Quantum Computer-Assisted Design of Quantum Optics Hardware

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the matter lab

Acknowledgement

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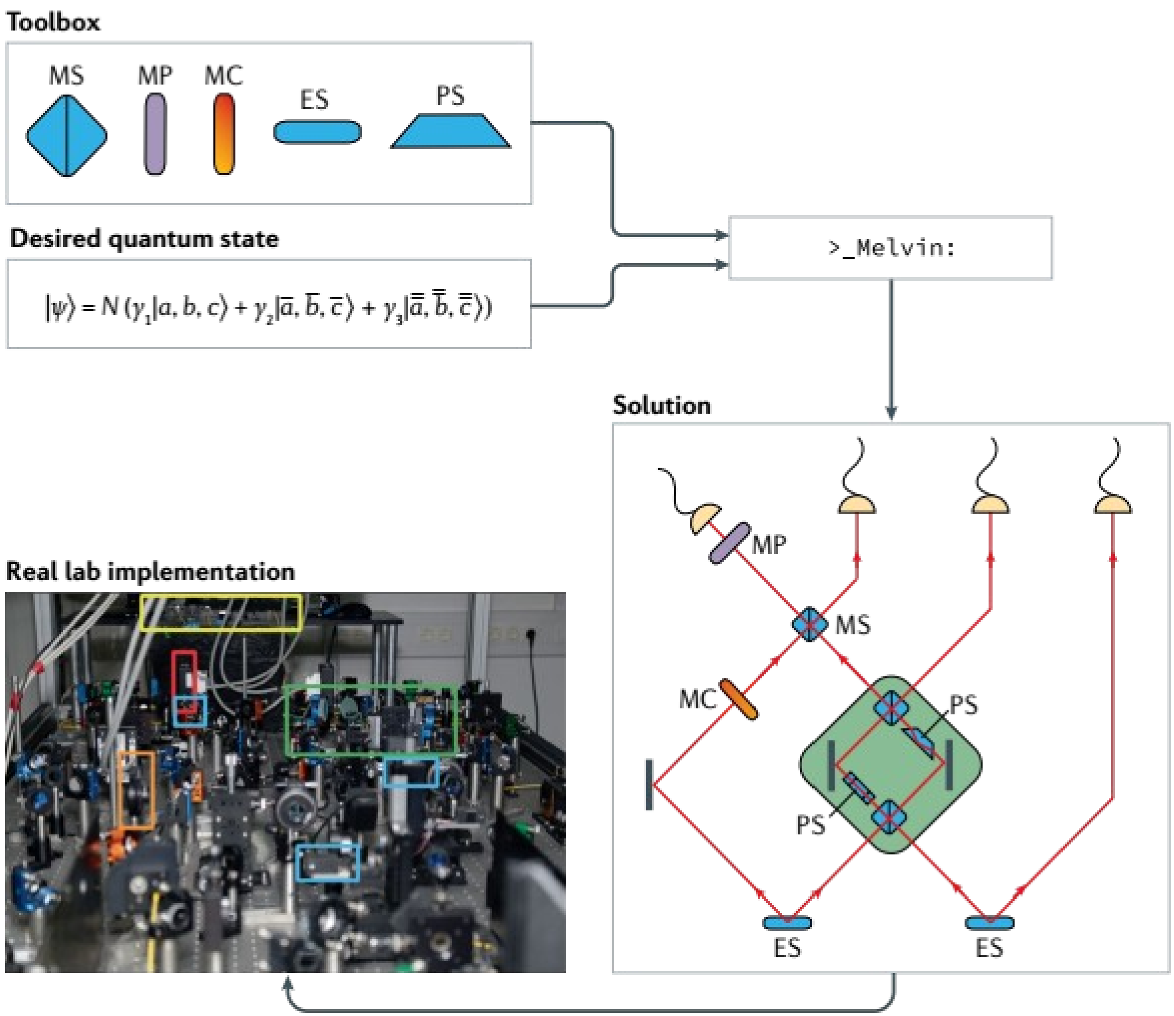
Vladyslav Verteletskyi
Artur Izmaylov

Designing Quantum Optical Experiments



Computer-inspired quantum experiments

Mario Krenn, Manuel Erhard and Anton Zeilinger

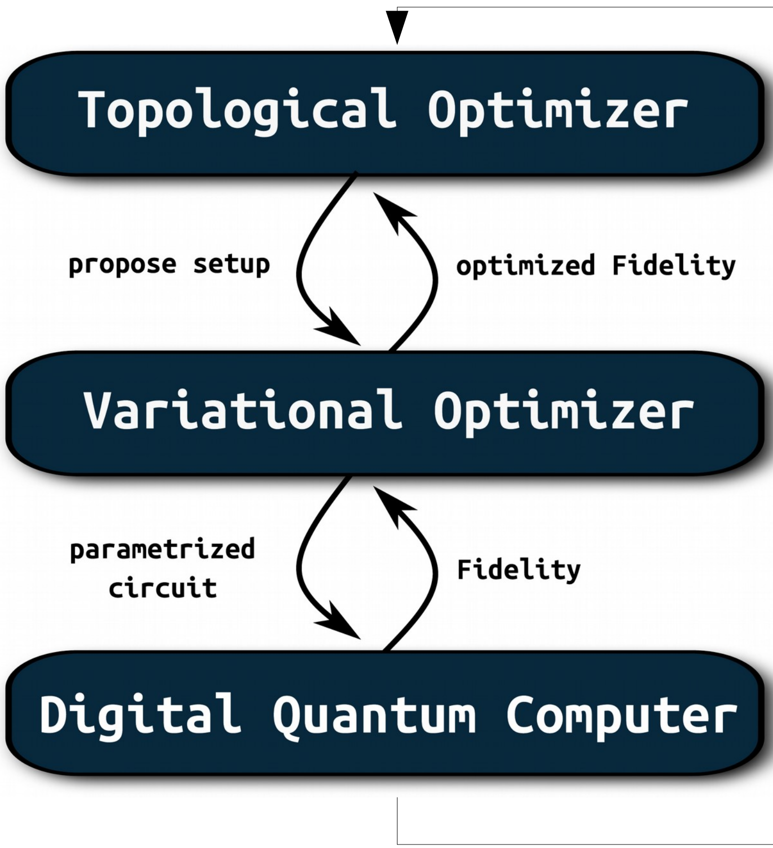
Conceptual understanding through efficient inverse-design of quantum optical experiments

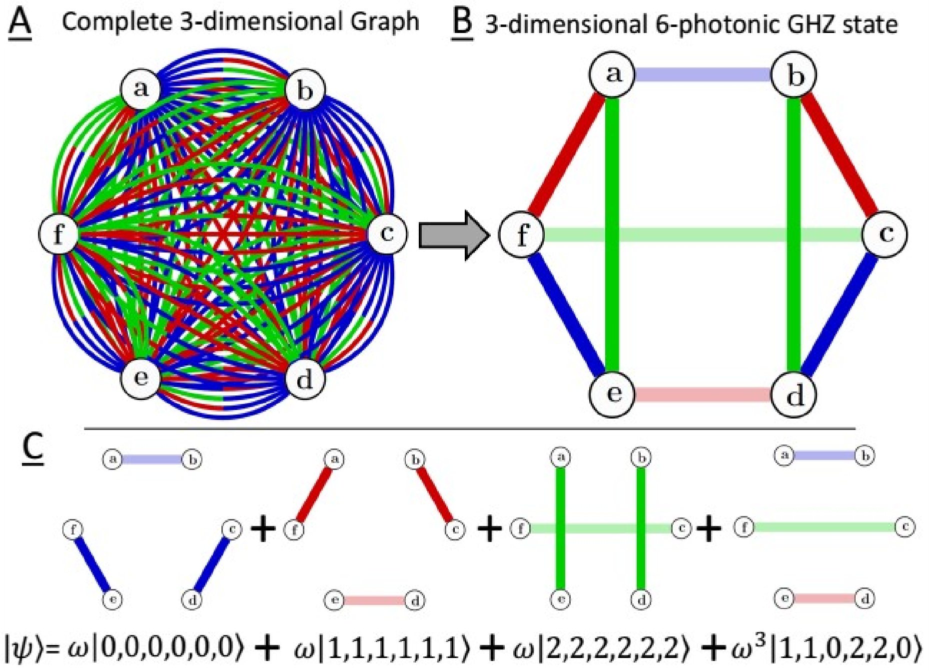
Mario Krenn,[1,2,*] Jakob Kottmann,[1] Nora Tischler,[3] and Alán Aspuru-Guzik[1,2,4,†]

