Toward a Quantum Internet

Talk @ VFCS 2017

Marcello Caleffi

National Laboratory of Multimedia Communication
CNIT: National InterUniversity Consortium for Telecommunications

Dept. of Electrical Engineering and Information Technologies
University of Naples *Federico II*

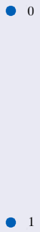
E-mail: marcello.caleffi@unina.it
Web-page: wpage.unina.it/marcello.caleffi

Motivations

Bit vs Qubit

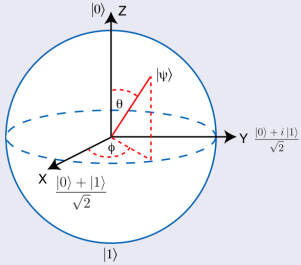
Outline
Motivations
What
Why
When
Quantum Networks
Conclusions

Bit



- either '0' or '1'

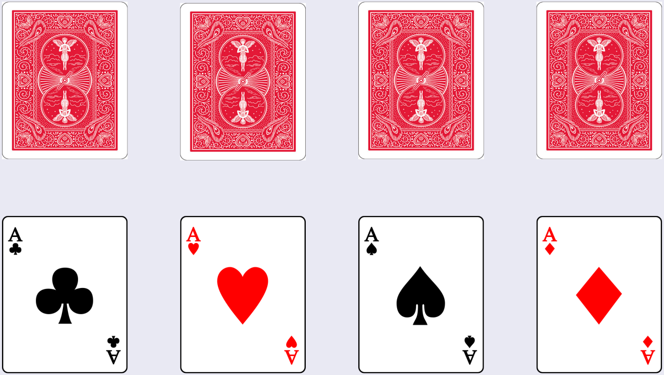
Qubit



- '0', '1', or both simultaneously
  - superposition principle

Quantum Supremacy 1/2

Simple Example: Finding the Ace of Hearts



Quantum Supremacy 1/2

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
    - $t \sim \mathcal{O}(n)$

Quantum Supremacy 1/2

Simple Example: Finding the Ace of Hearts

- classical computer
  - on average, 2.25 turns
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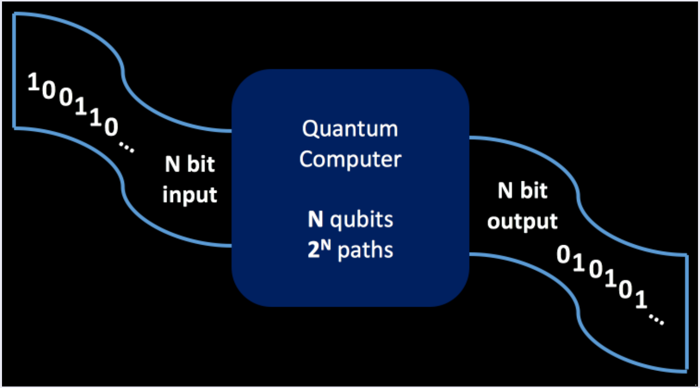
  - time complexity
    - $t \sim \mathcal{O}(n)$
- quantum computer
  - on average, 1 turn
    - quantum computer $\neq$ faster classical computer
  - time complexity
    - $t \sim \mathcal{O}(\sqrt{n})$

Quantum Approach to Problem Solving



Credits to: Dr. T. Gershon, *"A Beginner's Guide to Quantum Computing"*, IBM Research.

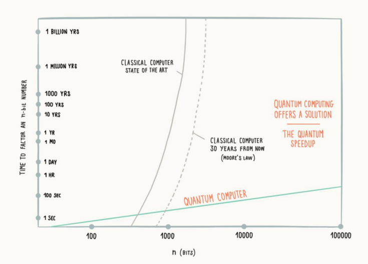
Quantum Impact 1/3

Killer Application: Integer Factorization

- Factor a number into primes: $M = p\,q$
  - basis of encryption schemes

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

- Quantum: $t \sim \mathcal{O}(n^3)$

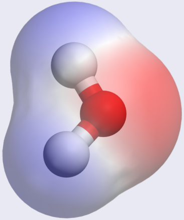


Source data: R. Van Meter, K.M. Itoh, and T.D. Ladd, *"Architecture-dependent execution of Shor's algorithm,"* in Controllable Quantum States, 2005. Image credit: New Enterprise Associates

Killer Application 2/2: Molecule Structure

- Bond Length

molecule	experimental	computed
NaCl	2.361 Å	2.212 Å
H2O	0.958 Å	1.020 Å



Source data: NIST Computational Chemistry Comparison and Benchmark Database.

