Toward a Quantum Internet

Talk @ VFCS 2017

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Motivations

What
Why
When

Quantum Networks

Conclusions
Bit vs Qubit

**Bit**

- 0
- 1
  
  - either '0' or '1'

**Qubit**

- '0', '1', or both simultaneously
  
  - superposition principle
Simple Example: Finding the Ace of Hearts
Simple Example: Finding the Ace of Hearts

- classical computer
  - on average, 2.25 turns
    \[ \sum_{i=1}^{n-1} \frac{i}{n} + \frac{n-1}{n} = \frac{(n-1)n}{2n} + \frac{n-1}{n} = \frac{(n+2)(n-1)}{2n} \]
  - time complexity
    \[ t \sim O(n) \]
Simple Example: Finding the Ace of Hearts

- **classical computer**
  - on average, 2.25 turns
  - \[ \sum_{i=1}^{n-1} \frac{i}{n} + \frac{n-1}{n} = \frac{(n-1)n}{2n} + \frac{n-1}{n} = \frac{(n+2)(n-1)}{2n} \]
  - time complexity
  - \( t \sim O(n) \)

- **quantum computer**
  - on average, 1 turn
  - quantum computer \( \neq \) faster classical computer
  - time complexity
  - \( t \sim O(\sqrt{n}) \)
Quantum Approach to Problem Solving


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M. Caleffi, "Toward a Quantum Internet"
Killer Application: Integer Factorization

- Factor a number into primes: \( M = p \cdot q \)
  - basis of encryption schemes

- Classical:
  \[ t \sim O\left(e^{n^{1/3} \log n^{2/3}}\right) \]

- Quantum:
  \[ t \sim O(n^3) \]

Killer Application 2/2: Molecule Structure

- Bond Length

<table>
<thead>
<tr>
<th>molecule</th>
<th>experimental</th>
<th>computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>2.361 Å</td>
<td>2.212 Å</td>
</tr>
<tr>
<td>H2O</td>
<td>0.958 Å</td>
<td>1.020 Å</td>
</tr>
</tbody>
</table>

Source data: NIST Computational Chemistry Comparison and Benchmark Database.
Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.

R. Feynman, 1982

Source data: NIST Computational Chemistry Comparison and Benchmark Database.
Impact Iconography

Impact on applications and industries

- Government
- Pharmaceutical
- Cryptography
- Optimization
- Materials Science
- Measurement
- Financial Services
- Chemistry
- Weather Services

Credits: IBM.
Short Answer

When the time for quantum computing will come?

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Short Answer

When the time for quantum computing will come?

now
2017: State of the Art 1/3

D-Wave 2000Q


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2017: State of the Art 2/3

IBM 17Q

Credits: Carl De Torres for IBM.
Chinese Quantum Satellite *Micius*

Credits: Xinhua News Agency.

2017: State of the Art 3/3
Too Big to be practical?

I think there is a world market for maybe five computers.

T. Watson, president of IBM, 1943.

Credits: Carl De Torres for IBM (left) - Grace Murray Hopper Collection, 1944-1965, National Museum of American History (right).
Too Big to be practical?

2017 vs 1945

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Simple Example: Finding the Ace of Hearts

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Running Quantum Experiments

Finding the Ace of Hearts on IBM 5Q 1/2

Quantum Circuit

Device Calibration

Date Calibration: 2017-02-06 20:05
Fridge Temperature: 0.019103 Kelvin

Q0
f: 5.07 GHz
TL: 52.5 μs
tc: 2.6 × 10⁻²
tc: 3.6 × 10⁻³

Q1
f: 5.23 GHz
TL: 42.5 μs
tc: 2.9 × 10⁻²
tc: 3.6 × 10⁻³

Q2
f: 5.09 GHz
TL: 40.3 μs
tc: 2.9 × 10⁻²
tc: 3.6 × 10⁻³

Q3
f: 5.09 GHz
TL: 40.3 μs
tc: 2.9 × 10⁻²
tc: 3.6 × 10⁻³

Q4
f: 5.06 GHz
TL: 49.3 μs
tc: 3.9 × 10⁻²
tc: 3.4 × 10⁻³

Number of shots: 1024

Credits: IBM Quantum Experience.

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Designing Quantum Networks
Quantum Internet

Present computer networks may be characterized as small to moderate in size (57 nodes for the ARPANET as of December 1975). Predictions indicate that, in fact, large networks of the order of hundreds (or even possibly thousands) of nodes are soon to come.


Quantum Internet

Distributed Quantum Computing

- quantum computing is **real**
- quantum networks are **mandatory** to fully unleash the ultimate vision of the quantum revolution
  - quantum web:
    - quantum computers, simulators and sensors interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement.

Present computer networks may be characterized as small to moderate in size (57 nodes for the ARPANET as of December 1975). Predictions indicate that, in fact, large networks of the order of hundreds (or even possibly thousands) of nodes are soon to come.