[1] *Department of Chemistry & Computer Science, University of Toronto, Canada.*
[2] *Vector Institute for Artificial Intelligence, Toronto, Canada.*
[3] *Centre for Quantum Dynamics, Griffith University, Brisbane, Australia.*
[4] *Canadian Institute for Advanced Research (CIFAR) Lebovic Fellow, Toronto, Canada*

(Dated: May 15, 2020)

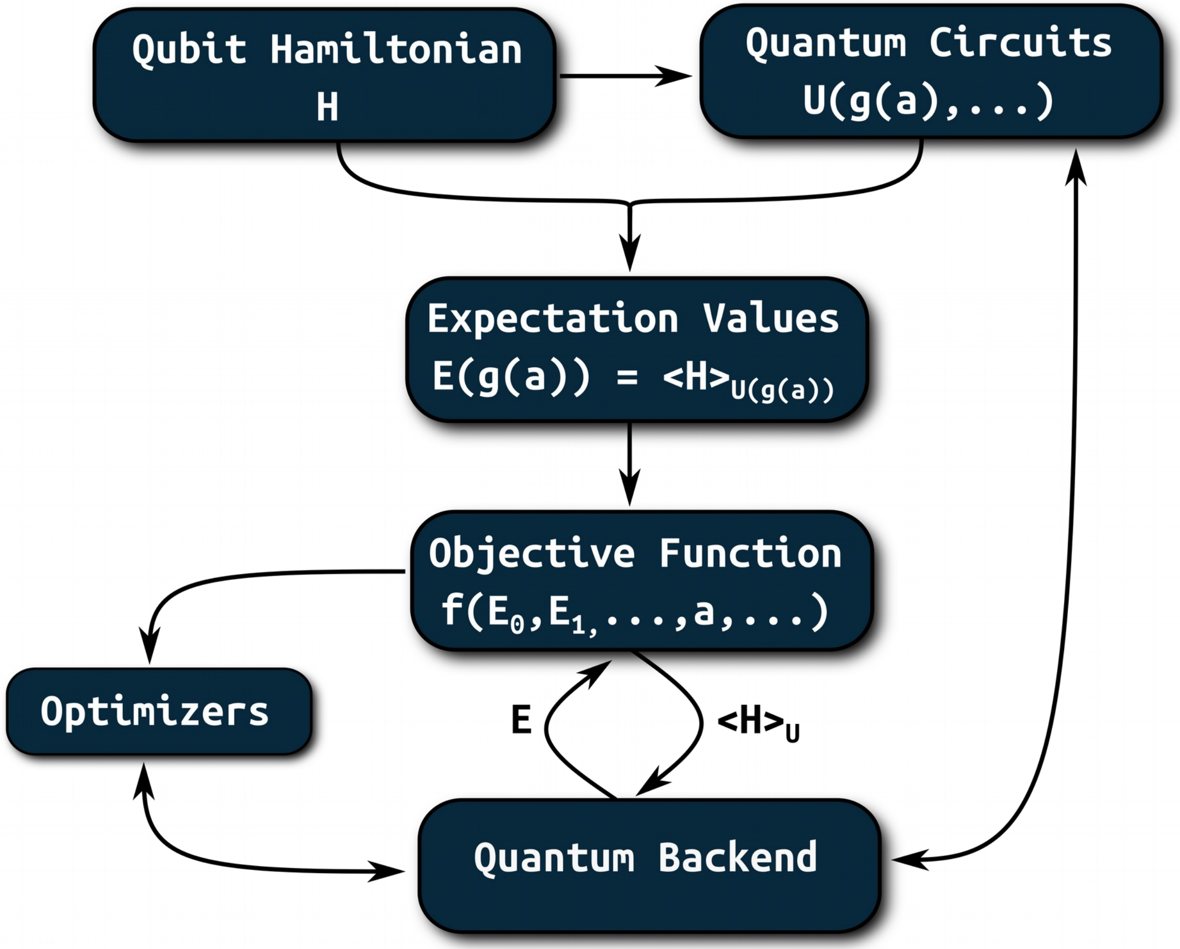
Designing Quantum Optical Experiments



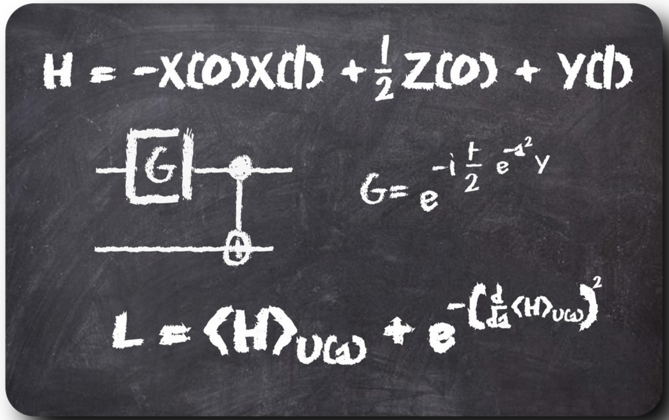


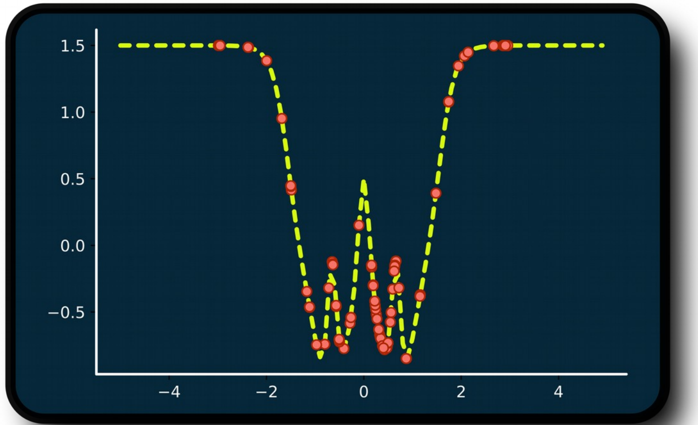
Qulacs
Qiskit
rigetti
Cirq
QIBO

Computational Framework: Tequila



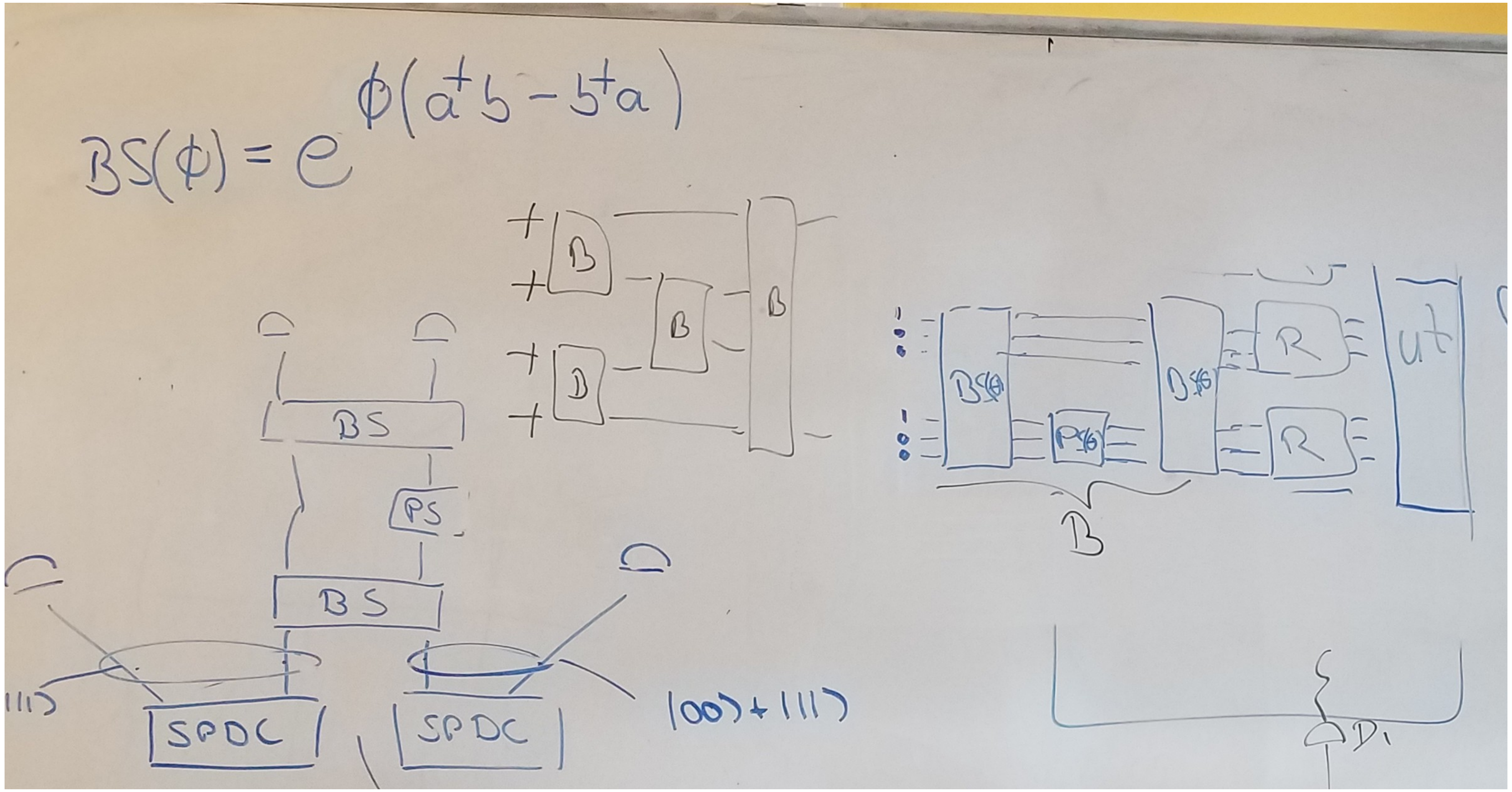
Tequila






```
a = tq.Variable("a")
U = tq.gates.Ry(angle=(-a**2).apply(tq.numpy.exp)*pi, target=0)
U += tq.gates.X(target=1, control=0)
H = tq.QubitHamiltonian.from_string("-1.0*X(0)X(1)+0.5Z(0)+Y(1)")
E = tq.ExpectationValue(H=H, U=U)
dE = tq.grad(E, "a")
objective = E + (-dE**2).apply(tq.numpy.exp)
result = tq.minimize(method="phoenics", objective=objective)
```

