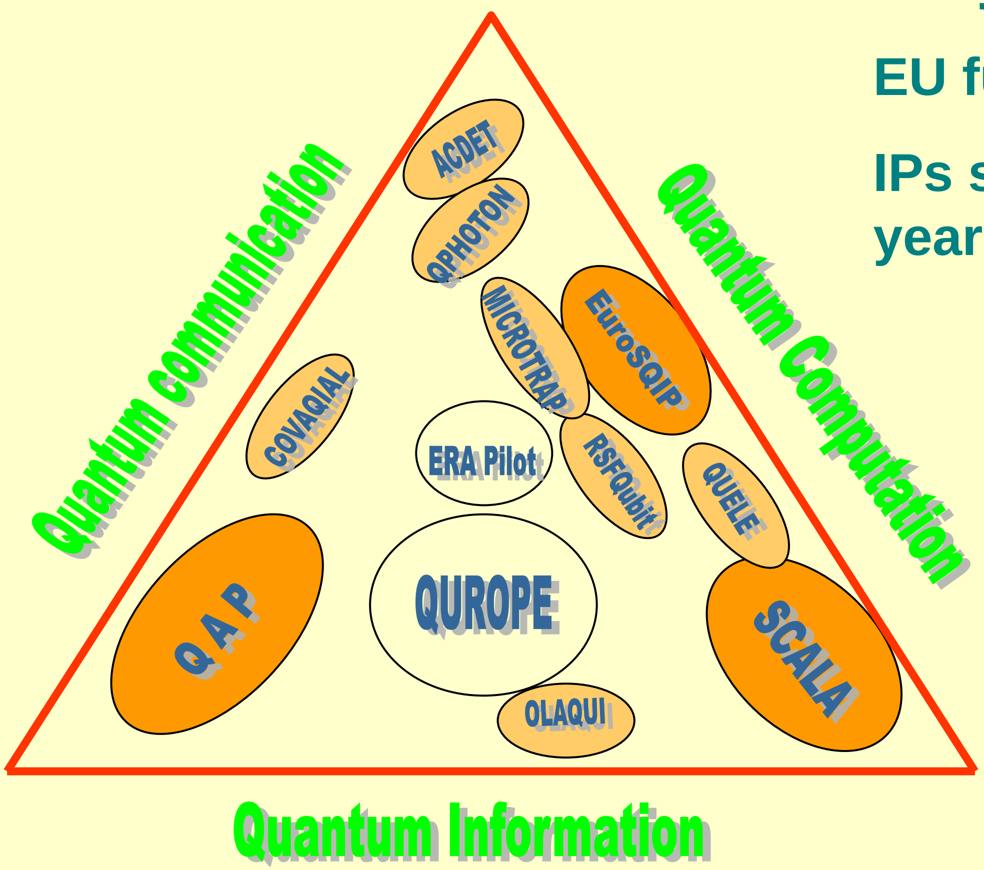
- **If Alice's Bell-state measurement results in exactly the same state as that used to prepare the ancillary photons (which will happen one time in four), Bob's ancillary photon immediately turns into the same state as $|\Psi>$. Since Bob has to do nothing to his photon to obtain $|\Psi>$, it might seem as if information has been transferred instantly - which would violate special relativity. However, although Bob's photon does collapse into the state $|\Psi>$ when Alice makes her measurement, Bob does not know that he has to do nothing until Alice tells him. And since Alice's message can only arrive at the speed of light, relativity remains intact.**

- **In the other three possible cases, Bob has to perform a unitary operation on his particle to obtain the original state, $|\Psi>$. It is important to note, however, that this operation does not depend at all on any properties of $|\Psi>$.**

FP5 QIPC cluster:

- Proactive Initiative: 25 projects - 31 M€
- FET Open: 10 projects - 5.6 M€
- 11 projects active till end 2005
- QUIPROCONE thematic network
- Cluster review:
  - Innsbruck Feb. 2005 - report written
  - Paris Feb. 2006 – report expected
- Evaluate the initiative as a whole

QIPC PI FP6



Very well structured PI

EU funding: 25 M€ + 12.230 M€

IPs started 1 Nov. 2005 for 4 years

ERA Pilot:

- Roadmap: started Sept. 2004
- QI Classification Scheme (QICS),
- QIPC databases on-line: *EU research groups (158); * EU Funding Agencies (78)
- Benchmarking & SWOT analysis
- Map of int'l research teams and funding agencies
- coordination of national research activities and policies

QUROPE:

start 1 Sept. 2006 for 3 years

Represent the research community

Governing board -> Legal partners -> Affiliated members

Objectives

Common vision, strategy and goals: the Roadmap

Public outreach and dissemination

Web portal and info exchange

Conferences

Young scientists training + NMS

Establish links with industry

International cooperation

QIPC cluster: strategy and planning

Traditional events since 2000

- Annual European QIPC workshop
- Cluster review with conference

Special sessions: Perspectives for QIPC in FP7

Sept. 2004 in Rome

Feb. 2005 in Innsbruck

May 2005 in Vienna

Feb. 2006 in Paris

What is important at European level?

