Optimal Control for Entangling Quantum Gates

Michael Goerz

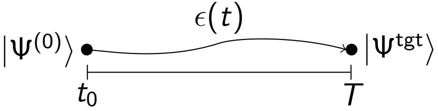
Stanford/Army Research Lab

UMBC Physics Colloquium
April 19, 2017

the quantum optimal control problem

quantum technology

steer quantum system in some desired way



$\epsilon(t)$: control field

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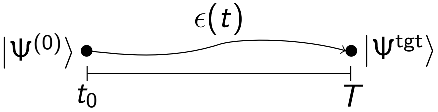
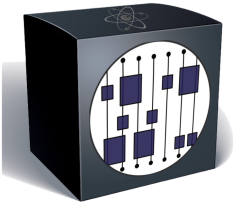


$\epsilon(t)$: control field

examples:

- **photo-chemistry:** form atomic bonds
- **medical imaging:** orient nuclear spin for max resolution
- **quantum networks:** prepare non-classical states
- **quantum computing:** apply logical operation ("gate")
- ...

optimizing quantum gates



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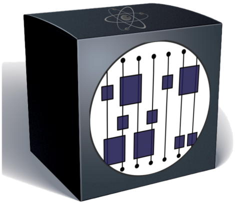

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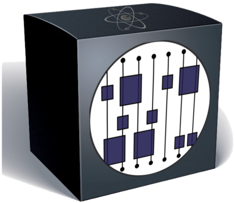

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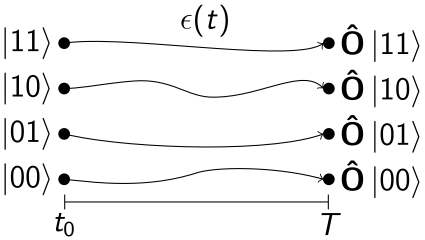
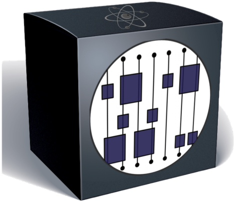


simultaneous targets (basis states)!

optimizing quantum gates



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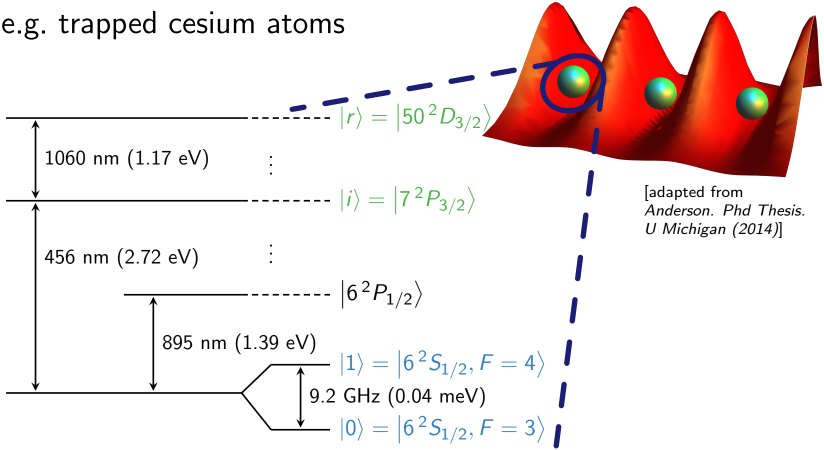
Implementations:

- trapped atoms
- superconducting circuits
- NV centers
- quantum dots
- ...

