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Quantum Computing at Volkswagen:

Traffic Flow Optimization using the D-Wave Quantum Annealer

D-Wave Users Group Meeting - National Harbour, MD

27.09.2017 – Dr. Gabriele Compostella

DATA:LAB MUNICH

WE ARE

an international team working for the Volkswagen Group across the automotive value chain in the areas of Advanced Analytics and Machine Learning.
Our innovation network consists of brands' business units, experts from leading technology providers, research facilities and universities as well as upcoming Startups.

WE HIRE

creative people with skills in data analytics, AI, technology scouting, software development, DevOps, data engineering, project management, business development & agile development.

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- Matlab
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- Solr
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WE FOCUS ON

- Advanced Analytics
- Artificial Intelligence
- Machine Learning
- Deep Learning
- Data Engineering
- Software Development
- DevOps
- Quantum Computing
- Smart Enterprise
- NLP & Chat Bots
- IoT & Smart City

WE ARE HAPPY TO SPEAK TO YOU

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twitter.com/VWDataLab

WE WORK

with a large amount of data in the Volkswagen Group on a state-of-the-art hybrid development environment which is highly secure, performant & flexible.

WE ARE PART OF THE VOLKSWAGEN GROUP

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Team

- Dr. Christian Seidel – Volkswagen Data:Lab, Munich
- Dr. Gabriele Compostella – Volkswagen Data:Lab, Munich
- Dr. Florian Neukart – Volkswagen Group of America Code:Lab, San Francisco
- David von Dollen – Volkswagen Group of America Code:Lab, San Francisco

Team

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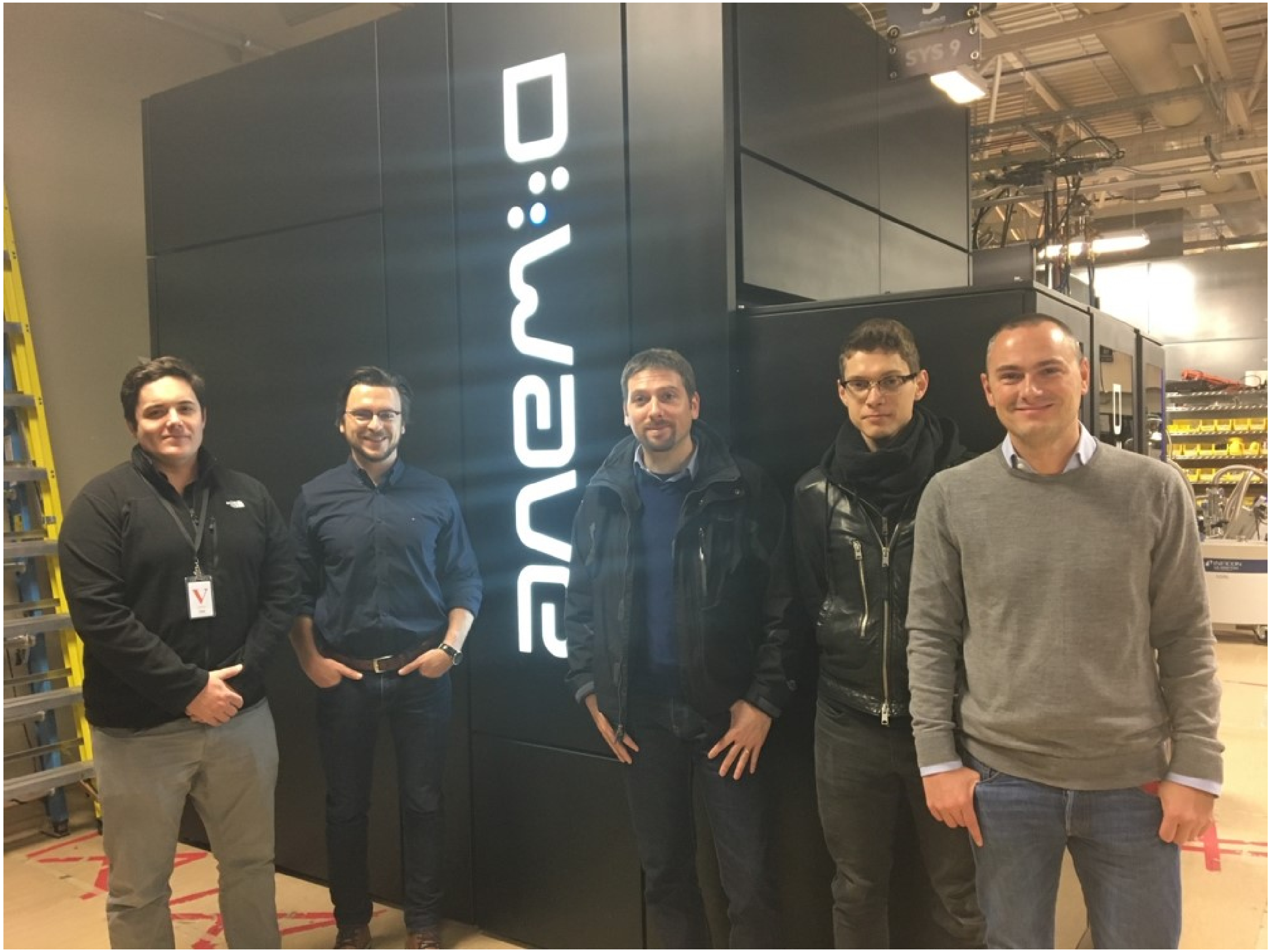

Quantum Computing – just a hype or a real thing?

