quantum information technology

Tad Hogg

HP Labs

Hype or reality?

- possible in principle
- difficult in practice
  - quantum states are fragile

- limited progress so far, *e.g.*,
  - factoring: 15 = 3x5
  - search: 3-variable MAXCUT
    - a graph partitioning problem

http://www.hpl.hp.com/research/qsr/

focus at HP

- identify uses of early technology
- use molecular electronics capabilities
  - currently: molecular memory & logic
  - maybe: quantum cellular automata?

🚫 what is possible?

what is feasible and useful?

relatively soon

compared to conventional methods

early technology

- few bits
  - ~20 or so
- few operations
  - before decoherence destroys state
- entanglement is a scarce resource
- high error rate
  - error correction needs many extra bits
  - so check & repeat instead of correct

uses of early technology

- sensors
- algorithm behaviors
- economic coordination
- chemistry simulation

sensors

- quantum states are fragile
  - destroyed by observation &
  - decoherence
- bad news:
  - limits computation time
- possible good news:
  - extremely sensitive sensors

study how decoherence depends on hardware, choice of operators,…

effect of decoherence

- examine experimentally
- one example:
  - implement quantum search algorithm
  - compare actual & ideal behaviors

  - joint work: MIT/HP/IBM

qubits based on spins

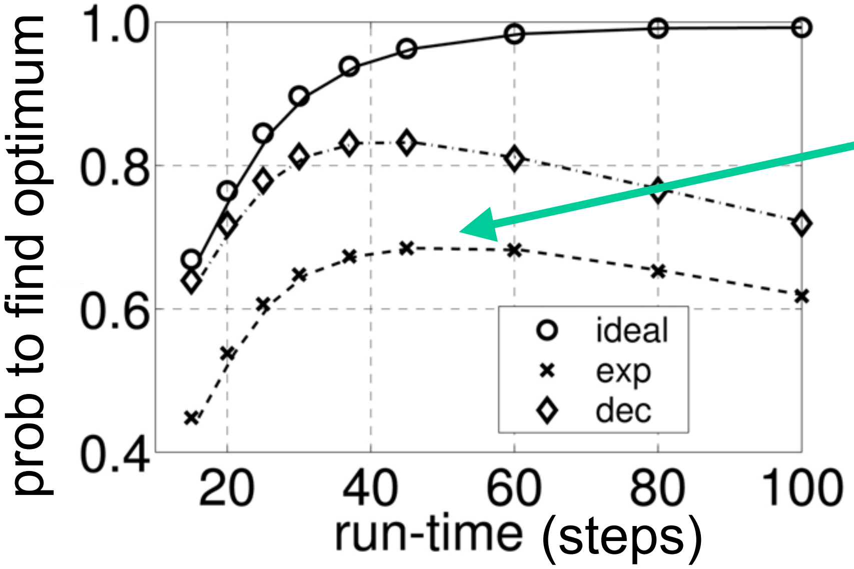
nuclear magnetic resonance (NMR)

one approach to quantum computing

-good for initial experiments

-difficult to scale to many bits

theory vs. experiment



experimentally, prob to find optimum reaches a maximum
(due to decoherence)

other errors:
pulses not perfect
discrete approx to adiabatic

Matthias Steffen et al., Experimental Implementation of an Adiabatic Quantum Optimization Algorithm, *Physical Review Letters* **90**, 067903 (2003)

uses of early technology

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combinatorial search

- shortest tour among several cities
- low energy shape for protein
- class scheduling
  - assign students to classes
  - constraints, e.g.,
    - pick popular professors
    - avoid early morning classes

quantum search

- a complex number for each state
  - “amplitude”
- rapid operations on all these numbers
  - even though exponentially many values!
- randomly produce single state
  - probability = $|\text{amplitude}|^2$
  - one-shot (watched computer doesn’t compute)
  - arrange large amplitudes for solutions

search algorithms

- unstructured (L. Grover, 1997)
  - amplitude amplification
- heuristics (T. Hogg, 1998, 2000)
  - tuned to typical structure
- adiabatic (E. Farhi et al., 2001)
  - slowly changing operators
- combinations
  - e.g., portfolios (S. Mauer et al., 2001)