logical subspace

e.g. trapped cesium atoms



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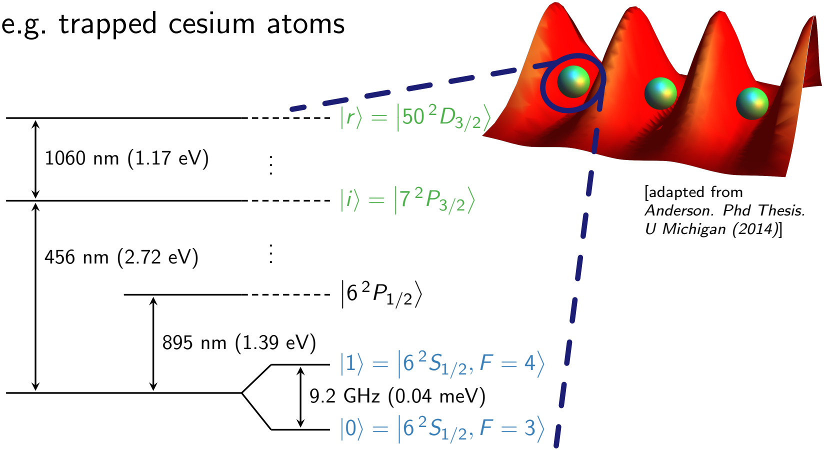

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logical subspace embedded in larger total Hilbert space!

numerical optimal control

analytical:

- geometric control – low dimension
- adiabatic schemes (e.g. STIRAP) – slow
- open quantum systems? noise? fundamental limits?

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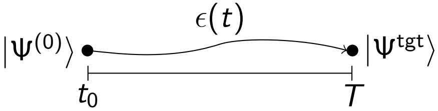

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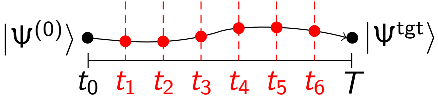

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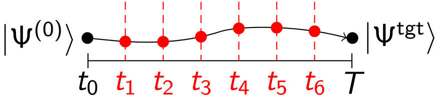

minimize functional J_T

e.g. $J_T = 1 - \frac{1}{d^2} \sum_{k=1}^{d} \left| \left\langle \Psi_k^{\text{tgt}} \,\middle|\, \Psi_k(T) \right\rangle \right|^2$

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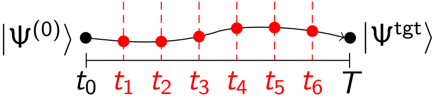

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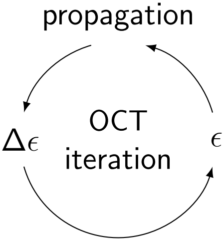
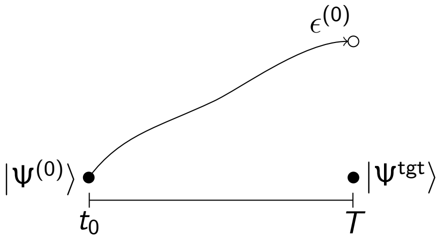
$\Rightarrow$ iterative scheme



Optimization Methods

gradient-free optimization



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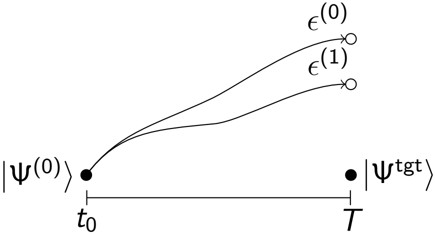

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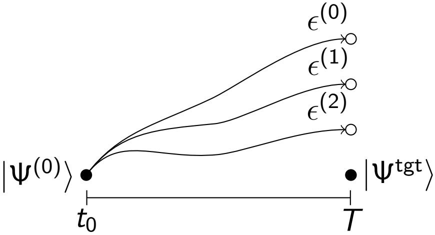

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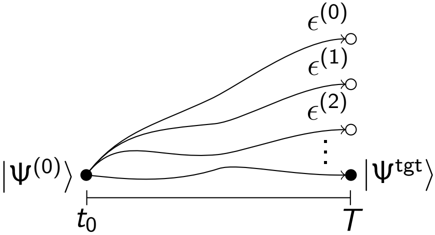

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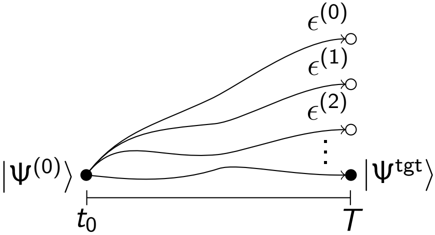

