Free software for quantum computation

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KQIS AGH
13 March 2019 Kraków

Outline

Outline

Introduction—Free software

Free software actions for quantum computation

- Quantum Open Source Foundation
- Fosdem 19 Quantum computing track
- Xanadu.ai

Julia and quantum computing

- Introduction to Julia
- QuantumInformation.jl

Programming D-Wave Annealer

- Quantum annealing
- D-Wave annealer
- D-Wave software stack

Future work—interesting challenges

- Interesting goals to pursue

Free software

IT Giants conference AGH 2009

Free software

A program is free software if the program's users have the four essential freedoms:

- The freedom to **run** the program as you wish, for any purpose (freedom 0).
- The freedom to **study** how the program works, and **change** it so it does your computing as you wish (freedom 1). Access to the source code is a precondition for this.
- The freedom to **redistribute** copies so you can help others (freedom 2).
- The freedom to distribute copies of your **modified** versions to others (freedom 3). By doing this you can give the whole community a chance to benefit from your changes. Access to the source code is a precondition for this.

`https://www.gnu.org/philosophy/free-sw.en.html`

Outline

Quantum Open Source Foundation I

Mission

The Quantum Open Source Foundation [...] is charged to expand the role of open source software in quantum computing and improve the standardization and quality thereof.

The objective of QOSF is to:

- Foster **collaboration** between the quantum hardware and software developer communities;
- Provide financial **funding** for selected projects and travel awards for selected QOSF members and maintainers of open source quantum projects;
- Incentivize and support the **distribution of free and open information** regarding advances in **quantum software engineering** and quantum computing in general;

Quantum Open Source Foundation II

- Provide a **forum** for physicists, software developers, quantum hardware providers and other parties to discuss common problems and obstacles related to open quantum software engineering;
- Organize free and open **conferences**, **workshops** and **informational sessions** on quantum software engineering;
- **Convey the fundamental concepts of quantum computing** and quantum software engineering to the general public.

`www.qosf.org`

In short

Do not (only) write proofs,
let's code!

Software resources

List of Open Quantum Projects

`https://www.qosf.org/project_list/`

List of Quantum Computation simulators

`https://www.quantiki.org/wiki/list-qc-simulators`

Short report from Fosdem I

Quantum computing devroom

- When open source meets quantum computing, Tomas Babej
  Fingerhuth M, Babej T, Wittek P (2018) **Open source software in quantum computing. PLoS ONE 13(12): e0208561.**
  `https://doi.org/10.1371/journal.pone.0208561`
- Forest: An Open Source Quantum Software Development Kit, Robert Smith
  Open-sourcing of quilc (compiler) and qvm (quantum virtual machine)
- Delivering Practical Quantum Computing, Murray Thom
  A review of D-Wave Annealer applications
- D-Wave's Software Development Kit, Alexander Condello
  `dwave-ocean-sdk` **review**
- D-Wave Hybrid Framework, Radomir Stevanovic
  How to build complex samplers using `dwave-ocean-sdk`

Short report from Fosdem II

- What is IBMQ, Mark Mattingley-Scott
- Qutip: Quantum simulations and collaborative code development, Shahnawaz Ahmed
  A widely used quantum mechanics and computation modelling framework written in python
- Strawberry Fields - software for photonic quantum computing, Nathan Killoran
  Quantum optics based gate model computation framework by Xanadu
- PennyLane - Automatic differentiation and ML of QC, Josh Izaac
  Neural networks with quantum optical components
- Quantum Computing at Google and in the Cloud, Kevin D. Kissell
- Promotion of open source and role of standardization in QC, Panel Discussion
- Exponential speedup in progress, Mark Fingerhuth

Short report from Fosdem III

Quantum computing workshop

- Towards Practical Quantum Machine Learning with NISQAI, Ryan LaRose
- Bayesforge: Elevating the QC Stack, Henning Dekant
  Quantum/classical Bayesian networks software distribution
- An Open-Source General Compiler for Quantum Computers, Kaitlin Smith
  A new yet unreleased quantum compiler
- Julia programming language for quantum software development, Piotr Gawron
- QCL - A Programming Language for Quantum Computers, Andrew Savchenko
  The first programming language for quantum computers
- Curry: A probabilistic quantum programming language, Lucas Saldyt

