

Future of QI

The Benasque Quantum Information Workshops 2011 – 2019

compiled by Adán Cabello and Géza Giedke

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2011

Quantum Computation

-) Q. Algorithms
-) "Linear" Optics
-) Robust 2D Topological QC & Memory

Q. Simulation

-) Validation (Error Correction)
-) Prediction: Q. Simulation
✓
Marek: 2 Years C. Simulation
Zynda: >1

+5 more...

2013

QUANTUM INFORMATION THEORY

- NPT BOUND ENTANGLEMENT
- Quantum Violate Ingleton ≥ 0
- Characterization M-part. entanglement + apps

- Q. Discord??

* Unw. Q.C. with Q. Walks

* Unifying Q. Correl. \Leftarrow Discord

* Q.C. with little entang.

- Charact. LOCC + POVM (measurements) LOSR
- Role ent. in Q.C.

* Security Device-indep QKD

- General framework security dev. indep
- Certification Spoo-like separation dev. indep
- Example non-sec C.C. Channels
- PPT \Rightarrow E. Breaking

NEUTRAL VS BESI FOUNDATIONS OF QUANTUM PHYSICS

* PBR THEOREM

* Activation Q. non-locality

- B.E.S violate B. ineq

- Beyond B. ineq.

- PRINCIPLES FOR Q CORRELATIONS

* Therm: Landauer pple + 2nd law

RELATIVITY

- QM & QIT IN LOW-ENERGY PHYSICS

- Firewall in BH.

- ARE LEGGETT-GARG INEQUALITIES USEFUL?

- Decidability in QIT

- NON-LOCALITY IN MANY-BODY PHYSICS

- MULT. PRINCIPLES ENOUGH?

- LIFE AFTER LOOPHOLE-FREE BIP?

- TSIRELSON'S PROBLEM

MANY-BODY PHYSICS

* TIME-DEPENDENT VARIATIONAL PRINCIPLE

* CRITICALITY IN OPEN Q SYSTEMS

- EFFICIENT SIMULATION OF Q DYNAMICS

- CLASS. PHASES HIGHER-D

- APPROXS. (TRUNCATION) TN

- THERMALIZATION PHYSICAL SYST.

- NON-EG. INEQUALITIES (QUANTUM)

- SIMULATION TN HET

- $TN \stackrel{?}{\Leftrightarrow} \text{ADS/CFT}$

- RELATIONS FLUCT - ENTANGLEMENT

- LOW-ENERGY EFFECTIVE THEORIES

- \exists SELF PROTECTING QIM IN $D < 4$

QUANTUM OPTICS & IMPLEMENTATIONS

* GROUND STATE OF NANOMECHANICAL RESONATOR

- What is D-wave doing?

- IMPLEMENTATIONS OF DI STUFF

* DETECTION-LOOPHOLE FREE PHOTONIC EXPERIMENT

- Def. entang. bosons/fermions

- LIMITATIONS OF Q SIMULATION

- BOSON SAMPLING (LIMITATIONS)

* SUPERCONDUCTING QUBITS

* SIMULATION OF HIGH-ENERGY PHYSICS IN OPTICAL LATTICES

- CHEAP QKD

- SATELLITE-BASED Q COMM.

- CERTIFICATION OF Q SIMULATION

- LONG-DISTANCE ENT. BASED QC

- EXP. MPL. OF IQCL-LIKE THEOREMS?

MANY-BODY STATE PREPARATION

2013: Achievements in the last few years

Quantum Info

- Universal qc w/ q walk
- Unifying q correlations
- QC w/ little entanglement
- security device-indep QKD

Foundations QP

- PBR Theorem
- activation of q nonlocality
- Q thermo: Landauer's principle & 2nd Laws

Q Optics & Implementations

- ground state nanomech syst
- detection-loop-hole-free photonic exp
- superconducting qubits
- q sim.: high-energy physics in opt lattices
- q sim.: beating class comp

Many-Body Physics

- complexity of Hamiltonians
- criticality in open systems
- time-dependent variational principle

2013: Open Problems I

Quantum Info

- NPT bound entanglement
- Q violation Ingleton ineq
- m -partite entanglement: characterization & applic
- Q discord ??
- LOCC: characterization
- rôle of entanglement in QC
- device-indep: general framework security; certification of spacelike sep
- non-additivity of EOF/class capacity: examples
- QC more powerful than CC?
- $PPT^2 \Rightarrow$ ent breaking

Foundations QP

- bound ent violate Bell Ineq?
- beyond Bell Ineq
- principles for Q correlations
- relativity & QM in low-energy physics
- QI + relativity
- B.H. info paradox / firewall
- are Leggett-Garg Ineq useful?
- decidability in QIT
- non-locality in many-body phys
- life after loophole-free Bell Exp
- Tsirelson's Problem
- Q chaos & entanglement