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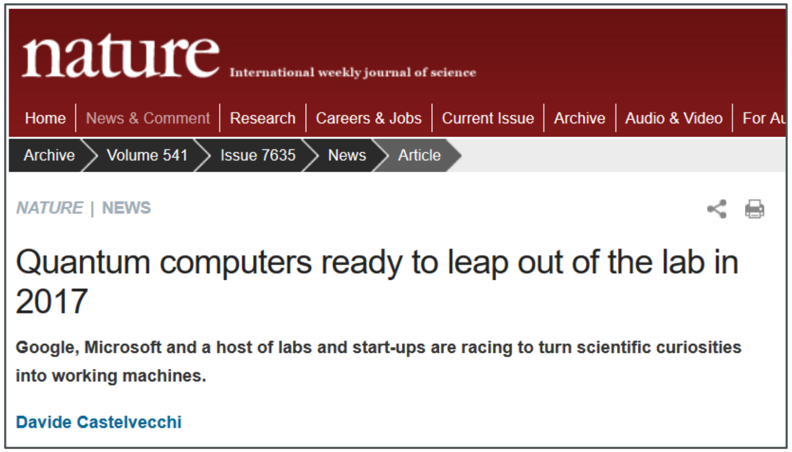

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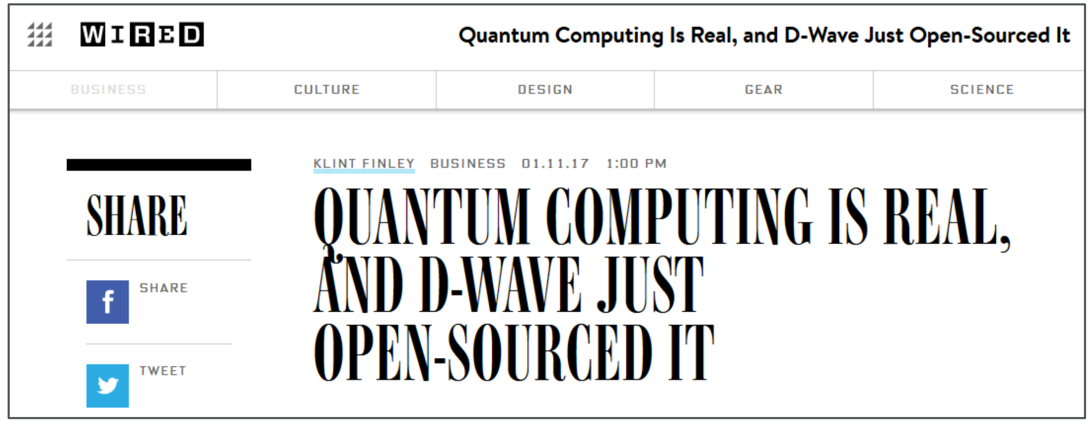
NATURE | NEWS

Quantum computers ready to leap out of the lab in 2017

Google, Microsoft and a host of labs and start-ups are racing to turn scientific curiosities into working machines.

Davide Castelvecchi



WIRED Quantum Computing Is Real, and D-Wave Just Open-Sourced It

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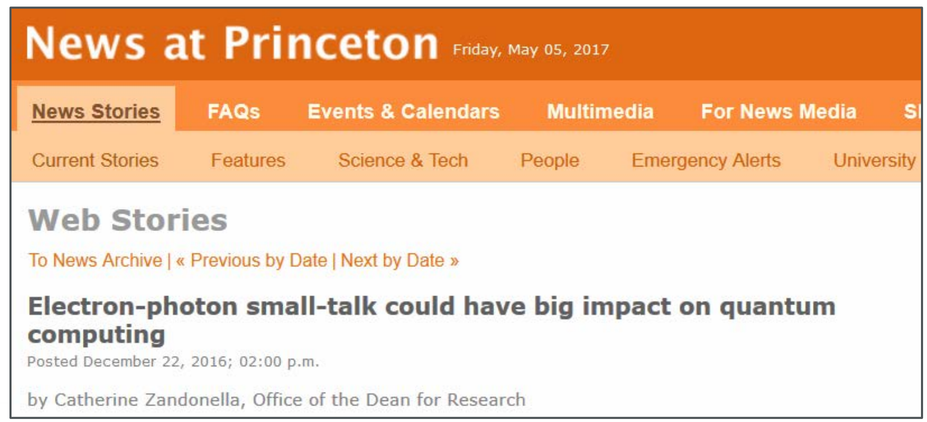
The strategy | Economy | Access & connectivity | DG CONNECT

European Commission will launch €1 billion quantum technologies flagship

Published on 17/05/2016



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Electron-photon small-talk could have big impact on quantum computing

Posted December 22, 2016; 02:00 p.m.

by Catherine Zandonella, Office of the Dean for Research

The Question that drove us …

Is there a ***real-world*** problem

that could be addressed with a

Quantum Computer?

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YES: Traffic flow optimisation

Everybody knows traffic (jam) and normally nobody likes it.