Short report from Fosdem IV

- PyZX: Graph-theoretic optimization of quantum circuits, John van de Wetering
  A category theory based quantum circuits optimization
- An implementation of a classifier on Qiskit, Carsten Blank
- Through the RevKit v3 implementation, Bruno Schmitt
  Reversible logic synthesis tool extension for quantum computing
- Q-bug: Visualizing Quantum Circuits, Felix Tripier
- SimulaQron — a simulator for developing quantum internet software, Axel Dahlberg
  Software stack for quantum internet developed in Netherlands

StrawberryFields I

	CV	**Qubit**
Basic element	Qumodes	Qubits
Relevant operators	Quadratures $\hat{x}, \hat{p}$ Mode operators $\hat{a}, \hat{a}^\dagger$	Pauli operators $\hat{\sigma}_x, \hat{\sigma}_y, \hat{\sigma}_z$
Common states	Coherent states $\|\alpha\rangle$ Squeezed states $\|z\rangle$ Number states $\|n\rangle$	Pauli eigenstates $\|0/1\rangle, \|\pm\rangle, \|\pm i\rangle$
Common gates	Rotation, Displacement, Squeezing, Beamsplitter, Cubic Phase	Phase shift, Hadamard, CNOT, T-Gate
Common measurements	Homodyne $\|x_\phi\rangle\langle x_\phi\|$, Heterodyne $\frac{1}{\pi}\|\alpha\rangle\langle\alpha\|$, Photon-counting $\|n\rangle\langle n\|$	Pauli eigenstates $\|0/1\rangle\langle 0/1\|, \|\pm\rangle\langle\pm\|$, $\|\pm i\rangle\langle\pm i\|$

Table I: *Basic comparison of the CV and qubit settings.*

StrawberryFields II

State family	Displacement	Squeezing
Vacuum state $\|0\rangle$	$\alpha = 0$	$z = 0$
Coherent states $\|\alpha\rangle$	$\alpha \in \mathbb{C}$	$z = 0$
Squeezed states $\|z\rangle$	$\alpha = 0$	$z \in \mathbb{C}$
Displaced squeezed states $\|\alpha, z\rangle$	$\alpha \in \mathbb{C}$	$z \in \mathbb{C}$
$\hat{x}$ eigenstates $\|x\rangle$	$\alpha \in \mathbb{C}$, $x = 2\sqrt{\frac{\hbar}{2}}\mathrm{Re}(\alpha)$	$\phi = 0$, $r \to \infty$
$\hat{p}$ eigenstates $\|p\rangle$	$\alpha \in \mathbb{C}$, $p = 2\sqrt{\frac{\hbar}{2}}\mathrm{Im}(\alpha)$	$\phi = \pi$, $r \to \infty$
Fock states $\|n\rangle$	N.A.	N.A.

Table II: *Common single-mode pure states and their relation to the displacement and squeezing parameters. All listed families are Gaussian, except for the Fock states. The* $n = 0$ *Fock state is also the vacuum state.*

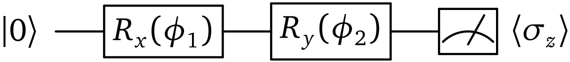
StrawberryFields III

Gate	Unitary	Symbol
Displacement	$D_i(\alpha) = \exp\left(\alpha \hat{a}_i^\dagger - \alpha^* \hat{a}_i\right)$	D
Rotation	$R_i(\phi) = \exp\left(i\phi \hat{n}_i\right)$	R
Squeezing	$S_i(z) = \exp\left(\frac{1}{2}(z^* \hat{a}_i^2 - z \hat{a}_i^{\dagger 2})\right)$	S
Beamsplitter	$BS_{ij}(\theta, \phi) =$ $\exp\left(\theta(e^{i\phi} \hat{a}_i \hat{a}_j^\dagger - e^{-i\phi} \hat{a}_i^\dagger \hat{a}_j)\right)$	BS
Cubic phase	$V_i(\gamma) = \exp\left(i \frac{\gamma}{3\hbar} \hat{x}_i^3\right)$	V

