Suppressing photon detection errors in nondeterministic state preparation

Csaba Czabán[1, 2] Zoltán Kolarovszki[1, 2] Márton Karácsony[1, 3] Zoltan Zimboras[1, 2]

[1]HUN-REN Wigner Research Centre for Physics

[2]Eötvös Loránd University, Faculty of Informatics

[3]Department of Physics, Duke University

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Quantum advantage using photons

The Quantum Information Group of USTC in Hefei (led by Jian-Wei Pan) demonstrated an advantage over classical computation in 2020, using the Gaussian Boson Sampling (GBS) scheme[1].

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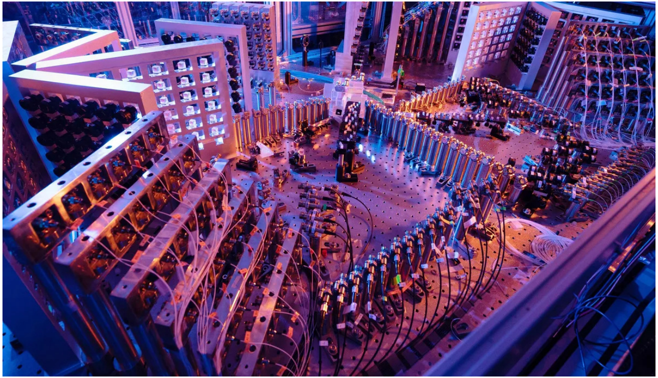

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Quantum advantage using photons

The Quantum Information Group of USTC in Hefei (led by Jian-Wei Pan) demonstrated an advantage over classical computation in 2020, using the Gaussian Boson Sampling (GBS) scheme[1].

However, GBS only uses linear optical quantum gates $\implies$ GBS is **non-universal**!

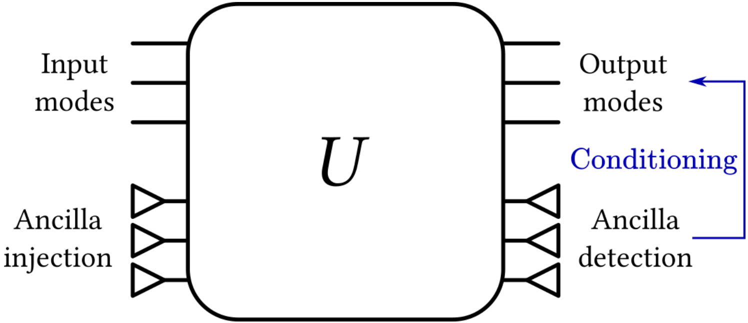
Difficult to implement non-linear (e.g., Kerr) gates in a photonic circuit $\implies$ We try to **avoid non-linear gates**.

Idea: include ancilla detections and postselection!

[1] H.-S. Zhong et al., *Quantum computational advantage using photons*, Science (2020)

Non-deterministic gates

Postselection is conditioning the output on the measurement result of ancilla modes.



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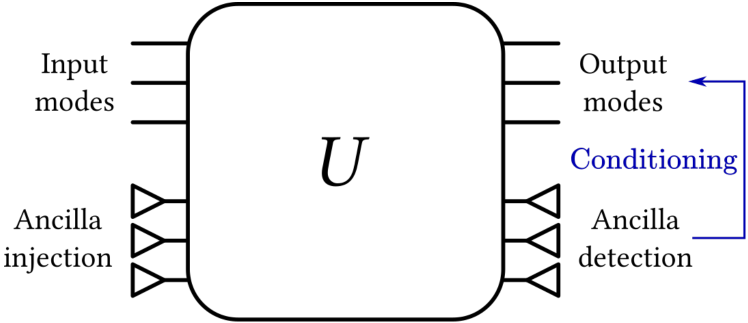

In our case, we use **particle number resolving detectors** (PNRDs).

Example: Nonlinear phaseshift (NS) gate

Goal: Implement the following gate[2]:

$$\mathrm{NS} : \alpha_0 |0\rangle + \alpha_1 |1\rangle + \alpha_2 |2\rangle \mapsto \alpha_0 |0\rangle + \alpha_1 |1\rangle - \alpha_2 |2\rangle \,. \tag{1}$$