2013: Open Problems II

Many-Body Physics

- efficient sim of Q Dynamics
- classific phases higher D
- approx TN
- thermalization
- non-equilib inequalities (quantum)
- simulation TN HEP
- TN $\stackrel{?}{\leftrightarrow}$ AdS/CFT
- relation fluctuat \leftrightarrow entang.
- low-energy effective theories
- self-protect. Q Mem. $D < 4$?
- robustness topolog memories

Q Optics & Implementations

- what is D-Wave doing?
- implementations of QI stuff
- Q networks
- cheap QKD
- satellite-based Q Comm
- certification of Q Sim
- long-distance ent-based QC
- exp test of PBR-like theorems
- many-body state prep
- def ent of bosons/fermions
- limitations of Q simulations
- Boson Sampling (limitations)

2013 – Concluding Session

•) NEW Q ALG. (45)

•) ROBUST TOPOLOGICAL QC & MEMORY (26)

•) VALIDATION OF Q SIMULATION & D-WAVE? (42)

•) Q PHENOMENA IN BIOLOGY (15)

•) APPLICATIONS OF MULTIPARTITE ENTANGLEMENT (28)

•) ONE-DISTANCE Q COMM. (NETWORKS, SATELLITES) (36)

•) Q RANDOMNESS GENERATION (19)

•) METROLOGY & NOISE (21)

•) BLACK-HOLE, RELATIVITY & QI (41)

•) QCD & QI (TENSOR NETWORKS) (25)

I WILL SEE A WORKING Q COMPUTER

•) FINITE

•) PERES'

•) BETTER

•) PRINCIP

•) EXAMPLES WITH CI.

•) Q

•) Q

•) Q

•) Q

•) Q

•) Q

•) Q

2013 – Concluding Session

A
 1) NPT BE (16)
 2) FINITE PREUS (5)
 3) PERES' CONJECTURE (36)
 PEREZ-GARCIA: WRONG
 ACIN: TRUE
 4) BETTER QEC (20)
 5) PRINCIPLES FOR Q CORRELATIONS (36)
 6) EXAMPLES OF CHANNELS WITH NON-ADDITIVE CL. CAPACITY (8)
 7) Q COMPUTER YES 50 NO 16
 8) LOOPHOLE-FREE BELL TEST CABELLO } 2 YEARS WEINFURTER } ATOMS (30)
 9) TIMESCALES FOR THERMALIZATION (10)
 10) IDENTIFY THE VARIATIONAL METHOD FOR 2D IGNACIO: PEP (20) (10 YEARS)
 11) COMPLEXITY PROOFS FOR NATURAL MODELS (21)
 12) LOCC CHARACTERIZATION (20)
 13) Q COMP > C COMP (62)

14) DE (29)
 15) IMPLEMENT (36)
 16) Q COMM (19)
 17) GENERATION (21)
 18) & NOISE (41)
 19) RELATIVITY (25)
 20) NETWORKS (WORKING)

The Top 10 of Open QIS Challenges 2013

- 1 Q computation more powerful than classical? **(62)**
- 2 New q algorithms **(45)**
- 3 Certification of q simulation **(42)**
- 4 Black Holes, general relativity & q information (black hole information paradox) **(41)**
- 6 Long-distance q communication (networks, satellites) **(36)**
- 6 Principles for q correlations **(36)**
- 7 Loophole-free Bell test (30)
- 8 better QECC (29)
- 9 robust topological QC & QMemory (26)
- 10 timescales for thermalization (25)
- 10 high-energy physics and QI (tensor networks) (25)

2015

2015 Open Problems

OPEN PROBLEMS SESSION

Benasque 2015

Adán Cabello & Géza Giedke

July 8th, 2015

208	INFORMATION/COMPUTATION
30	black holes & holography
30	demonstrate supremacy/speedup of QC
28	better quantum error correcting codes
21	multipartite entanglement
16	QFT and tensor networks
10	macroscopic qubits/QI
10	quantum artificial intelligence (machine learning, etc.)
10	the existence of NPT bound entanglement

176	FOUNDATIONS
28	principles for quantum correlations
26	incorporating time into the foundations of QT
19	quantum mechanics and relativity at low energies
17	experiment to rule out realist interpretation
15	role of causality
13	quantum thermo: work and heat?
12	are all states useful?
11	protocols using QT + relativity

178	MANY-BODY PHYSICS
32	better numerical algorithms for simulation
24	Quantum PCP conjecture
19	understanding the interplay of equilibration/transport/localization
18	entanglement detection
18	variational methods/tensor networks for field theories/continuous models in $\gg 2D$
14	uses for many-body phases
13	classifying topological phases in $D=2$ or higher
12	timescales of equilibration (also thermalization)

