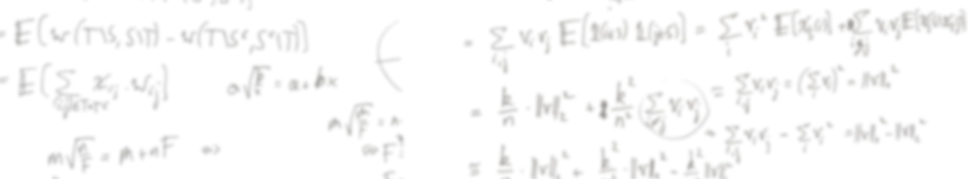
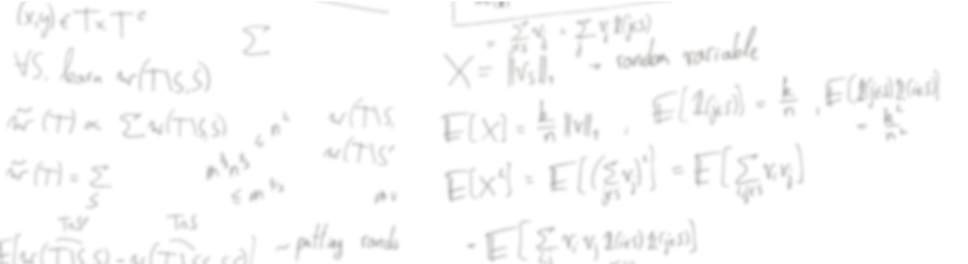


INTERVIEW CNRS (SECTION 6)

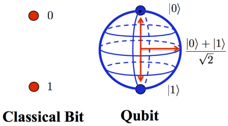
Simon Apers
(CWI, ULB)

April 2021



Quantum computers

fundamentally new way of computing,
built on quantum theory



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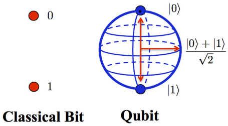
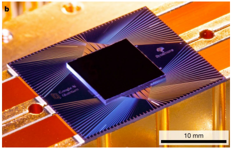


on cusp of revolution:
first quantum computing devices being built



(Google Sycamore quantum processor)

critical to understand:

what are quantum computers good for?

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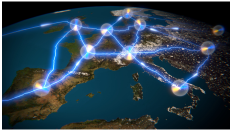
- cryptography and communication

(network of quantum computers)



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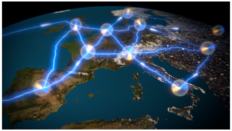


- **algorithms** and simulation

(single quantum computer)

Background

2014 - 2018: PhD student at **Ghent University**
$\supset$ long term visit to **University of Calgary**

2019 - 2020: postdoc at **INRIA** (Paris)
and **CWI** (Amsterdam)

2020 - ... : postdoc at **CWI** (Amsterdam)
and **ULB** (Brussels)

RESEARCH THEMES

- **quantum algorithms** and quantum walks
- graph theory and random walks

PUBLICATIONS

- 5 **conference** publications (FOCS, STACS, ESA, ...)
- 6 **journal** publications (PRL, Quantum, PRA, ...)
- among those, 2 **single author** publications
- 3 preprints (2 submitted)

CONTRIBUTION

qLx = b

or

“quantum speedups in modern optimization”

starting point is

"Quantum Speedup for Graph Sparsification, Cut Approximation and Laplacian Solving"

by Simon Apers and Ronald de Wolf

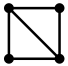
in **FOCS'20**

presented at **QIP'21**

invited talks at
Simons institute (Berkeley), University of Cambridge, University of Bristol, . . .

MODERN OPTIMIZATION

combinatorics $\leftrightarrow$ linear algebra

graph $G =$  $\leftrightarrow$ Laplacian $L_G = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 2 & -1 & 0 \\ -1 & -1 & 3 & -1 \\ -1 & 0 & -1 & 2 \end{bmatrix}$

electrical flow on G $\leftrightarrow$ Laplacian system $L_G x = b$

Modern optimization

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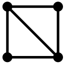
graph $G =$  $\leftrightarrow$ Laplacian $L_G = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 2 & -1 & 0 \\ -1 & -1 & 3 & -1 \\ -1 & 0 & -1 & 2 \end{bmatrix}$

electrical flow on G $\leftrightarrow$ Laplacian system $L_G x = b$

landmark result by Spielman and Teng ('04):
solve Laplacian system $L_G x = b$ in **near-linear time** $\widetilde{O}(m)$