Table III: *Some important CV model gates. All listed gates except the cubic phase gate are Gaussian.*

Source: arXiv:1804.03159

PennyLane




```
import pennylane as qml
from pennylane.optimize import GradientDescentOptimizer
# Create device
dev = qml.device('default.qubit', wires=1)
# Quantum node
@qml.qnode(dev)
def circuit1(var):
    qml.RX(var[0], wires=0)
    qml.RY(var[1], wires=0)
    return qml.expval.PauliZ(0)
# Create optimizer
opt = GradientDescentOptimizer(0.25)
# Optimize circuit output
var = [0.1, 0.2]
for it in range(30):
    var = opt.step(circuit1, var)
    print("Step {}: cost: {}".format(it, circuit1(var)))
```

Source: arXiv:1811.04968

Outline

Julia

- Julia is a modern programming language focused on **numerical computing**.
- Julia is an **imperative**, **structural**, **dynamical**, **just-in-time compiled** programming language supporting **multiple dispatch**.
- Julia is equipped with a simple yet powerful type system consisting of **abstract** and **concrete**, potentially **parametrised**, types.
- Julia supports **meta programming** trough macros which allow for creation of domain specific languages.
- Julia natively supports **concurrent**, **parallel** and **distributed** computing models.

Julia and quantum computing

Julia vs. Python as a language for QC

- Julia solves **two languages problem** that exists with application of Python in numeric applications.
- Julia allows for **elegant notation** that closely resembles mathematical notation.
- Julia can be used as a **full-stack numerical computation language** able to handle and process petabytes of data therefore it is suitable to become the core element of **quantum computation infrastructure**.

Quantum landscape in Julia

Numerics

- QuantumOptics.jl — focused on quantum optics and open quantum systems.
- JuliaQuantum — ambitious, extensive but dead.

Quantum computation

- Yao.jl — A DSL for quantum computation.
- QuAlgorithmZoo.jl — implementation of a couple of quantum algorithms in Yao.jl

Raytheon BBN Technologies - Quantum Group

Has full stack for running their superconducting quantum system.

- QuantumInfo.jl, RandomQuantum.jl — strong overlap with our library.
- SchattenNorms.jl, Cliffords.jl, QSimulator.jl, ...

QuantumInformation.jl—goals

Goals

- Provide a simple numerical library for performing calculations in quantum information theory.
- Focus on mixed states and quantum channels.
- Provide fast and tested (!) generation methods of random quantum objects.
- Provide a wide selection of functionals (distances, entanglement measures, norms).

Gawron P, Kurzyk D, Pawela Ł (2018) QuantumInformation.jl—A Julia package for numerical computation in quantum information theory. PLoS ONE 13(12): e0209358.
`https://doi.org/10.1371/journal.pone.0209358`

QuantumInformation.jl—overview I

Listing 1: Quantum pure states are represented as 1d arrays. The inner product is expressed naturally.

```
julia> ψ=(1/sqrt(2)) * (ket(1,2) + ket(2,2))
2-element Array{Complex{Float64},1}:
 0.7071067811865475 + 0.0im
 0.7071067811865475 + 0.0im

julia>  ϕ=(1/2) * ket(1,2) + (sqrt(3)/2) * ket(2,2)
2-element Array{Complex{Float64},1}:
 0.5 + 0.0im
 0.8660254037844386 + 0.0im

julia> ϕ' * ψ
 0.9659258262890682 + 0.0im

julia> sqrt(ϕ' * ϕ)
 0.9999999999999999 + 0.0im
```

