Quantum Simulation and Control

Universal Quantum Computation

⇙ ⇘

"Large" number of qubits

Demanding precision of quantum gates

Quantum Simulation ⇔ Control of quantum evolution

"Small" number of qubits.

Less precision and local control required.

Robust and optimised quantum gates.

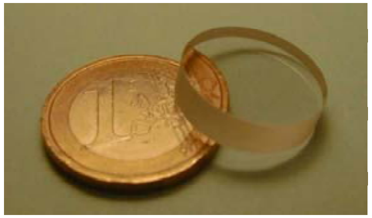
Characterisation and control of decoherence

Create, characterise, use entanglement

Quantum Simulation and Control

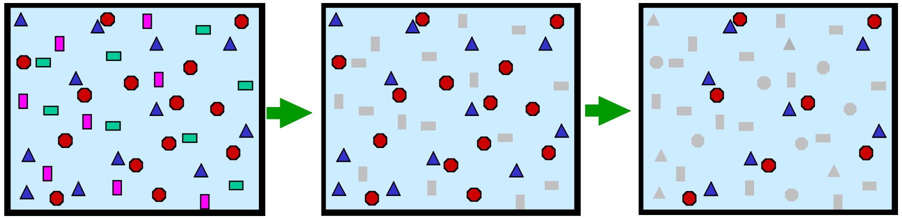
Rare Earth Ion-Doped Crystals, S. Kröll, Lund

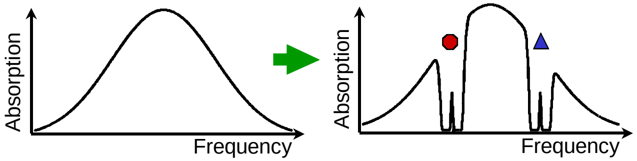
Pr doped yttrium silicate crystal

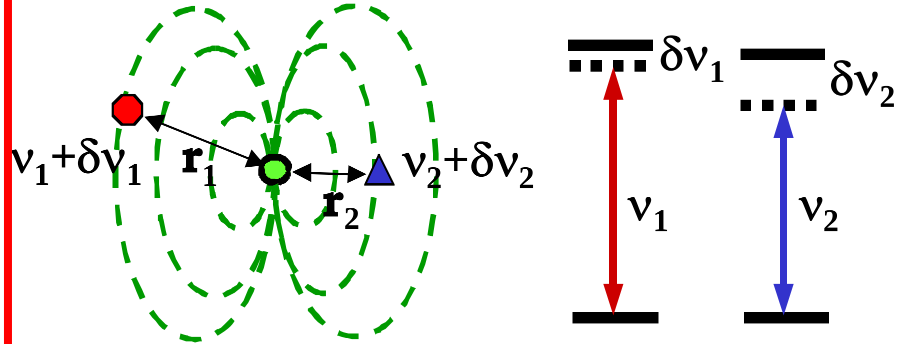


- Hyperfine qubits
- Dipole interaction for cond. dynamics

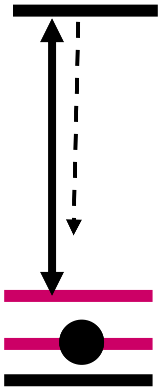
”Distillation” of qubits







State dependent permanent electric dipole interaction enables ion-ion control

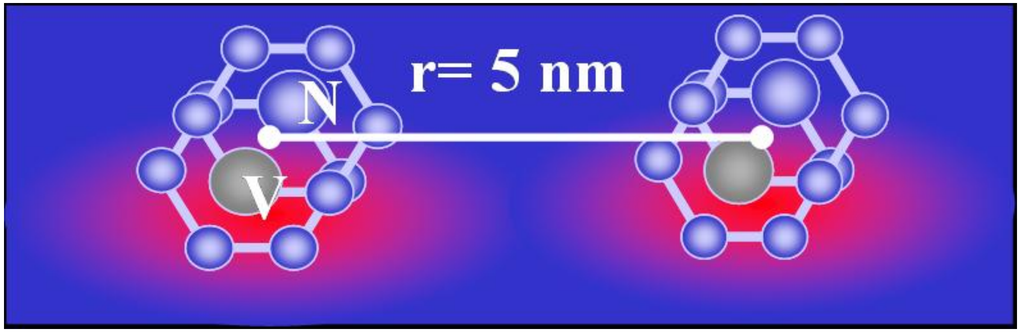


Quantum Simulation and Control

NV Defects in Diamond, J. Wrachtrup, Stuttgart

Coupled Nitrogen Vacancy (NV) defects in diamond:

- Qubit: electron spin
- Optical readout of spin state available
- Technology of defect generation exists



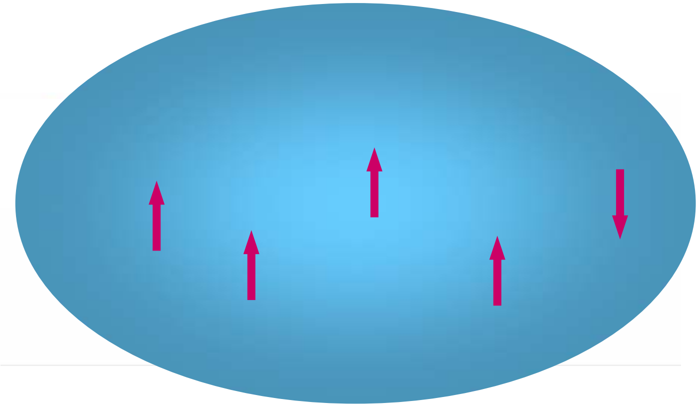
Cond. Dynamics:

- optical dipole interaction
- magnetic dipole interaction

Quantum Simulation and Control

Nuclear Magnetic Resonance Exp., S. Glaser, Munich.

- Qubits: Nuclear spins
- Conditional quantum dynamics: $\hbar \sum_{n<l}^{N} \sigma_{z,n} \sigma_{z,l} \; J_{nl}$

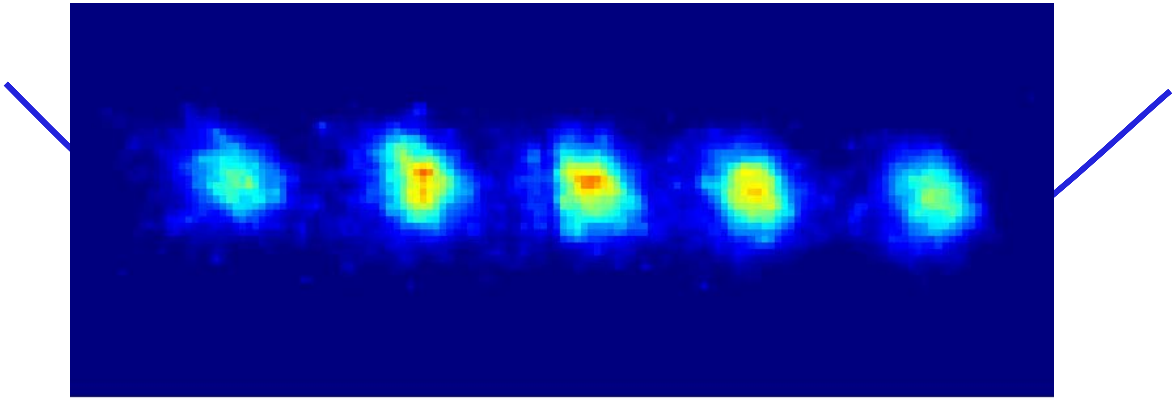


- Experiments:
    - Quantum algorithms and simulations with 5 to >10 qubits
    - Provide polymer chain of (A-B-C) units with ^{13}C, ^{15}N, ^{31}P.

Quantum Simulation and Control

Trapped Ion “Spin Molecule”, Chr. Wunderlich, Siegen

- Qubits: Hyperfine states
- Conditional quantum dynamics: $\hbar\sum_{i<j}^{N} J_{ij}\ \sigma_{z,i}\sigma_{z,j}$ ← Spin-Spin coupling



- Single Spin initialization/read-out, close to 100% efficiency.
- Precise quantum gates using microwave/rf radiation.