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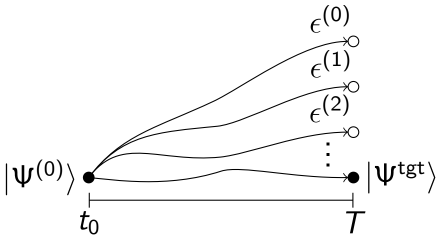

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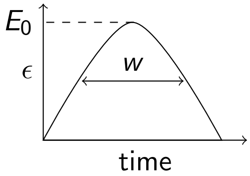

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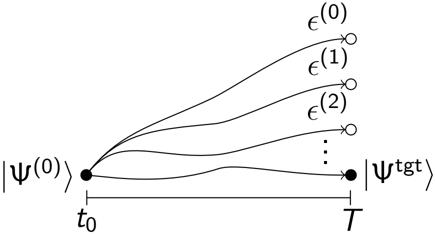

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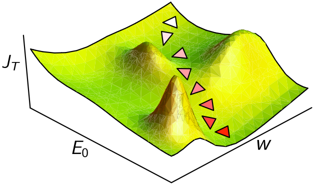
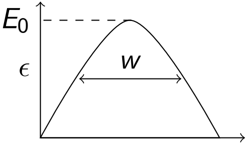
Nelder-Mead simplex:





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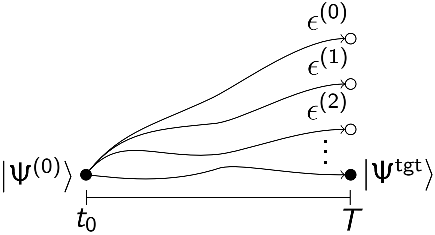

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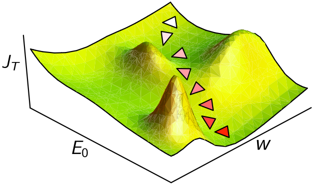

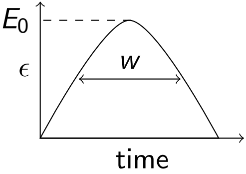

easy to use: `scipy.optimize`, Matlab, ...

GRAPE/LBFGS

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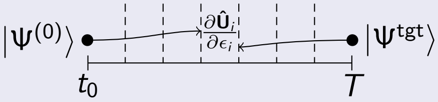

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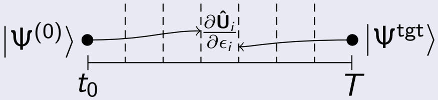

Khaneja et al. J. Magnet. Res. 172, 296 (2005)

library implementation: L-BFGS-B

Krotov's method

- variational calculus, for *continuous* $\epsilon(t)$

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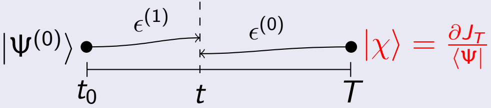

Reich et al. J. Chem. Phys. 136, 104103 (2012)

Krotov's method vs GRAPE

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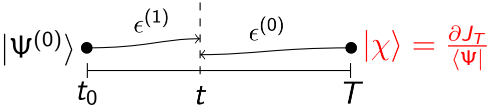

- sequential update
- continuous → discrete
- guaranteed monotonic convergence
- J_T only in boundary condition

GRAPE

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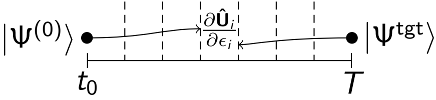

- concurrent update
- inherently discrete
- parametrization through chain rule

Applications

the quantum speed limit

- progressively decrease gate duration

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- QSL is reached when objective can no longer be reached