Image courtesy of think4photop at FreeDigitalPhotos.net

Public data set: T-Drive trajectory

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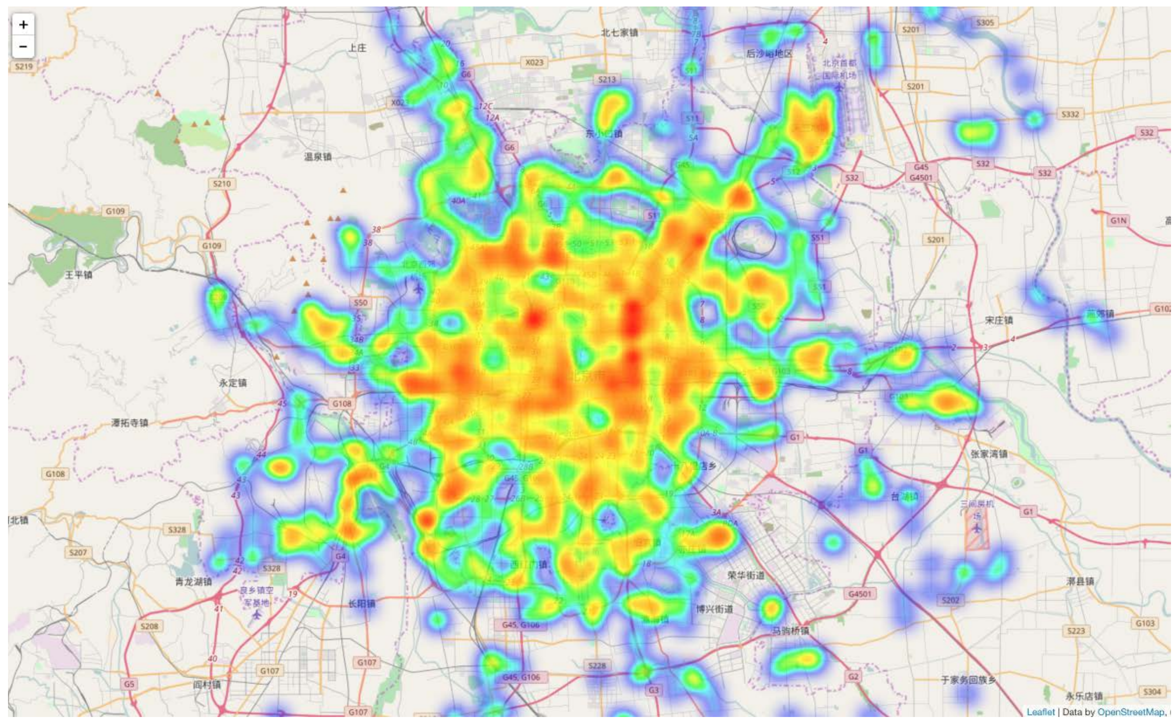
https://www.microsoft.com/en-us/research/publication/t-drive-trajectory-data-sample/

Beijing

- ~ 10.000 Taxis
- 2.2. – 8.2.2008



data example:

```
1,2008-02-02 15:36:08,116.51172,39.92123
1,2008-02-02 15:46:08,116.51135,39.93883
1,2008-02-02 15:46:08,116.51135,39.93883
1,2008-02-02 15:56:08,116.51627,39.91034
1,2008-02-02 16:06:08,116.47186,39.91248
1,2008-02-02 16:16:08,116.47217,39.92498
1,2008-02-02 16:26:08,116.47179,39.90718
1,2008-02-02 16:36:08,116.45617,39.90531
```

D-Wave calculation model

Quadratic Unconstraint Binary Optimisation (QUBO)

During the quantum annealing process the system evolves to the lowest energy level.

This requires the problem to be formulated as an Ising Model:

$$H_{\text{Ising}} = -\sum_{j=1}^{N} h_j \sigma_j^z + \sum_{1 \leq j < k}^{N} \mathbf{J}_{jk} \sigma_j^z \sigma_k^z,$$

or as a QUBO:

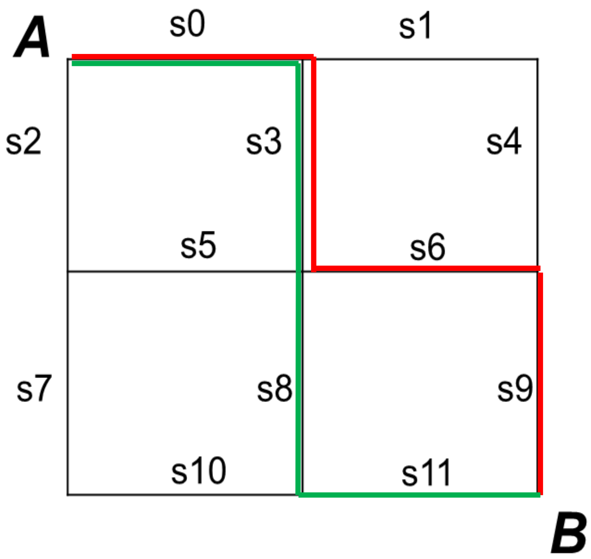
$$f(x_1, \ldots, x_n) = -\sum_{m=1}^{N} c_m x_m + \sum_{1 \leq m < n}^{N} J_{mn} x_m x_n,$$

Transforming the *real world problem* for the Quantum Computer

Example:

Simplified graph structure representing a route grid.