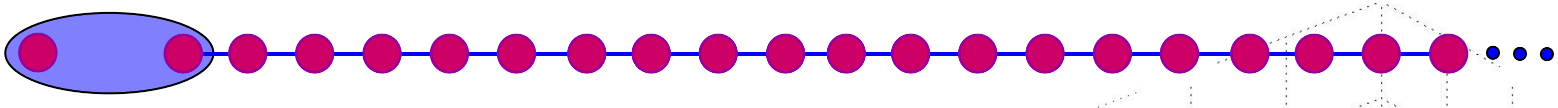
Quantum Simulation and Control

Entanglement Generation / Propagation, Phase Transitions

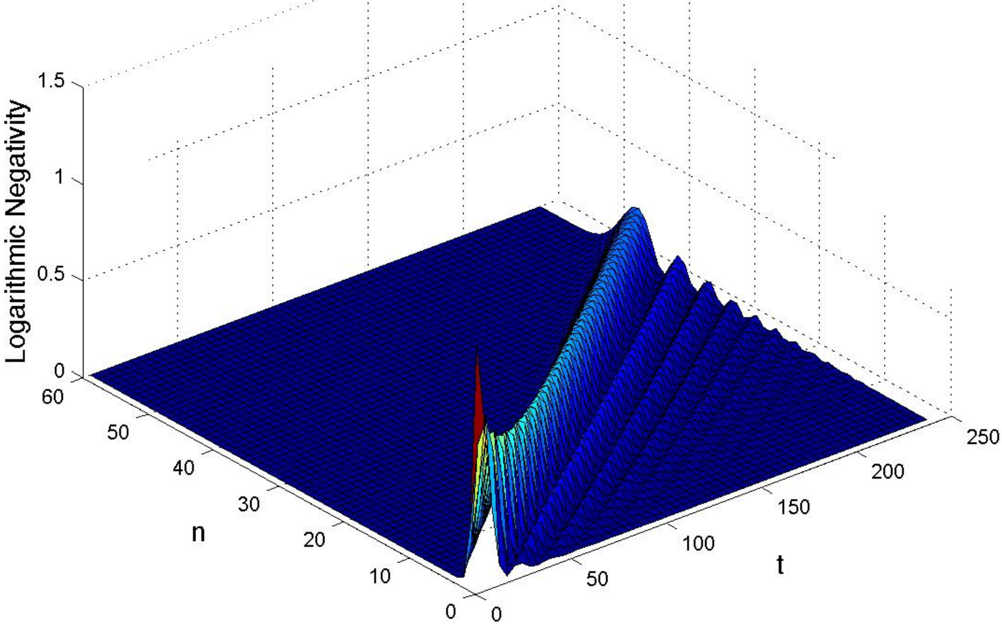
V. Buzek, Bratislava; J.I. Latorre, Barcelona, M. Plenio, London

- Internal dynamics of quantum many body systems may be employed for entanglement propagation, manipulation and for computation.

Example:



- Optimize transfer probabilities
- Characterize transport behaviour near critical point of a chain.
- Adapt to actual experimental technologies developed under QAP.