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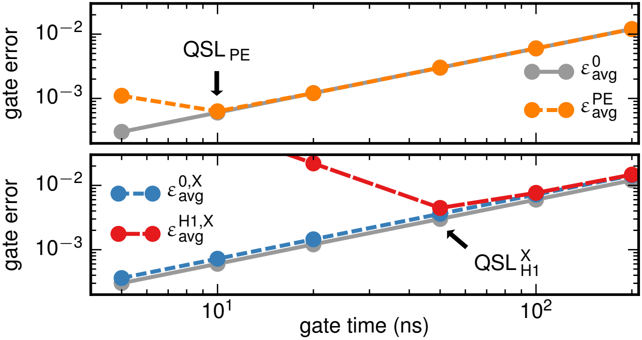
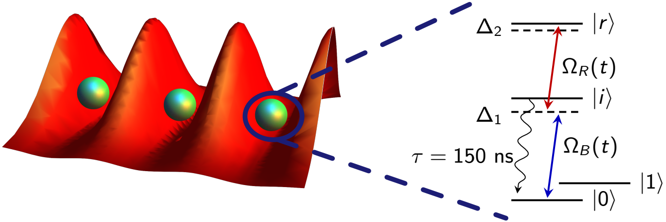
example: optimization of entangling and local gates
in superconducting transmon qubits



Goerz et al. arXiv:1606.08825 (2017)

robustness to classical fluctuations



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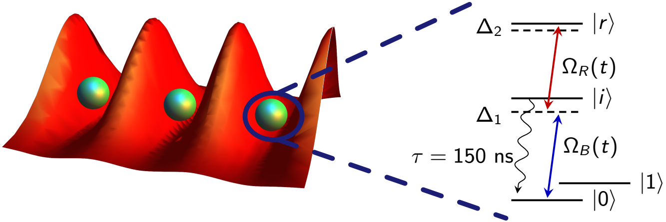

noise sources: fluctuation of Rydberg level, field amplitude

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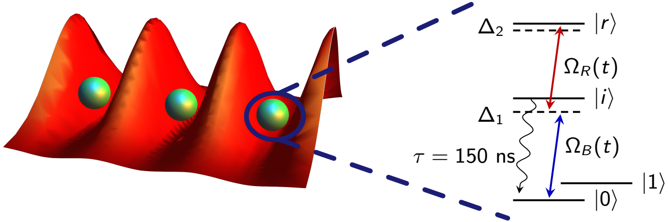

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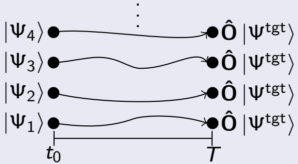
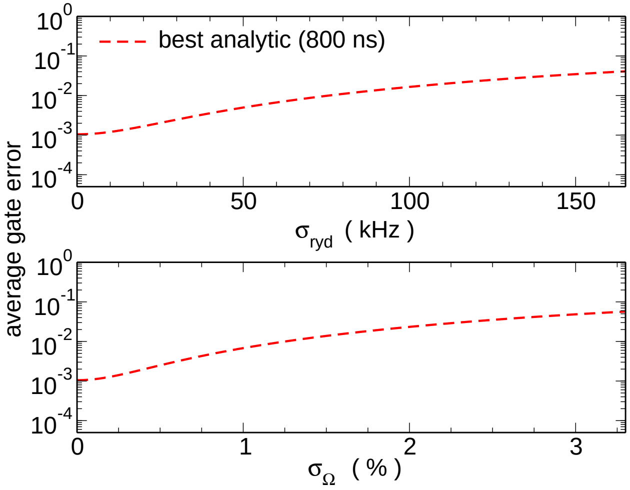
ensemble optimization

simultaneously optimize over multiple copies of the system with different noise realizations



robustness Rydberg gates



⇒ Goerz, Halperin, Aytac, Koch, Whaley. PRA 90, 032329 (2014)