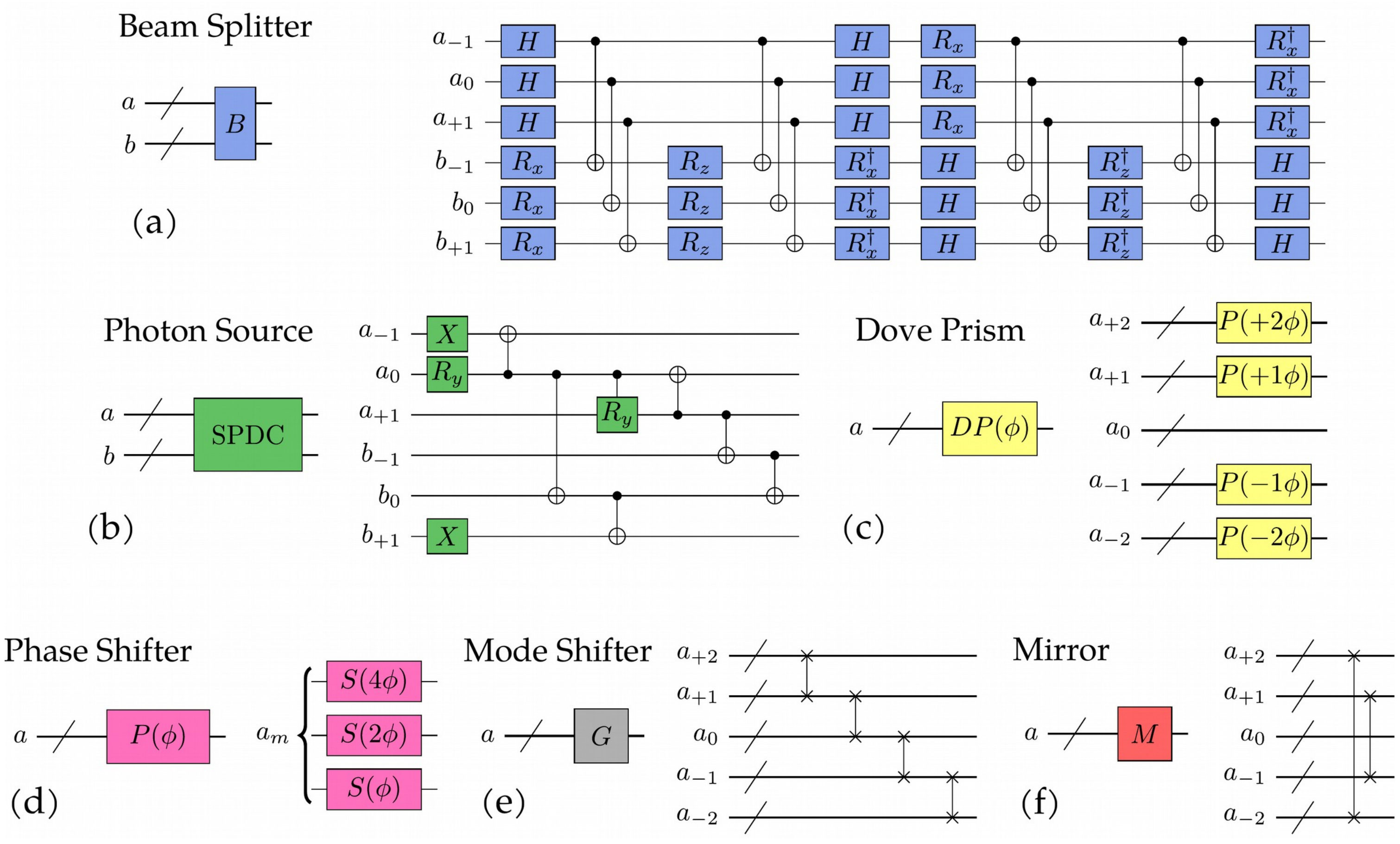
Optimizing Quantum Optical Setups



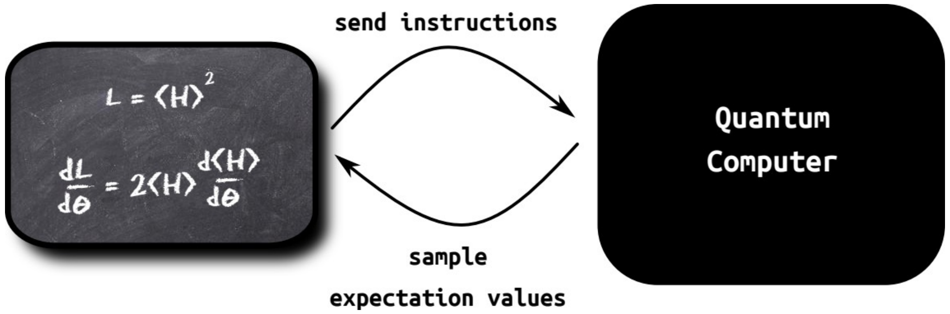
Mario Krenn

Thi Ha Kyaw

Quantum Optics to Quantum Circuits



Quantum Chemistry Workflow



Generators: Hermitian Operators

$$G_{abkl} = i(a_a^\dagger a_i a_b^\dagger a_j - h.c.)$$

Circuits from unitaries

$$U(\theta) = e^{-i\frac{\theta}{2}G}$$

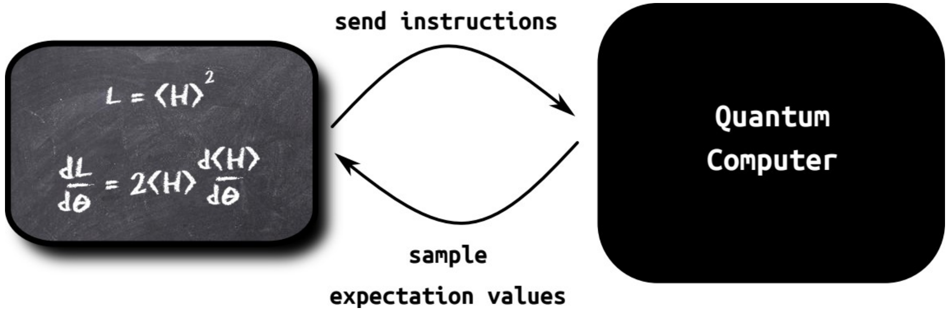
Fermionic operators are mapped to Pauli strings

$$a_k^\dagger = 1^{\otimes k-1} \sigma_k^- \sigma_Z^{\otimes n-k}$$

Variational optimization

$$\min_\theta \left(\langle H \rangle_{U_\theta}\right) \equiv \min_\theta \left(\langle 0 | U^\dagger(\theta) H U(\theta) | 0 \rangle\right)$$