Unify, structure and strengthen the research community

Create a sense of community, a sense of identity, a sense of belonging

Coordinate efforts and actions

Develop a common European strategy for research

QIPC Roadmap:
common EU research strategy

FP7 preparations

WHEN?

Start Sept. 2004 Rome

1st stable version April 20005

1st update: July 2005

Published in EPJD Nov. 2005

FET/EC publication Jan 2006

2nd update: Feb 2006

Updates: 2x per year indefinitely

WHO?

40 contributing authors

each is the center of a group of indirect contributors

ERA Pilot WP1 from Feb. 2005

Consultation and feedback from the research community via the ERA Pilot WP1 web site: for each update and for the EC (Feb. – March 2005)

QIPC Roadmap: the European flavor

Executive summary, introduction (why, what), int'l context, funding

Q. Communication

Fiber based

Free space

Q. memories

Q. repeaters

Q. interfaces

Q. protocols

Q. Information theory

Q. algorithms

Computational models and architectures

Q. simulations

Error correction + purification

Entanglement

Noisy comm. channels

Q. Computing

Trapped ions

Trapped electrons

Optical traps

Cavity QED

Atom chips

Superconducting JJ

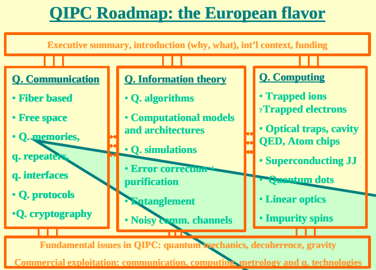
Quantum dots

Linear optics

Impurity spins

Fundamental issues in QIPC: quantum mechanics, decoherence, gravity

Commercial exploitation: communication, computing, metrology and q. technologies



Q. Communication:

- long-distance (~5 km) free-space QKD via weak laser pulses

- long-distance free-space quantum teleportation

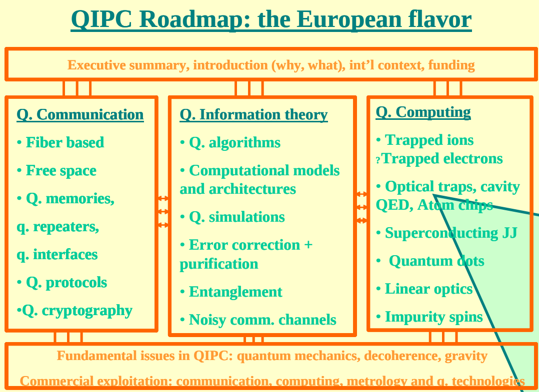
- fibre-based single-photon transmission over 70 km

- fibre-based entanglement distribution up to 50 km

- high-fidelity generation of single-photon pulses

- real-world QC demonstrations, like teleportation across the river Danube and a bank transfer via quantum cryptography in an intra-city link.

Elementary q. processors:



Ion traps:3-4 qubits, 8 entangled

Atoms in optical lattices: 50 entangled via 2-qubit gates, without single-atom control, relevant for cluster-state q.comp.

Atoms in cavity QED: 2 qubits

Atom chips: 1 qubit

Linear optics: 4-5 qubits, cluster-state

Electrons in Penning traps: starting

Superconducting JJ: 2 qubits entangled

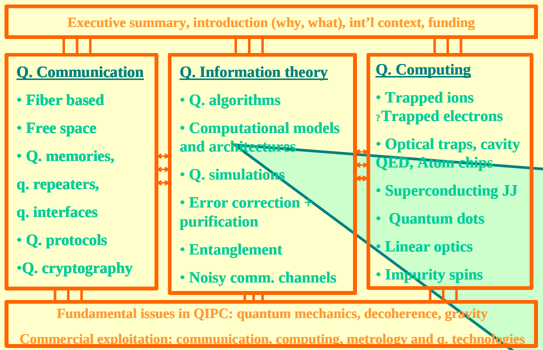
Electrons in quantum dots: 2-qubit gate

Excitons in QD: 1 qubit

Impurity spins: 2 qubits

Liquid-state NMR: 7 qubits; not scalable; max 15-20

QIPC Roadmap: the European flavor



Q. Information Theory

-alternative concepts and paradigms for QIPC

- fault-tolerant QIPC schemes using quantum error correction, purification, error-avoiding codes, decoherence-free subspaces;