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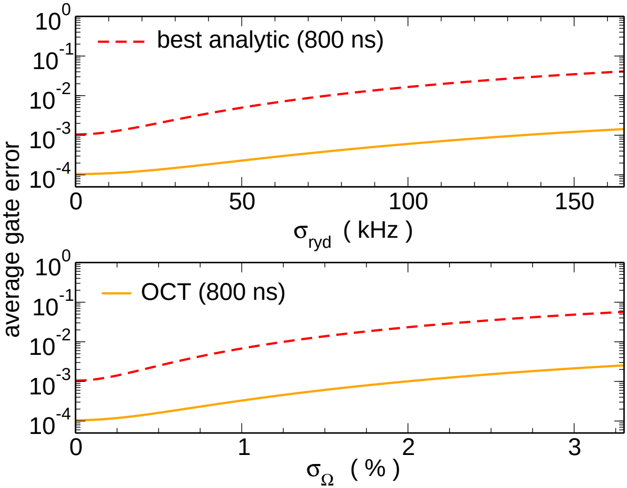

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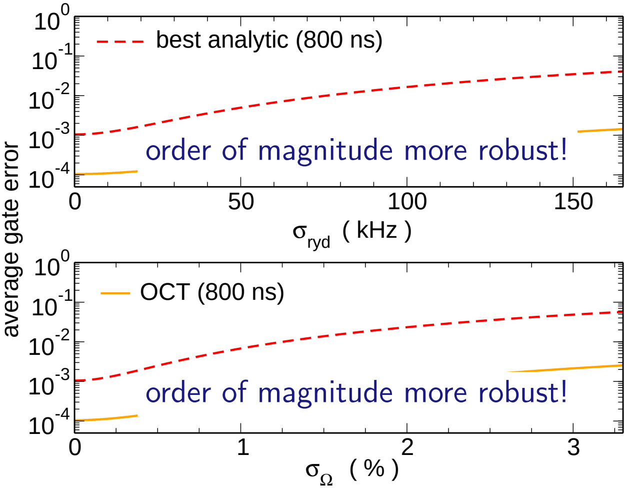

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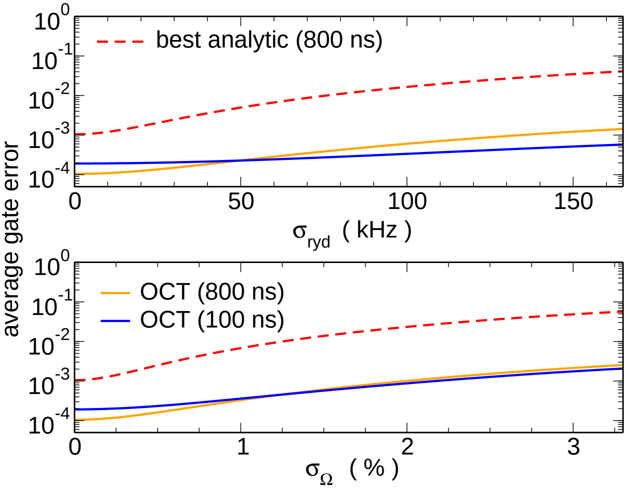

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robustness to dissipation

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$$\underbrace{\hat{\rho}_1 = \frac{1}{20}\begin{pmatrix} 8 & 0 & 0 & 0 \\ 0 & 6 & 0 & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 2 \end{pmatrix}}_{\text{populations}}, \quad \underbrace{\hat{\rho}_2 = \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix}}_{\text{phases}}, \quad \underbrace{\hat{\rho}_3 = \frac{1}{4}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{subspace}}$$

$\Rightarrow$ Goerz, Reich, Koch. NJP 16, 055012 (2014).

always 3 states, independent of dimension!

robustness to dissipation

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populations | phases | subspace

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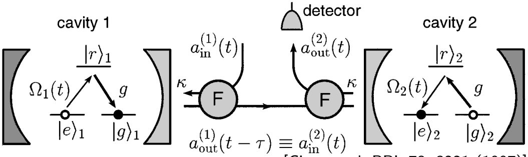
Alternative: MCWF trajectories

trajectory optimization



[Cirac et al, PRL 78, 3221 (1997)]

$$\hat{\mathbf{H}} = \hat{\mathbf{H}}_1 + \hat{\mathbf{H}}_2 + i\kappa(\hat{\mathbf{a}}_1^\dagger \hat{\mathbf{a}}_2 - \hat{\mathbf{a}}_1 \hat{\mathbf{a}}_2^\dagger)\,, \quad \hat{\mathbf{L}} = \sqrt{2\kappa}(\hat{\mathbf{a}}_1 + \hat{\mathbf{a}}_2)$$