QuantumInformation.jl—overview II

Listing 2: Density matrices are 2d arrays.

```
julia> ρ = [0.25 0.25im; -0.25im 0.75]
2×2 Array{Complex{Float64},2}:
 0.25+0.0im   0.0+0.25im
-0.0-0.25im   0.75+0.0im

julia> σ = [0.4 0.1im; -0.1im 0.6]
2×2 Array{Complex{Float64},2}:
 0.4+0.0im   0.0+0.1im
-0.0-0.1im   0.6+0.0im

julia> ptrace(ρ ⊗ σ, [2, 2], [2])
2×2 Array{Complex{Float64},2}:
 0.25+0.0im    0.0+0.25im
 0.0-0.25im    0.75+0.0im
```

QuantumInformation.jl—overview III

Listing 3: Quantum Channels are in four representations, each having its own type.

```
julia> γ=0.4
 0.4

julia> K0 = Matrix([1 0; 0 sqrt(1-γ)])
2×2 Array{Float64,2}:
 1.0  0.0
 0.0  0.774597

julia> K1 = Matrix([0 sqrt(γ); 0 0])
2×2 Array{Float64,2}:
 0.0  0.632456
 0.0  0.0

julia> Φ = KrausOperators([K0,K1])
KrausOperators{Array{Float64,2}}
dimensions: (2, 2)
 [1.0 0.0; 0.0 0.774597]
 [0.0 0.632456; 0.0 0.0]

julia> iscptp(Φ)
 true
```

QuantumInformation.jl—overview IV

Listing 4: Convertions between chanels representations are implemented.

```
julia> Ψ1 = convert(SuperOperator{Matrix{ComplexF64}}, Φ)
SuperOperator{Array{Complex{Float64},2}}
dimensions: (2, 2)
Complex{Float64}
 [1.0+0.0im 0.0+0.0im 0.0+0.0im 0.4+0.0im;
 0.0+0.0im 0.774597+0.0im 0.0+0.0im 0.0+0.0im;
 0.0+0.0im 0.0+0.0im 0.774597+0.0im 0.0+0.0im;
 0.0+0.0im 0.0+0.0im 0.0+0.0im 0.6+0.0im]

julia> Ψ2 = convert(DynamicalMatrix{Matrix{Float64}}, Φ)
DynamicalMatrix{Array{Float64,2}}
dimensions: (2, 2)
 [1.0 0.0 0.0 0.774597;
 0.0 0.4 0.0 0.0;
 0.0 0.0 0.0 0.0;
 0.774597 0.00.0 0.6]

julia> Ψ3 = convert(Stinespring{Matrix{Float64}}, Φ)
Stinespring{Array{Float64,2}}
dimensions: (2, 2)
 [...]
```

QuantumInformation.jl—overview V

Listing 5: Channels can be composed in parallel and in series. Application of channels is done naturally.

```
julia> ρ2=ϕ * ϕ'
2×2 Array{Complex{Float64},2}:
 0.25+0.0im      0.433013+0.0im
 0.433013+0.0im  0.75+0.0im

julia> (Φ ⊗ Φ)(ρ1 ⊗ ρ2)
4×4 Array{Complex{Float64},2}:
 0.385+0.0im     0.234787+0.0im  0.213014+0.0im  0.129904+0.0im
 0.234787+0.0im  0.315+0.0im     0.129904+0.0im  0.174284+0.0im
 0.213014+0.0im  0.129904+0.0im  0.165+0.0im     0.100623+0.0im
 0.129904+0.0im  0.174284+0.0im  0.100623+0.0im  0.135+0.0im

julia> (Ψ1 ∘ Ψ2)(ρ1)
2×2 Transpose{Complex{Float64},Array{Complex{Float64},2}}:
0.82+0.0im   0.3+0.0im
0.3+0.0im  0.18+0.0im
```

QuantumInformation.jl—overview VI

Listing 6: A sub-package for random matrices is implmented. Random Hermitian matrices.

```
julia> g = GinibreEnsemble{2}(2,3)
 GinibreEnsemble{2}(m=2, n=3)

julia> rand(g)
2×3 Array{Complex{Float64},2}:
 0.835803+1.10758im   -0.622744-0.130165im  -0.677944+0.636562im
 1.32826+0.106582im   -0.460737-0.531975im  -0.656758+0.0244259im
```