Quantum Impact 2/3

Killer Application 2/2: Molecule Structure

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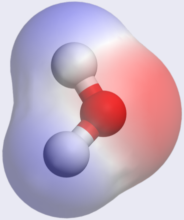
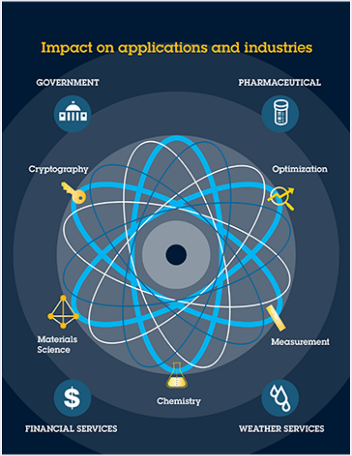


> Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.
>
> R. Feynman, 1982

Source data: NIST Computational Chemistry Comparison and Benchmark Database.

Quantum Impact 3/3

Impact Iconography



Credits: IBM.

Short Answer

When the time for quantum computing will come?

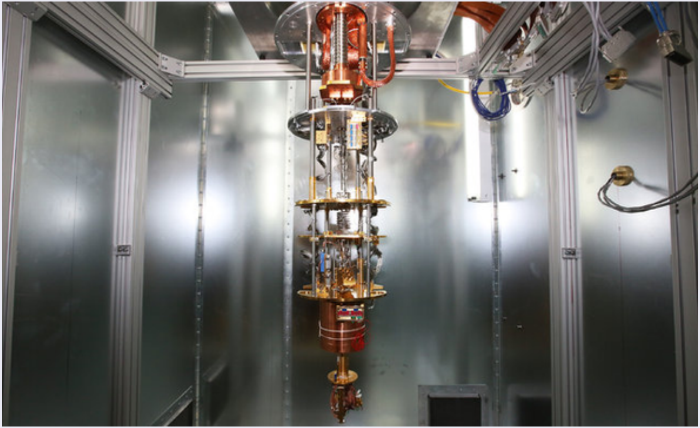
Short Answer

When the time for quantum computing will come?

now

2017: State of the Art 1/3

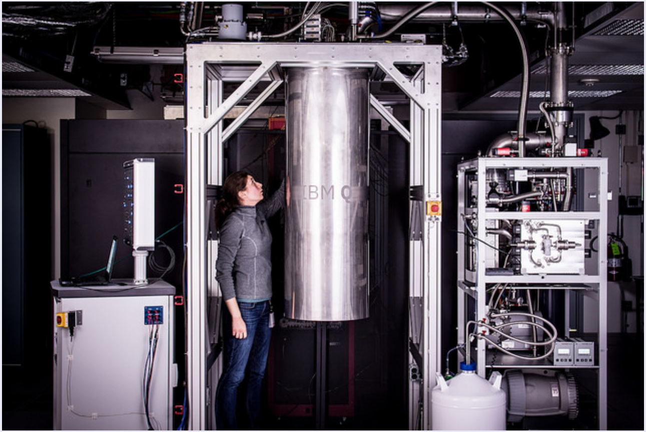
D-Wave 2000Q



Credits: Kim Stallknecht for The New York Times.

2017: State of the Art 2/3

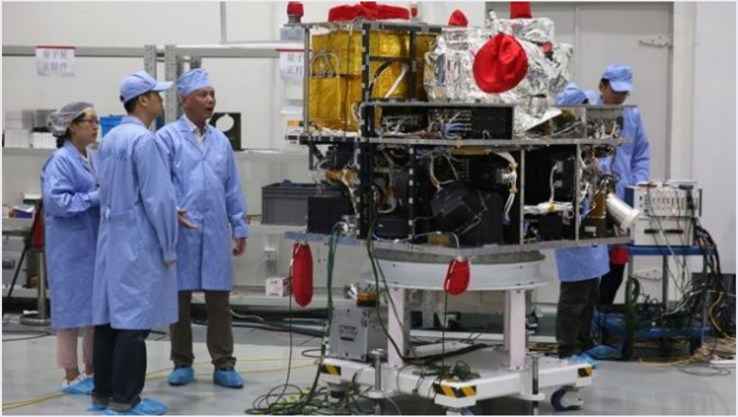
IBM 17Q



Credits: Carl De Torres for IBM.