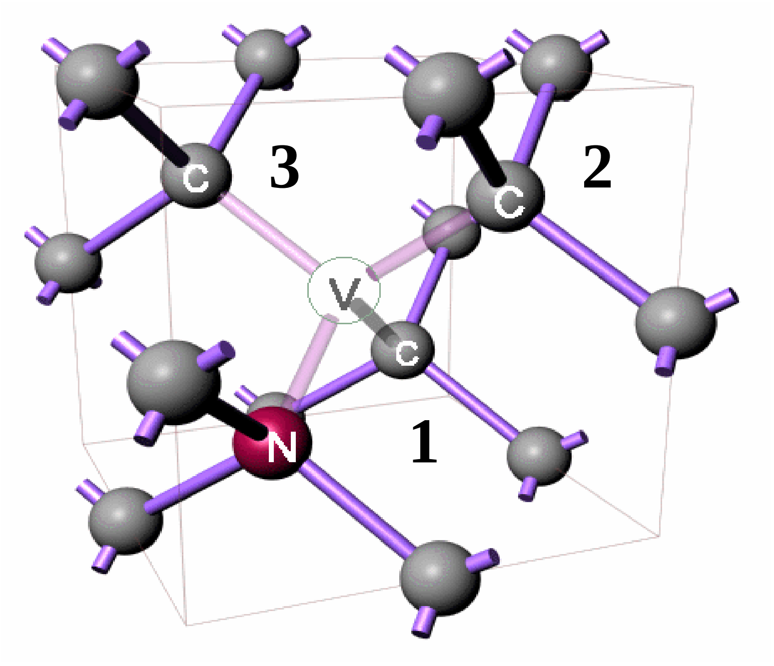
Quantum Simulation and Control

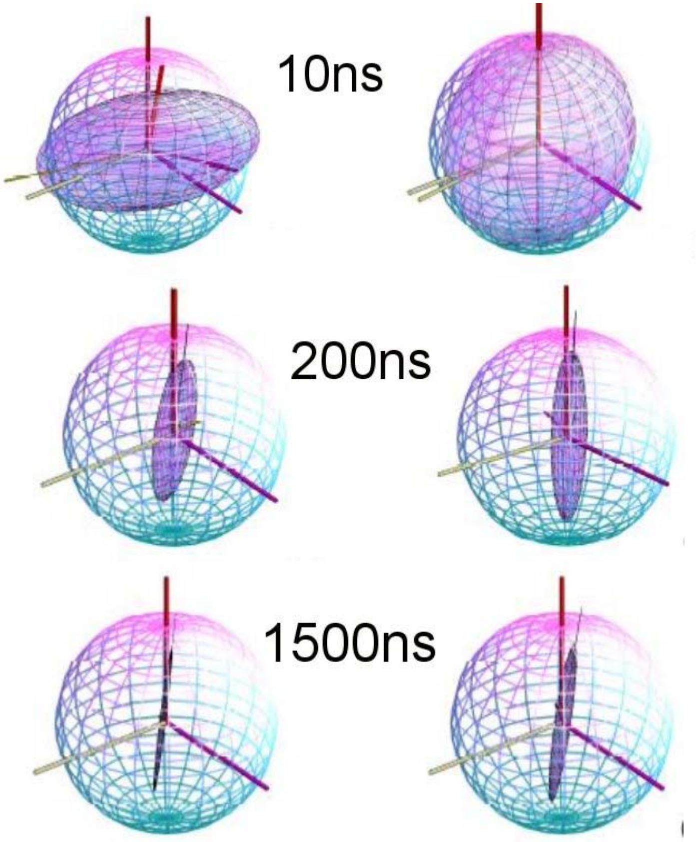
State/Process Estimation, Decoherence Studies/Protection

V. Buzek, Bratislava; G. Milburn, Queensland, J. Twamley, Sidney

Example:

Develop new techniques to probe for systematic decoherence effects and decoupling techniques to dynamically correct: e.g. quantum process tomography in a NV Centre in Diamond:





- Experimental QPT
- Nearest physical QPT

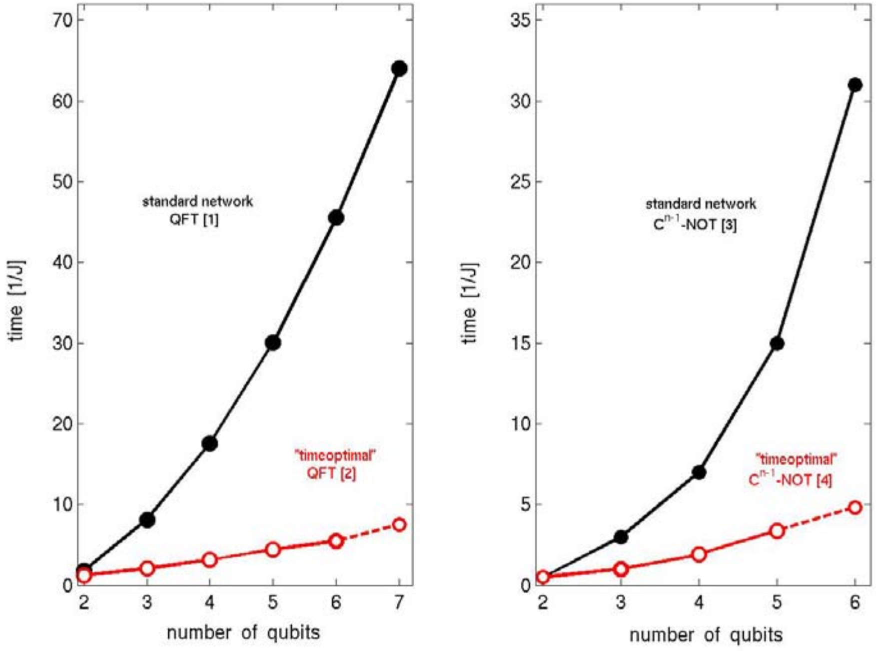
Quantum Simulation and Control

Nuclear Magnetic Resonance Theory, S. Glaser, Munich.

- Extend optimal control theory to other quantum systems: optimal quantum gates.
- Investigate simulation of arbitrary quantum evolution with given Hamiltonians
- Investigate decoherence-free subspaces.