170	IMPLEMENTATIONS
25	experimental demonstration of a protocol enhanced by quantum error correction
25	a 2D topological (e.g. surface) code
24	a quantum computer
23	long-distance quantum teleportation
23	q. chemistry simulation
22	gravity tested in the lab
20	quantum repeaters
8	more efficient process tomography

2015 Open Problems

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2015 Open Problems

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2017

Open problems

QI

Physical multipartite entanglement
Coherence theory and entanglement
QI and gravity (ECC)
Black holes / holography
Quantum learning theory
Supremacy
New killer applications of QC
Resources for delegated QC
AQ approach to nonlinear channels
Q Speedup before QEC?
Existence of NPT bound entanglement +
No. of witnesses

2017

Foundations

The role of causality
New reconstructions based on
interpretations
Q thermodynamics
Networks vs Bell nonlocality
Certification of randomness and quantum
in temporal correlations
QT - exotic space-times
connection
Feeling sensitive collapse
brackets
Why probabilities

Many body

More applications of tensor networks
Many body localization
Applications of tensor networks to
- The renormalization group
- QFT
- Quantum learning
- Classical "
Quantum FCP conjecture
Efficient algorithms
Gapless
Open Q systems Non-Markovian
effects

Implementations

Useful to metrology
Understanding Fermi-Hubbard models
Q thermo machines to use
Q supremacy without universality
Certifying / with
Q certification
DI QKD
Q nanophotonics for QI
Is FTQC really possible?
Is adiabatic " " " " ?
* Politically correct words:
(e.g. Supremacy)
Make a surface code
* Supporting new journals

2017 Open Problems I

QI

- physical multipartite entanglement
- coherence theory and entanglement
- QI and gravity (ECC)
- Black Holes / holography
- (supreme) quantum machine learning
- new killer applications for QC
- resources for delegated QC
- q approach to nonlinear channels
- q speedup before QECC?
- NPT bound entanglement?

Foundations

- role of causality
- new reconstructions based on interpretations
- q thermodynamics
- network vs Bell nonlocality
- certification of randomness and quantumness in temporal correlations
- QT–exotic space-times connection
- falsifying sensitive collapse models
- why probabilities?

Many-body

- more applications tensor networks
- many-body localization
- applications of TN to: RNG, QFT, q learning, c learning
- quantum PCP conjecture
- efficient algorithms for gapless systems
- open q systems w non-Markovian effects

Implementations

- useful q metrology
- understanding Fermi-Hubbard model
- q thermo machines to use
- certifying q supremacy without (or with) universality
- q certification
- device-independent QKD
- q nanophotonics for QIP
- is FTQC really possible?
- is adiabatic QC really possible?
- make a surface code

Bets over the years

- NPT bound entanglement? 2011 Ruskai: No
- general composable security proof for DI-QKD 2011 Winter: yes; Acín: 2 yrs
- Peres' Conjecture? 2011 Perez-García: False ✓
Vertesi and Brunner 2014
- optimal states for 1-mode Gaussian channels? 2011
García-Patrón: vacuum (✓)
- loophole-free Bell test
2011 Kleinmann: > 2y ✓ 2013 Cabello: 2y, Weinfurter (✓)
2015: Hensen et al; Giustina et al; Shalm et al
- D-wave QC? 2011 Cirac: No (2y) ✓
- q repeater better than direct transmission 2011 Brask Bohr: 3y
- q sim better than c sim Lewenstein: 2y; Cirac: > 1y
- **the** variational method? 2013 Cirac: PEPS (10y)
- business interest in QC will increase 2015 Latorre: yes (2y) ✓

Voted predictions

- a universal quantum computer within our lifetimes?
in 2013: **YES: 50**; NO: 16 in 2015: **YES: 60**; NO: 11; ABS: 5.
- predictions 2017 (for 2019):
 - quantum computers with X qubits and 10^3 gates:
(A) > 100 qubits (3; 4%) (B) **50 – 100 (37; 58%)** (C) < 50 (24; 46%)
 - device-independent QKD:
(A) $< 1\text{km}$ (3; 6%) (B) **1 – 10km (35; 71%)** (C) $> 10\text{k}$ (11, 23%)
 - reliable phase diagram Hubbard model:
(A) Yes (9; 29%) (B) **NO (22; 71%)**
 - q metrology: commercial device using
(A) **only entanglement (24; 61%)** (B) entanglement and (Q?)EC
(2; 5%) (C) none (13, 33%)

2019

recent advances – major open problems – bets/predictions

The 2019 Quantum Information Workshop

Recent advances 2017-2019

Quantum information

- * Prog of DI QKD (Roten et al)
- * Q separation in constant depth circuit (Bravyi et al Science)
- * Classical verification of Q computation (Mahadev)
- * Simulation of Boson Sampling