2017: State of the Art 3/3

Chinese Quantum Satellite *Micius*



Credits: Xinhua News Agency.

Too Big to be practical?

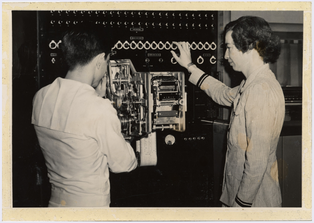
I think there is a world market for maybe five computers.

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



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

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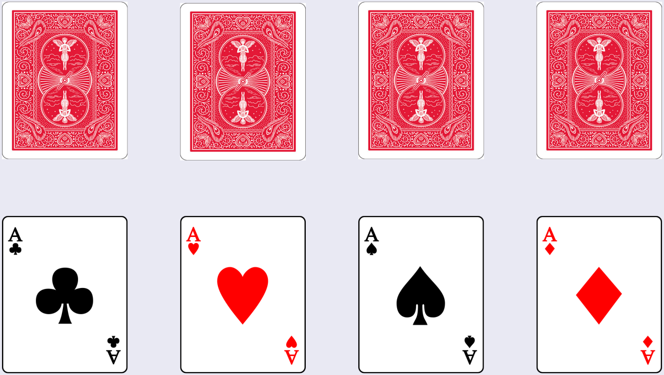
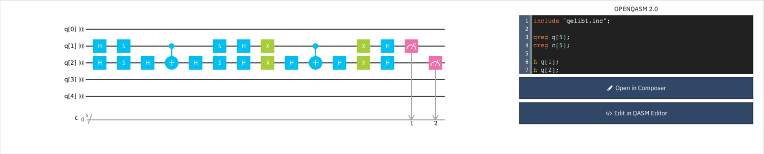
Running Quantum Experiments

Simple Example: Finding the Ace of Hearts



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

Quantum Circuit



Device Calibration

Date Calibration: 2017-02-06 20:05

Fridge Temperature: 0.019101 Kelvin

Q_0	Q_1	Q_2	Q_3	Q_4
f: 5.27 GHz	f: 5.21 GHz	f: 5.03 GHz	f: 5.30 GHz	f: 5.06 GHz
T_1: 57.5 μs	T_1: 62.5 μs	T_1: 49.2 μs	T_1: 49.8 μs	T_1: 53.2 μs
T_2: 30 μs	T_2: 29.9 μs	T_2: 84.8 μs	T_2: 47.2 μs	T_2: 80 μs
ϵ_g: 2.6×10^{-3}	ϵ_g: 2×10^{-3}	ϵ_g: 4.1×10^{-3}	ϵ_g: 3.8×10^{-3}	ϵ_g: 3.2×10^{-3}
ϵ_r: 2.4×10^{-2}	ϵ_r: 1.1×10^{-1}	ϵ_r: 1.1×10^{-2}	ϵ_r: 3.3×10^{-2}	ϵ_r: 6.6×10^{-2}
ϵ_g^{01}: 3.62×10^{-2}	ϵ_g^{12}: 3.67×10^{-2}		ϵ_g^{34}: 3.81×10^{-2}	ϵ_g^{42}: 3.47×10^{-2}
ϵ_g^{02}: 3.6×10^{-2}			ϵ_g^{32}: 5.67×10^{-2}	

Executed on: Sep 6, 2017 1:09:39 PM
Results date: Sep 6, 2017 1:09:39 PM
Results from Cache: Feb 7, 2017 4:07:18 AM

Number of shots: 1024

Credits: IBM Quantum Experience.

Designing Quantum Networks

Outline
Motivations
Quantum Networks
Quantum Internet
Quantum-Aware
Case Study
Conclusions

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.

L. Kleinrock and F. Kamoun, "*Hierarchical routing for large networks*", Elsevier Computer Networks, Vol. 1, pp. 155-174, 1977.

Quantum Web definition: *Quantum Technologies Flagship Final Report*, June 28 2017.

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.