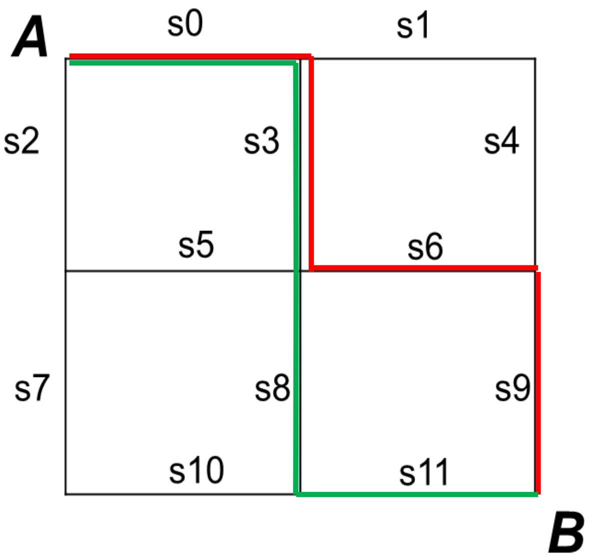
2 cars with 3 route options on a 2 x 2 grid.



Car	Route		Binary variable
Car 1	#1:	s0,s3,s6,s9	Q_{11}
Car 1	#2:	s0,s3,s8,s11	Q_{12}
Car 1	#3:	s2,s7,s10,s11	Q_{13}
Car 2	#1:	s0,s3,s6,s9	Q_{21}
Car 2	#2:	s0,s3,s8,s11	Q_{22}
Car 2	#3:	s2,s7,s10,s11	Q_{23}

Creating the cost function for each street segment

More cars on one street lead to higher costs



Street segment	Associated cost function	Value
s0	$(Q_{11} + Q_{12} + Q_{21} + Q_{22})^2$	4
s3	$(Q_{11} + Q_{12} + Q_{21} + Q_{22})^2$	4
s6	$(Q_{11} + Q_{21})^2$	1
s9	$(Q_{11} + Q_{21})^2$	1
s8	$(Q_{12} + Q_{22})^2$	1
s11	$(Q_{12} + Q_{22} + Q_{13} + Q_{23})^2$	1
s2	$(Q_{13} + Q_{23})^2$	0
s7	$(Q_{13} + Q_{23})^2$	0
s10	$(Q_{13} + Q_{23})^2$	0

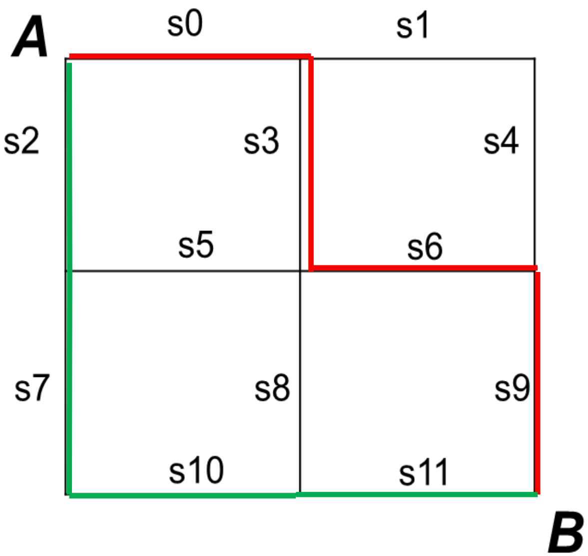
Example:

$$(Q_{11} + Q_{12} + Q_{21} + Q_{22})^2 + (Q_{11} + Q_{12} + Q_{21} + Q_{22})^2 + (Q_{11} + Q_{21})^2 + (Q_{11} + Q_{21})^2$$
$$+ (Q_{12} + Q_{22})^2 + (Q_{12} + Q_{22} + Q_{13} + Q_{23})^2 + (Q_{13} + Q_{23})^2 + (Q_{13} + Q_{23})^2 + (Q_{13} + Q_{23})^2 = \mathbf{12}$$

Goal: minimise the overall costs => distribute cars to different streets

Creating the cost function for each street segment

Optimal route selection:



Street segment	Associated cost function	Value
s0	$(Q_{11} + Q_{12} + Q_{21} + Q_{22})^2$	1
s3	$(Q_{11} + Q_{12} + Q_{21} + Q_{22})^2$	1
s6	$(Q_{11} + Q_{21})^2$	1
s9	$(Q_{11} + Q_{21})^2$	1
s8	$(Q_{12} + Q_{22})^2$	0
s11	$(Q_{12} + Q_{22} + Q_{13} + Q_{23})^2$	1
s2	$(Q_{13} + Q_{23})^2$	1
s7	$(Q_{13} + Q_{23})^2$	1
s10	$(Q_{13} + Q_{23})^2$	1

Minimum:

$$(Q_{11} + Q_{12} + Q_{21} + Q_{22})^2 + (Q_{11} + Q_{12} + Q_{21} + Q_{22})^2 + (Q_{11} + Q_{21})^2 + (Q_{11} + Q_{21})^2$$
$$+ (Q_{12} + Q_{22})^2 + (Q_{12} + Q_{22} + Q_{13} + Q_{23})^2 + (Q_{13} + Q_{23})^2 + (Q_{13} + Q_{23})^2 + (Q_{13} + Q_{23})^2 = \mathbf{8}$$