Quantum-Aware Design

- no-cloning theorem
- entanglement
- decoherence
No-Cloning Theorem

- an arbitrary unknown qubit cannot be copied

\[ \text{Clone}(\lvert \psi \rangle + \lvert \phi \rangle) = (\lvert \psi \rangle + \lvert \phi \rangle) \times (\lvert \psi \rangle + \lvert \phi \rangle) \]

\[ = (\lvert \psi \rangle \times \lvert \psi \rangle) + (\lvert \phi \rangle \times \lvert \phi \rangle) \]

\[ + (\lvert \psi \rangle \times \lvert \phi \rangle) + (\lvert \phi \rangle \times \lvert \psi \rangle) \]

\[ \neq \]

\[ \text{Clone}(\lvert \psi \rangle) + \text{Clone}(\lvert \phi \rangle) = (\lvert \psi \rangle \times \lvert \psi \rangle) + (\lvert \phi \rangle \times \lvert \phi \rangle) \]

Credits to: Henry Reich, MinutePhysics.
Quantum Entanglement

### Quantum Teleportation

- **no-cloning theorem**
  - an arbitrary unknown qubit cannot be copied
  - to obtain the qubit at the destination
  - the original qubit at the source must be destroyed
  - hence, the name **quantum teleportation**

- based on **quantum entanglement**

"I cannot seriously believe in it because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from **spooky actions at a distance**."

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Quantum Decoherence

Decoherence

- information corruption as time passes
- as a consequence of interaction with the environment

Credits: IBM Quantum Experience.
Quantum-Aware Design

Need of a paradigm shift

- no-copying
- entanglement distribution
- decoherence
- automatic repeat request
- relaying
- store-and-forward
- best effort
- caching

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Optimal Quantum Routing Metric Design

**Optimal Routing Metric**

**Definition 8. (Optimality)** A route metric is defined *optimal* if there exists a routing protocol that, when used in conjunction with such a metric, always discovers the most favorable path between any pair of nodes in any connected network.

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**Quantum Routing Metric Design**

- challenges
  - remote entanglement generation
  - quantum decoherence
  - stochastic underlying physical mechanisms

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Optimal Quantum Routing Metric Design

Optimal vs Suboptimal Routing Metric Design

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Entanglement Rate for a Simple Path

Algorithm 1 Expected Entanglement Rate

1: function \( X(r_{ij}, \{ d_{im} \} e_{im} \in r_{ij}, T^{ch}) \)
2: for link \( e_{im} \in r_{ij} \) do
3: \( p_{i,m} = \frac{1}{2} \nu_{ij}^2 e^{-d_{im}/L_0} \)
4: \( \tau_{im} = d_{im}/2 c_f \)
5: \( \tau_{im} = \tau_d + \tau_o + d_{im}/(2 c_f) + \tau_e \)
6: \( T^{+}_{im} = \tau_p + \max\{\tau_{im}, \tau_d\} \)
7: \( T^{-}_{im} = \tau_{im} + \max\{\tau_{im}, \tau_d\} \)
8: \( \xi_{r_{ij}} = (1-p_{i,m}) T^{+}_{im} + p_{i,m} T^{-}_{im} / p_{i,m} \)
9: end for
10: \( n = \text{NUMLINKS}(r_{ij}) \)
11: if \( n = 1 \) then
12: if \( \tau_{im} \geq T^{ch} \) then
13: \( \xi_{r_{ij}} = 1/T_{im} \)
14: end if
15: else
16: \( k = \lceil (n+1)/2 \rceil \)
17: \( T_{r_{ij}} = \text{RECT}(r_{ij}, \{ T_{im} \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
18: \( T_{r_{ij}} = \text{RECT}(r_{ij}, \{ T_{im} \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
19: \( \bar{T} = \max\{T_{r_{ij}}, T_{r_{jk}}\} \)
20: \( T^+ = \max\{\sum_{m=1}^{n} e_{im} \tau_{im}, \sum_{m=1}^{n} e_{im} \tau_{im}\} \)
21: \( T^{\sim}_{r_{ij}} = (\bar{T} + \tau^o + T^+) / \nu_n \)
22: \( \tau_{r_{ij}} = \text{RECTAU}(r_{ij}, \{ T^+ \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
23: \( \tau_{r_{ij}} = \text{RECTAU}(r_{ij}, \{ T^+ \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
24: \( \bar{T} = \max\{\tau_{r_{ij}}, \tau_{r_{jk}}\} \)
25: \( \tau_{r_{ij}} = \bar{T} + \tau^o + T^+ \)
26: if \( \tau_{r_{ij}} - \min\{T^{ch}_{im} - \tau_{im} \} \geq T^{ch} \) then
27: \( \xi_{r_{ij}} = 1/T_{r_{ij}} \)
28: end if
29: end if
30: return \( \xi_{r_{ij}} \)
31: end function

Algorithm 2 Auxiliary Functions

1: function \( \text{RECT}(r_{ij}, \{ T_{im} \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
2: \( n = \text{NUMLINKS}(r_{ij}) \)
3: if \( n = 1 \) then
4: \( T_{r_{ij}} = T_{a,b} \)
5: else
6: \( k = \lceil (n+1)/2 \rceil \)
7: \( T_{r_{ij}} = \text{RECT}(r_{ij}, \{ T_{im} \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
8: \( T_{r_{ij}} = \text{RECT}(r_{ij}, \{ T_{im} \}, \{ \tau_{im} \}, \tau_o, \tau_p) \)
9: \( \bar{T} = \max\{T_{r_{ij}}, T_{r_{jk}}\} \)
10: \( T^+ = \max\{\sum_{m=1}^{n} e_{im} \tau_{im}, \sum_{m=1}^{n} e_{im} \tau_{im}\} \)
11: \( T^{\sim}_{r_{ij}} = (\bar{T} + \tau^o + T^+) / \nu_n \)
12: end if
13: end function
Conclusions

- quantum computing is real
- quantum networks are mandatory to fully unleash the ultimate vision of the quantum revolution
- a major network architecture paradigm shift is required to design quantum communications