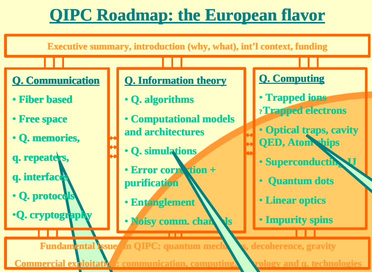
- new protocols and security proofs for distributed QIPC

- methods for universal quantum simulation with limited physical resources

- characterization of multipartite entanglement

Challenges: 1999 - 2005

- Entanglement
- Harnessing de-coherence
- Quantum information storage and retrieval
- Read-out (measurement) of intermediate and final results



Challenges (next 5 years):

Integration across different sub-domains and experimental approaches in order to reach concrete research objectives => From components to complete working q. systems

- Reliable q. interfaces, memory; repeaters
- Higher bit rates and larger distances
- New applications and protocols

Q. networks

- Q computer architectures
- Q algorithms
- Integration between physics, mathematics and computer science

-> **QI science**

Engineering of:

-elementary q processor with **reliable control** of the individual qubits (~10) and their entanglement

- Q simulator (~100)

Conclusions

At this point in time:

Development of a common EU research strategy: QIPC Roadmap

Some applications are mature enough for real-world deployment

The year 2006: advance from one stage of development to another one, which is more mature: integration of components to build working q. systems (SCALA and QAP have started the process)

- The EU QIPC research community has reached critical mass and is scientifically competitive on world scale; it is leading in many domains

- The FET QIPC PI has started a powerful process to strengthen, unify and structure the research community at EU level and to build a common European identity

Actions for the QIPC cluster: permanent

- Overview at EU level: It is imperative that at each moment in time we have a clear understanding of the results obtained, an assessment of the strengths and weaknesses in present research, as well as a clear definition of the challenges and the objectives.

- Continue and enhance the development of a common strategy and vision for research at EU level:

  - assess the state-of-the-art and trace the way to the future: the **roadmap**

  - continuously keep up-to-date

  - implement both at funding and at research level

Actions for the QIPC cluster: permanent

• Continue and enhance the process to unify, structure and strengthen the community.

• Active collaboration between FET, the projects and the research community in order to respond on time and proactively to:
- the changing needs of the community
- the fast research developments
- changes at EU and Commission level
- changes at international level

• Bottom-up approach, active participation of the entire research community, comprehensive and no-nonsense feedback channel, discussions…

Actions for the QIPC cluster: permanent

- Continue the tradition of the annual QIPC workshop and review-conference: serve as a platform for information exchange and a feedback channel between the research community and FET
- At each of these events organize a ‘special session’ to discuss policy and planning of the QIPC cluster
- Wide dissemination and promotion of QIPC at all levels
- Support emerging new areas, research topics and applications

Actions for the QIPC cluster: short-term (1y)

- QUROPE: make an active project that complements the rest of the activities and is a focal point for all other projects and the entire community
- ERA Pilot: make the necessary adjustments to the work in order to meet the current needs
- Updates and improvement of the databases: research teams and funding agencies
- Short publication – one page project overview
- Special issue EJPD

Actions for the QIPC cluster: mid-term (3y)

- QUROPE to develop (in collaboration with FET and the entire community) an European QIPC web portal
- Prepare the first QIPC call in FP7: research topics, collaborations, research goals, etc.
- Work towards integration across different disciplines and approaches in order to reach concrete research objectives (physics – computer science; different experimental realizations; interfaces, etc.)

Actions for the QIPC cluster: long-term (5y)

- Coordination between national initiatives or programs and the EU program so that they can complement each other
- Develop a common European strategy and platform for international collaboration according to the common EU research strategy: with whom, why, how…
- For certain applications: develop collaboration with industry

Conclusion

- **The FET program in QIPC has influenced in a significant way the development of QIPC research in Europe and has led to the emergence of qualitatively new approach and vision**


Thank you for your attention!