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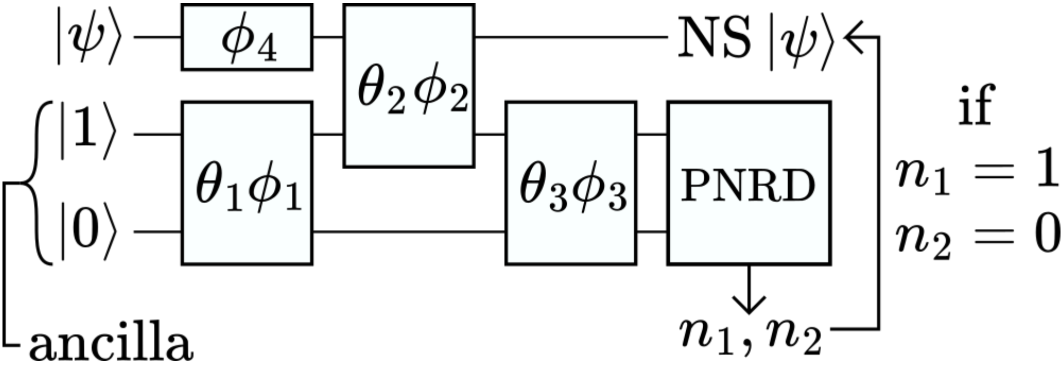

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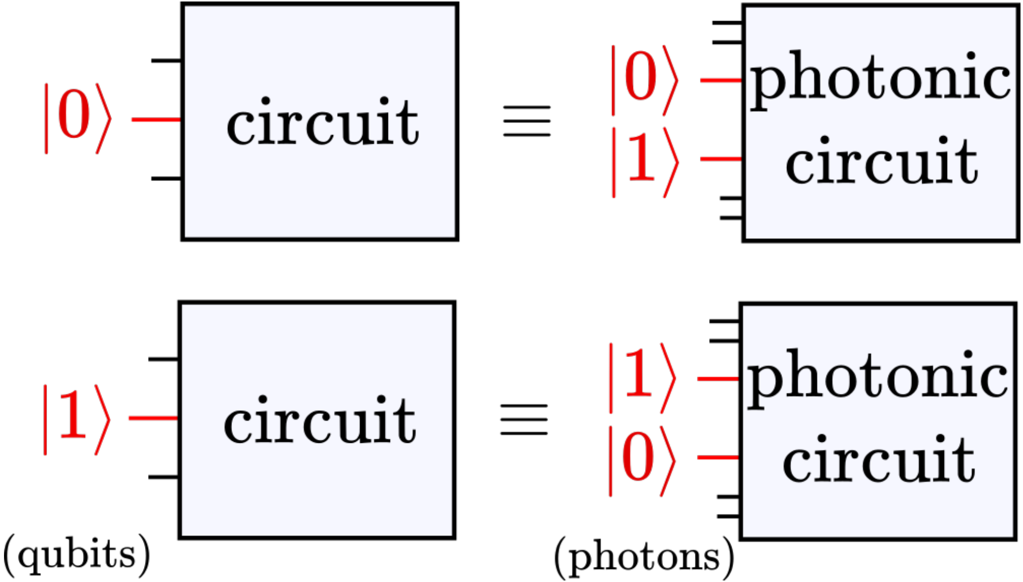
Dual-rail encoding



Conditional sign flip gate

Goal: Implement the following transformation[3]:

$$\text{CZ} : |{+}{+}\rangle_{\text{qubit}} \mapsto |\psi_*\rangle = \frac{1}{2}\left(|0,0\rangle + |1,0\rangle + |0,1\rangle - |1,1\rangle\right)_{\text{qubit}} \tag{2}$$

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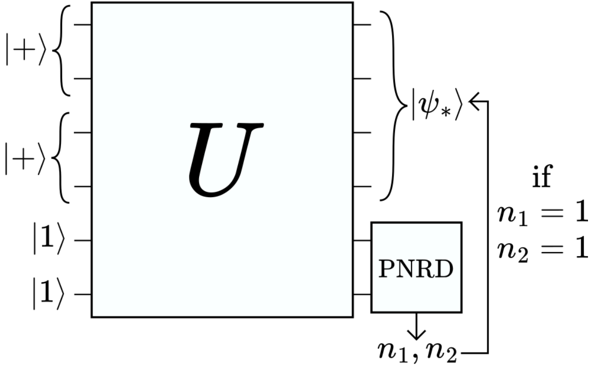

We can implement this by using a specific interferometer denoted by U!

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KLM protocol

The **KLM protocol** combines postselection and dual-rail encoding (+ gate teleportation).

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Problem: PNRDs are **biased** in practice $\implies$ incorrect state may be postselected after faulty postselection!

Detector efficiency matrix

The imperfections in the PNRD can be characterized by the **detector efficiency matrix**:

$$P_{m,n} := \mathbb{P}_{\text{readout}}(m|n). \tag{3}$$

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An example[4]:

$$P = \begin{pmatrix} 1.0 & 0.1050 & 0.0110 & 0.0012 & 0.001 \\ 0.0 & 0.8950 & 0.2452 & 0.0513 & 0.0097 \\ 0.0 & 0.0 & 0.7438 & 0.3770 & 0.1304 \\ 0.0 & 0.0 & 0.0 & 0.5706 & 0.4585 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.4013 \end{pmatrix}. \tag{4}$$

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This will introduce an error in the nondeterministic gates!