Quantum Optics Workflow



Generators: Hermitian Operators

$$G = a^\dagger b \ + h.c.$$

Circuits from unitaries

$$U(\theta) = e^{-i\frac{\theta}{2}G}$$

Bosonic operators are mapped to Pauli strings

$$a_k^\dagger = \sum c_i \boldsymbol{\sigma}_i$$

Variational optimization

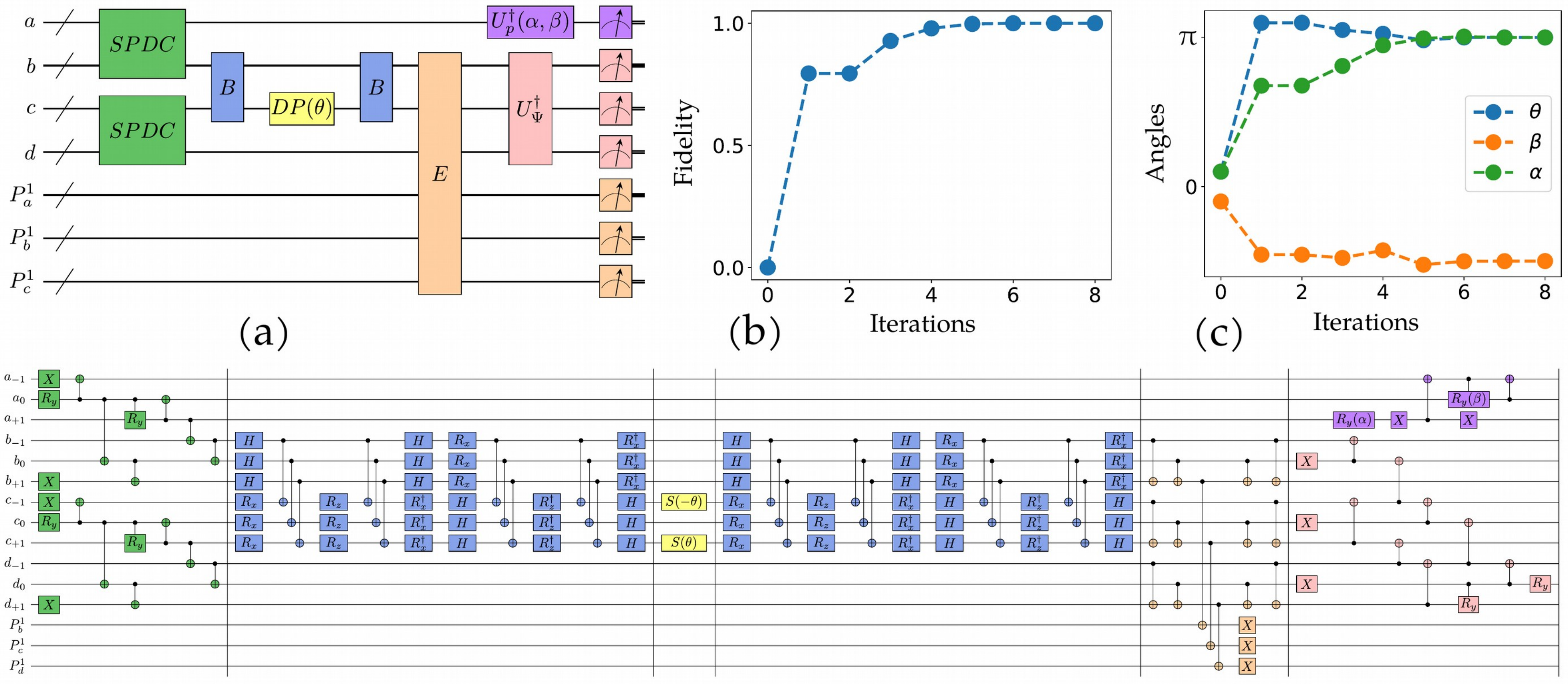
$$\min_\theta \left(f(\theta)\right)$$

ARTICLE OPEN

Resource-efficient digital quantum simulation of d-level systems for photonic, vibrational, and spin-s Hamiltonians

Nicolas P. D. Sawaya[1], Tim Menke[2,3,4], Thi Ha Kyaw[5,6], Sonika Johri[7], Alán Aspuru-Guzik[5,6,8,9] and Gian Giacomo Guerreschi[1]