QuantumInformation.jl—overview VII

Listing 7: Random unitaries.

```
julia>  c = CircularEnsemble{2}(3)
CircularEnsemble{2}(
d: 3
g: GinibreEnsemble{2}(m=3, n=3)
)

julia> u = rand(c)
3×3 Array{Complex{Float64},2}:
 0.339685+0.550434im  -0.392266-0.3216im      -0.53172+0.203988im
 0.515118-0.422262im   0.392165-0.626859im    -0.0504431-0.084009im
 0.297203+0.222832im  -0.418737-0.143578im     0.607012-0.545525im


julia> u*u'
3×3 Array{Complex{Float64},2}:
 1.0+0.0im                    -5.55112e-17-5.55112e-17im   -2.77556e-17-4.16334e-17
-5.55112e-17+5.55112e-17im     1.0+0.0im                   -2.498e-16+0.0im
-2.77556e-17+4.16334e-17im    -2.498e-16+0.0im              1.0+0.0im
```

QuantumInformation.jl—overview VIII

Listing 8: Random quantum pure sates.

```
julia> h = HaarKet{2}(3)
HaarKet{2}(d=3)

julia> ψ = rand(h)
3-element Array{Complex{Float64},1}:
 0.1687649644765863 - 0.3201009507269653im
 0.7187423269572294 - 0.3940502277043476 7im
 0.1342475675218075 + 0.4232791563609603 6im

julia> norm(ψ)
 1.0
```

QuantumInformation.jl—overview IX

Listing 9: Random quantum channels are returned in appropriate channel type.

```
julia> c = ChoiJamiolkowskiMatrices(2, 3)
ChoiJamiolkowskiMatrices{2,1}(WishartEnsemble{2,1}(d=6), 2, 3)

julia> Φ = rand(c)
DynamicalMatrix{Array{Complex{Float64},2}}
dimensions: (2, 3)
Complex{Float64}
 [0.307971-4.98733e-18im -0.00411588+0.0368471im...
-0.0676732+0.024328im  0.0860858+0.00302876im;
-0.00411588-0.0368471im 0.167651+2.1684e-19im...
-0.0428561+0.0266119im    0.0191888+0.0101013im;
...;
-0.0676732-0.024328im -0.0428561-0.0266119im...
 0.210419+0.0im -0.103401-0.142753im;
 0.0860858-0.00302876im 0.0191888-0.0101013im...
-0.103401+0.142753im 0.411068+0.0im]

julia> ptrace(Φ.matrix, [3, 2],[1])
2×2 Array{Complex{Float64},2}:
 1.0-1.53957e-17im            -1.38778e-17-3.05311e-16im
 1.38778e-17+3.05311e-16im      1.0+2.1684e-19im
```

Outline

Adiabatic model of quantum computation – the basics I

Classical Ising model

Let a classical Hamiltonian (energy function) be given:

$$H(s) = -\sum_{i\in\mathcal{I}} h_i s_i - \sum_{(i,j)\in\mathcal{I}\times\mathcal{I}} J_{ij} s_i s_j,$$

Where

$$s = [s_i]_{i\in\mathcal{I}} \in \{-1, 1\}^{\mathcal{I}}, h_i \in \mathbb{R}, J_{ij} \in \mathbb{R}.$$

The goal is to find

$$s^\star = \arg\min_s H(s),$$

the minimal energy state.