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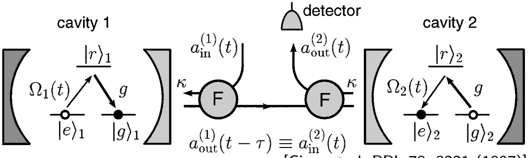

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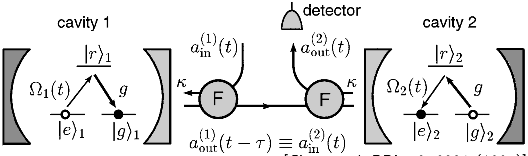

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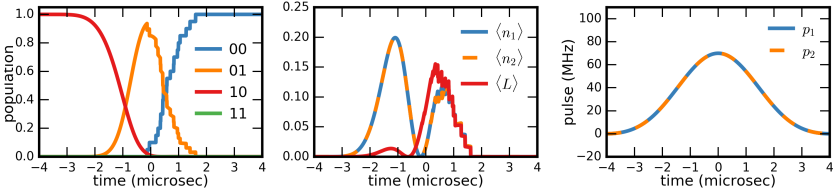

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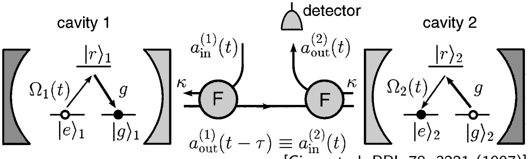

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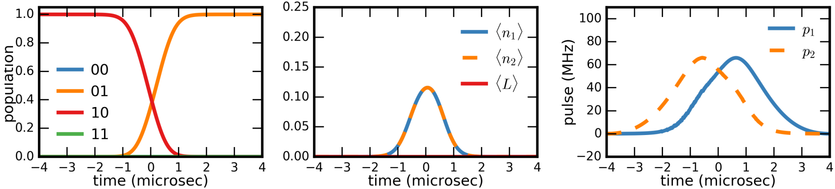

optimization in the Weyl chamber

- for two-qubit gates: many quantum gates are useful

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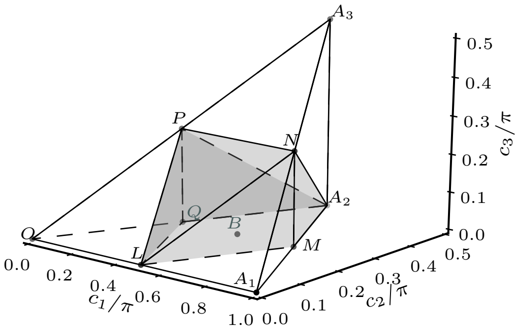

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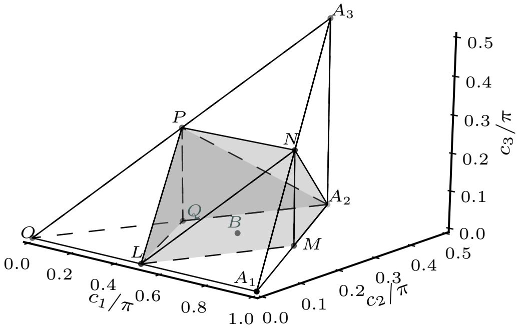
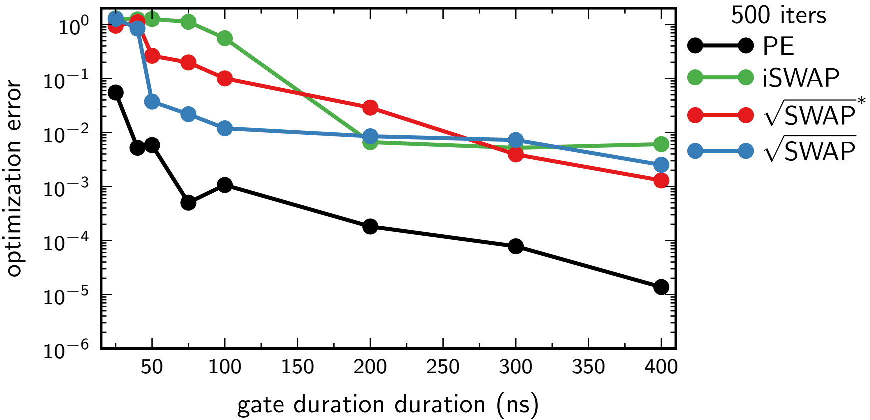