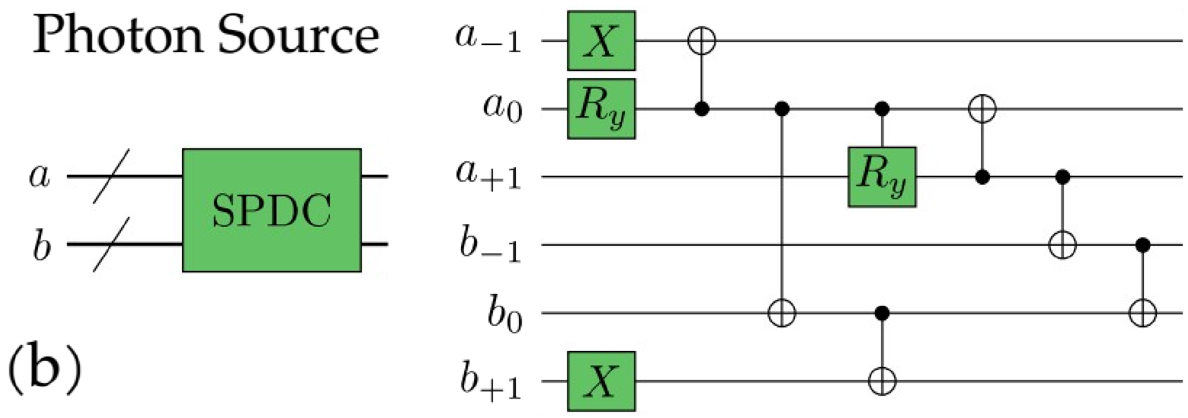
Optimizing Quantum Optical Setups



(a) (b) (c)

(d)

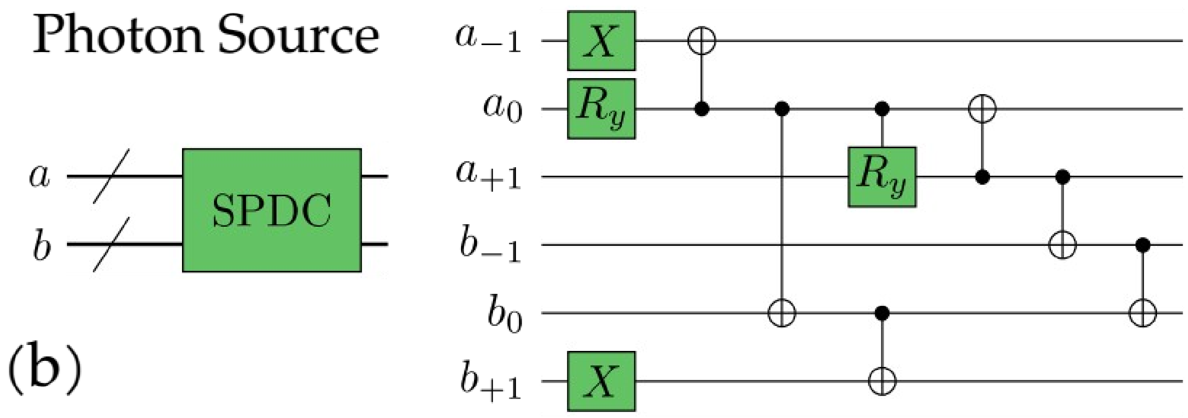
Quantum Optics to Quantum Circuits



$$\frac{1}{\sqrt{3}}\left(|001100\rangle + |010010\rangle + |100001\rangle\right)$$

```
target = tq.QubitWaveFunction("1.0*|001100>+1.0*|010010>+1.0*|100001>").normalize()
P = tq.paulis.Projector(target)
F = tq.ExpectationValue(U=U, H=P)
result = tq.minimize(objective=-F, method="bfgs")
```

Quantum Optics to Quantum Circuits



$$\rightarrow \frac{1}{\sqrt{3}}\left(|001100\rangle + |010010\rangle + |100001\rangle\right)$$

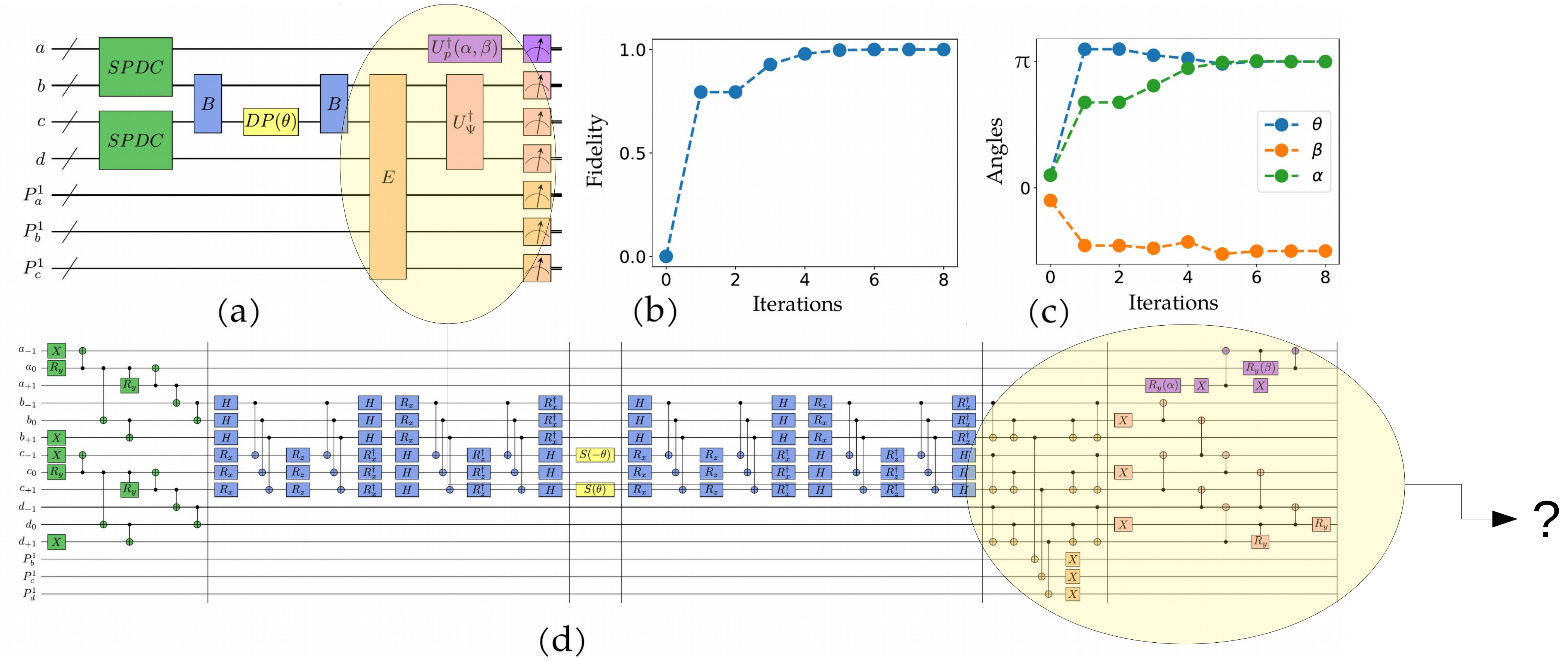
160 Pauli String → 3 Commuting Groups

```
target = tq.QubitWaveFunction("1.0*|001100>+1.0*|010010>+1.0*|100001>").normalize()
P = tq.paulis.Projector(target)
F = tq.ExpectationValue(U=U, H=P, optimize_measurements=True)
result = tq.minimize(objective=-F, method="bfgs")
```

```
Objective with 3 unique expectation values
variables = [x, y]
types     = not compiled
```

T.C. Yen, V. Verteletskyi, A.F. Izmaylov: Series of works on measurement optimization