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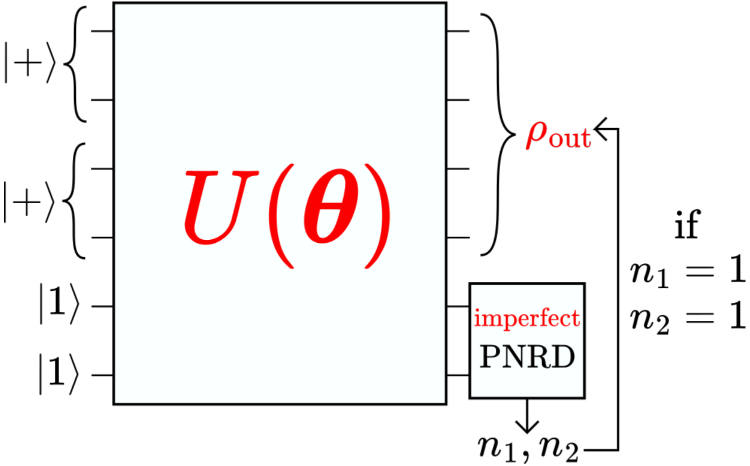
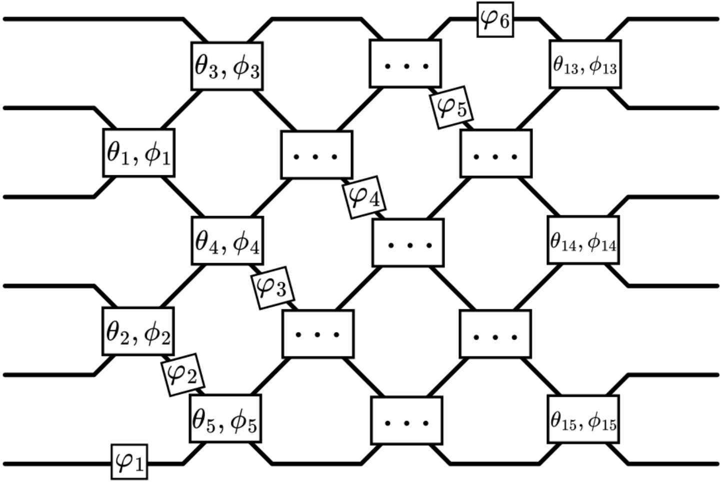
Idea: adjust interferometer!

Changing the $\boldsymbol{\theta}$ angles in the interferometer can increase the output state fidelity or the success probability of nondeterministic gates with imperfect PNRDs!



Parametrizing the interferometer[5]

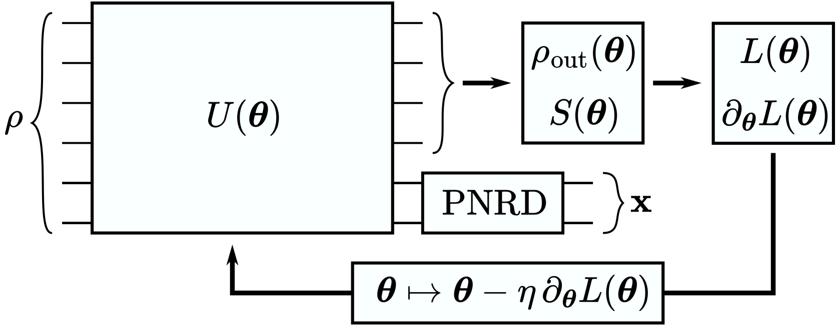
$$U(\boldsymbol{\theta}) \equiv$$



$$(\boldsymbol{\theta} = \{\theta_i, \phi_i, \varphi_i\}_i)$$

[5]W. R. Clements et al., *An Optimal Design for Universal Multiport Interferometers*, Optica (2016), arXiv:1603.08788