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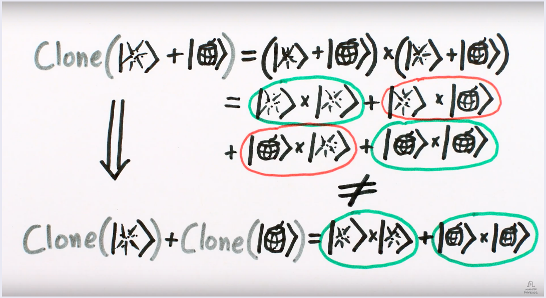
Quantum-Aware Design

- no-cloning theorem
- entanglement
- decoherence

OSI Model	TCP/IP Protocol Suite	TCP/IP Model
Application	HTTP, DNS, DHCP, FTP	Application
Presentation		
Session		
Transport	TCP, UDP	Transport
Network	IPv4, IPv6, ICMPv4, ICMPv6	Internet
Data Link	PPP, Frame Relay, Ethernet	Network Access
Physical		

No-Cloning Theorem

- an arbitrary unknown qubit cannot be copied



Credits to: Henry Reich, MinutePhysics.

Quantum Entanglement

Quantum Teleportation

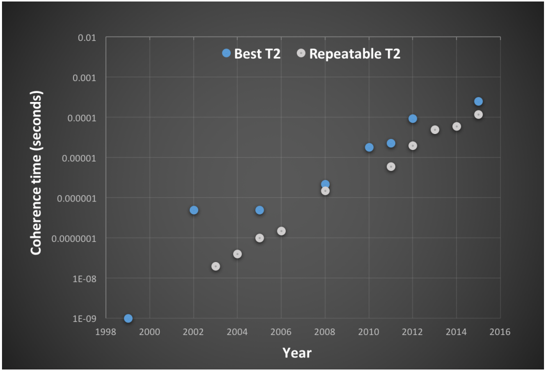
- no-cloning theorem
  - an arbitrary unknown qubit cannot be copied
- to obtain the qubit at the destination
  - the original qubit at the source must be destroyed
  - hence, the name quantum teleportation
- based on quantum entanglement

"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."

A. Einstein, *letter to M. Born*, March 3, 1947.

Decoherence

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



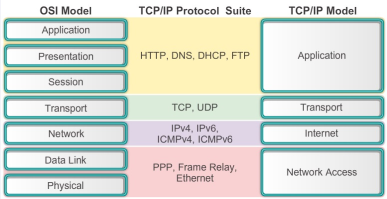
Credits: IBM Quantum Experience.

Quantum-Aware Design

Need of a paradigm shift

- no-copying
- entanglement distribution
- decoherence

- automatic repeat request
- relaying
- store-and-forward
- best effort
- caching



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.

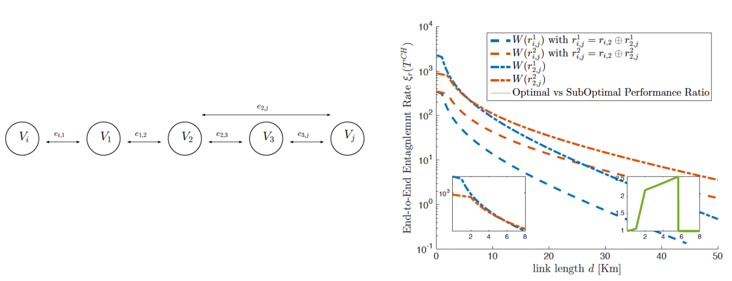
Quantum Routing Metric Design

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

M. Caleffi, *"End-to-end entanglement rate: Toward a quantum route metric,"* in IEEE Globecom Workshops (GC Wkshps), Dec 2017, pp. 1-6.