Optimizing Quantum Optical Setups



Measuring Fidelities

$$F = \left| \langle \Phi \left(\theta \right) | \Psi \rangle \right|^2$$

Measuring Fidelities

$$F = \left|\langle\Phi\left(\theta\right)|\Psi\rangle\right|^2$$

$$H = \underbrace{|\Psi\rangle\langle\Psi|}$$

Many Measurements

$$F = \langle\Phi\left(\theta\right)|H|\Phi\left(\theta\right)\rangle = \langle H\rangle_{U(\theta)}$$

Measuring Fidelities

$$F = \left|\langle\Phi\left(\theta\right)|\Psi\rangle\right|^2$$

Many Measurements

$$H = |\Psi\rangle\langle\Psi|$$

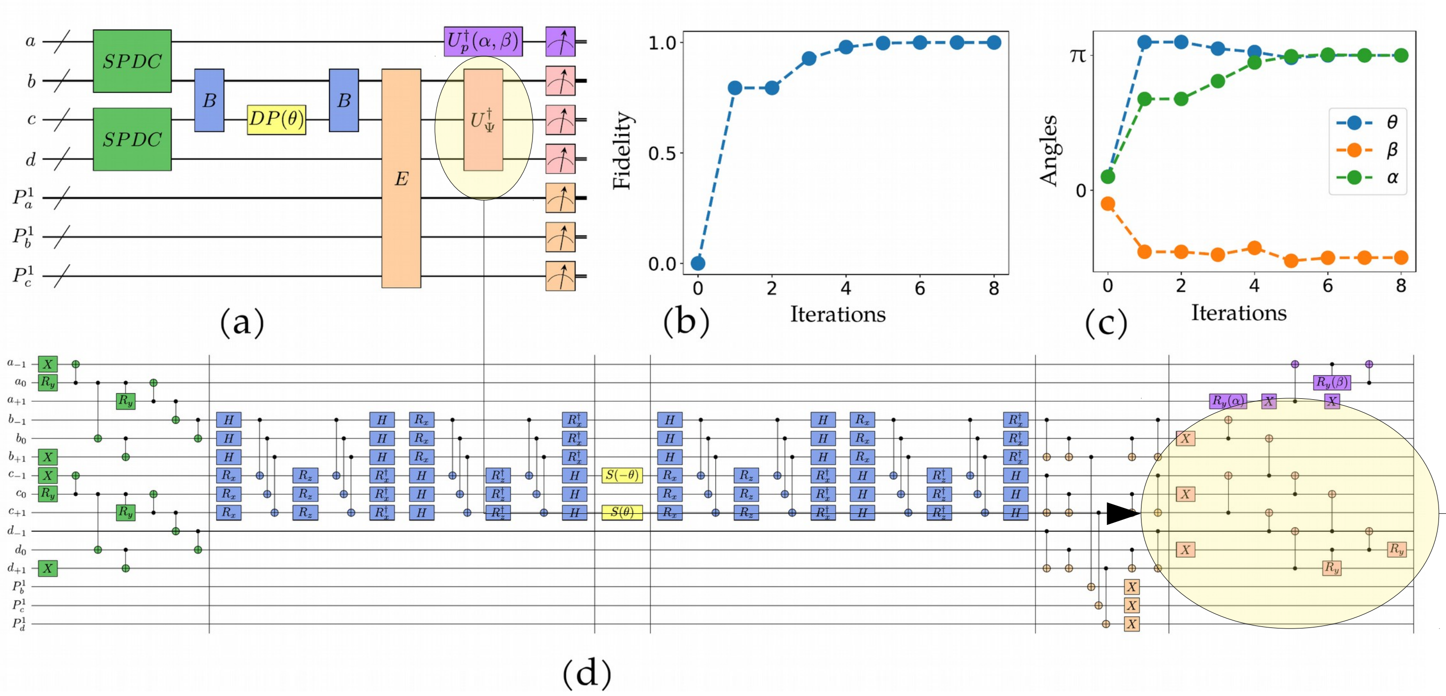
$$F = \langle\Phi\left(\theta\right)|H|\Phi\left(\theta\right)\rangle = \langle H\rangle_{U(\theta)}$$

$$F = \langle P_0\rangle_{U_\Psi^\dagger U(\theta)}$$

$$H = U_\Psi|0\rangle\langle 0|U_\Psi^\dagger$$

1 Measurement

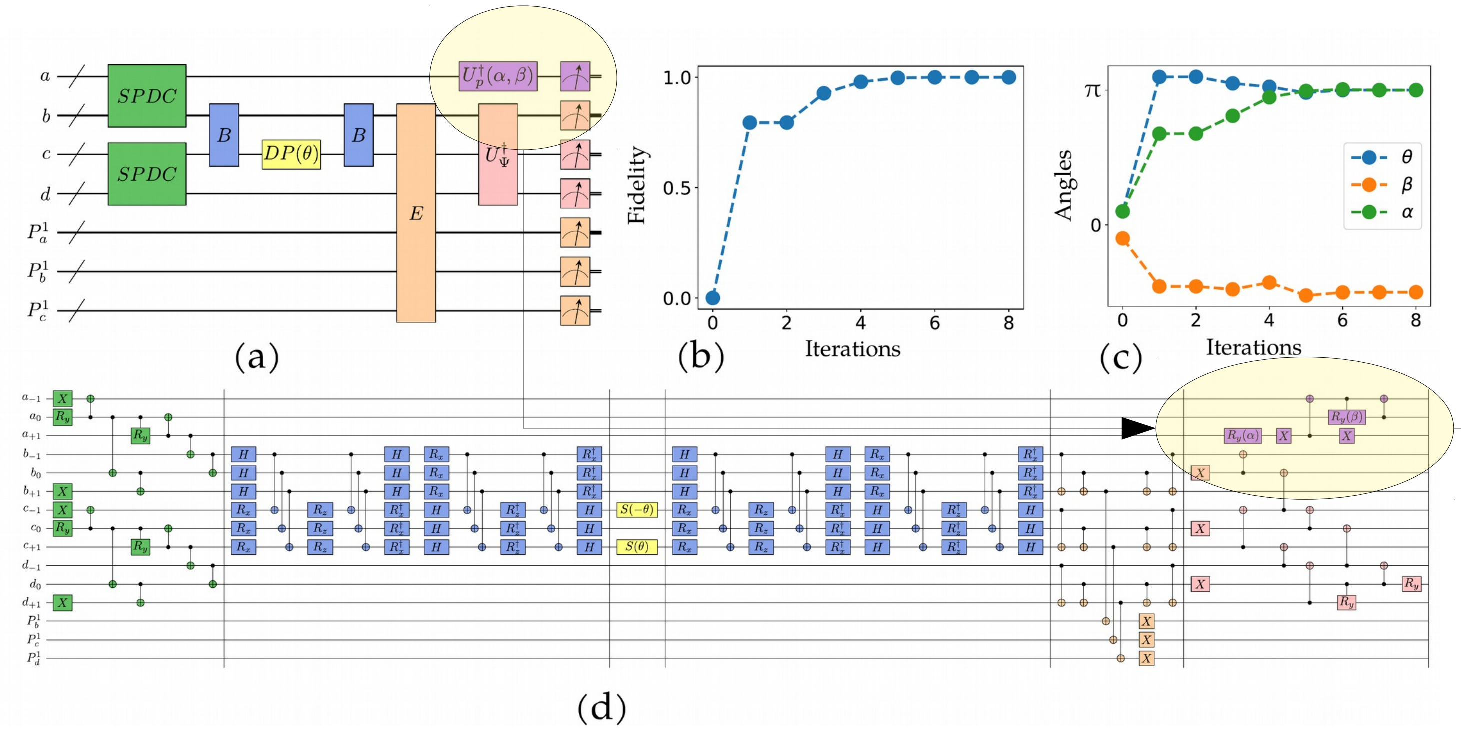
Optimizing Quantum Optical Setups



$$|\Psi\rangle = \frac{1}{\sqrt{3}}\left(|-1,1,-1\rangle + |0,0,0\rangle + |1,1,-1\rangle\right)$$

$$F = \langle P_0 \rangle_{U_\Psi^\dagger U(\theta)}$$

Optimizing Quantum Optical Setups



(a) (b) (c)
(d)