Adding constraints

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We want to make sure that the solution will contain only one route for each car:

- Only one binary variable per car can be 1 (otherwise the car would be on multiple routes simultaneously)
- Wrong solutions must contain a penalty term
- The magnitude of the penalty term, K, is tuned based on the size of the problem (i.e. violating one constraint increases the energy of the state as if one more car was present on every road segment)

Additional constraints
$K * (Q_{11} + Q_{12} + Q_{13} - 1)^2$
$K * (Q_{21} + Q_{22} + Q_{23} - 1)^2$

For every constraint, the overall cost function will contain a term similar to:

$$K * (Q_{11} + Q_{12} + Q_{13} - 1)^2 = K * (- Q_{11} - Q_{12} - Q_{13} + 1 + 2 Q_{11} Q_{12} + 2 Q_{11} Q_{13} + 2 Q_{12} Q_{13})$$

Matrix formulation

Finally, the overall cost function including the constraints can be expressed in a matrix form as a function of the input binary variables:

$$F = \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{21} & Q_{22} & Q_{23} \end{pmatrix} \begin{pmatrix} 1-K & 2+2K & 2K & 2 & 2 & 0 \\ & 1-K & 2K & 2 & 2 & 0 \\ & & -K & 0 & 0 & 0 \\ & & & 1-K & 2+2K & 2\mathrm{K} \\ & & & & 1-\mathrm{K} & 2\mathrm{K} \\ & & & & & -K \end{pmatrix} \begin{pmatrix} Q_{11} \\ Q_{12} \\ Q_{13} \\ Q_{21} \\ Q_{22} \\ Q_{23} \end{pmatrix}$$

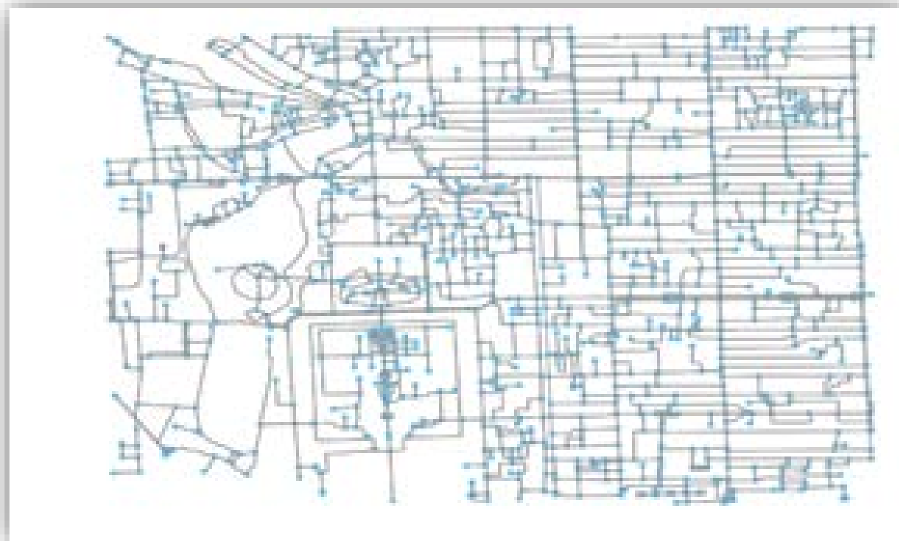
This is the QUBO matrix representing the overall cost that will be minimized by the quantum computer corresponding to the 2x2 grid example.

Data preprocessing

- Identification of street segments in the map by turning it into a graph using OSMnx, a Python package for street networks

- Get *valid* alternative routes for every car that needs to be rerouted

- Determine overlapping segments in the possible routes and define the cost function for the problem