Adiabatic model of quantum computation – the basics II

Quantum Ising Hamiltonian

$$H(t) = (1-\frac{t}{\tau})\underbrace{\left(-\sum_{i\in\mathcal{I}}\sigma_x^{(i)}\right)}_{H_0}+\frac{t}{\tau}\underbrace{\left(-\sum_{i\in\mathcal{I}}h_i\sigma_z^{(i)}-\sum_{(i,j)\in\mathcal{I}\times\mathcal{I}}J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right)}_{H_p},$$

where

$$\sigma_{\{x,z\}}^{(i)} = \mathbb{1}_2^{\otimes(i-1)}\otimes\sigma_{\{x,z\}}\otimes\mathbb{1}_2^{\otimes(|\mathcal{I}|-i-1)}$$

$$\mathbb{1}_2 = \begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}, \sigma_z = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}, \sigma_x = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}.$$

Adiabatic model of quantum computation – the basics III

Eigenstates of a Hamiltonian

Hamiltonians have eigenvalues E_n ($E_0 \leq E_1 \leq \ldots \leq E_n$) and corresponding eigenstates $|\psi\rangle_n$:

$$H\,|\psi\rangle_n = E_n\,|\psi\rangle_n\,.$$

If we will begin computation in the state

$$\left|\psi^{(0)}\right\rangle_0 : H_0 \left|\psi^{(0)}\right\rangle_0 = E_0^{(0)} \left|\psi^{(0)}\right\rangle_0 = \left(\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)\right)^{\otimes|\mathcal{I}|},$$

then for large τ we will end up in the state:

$$\left|\psi^{(p)}\right\rangle_0 : H_p \left|\psi^{(p)}\right\rangle_0 = E_0^{(p)} \left|\psi^{(p)}\right\rangle_0\,.$$

Adiabatic model of quantum computation – the basics IV

Finally we perform a measurement:

$$\left\{ P_{\pm 1}^{\otimes|\mathcal{I}|} \right\},$$

where

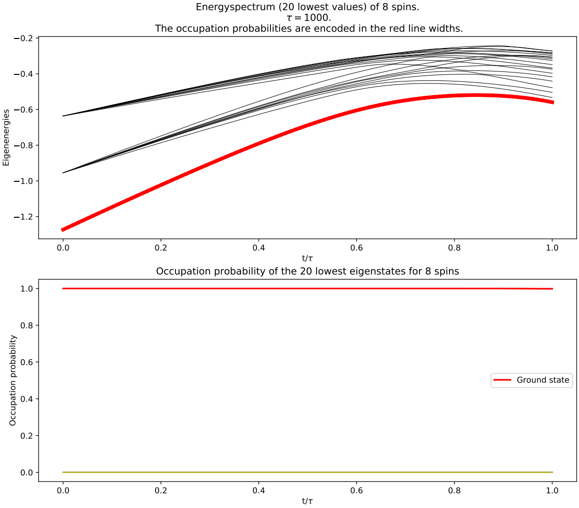
$$\{P_{-1} = |0\rangle\langle 0|\,, P_1 = |1\rangle\langle 1|\}.$$

As a result we obtain:

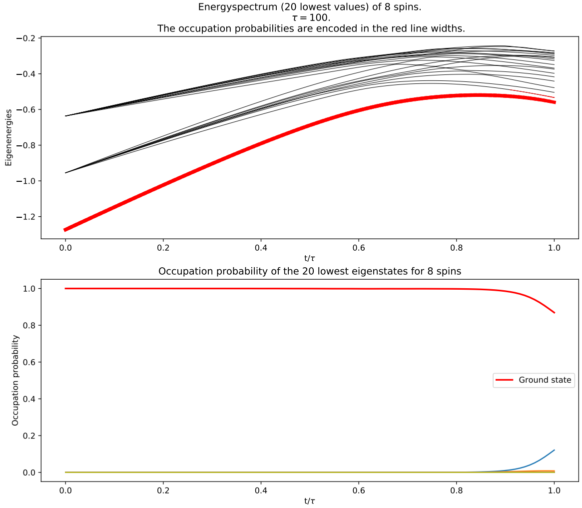
$$s = \{\pm 1\}^{|\mathcal{I}|},$$

what is the result of our minimization problem.