- optimize for arbitrary perfect entangler

optimization for a perfect entangler

PE optimization for superconducting transmon qubits



⇒ Goerz et al. Phys. Rev. A 91, 062307 (2015)

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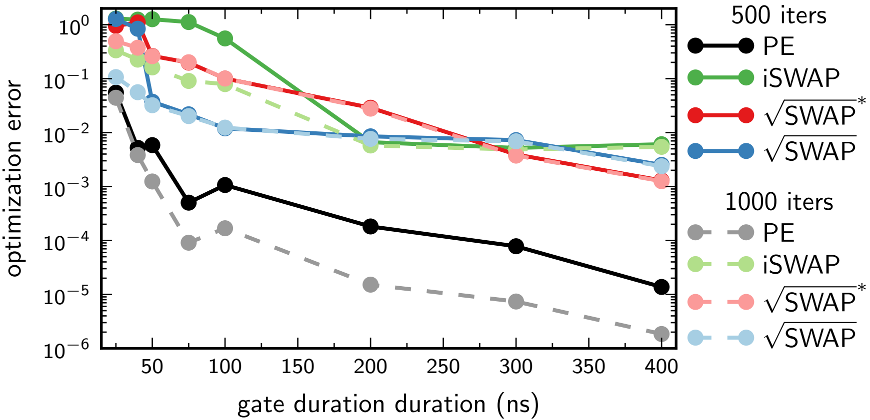

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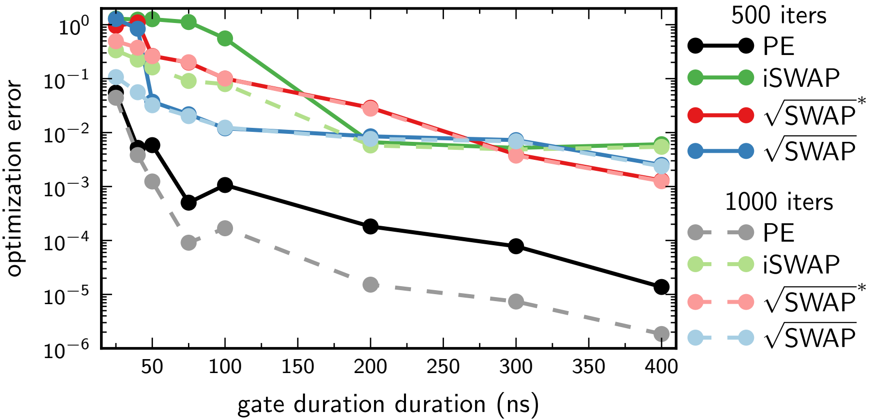

much lower errors and much better convergence $\Rightarrow$ faster gates

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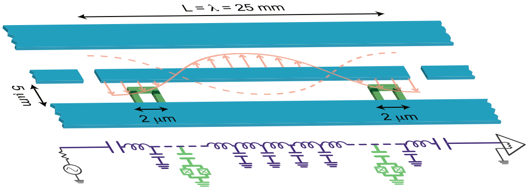
design landscape exploration

two transmon qubits with shared transmission line



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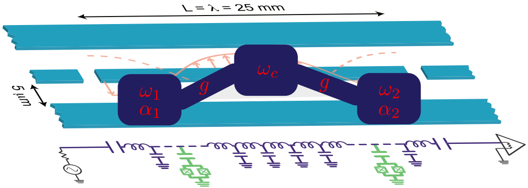