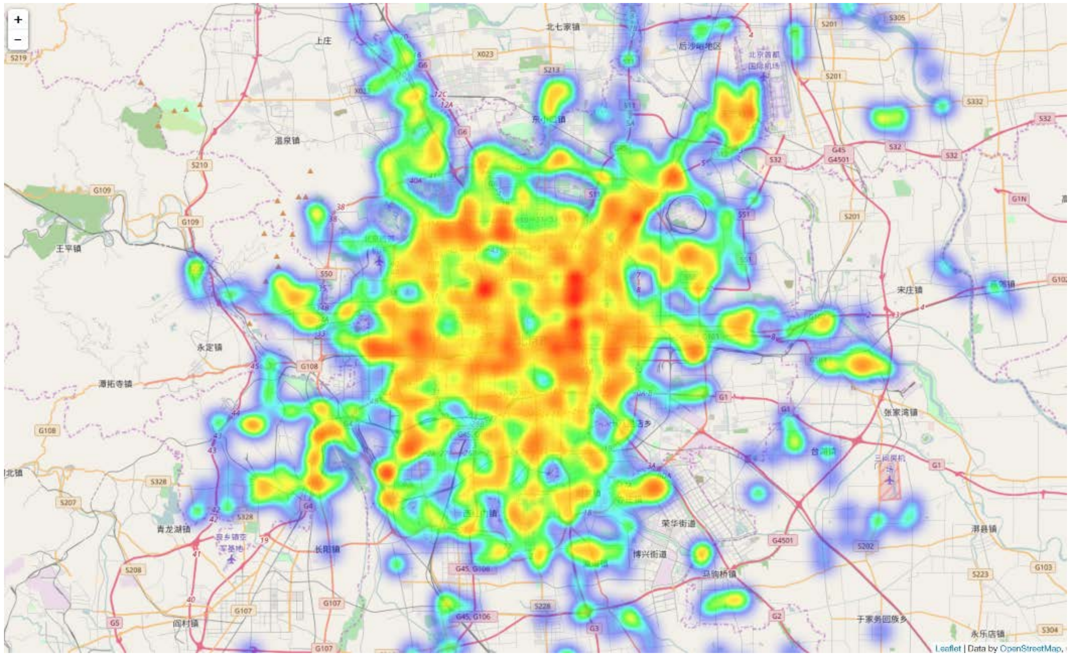


Graph representation of the street map

Beijing – Traffic Heatmap

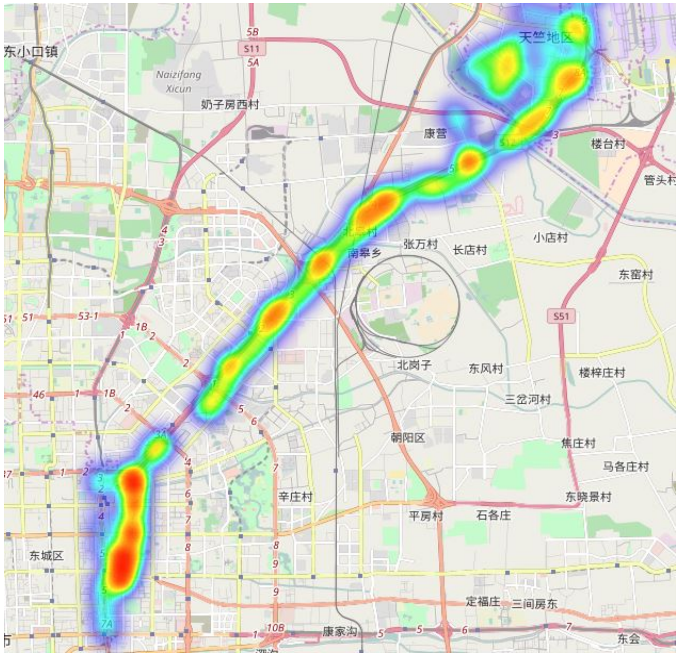
Traffic in the city

- 10.000 cars



Detail: route to the Airport

- 418 cars



→ We assigned each of the 418 cars 3 possible routes to reach the airport

→ Size of the problem space: 3^418

Code snippet and output


```
from dwave_sapi2.core import solve_ising, solve_qubo, async_solve_ising,
from dwave_sapi2.util import ising_to_qubo, qubo_to_ising, get_hardware_
from dwave_sapi2.embedding import find_embedding, embed_problem, unembed
from dwave_sapi2.remote import RemoteConnection

rc = RemoteConnection(url, token)
solver = rc.get_solver(solver_name)

# # construct Ising problem
h, J, _ = qubo_to_ising({(i, j): qubo[i][j]
        for i in range(nCars*nVars) for j in range(nCars*nVars)})

## Embedding onto hardware-like solvers:
embedding = find_embedding(J, adj)

if embedding is successful, continue
    if len(embedding):
#     print 'Total number of physical qubits:'
#     print sum(map(len, embedding))

hemb, jemb, jchain, embedding = embed_problem(h, J, embedding, adj)
high = max(map(abs, jemb.values()))
chain_strength = 5
for (i, j) in jchain.keys():
    jemb[(i, j)] = -high * chain_strength
    params = { "answer_mode": "histogram", "num_reads": 1000}
    num_iterations = 2
    # solve Ising problem with parameters
    answer = solve_ising(solver, hemb, jemb, **params)
```

```
                                 ---------------------------------
17-05-2017 10:33:16              --- TRAFFIC FLOW OPTIMIZATION ---
                                 ---------------------------------

Number of cars:                    418
Number of possible routes per car: 3
Complexity of traffic flow problem: 3^418

Number of constraint equations:    2491
Number of qubits needed:           1254

Creating quadratic unconstrained binary optimization (QUBO) problem:

Matrix size: 1254 x 1254
[[-2066  4156  4148 ...,     0     0     0]
 [    0 -2065  4148 ...,     0     0     0]
 [    0     0 -2070 ...,     0     0     0]
 ...,
 [    0     0     0 ..., -2072  4148  4148]
 [    0     0     0 ...,     0 -2071  4150]
 [    0     0     0 ...,     0     0 -2071]]

Connecting to the D-Wave Quantum Computer in Vancouver, Canada...

D-Wave solver name:              DW2X
Number of available qubits:      1135
Number of available couplers:    3265

Number of qubits needed (1254) > number of available qubits (1135)!

Using problem decomposition algorithm (QSage)

Starting D-Wave QPU calls
Updating route selections...
Updating route selections...
Updating route selections...
Updating route selections...
Updating route selections...
Updating route selections...
Updating route selections...
Updating route selections...

Finished successfully
```