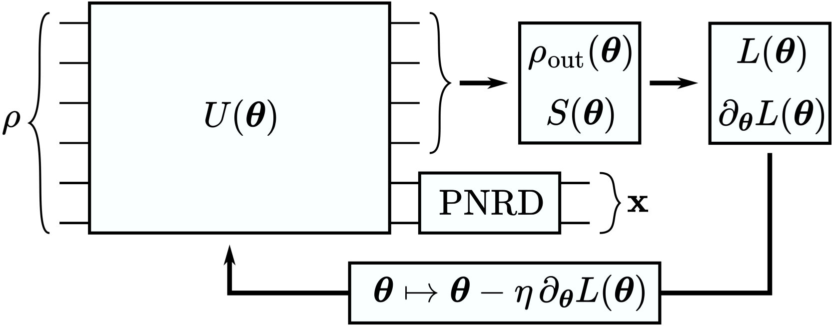
Gradient-based optimization



$$\rho_{\text{out}}(\boldsymbol{\theta}) := \frac{1}{S(\boldsymbol{\theta})} \sum_{\mathbf{n}} \mathbb{P}(\mathbf{x}|\mathbf{n})\, \mathrm{tr}_2 \left\{ U(\boldsymbol{\theta}) \rho U^{\dagger}(\boldsymbol{\theta}) \left(I \otimes |\mathbf{n}\rangle \langle \mathbf{n}| \right) \right\} \qquad \textbf{(Final state)}$$

$$S(\boldsymbol{\theta}) := \sum_{\mathbf{n}} \mathbb{P}(\mathbf{x}|\mathbf{n})\, \mathrm{tr} \left\{ U(\boldsymbol{\theta}) \rho U^{\dagger}(\boldsymbol{\theta}) \left(I \otimes |\mathbf{n}\rangle \langle \mathbf{n}| \right) \right\} \qquad \textbf{(Success rate)}$$

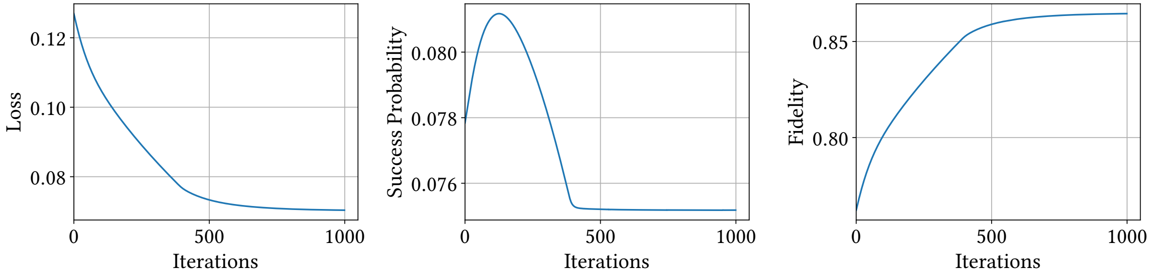
Gradient-based optimization



$$L(\boldsymbol{\theta}) := 1 - \sqrt{\langle \psi^* |\, \rho_{\text{out}}(\boldsymbol{\theta})\, | \psi^* \rangle} + \alpha\, \text{softplus}_\beta(S^* - S(\boldsymbol{\theta})) \qquad (S^* = \textbf{ Target success rate})$$

$$\text{softplus}_\beta(x) := \frac{1}{\beta} \log(\exp(\beta x) + 1) \tag{5}$$

Optimization of conditional phase shift gate with imperfect PNRDs[7]

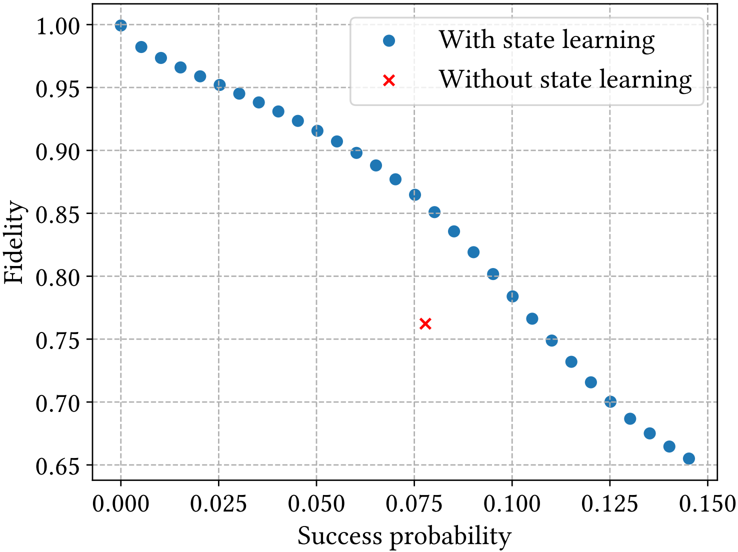


The simulations were executed using Piquasso[6].

[6] ZK et al., *Piquasso: A Photonic Quantum Computer Simulation Software Platform*, arXiv:2403.04006 (2024)

[7] In this example, with target success rate $S^* = 0.075$, code available at `https://github.com/Budapest-Quantum-Computing-Group/supressing-loqc-pd-errors`

Tradeoff between fidelity and success rate



Thank you for your attention!

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