Social impact

- * Higher

Foundations

→ * Wigner's friends (Leifer)

* Sloppy and more
Bell correlations are not classical

- * Emergence of algebra (Muller)
- * Redundancy in Q protocols (Muller, Masser)

Experimental

- * Many-body localization in 2D (Bloch)
- * Quantum crystal in an optical lattice
- * Bigger Q processors
- * Rydberg atoms
- * Satellite (Micius)

Many body

- * Progress in Fermi-Hubbard model
- * Connections from free fermions
- * Progress in QMC models

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Open Problems 2019

Quantum information

- * Verification benchmarks
- * Machine learning techniques
- * MPT bound entanglement
- * Can a Q computer break some post-quantum cryptos?
- * Are the resources to break post-quantum cryptos?
- * Q Supremacy proof
- * Problems useful for Q machine learning
- * Multiparticle entanglement
- * Less overhead QEC

Foundations

- * Unified framework for temporal and spatial Q correlations
- * Principles for Q correlations
- * Why Q correlations for Bell scenarios are not closed?
- * Indefinite causal order

Experimental

- * Room temperature superconductors?
- * Simulations of Q gravity
- * Q gravity effects
- * Proof of Q Supremacy
- * Commercial devices for metrology and sensing
- * DI QKD

* European Q unions

Many body

- * Topological
- * Other applications
- * Finite temperature
- * Tensor networks and QFT
- * Proof of many body local
- * Out of equilibrium dynamics
- * Foundations of QFT
- * Tensor network investigations
- * Experiments-theory connections

Bosonics and related

- * Large interactions
- * Chiral
- * Ethics
- * Q bubble?
- * Atomic clocks
- * Open access publishing

The 2019 Quantum Information Workshop



2019: Recent Advances

Quantum Information

- Proof of DI QKD (Arnon-Friedman et al., '16)
- Q separation constant-depth circuit (Bravyi, Gosset, Koenig '18)
- Classical verification of QC (Mahadev, 2018)
- Simulation of Boson sampling

Quantum foundations

- Wigner's friend (Frauchinger & Renner)
- Bell correlations (Slofstra 2017...)
- Emergence object. reality (Müller)
- Redundancy in Q postulates (Masanes, Galley, Müller 2018)

Many-body

- Fermi Hubbard (Corboz et al.)
- Constructions from free fermions
- Frustrated q spin models not tractable by Q Monte Carlo

Implementations

- Many-body localization in 2d (Bloch)
- Quasicrystals in optical lattices (Bloch?)
- Tweezer technology (Lukin)
- Scaling up to 50 qubits (ions, atoms, and sc qubits)
- Satellite (Micius)

Quantum information

- verification & benchmarks of QC
- quantum machine learning
- NPT bound entanglement?
- Can QC break post-q crypto?
- Resources to break position-based crypto
- Q supremacy proof
- Problems useful for QML
- Multipartite entanglement
- QEC: Higher-threshold error correcting codes with less overhead

Many-body

- TNs and QFT
- Proof of MBL phase
- Out-of-equilibrium dynamics
- Foundations of QFT
- TN investigations of strong correlations
- Experiment theory corrections
- Classification of topological phases in 3D
- Applications of TNs outside QMB physics
- Finite temperature results

Foundations

- Unified Framework for temporal and spatial Q correlations
- Principles (and bounds) for Q correlations
- Why are Q correlations for bell scenarios not closed?
- Indefinite causal order

Business & Societal

- large investments (financial, chemical,...)
- ethics?
- q bubble? and consequences?
- open access publishing

Implementations/Experiment

- Room-temp SC
- QSim of Q gravity
- detection of Q Gravity effects
- Proof of Q supremacy
- Commercial devices for metrology and sensing
- DI QKD

Will it be shown within 2 years that...?

- QC is better than CC
YES: 9; **No: 30**
- q supremacy proof without depth restrictions
YES: 9; NO: 7
- Slofstra “problem” is not a problem: YES: Adán, Alex, Barbara; NO: David, Pepe
- usable DI-QKD (> 1 Mbit/s)
YES: 8; **NO: 23**
- QECC-corrected (& improved) qubit: **YES: 30**; NO: 8
- q supremacy
YES: 20; **NO: 23**
- reliable algorithm for simulating dynamics ($\geq 1d$):
YES: 8; **NO: 21**
- major qtech investment (≥ 100 MEUR) by *European* company? **YES: 28**; NO: 7
- will investment hurt the way we do science? **YES: 26**; NO: 17

A fault-tolerant scalable QC within your lifetime? **YES: 40**; NO: 12