$\downarrow$

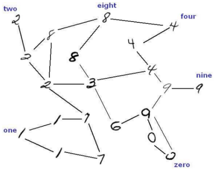
faster algorithms for many fundamental problems in optimization and learning

- flow problems

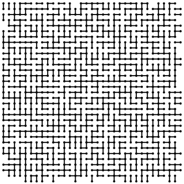
  (max flow, min cost flow, ...)
- learning on graphs

  (clustering, semi-supervised learning, ...)
- combinatorial optimization

  (graph matching, matrix scaling, random spanning trees, ...)



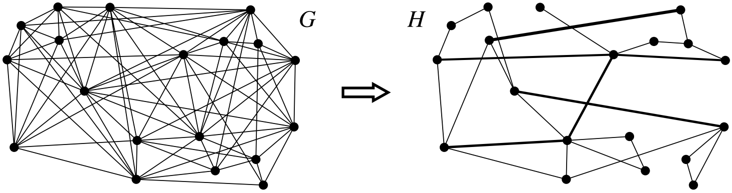
(semi-supervised learning)



(random spanning tree)

cornerstone of fast Laplacian solvers:

graph sparsification

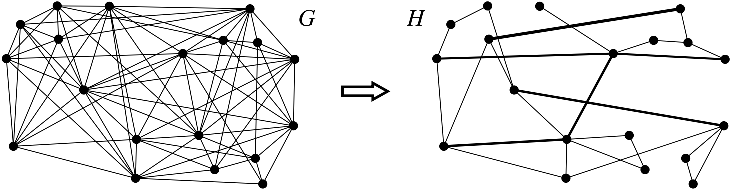


$m_G \in O(n^2)$ $m_H \in \tilde{O}(n)$

such that $G \approx H$

classically: sparsification in time

$\widetilde{O}(m) \in \widetilde{O}(n^2)$



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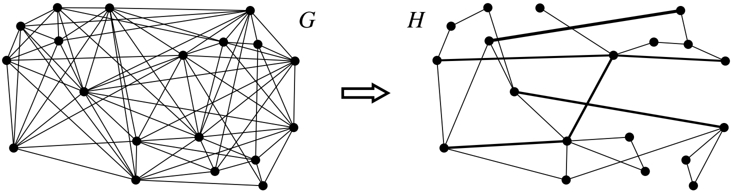

$m_G \in O(n^2)$ $\qquad$ $m_H \in \tilde{O}(n)$

Apers - de Wolf '19:
(optimal) quantum speedup for graph sparsification

$\widetilde{O}(\sqrt{mn}) \in \widetilde{O}(n^{3/2})$

“LOW-HANGING FRUIT”:

- ✓ first quantum speedups for approximating max cut, min cut, sparsest cut, . . .

- ✓ first quantum speedups for approximately solving Laplacian systems, electrical flows, . . .

"LOW-HANGING FRUIT":

✓ first quantum speedups for approximating max cut, min cut, sparsest cut, . . .

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$\downarrow$ "HIGHER-HANGING FRUIT": $\Downarrow$

✓ first quantum speedup for **exact** min cut (Apers-Lee '20, Apers-Gawrychowski-Lee '21)

? quantum speedups for modern combinatorial optimization algorithms (IPMs, max flow, learning, . . .)

EXISTING WORK:
QUANTUM ALGORITHMS FOR LINEAR SYSTEMS

$$Ax = b$$

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speedup for sparse, well-conditioned systems

= *key primitive in quantum algorithms*

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$\downarrow$

our work:
quantum speedup for **explicit** solution
of **general Laplacian system**

EXISTING WORK:
QUANTUM ALGORITHMS FOR COMBINATORIAL OPTIMIZATION

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QUANTUM ALGORITHMS FOR COMBINATORIAL OPTIMIZATION

- quantum speedup over "classic" algorithms for spanning tree, max flow, ...

  (Dürr (CNRS, LIP6) et al. '06, Ambainis-Špalek '06, ...)

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quantum algorithms for combinatorial optimization

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  open question: quantum speedup for max cut?