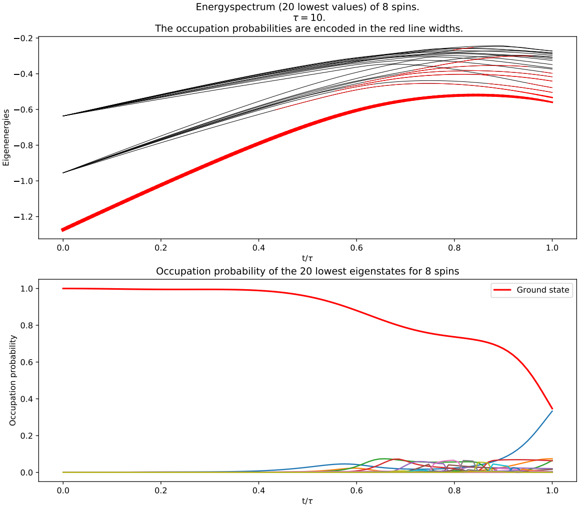
Adiabatic evolution – example



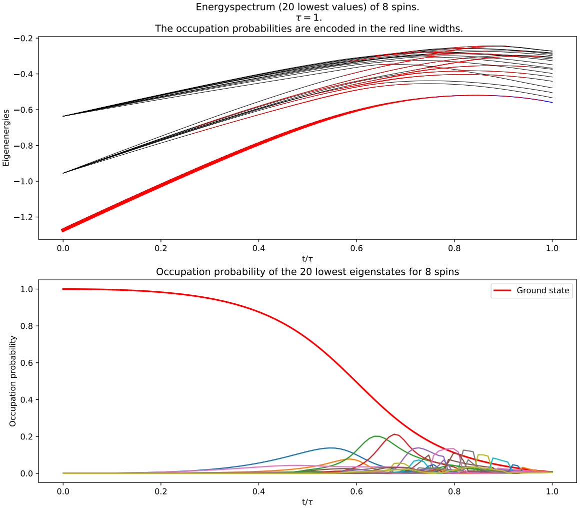
Adiabatic evolution – example



Adiabatic evolution – example



Adiabatic evolution – example



D-Wave annealer

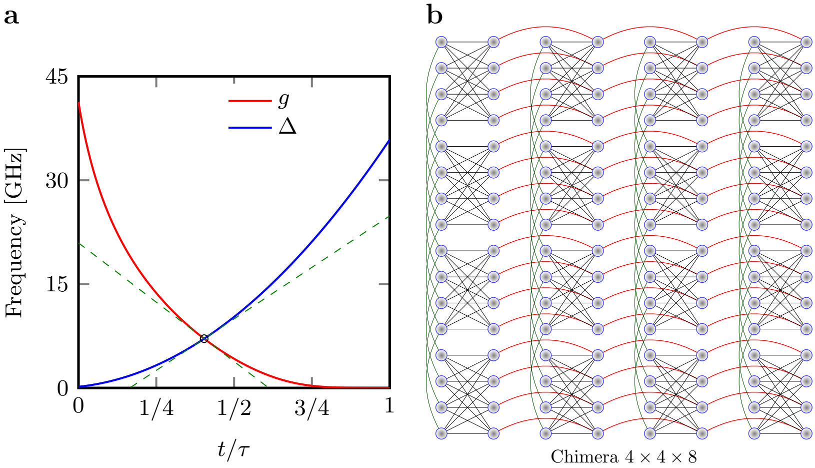
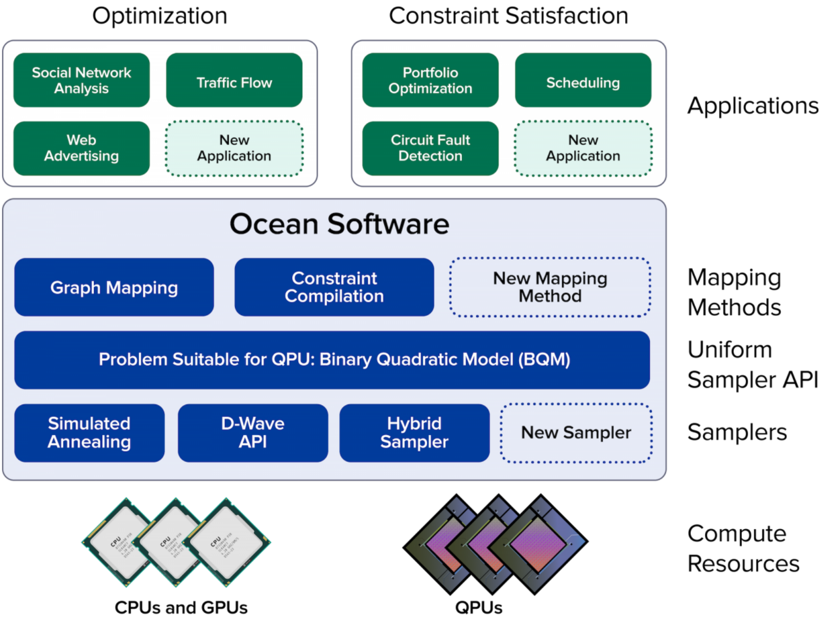