Result: unoptimised vs optimised traffic

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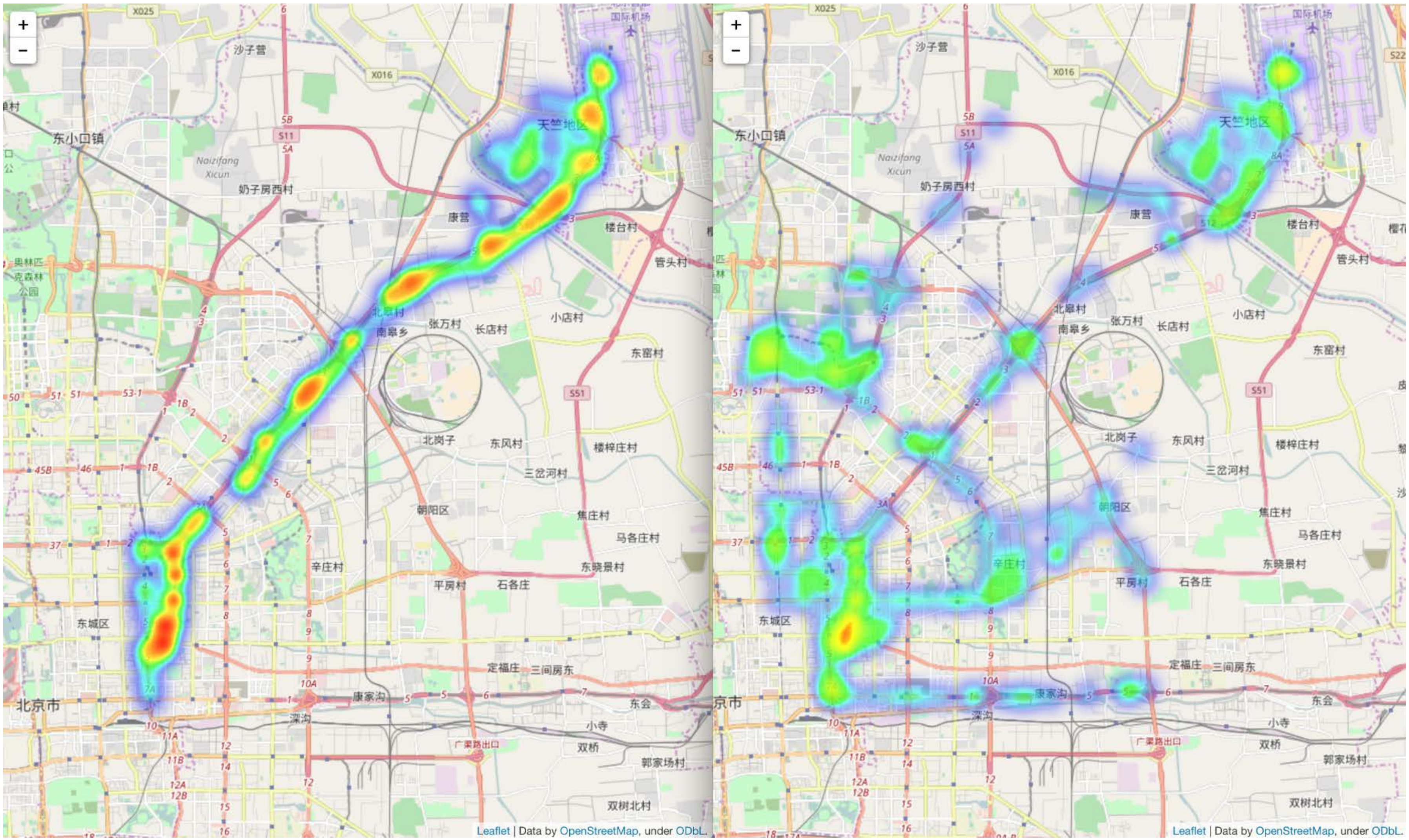

Volkswagen Quantum Computing in the news

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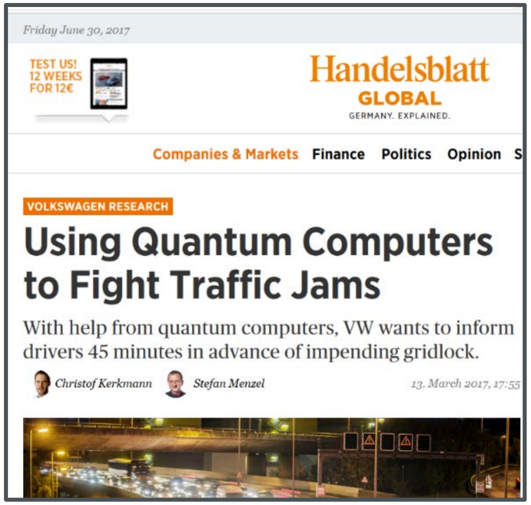

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VOLKSWAGEN RESEARCH

Using Quantum Computers to Fight Traffic Jams

With help from quantum computers, VW wants to inform drivers 45 minutes in advance of impending gridlock.