  (Brandão-Svore '17, van Apeldoorn et al. '17, ...)

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↓

our work:

quantum speedup over **"modern"** algorithms,

quantum speedup for **max cut**

TECHNIQUES:

1. **sequential quantum** algorithm built from **distributed classical** algorithm

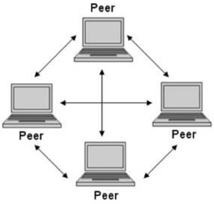
2. quantum speedup for **graph spanners**

3. simulate randomness using **hash functions**

1. SEQUENTIAL QUANTUM ALGORITHM BUILT FROM DISTRIBUTED CLASSICAL ALGORITHM

connection to

distributed algorithms & *streaming algorithms*



= important trend in modern quantum algorithms!

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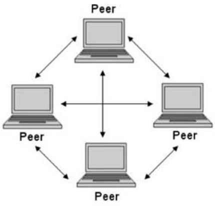

= important trend in modern quantum algorithms!

↓

relevant expertise in IRIF/LIP6 on distributed/streaming algorithms

1. **SEQUENTIAL QUANTUM** ALGORITHM BUILT FROM **DISTRIBUTED CLASSICAL** ALGORITHM

based on distributed sparsification algorithm (Koutis-Xu ’16):

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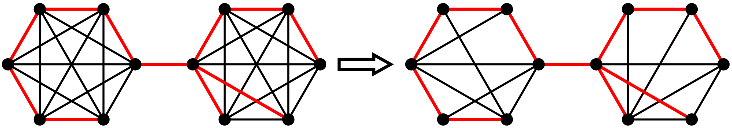
a) detect "important" edges by constructing **spanner** (see next slide)

b) sample remaining edges with constant probability



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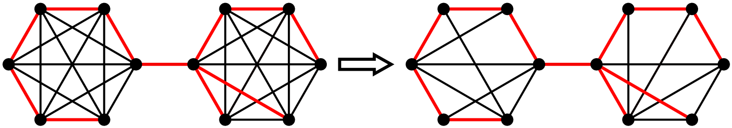

c) repeat a)-b) until $\widetilde{O}(n)$ edges

2. QUANTUM SPEEDUP FOR **GRAPH SPANNERS**

"graph spanner" =
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buildings blocks:
Thorup-Zwick ('01) spanner algorithm
& Dürr et al. ('06) quantum algorithm for shortest-path tree

2. QUANTUM SPEEDUP FOR **GRAPH SPANNERS**

follow-up work:
build on distributed spanner algorithm by Baswana et al. ('12)

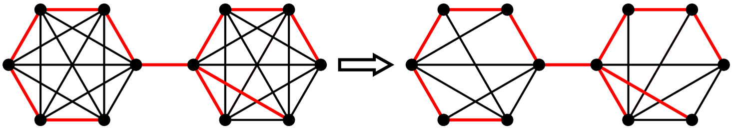
$\downarrow$

faster quantum algorithms for spanners and sparsification
of *unweighted* graphs (Apers-Lee-Le Gall, in preparation)

3. SIMULATE RANDOMNESS USING **HASH FUNCTIONS**

a) detect "important" edges by constructing spanner

b) sample remaining edges with constant probability



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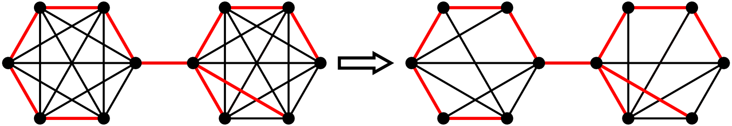

in sublinear time,

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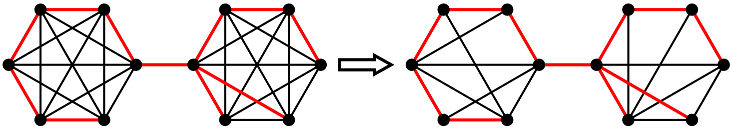

in sublinear time,

can explicitly write down spanners

cannot explicitly sample $\Omega(n^2)$ edges
($= \Omega(n^2)$ coin tosses)

3. SIMULATE RANDOMNESS USING **HASH FUNCTIONS**

n^2 coin tosses

1	1	0	1	0	0	1	1	0	0	0	$\cdots$

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$\uparrow$ access?