M. Caleffi, *"Optimal routing for cavity-based quantum networks,"* in IEEE Access, June 2017.

Optimal vs Suboptimal Routing Metric Design



Entanglement Rate for a Simple Path

Algorithm 1 Expected Entanglement Rate

function $\textsc{Xi}(r_{i,j}, \{d_{l,m}\}_{e_{l,m} \in r_{i,j}}, T^{\text{ch}})$
  for link $e_{lm} \in r_{i,j}$ **do**
    $p_{l,m} = \frac{1}{2}\nu_o p^2 e^{-d_{l,m}/L_0}$
    $\tau^{\text{c}}_{l,m} = d_{l,m}/2c_f$
    $\tau_{l,m} = \tau^t + \tau^o + d_{l,m}/(2c_f) + \tau^{\text{c}}_{l,m}$
    $T^s_{l,m} = \tau^p + \max\{\tau^h, \tau_{l,m}\}$
    $T^f_{l,m} = \tau^p + \max\{\tau^h, \tau_{l,m}, \tau^d\}$
    $T_{l,m} = \left((1 - p_{l,m})T^f_{l,m} + p_{l,m}T^s_{l,m}\right)/p_{l,m}$
  end for
  $n = \textsc{NumLinks}(r_{i,j})$
  if $n = 1$ **then**
    if $\tau_{l,m} \geq T^{CH}$ **then**
      $\xi_{r_{i,j}} = 1/T_{l,m}$
    end if
  else
    $k = \lceil (n+1)/2 \rceil$
    $T_{r_{i,k}} = \textsc{RecT}(r_{i,k}, \{T_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a, \nu^a)$
    $T_{r_{k,j}} = \textsc{RecT}(r_{k,j}, \{T_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a, \nu^a)$
    $\tilde{T} = \max\{T_{r_{i,k}}, T_{r_{k,j}}\}$
    $\tilde{T}^{\text{c}} = \max\{\sum_{e_{l,m} \in r_{i,k}} \tau^{\text{c}}_{l,m}, \sum_{e_{l,m} \in r_{k,j}} \tau^{\text{c}}_{l,m}\}$
    $T_{r_{i,j}} = \left(\tilde{T} + \tau^a + \tilde{T}^{\text{c}}\right)/\nu^a$
    $\tau_{r_{i,k}} = \textsc{RecTau}(r_{i,k}, \{T^s_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a)$
    $\tau_{r_{k,j}} = \textsc{RecTau}(r_{k,j}, \{T^s_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a)$
    $\tilde{\tau} = \max\{\tau_{r_{i,k}}, \tau_{r_{k,j}}\}$
    $\tau_{r_{i,j}} = \tilde{\tau} + \tau^a + \tilde{T}^{\text{c}}$
    if $\tau_{r_{i,j}} - \min\{T^s_{l,m} - \tau_{l,m}\} \geq T^{CH}$ **then**
      $\xi_{r_{i,j}} = 1/T_{r_{i,j}}$
    end if
  end if
  return $\xi_{r_{i,j}}$
end function

Algorithm 2 Auxiliary Functions

function $\textsc{RecT}(r_{a,b}, \{T_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a, \nu^a)$
  $n = \textsc{NumLinks}(r_{a,b})$
  if $n = 1$ **then**
    $T_{r_{a,b}} = T_{a,b}$
  else
    $k = \lceil (a+b)/2 \rceil$
    $T_{r_{a,k}} = \textsc{RecT}(r_{a,k}, \{T_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a, \nu^a)$
    $T_{r_{k,b}} = \textsc{RecT}(r_{k,b}, \{T_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a, \nu^a)$
    $\tilde{T} = \max\{T_{r_{a,k}}, T_{r_{k,b}}\}$
    $\tilde{T}^{\text{c}} = \max\{\sum_{e_{l,m} \in r_{a,k}} \tau^{\text{c}}_{l,m}, \sum_{e_{l,m} \in r_{k,b}} \tau^{\text{c}}_{l,m}\}$
    $T_{r_{i,j}} = \left(\tilde{T} + \tau^a + \tilde{T}^{\text{c}}\right)/\nu^a$
  end if
end function

function $\textsc{RecTau}(r_{a,b}, \{T^s_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a)$
  $n = \textsc{NumLinks}(r_{a,b})$
  if $n = 1$ **then**
    $T_{r_{a,b}} = T^s_{a,b}$
  else
    $k = \lceil (a+b)/2 \rceil$
    $\tau_{r_{a,k}} = \textsc{RecTau}(r_{a,k}, \{T^s_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a)$
    $\tau_{r_{k,b}} = \textsc{RecTau}(r_{k,b}, \{T^s_{l,m}\}, \{\tau^{\text{c}}_{l,m}\}, \tau^a)$
    $\tilde{\tau} = \max\{\tau_{r_{a,k}}, \tau_{r_{k,b}}\}$
    $\tilde{T}^{\text{c}} = \max\{\sum_{e_{l,m} \in r_{a,k}} \tau^{\text{c}}_{l,m}, \sum_{e_{l,m} \in r_{k,b}} \tau^{\text{c}}_{l,m}\}$
    $\tau_{r_{i,j}} = \tilde{\tau} + \tau^a + \tilde{T}^{\text{c}}$
  end if
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