evaluate algorithm behavior

- simulation with classical computer
- theory
- use a quantum computer

http://www.hpl.hp.com/shl/projects/quantum/demo

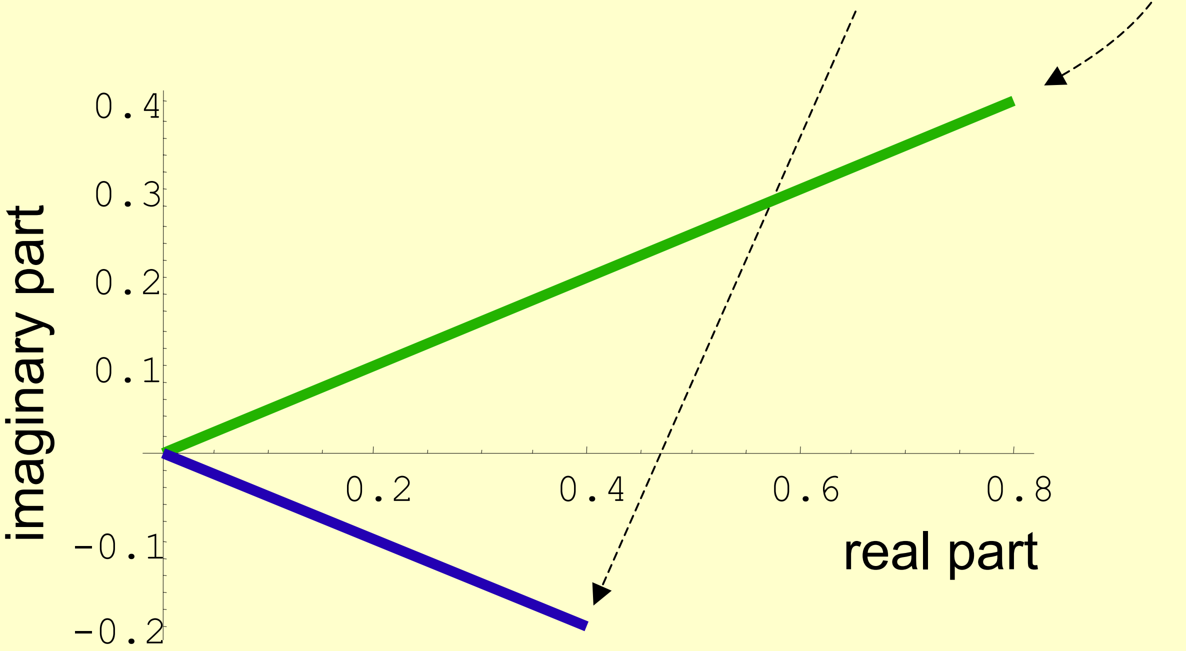
visualizing algorithms

- complex number for each state
- draw each as line segment
  - in complex plane
  - color according to number of conflicts
- algorithm steps change amplitudes
  - visualized as moving lines

http://www.hpl.hp.com/shl/projects/quantum/demo

example: 2 states

- amplitudes
  - state 1 with 2 conflicts: (4+2i)/5
  - state 2 with 4 conflicts: (2-i)/5



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demo

theory

- difficult math problem
  - as with theory for classical computing
  - focus often on worst case behaviors
- quantum useful even if only for typical case
  - e.g., typical hard problems:
    - exponentially many solutions
    - though only a small fraction of all possibilities
  - theory often treats single-solution cases

algorithm behavior

- simulation: limited to ~30 bits
  - too small to identify trend?
- theory: difficult
  - usually worst case, while major benefit only requires improved typical case
- quantum computer
  - help understand algorithms beyond ~30 bits
    - even though this size too small for practical use

uses of early technology

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economic coordination

- entanglement: correlated choices
- improve economic mechanisms?
  - e.g., public goods provision
- open questions
  - better than cryptographic methods?
  - how would people use quantum methods?
    - laboratory economic experiments

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quantum helps nanotech?

- molecular devices with quantum behaviors (e.g., bond formation)
  - difficult to compute with many atoms
  - quantum computers could help
  - alternatives:
    - conventional *approximate* computation
    - engineering design to avoid hard cases
      - e.g., molecular manufacturing with stiff structures

nanotech helps quantum

- atomically precise structures
  - e.g., self-assembly
    - such as DNA patterning (E. Winfree, Caltech)
  - e.g., molecular manufacturing

- could improve quantum hardware

summary:
early quantum technology

- sensors
- algorithm behaviors
- economic coordination
- chemistry simulation