sublinear $k \in o(n^2)$-time quantum algorithm

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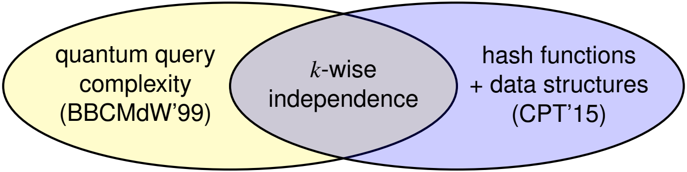
sublinear $k \in o(n^2)$-time quantum algorithm

solution:



FOLLOW-UP/RELATED WORK:

- *“Quantum complexity of minimum cut”*
  by Apers and Lee (submitted to CCC ’21)
- *“Faster quantum algorithms for unweighted spanners and sparsification”*
  by Apers, Lee and Le Gall *
- *“Approximate minimum cut partition in near-linear time”*
  by Apers, Gawrychowski and Lee *
- *“Quantum cut query complexity of minimum cut”*
  by Apers, Efron, Lee, Mukhopadhyay and Nanongkai *

* in preparation

= collaborations with
University of Technology Sydney (Australia),
Nagoya University (Japan),
University of Wrocław (Poland),
University of Toronto (Canada),
KTH Royal Institute of Technology (Sweden),
University of Copenhagen (Denmark)

RESEARCH PROGRAMME:

QUANTUM ALGORITHMS

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QUANTUM ALGORITHMS

FOR

NEAR-TERM QUANTUM COMPUTERS:

$\sim$ *applications*

focus on sampling problems

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FOR

NEAR-TERM QUANTUM COMPUTERS:

$\sim$ *applications*

focus on
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LONG-TERM QUANTUM COMPUTERS:

$\sim$ *foundations*

focus on
optimization

NEAR-TERM QUANTUM COMPUTERS
and their *applications*

’19: Google claims *“quantum supremacy”*

=

artificial sampling problem

solved exponentially faster on quantum device

NEAR-TERM QUANTUM COMPUTERS
and their *applications*

'19: Google claims *"quantum supremacy"*

=

artificial sampling problem
solved exponentially faster on quantum device

$\downarrow$

? $\exists$ natural sampling problem
solved exponentially faster on quantum device

e.g., near-term quantum devices for
Monte Carlo method?

e.g., near-term quantum devices for
Monte Carlo method?

=

use of sampling to approximate intractable problems

e.g., near-term quantum devices for
Monte Carlo method?

=

use of sampling to approximate intractable problems

=

key algorithmic technique in

- machine learning and statistics
    - combinatorial optimization
        - finance, chemistry, . . .

Monte Carlo method on **near-term quantum devices?**

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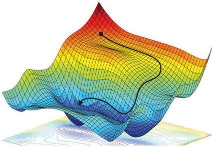
- need heuristics!

$\rightarrow$ Schrödinger Monte Carlo



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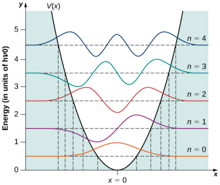

Monte Carlo method on **near-term quantum devices?**

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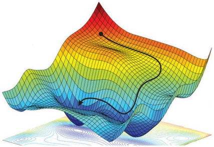
$\to$ Schrödinger Monte Carlo



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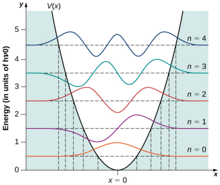
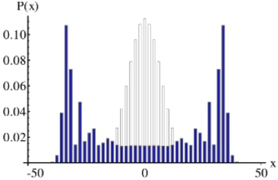


- quantum walk speedup?

$\to$ build on *quantum fast-forwarding* (Apers-Sarlette QIC'19)

$\to$ ongoing work with Laurent Miclo (CNRS, Toulouse)



LONG-TERM QUANTUM COMPUTERS
or *foundations of quantum algorithms*

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- use cases of large error-corrected quantum computers?

LONG-TERM QUANTUM COMPUTERS
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- fundamental limits of quantum computation?

LONG-TERM QUANTUM COMPUTERS
or *foundations of quantum algorithms*

- use cases of large error-corrected quantum computers?

- fundamental limits of quantum computation?

- new algorithmic primitives?

- **qLx=b or quantum Laplacian paradigm**

quantum algorithms for
optimization, machine learning, ...