Figure: $\mathcal{H}(t)/(2\pi\hbar) = -g(t)\sum_i \sigma_x^{(i)} - \Delta(t)\mathcal{H}_1, \quad t \in [0, \tau].$

Source: Bartłomiej Gardas



Source: Copyright © D-Wave Systems Inc.

Example of dimod application

Program:

```
import dimod
from dwave.system.samplers import DWaveSampler

J = {("a", "b"): -1.0, ("a", "c"): -0.5, ("c", "a"): 0.1}
h = {"a": 0, "b": -1, "c":0.5}

bqm = dimod.BinaryQuadraticModel.from_ising(h, J)
sampler = dimod.ExactSolver() # or DWaveSampler()
response = sampler.sample(bqm)
for datum in response.data(['sample', 'energy']):
    print(datum.sample, datum.energy)
```

Output:

```
{'a': 1, 'b': 1, 'c': -1} -2.1
{'a': 1, 'b': 1, 'c': 1} -1.9
{'a': -1, 'b': -1, 'c': -1} -0.9
{'a': -1, 'b': 1, 'c': -1} -0.9
{'a': -1, 'b': 1, 'c': 1} 0.9
{'a': -1, 'b': -1, 'c': 1} 0.9
{'a': 1, 'b': -1, 'c': -1} 1.9
{'a': 1, 'b': -1, 'c': 1} 2.1
```

Outline

Interesting goals to pursue I

QuantumInformation.jl

- Quantum channel composition using **tensor networks** (help needed!).
- Managing the **rank of quantum channels** in order to speed-up computation.
- Adding support for **sparse arrays** (moderate difficulty).
- Clean-up and enhancements.

Interesting goals to pursue II

AcausalNets.jl

- Finishing, polishing and publishing
  https://github.com/mikegpl/AcausalNets.jl
- Possible cooperation with http://artiste-qb.net/
  https://github.com/artiste-qb-net

Interesting goals to pursue III

Ising samplers Julia stack

- Existing project ThreeQ.jl: `https://github.com/omalled/ThreeQ.jl`.
- Maybe a new project with well developed type system is more suitable (moderate difficulty — MSc level).

Interesting goals to pursue IV

Assessment of existing gate model for quantum computation Julia stack

- QuantumBFS/Yao.jl `https://github.com/QuantumBFS/Yao.jl`.
- Quantum Bayesian networks to Yao.jl compiler (difficult — PhD level project).
- Quantum Gate Language compiler `https://github.com/BBN-Q/QGL.jl`.
- Quantum gate model compiler for dedicated architectures (difficult — PhD level project).

Interesting goals to pursue V

A general gate model compiler

- Based on quilc `https://github.com/rigetti/quilc` (very difficult).

Interesting goals to pursue VI

Quantum Computation Language to QASM / QUIL compiler

- Based on qcl2qml `https://github.com/ZKSI/qcl2qml` (easy).

Interesting goals to pursue VII

A general question

- How to **integrate** quantum computation with super-computing infrastructure for big data processing?

!!!

Thank you for your attention!

Questions?

Websites, e-mail

`www.quantiki.org`
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