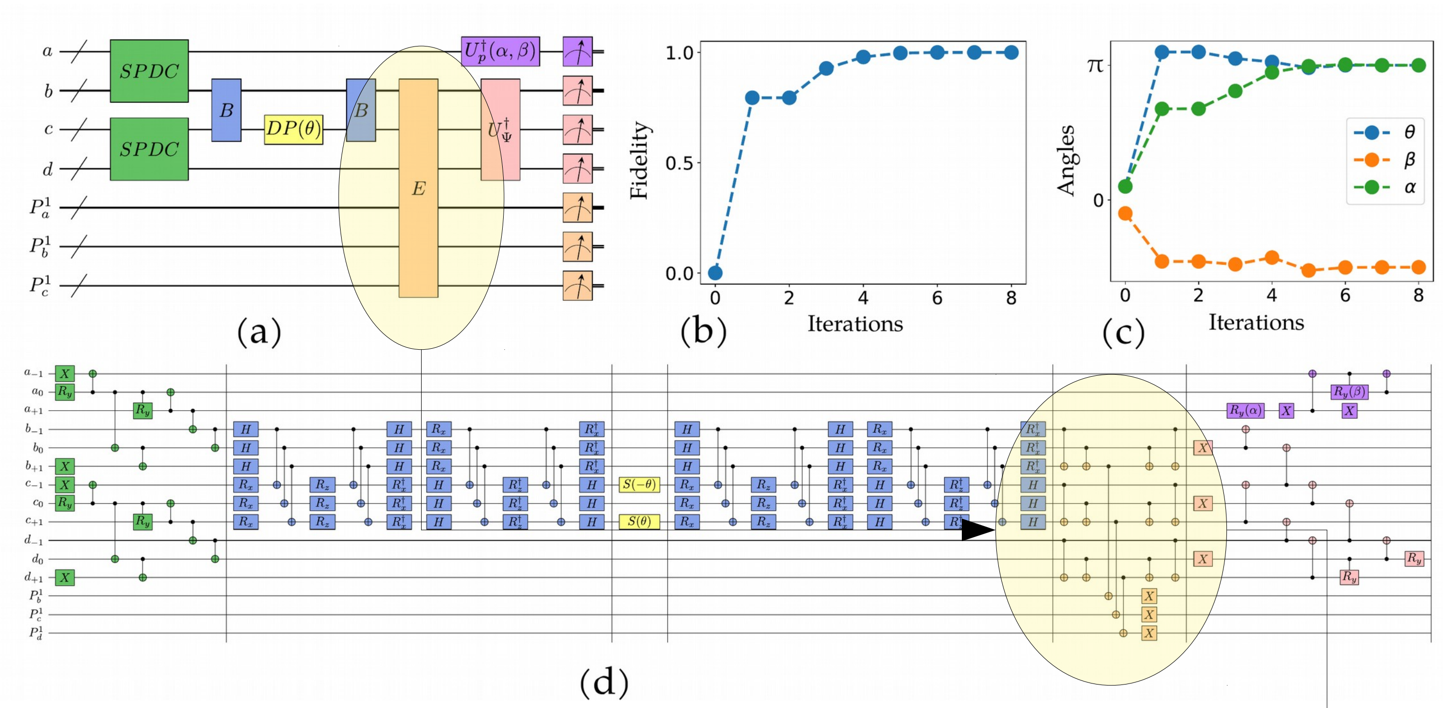
Heralding Projector
Same principle but parametrized

Neat Tool: UntaryStatePrep

```
target_space = ["001", "010", "100"]
USP = tq.apps.UnaryStatePrep(target_space)
target=tq.QubitWaveFunction("1.0*|001> + 2.0*|010> + 3.0*|100>").normalize()
circuit = USP(target)
```

```
0: ───X───@──────────────X───X───@──────────────X───
          │              │       │
1: ───────Ry(0.408π)─────@───────┼──────────────X───
                                 │              │
2: ──────────────────────────────Ry(0.295π)─────@───
```

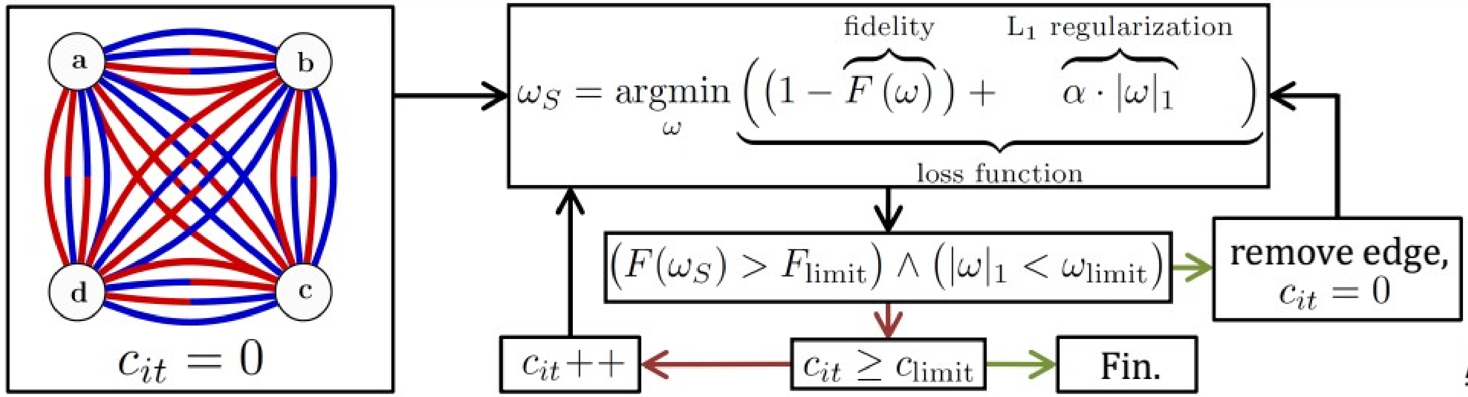
Optimizing Quantum Optical Setups



$$\mathcal{F}_\Psi = \frac{\langle\Phi|P_p \otimes H P_1|\Phi\rangle}{\langle\Phi|P_p \otimes P_1|\Phi\rangle}$$

Post-Processing:
Count only states
with one Photon in each path

Abstract Graph Representation: Theseus



Conceptual understanding through
efficient inverse-design of quantum optical experiments

Mario Krenn,[1,2,*] Jakob Kottmann,[1] Nora Tischler,[3] and Alán Aspuru-Guzik[1,2,4,†]