Example: Time-Optimal Quantum Modules

Quantum Fourier Transform & Multiply-Controlled NOT



- "timeoptimal" gates
- ~ 7–9 times faster than standard-gate decompositions

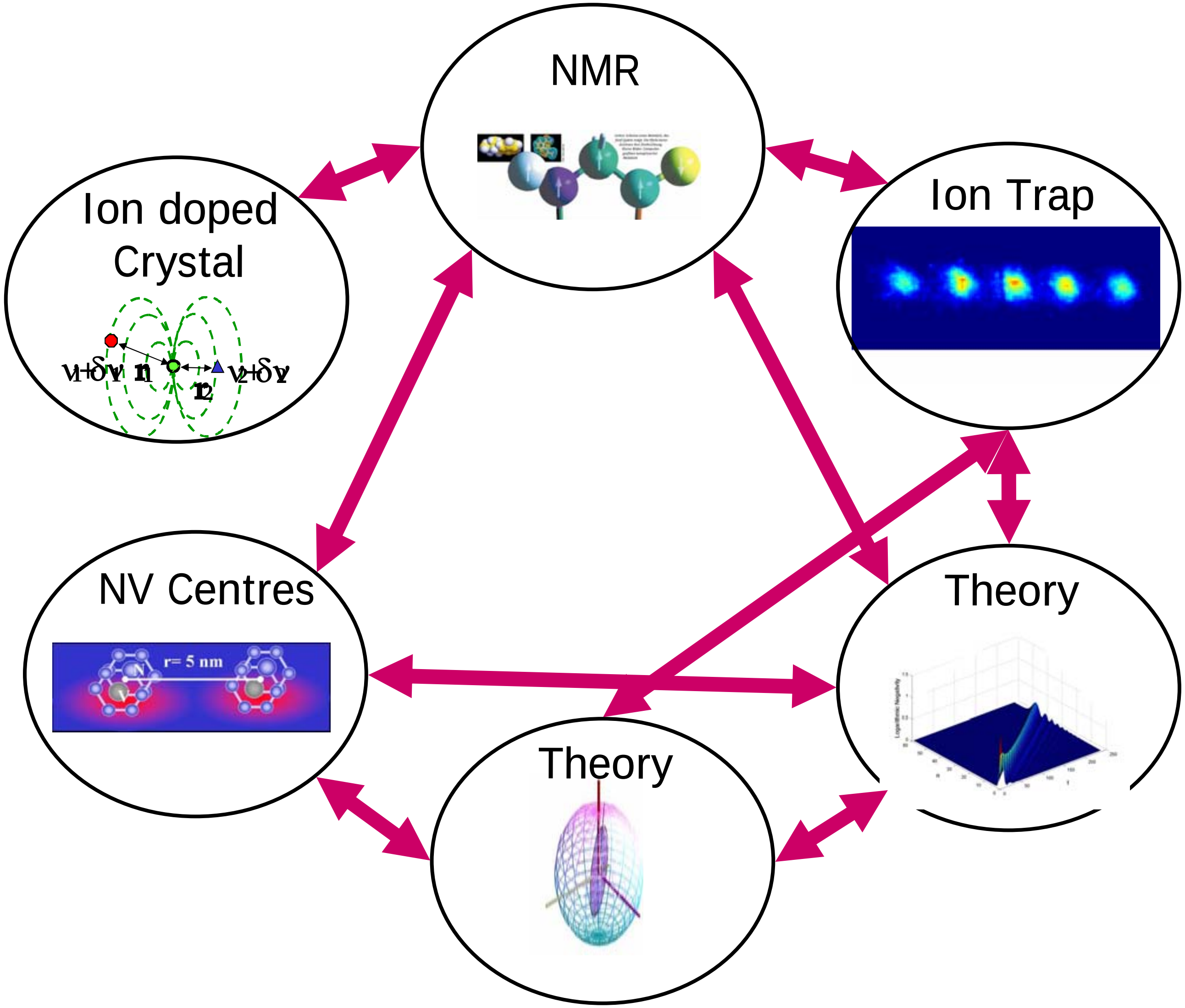
Quantum Simulation and Control

Quantum Simulation ⇔ Control of quantum evolution

- Quantum phase transitions
  (NMR, NV-Centres, Ion trap)
- Entanglement ↔ Phase transitions
- General Hamiltonian simulation
  (NMR: 5 … >10 qubits)

- Use Optimal Control Theory to
  - optimise quantum gates (e.g. Toffoli, QFT, ...)
  - explore decoherence free subspaces.
- Apply to various experimental systems: Experimental demonstration of speed-up and robustness.
- Global control versus local control: Investigate efficiency, speed, quality, cost for entanglement generation and transfer of QI in spin chains.
- Experimental probes for multi-particle entanglement.
- Develop new techniques to probe for systematic decoherence effects and their remedy.
- Effcient numerical simulation of spin networks.

Quantum Simulation and Control



NMR

Ion Trap

Ion doped Crystal

NV Centres

Theory

Theory