Christof Kerkmann *Stefan Menzel* *13. March 2017, 17:55*

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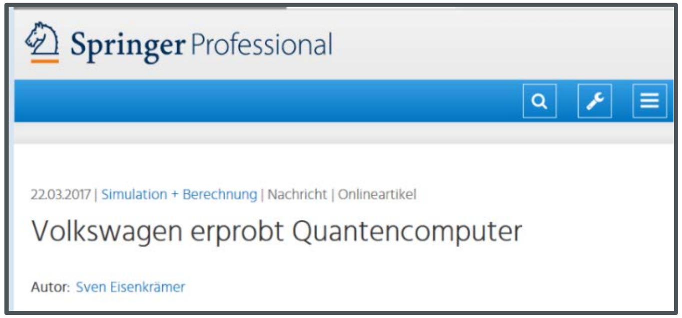
Volkswagen Pilots Quantum Computing Experiments

Quantum computing has vast potential, but high technology hurdles remain

By *Sara Castellanos*
May 8, 2017 10:10 am ET

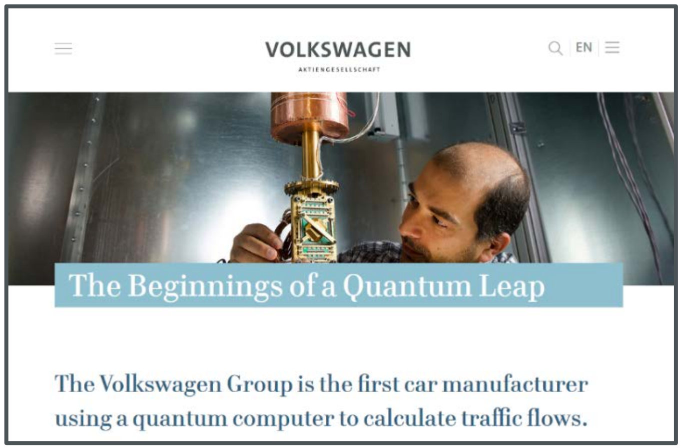


Springer Professional

22.03.2017 | Simulation + Berechnung | Nachricht | Onlineartikel

Volkswagen erprobt Quantencomputer

Autor: Sven Eisenkrämer



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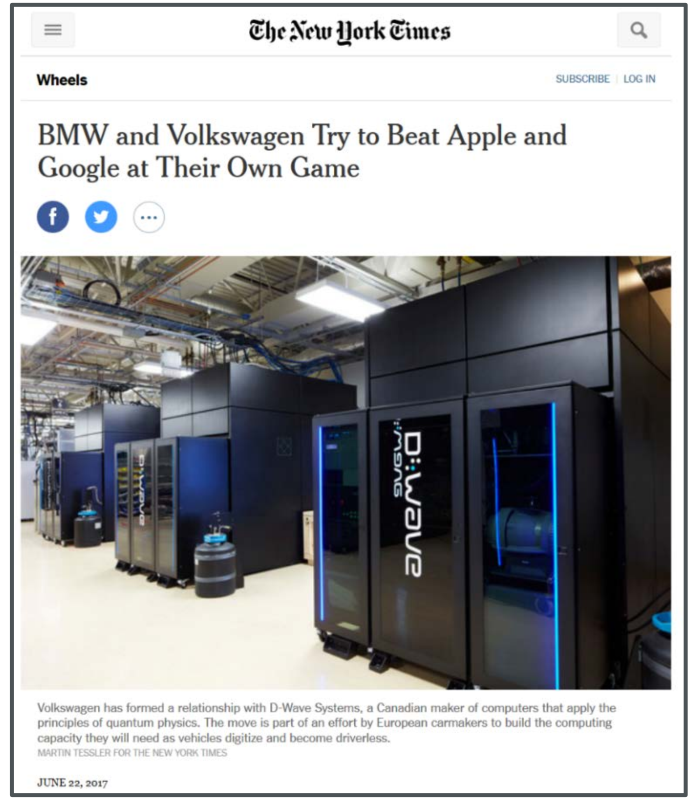
EN

The Beginnings of a Quantum Leap

The Volkswagen Group is the first car manufacturer using a quantum computer to calculate traffic flows.



The New York Times

Wheels

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BMW and Volkswagen Try to Beat Apple and Google at Their Own Game

Volkswagen has formed a relationship with D-Wave Systems, a Canadian maker of computers that apply the principles of quantum physics. The move is part of an effort by European carmakers to build the computing capacity they will need as vehicles digitize and become driverless.
MARTIN TESSLER FOR THE NEW YORK TIMES

JUNE 22, 2017

Further improvements

Due to the 2.5 months project time we treated in this test all the streets equally.

This is obviously a simplification.

Additional constraints could be:

- Street capacity (highway vs alley)
- Residential zones

Dataset improvements:

- Frequent updates to react on constantly changing traffic situations (other datasets)
- More cars
- Etc.

Lessons learned

- The D-Wave Quatum Annealer can help solving **real world problems** (prototype was done in 2.5 months)
- **transforming** the real world problem into a QUBO takes the most time
- Problems **larger** than the chip capacity **can be solved** by decomposition using a **hybrid solver** (i.e. Qsage, qbsolv)

Due to the **chimera graph structure** of the quantum chip:

- The chip is not fully connected, so **Qubit chains** need to be created
- Challenging the Precision: find the right values for **chain strengths** (Qubit connection) and **penalty weights**

Nice to have (Christmas wishlist?):

- JAVA API: would help attracting a larger audience

Publication

- Joint publication by Volkswagen and D-Wave is currently under peer review

- Draft available on the ArXiv:

https://arxiv.org/abs/1708.01625

Questions ?