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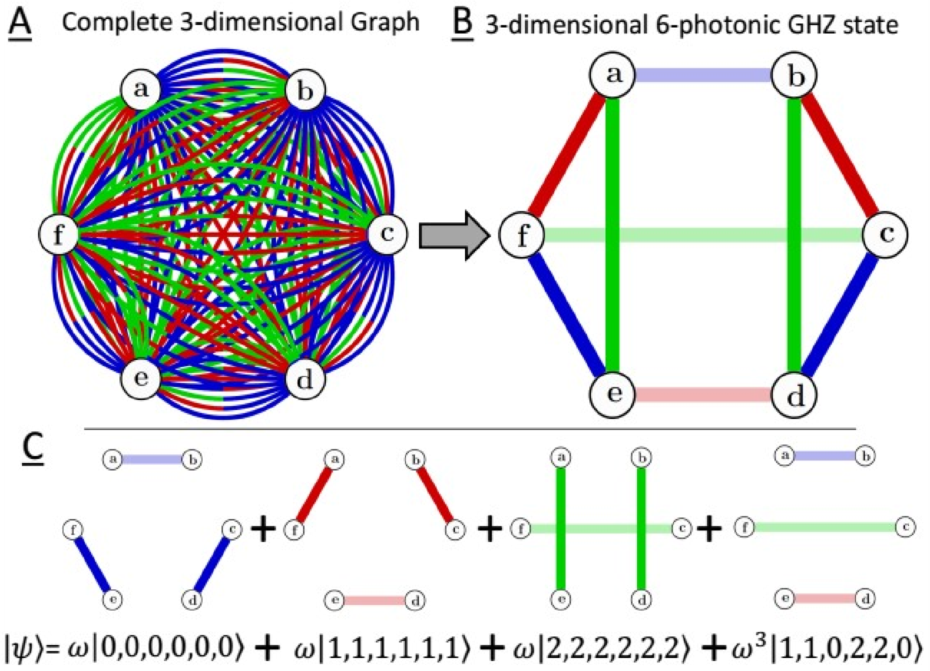
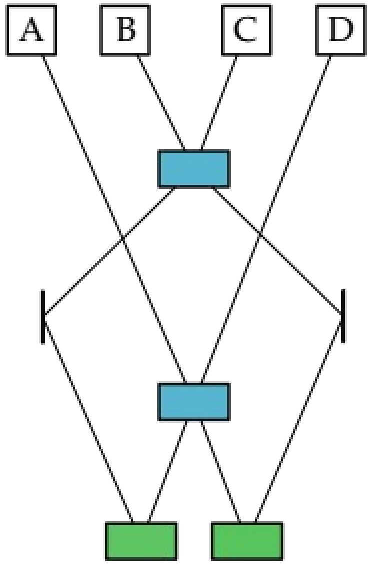
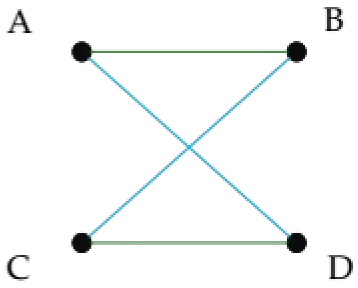


Abstract Graph Representation: Theseus



Optical Setup



Abstract Graph

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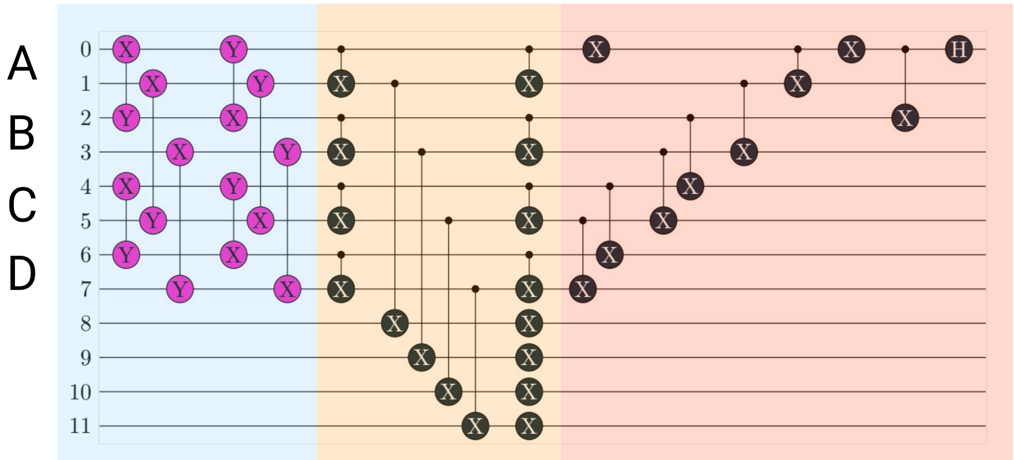
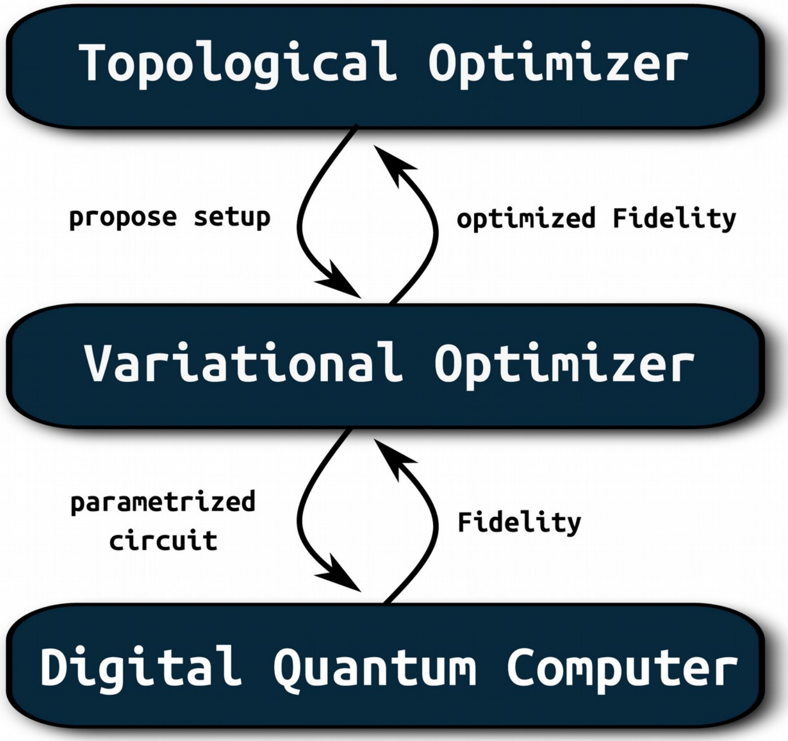
Quantum Circuit Post-Processing Fidelity Estimation



Outlook

Many fields face similar technical problems:
New bridges through language of quantum computing

Abstract and easy to use computational frameworks:
Ready for advancements in classical simulators



Acknowledgement

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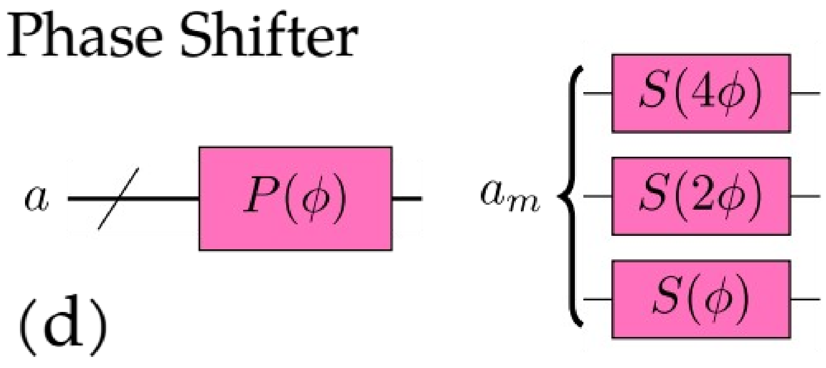

$$\longrightarrow |n\rangle_a \longrightarrow e^{in\phi}|n\rangle_a$$

$$S\,(\phi)\,|0\rangle = |0\rangle$$

$$S\,(\phi)\,|1\rangle = e^{i\phi}|1\rangle$$

n=0	000
n=1	001
n=2	010
n=3	011
n=4	100
.	.
.	.
.	.