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quantum algorithms for
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- **theory of quantum walks**

connection with electric networks

algorithms for graph problems

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- **exponential quantum speedups?**

candidate: submodular function optimization

INTEGRATION

Paris region:

INTEGRATION

Paris region:

- quantum hub

PARIS CENTRE FOR QUANTUM COMPUTING

PCQC

INTEGRATION

Paris region:

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PARIS CENTRE FOR QUANTUM COMPUTING

PCQC

- bright prospects thanks to *plan quantique*

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PARIS CENTRE FOR QUANTUM COMPUTING PCQC

- bright prospects thanks to *plan quantique*

- connections with INRIA:

postdoc at COSMIQ

INRIA-Microsoft joint project, partially based on QFF (Apers-Sarlette QIC'19)

IRIF:

- most overlap with *foundations* of quantum algorithms
- collaboration:
  - quantum algorithms/complexity (Laplante, Magniez, Santha)
  - quantum machine learning (Kerenidis)
  - combinatorial optimization (Mathieu, Vladu)
  - distributed/streaming algorithms (Fraigniaud, Rosén)
  - graph theory/combinatorics (Charbit, Habib)

LIP6:

- most overlap with *near-term applications* of quantum computers
- collaboration:
  - quantum computation (Diamanti, Grilo, Grosshans, Kashefi, Markham)
  - operations research (Dürr, Escoffier, Cohen-Addad)
  - learning theory (Gallinari, Piwowarski)

SIMON APERS

’14-’18: Ghent University
’19-’20: INRIA (Paris) and CWI (Amsterdam)
’20-’21: CWI (Amsterdam) and ULB (Brussels)

10 publications (FOCS, PRL, . . .), 3 preprints

focus on
quantum algorithms

research programme on

1. *near-term* quantum computers for *sampling*
2. *long-term* quantum computers for *optimization*

* application updates:
- awarded Marie Skłodowska-Curie Seal of Excellence
- invited to European Symposium on Algorithms ’21 PC

NETWORK

(active collaboration or paper under review in past year)

Sweden:	Danupon Nanongkai (KTH), Sagnik Mukhopadhyay (KTH), Florian Adriaens (KTH)
France:	Anthony Leverrier (INRIA), Christophe Vuillot (INRIA), Alain Sarlette (INRIA), Laurent Miclo (Toulouse)
Belgium:	Jérémie Roland (ULB), Shantanav Chakraborty (ULB), Leonardo Novo (ULB)
Italy:	Francesco Ticozzi (Padova)
the Netherlands:	Stacey Jeffery (CWI), Ronald de Wolf (CWI), Ido Niesen (CWI), Kirill Neklyudov (CWI)
Poland:	Pawel Gawrychowski (Wrocław)
USA:	András Gilyén (Caltech)
Canada:	Yuval Efron (Toronto)
Australia:	Troy Lee (Sydney)
Japan:	Francois Le Gall (Nagoya University)

quantum algorithms/complexity, combinatorial optimization, data science/machine learning, quantum control, quantum error correction, probability theory, data structures

IMAGE CREDITS

- **Bit-qubit (slide 1):** Hussain, Zahid. (2016). Strengths and Weaknesses of Quantum Computing. International Journal of Scientific and Engineering Research. 7.
- **Sycamore processor (slide 1):** Google AI Blog (link).
- **Quantum internet (slide 2):** KPN (link).
- **IBMQ (slide 2):** IBM (link).
- **Semi-supervised learning (slide 9):** Zhu, Xiaojin, Zoubin Ghahramani, and John D. Lafferty. "Semi-supervised learning using gaussian fields and harmonic functions." Proceedings of the 20th International conference on Machine learning (ICML-03). 2003.
- **Spanning tree (slide 9):** Lyons, Russell, and Yuval Peres. Probability on trees and networks. Vol. 42. Cambridge University Press, 2017.
- **Distributed computing (slide 16):** C# corner (link).
- **Streaming (slide 16):** DZone (link).
- **World map (slide 22):** clker (link).
- **Optimization landscape (slide 26):** Medium (link).
- **Quantum harmonic oscillator (slide 26):** Physics Libretexts (link).
- **Quantum walks plot (slide 26):** University of Paderborn (link).

All other images by Simon Apers.