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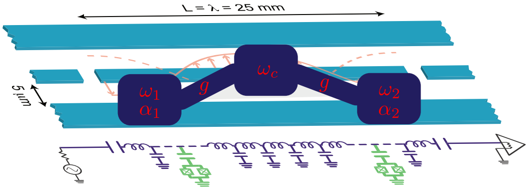

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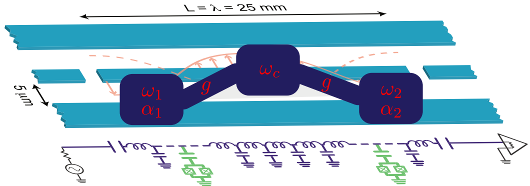

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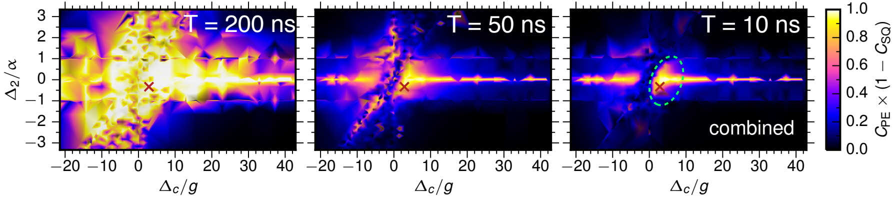

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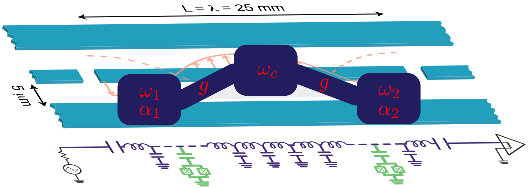

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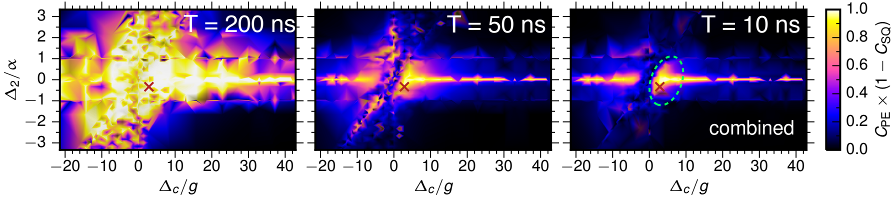

Identification of new QuaDiSQ regime

$\Rightarrow$ Goerz et al. arXiv:1606.08825 (2016).

hybrid optimization schemes

combine gradient-free and gradient-based optimization in multiple stages

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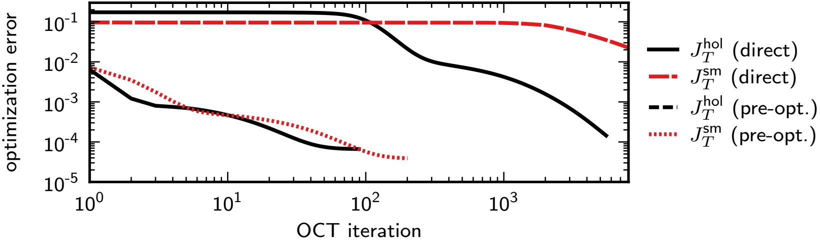

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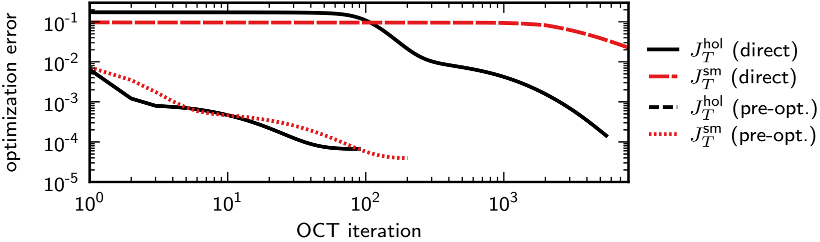

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Bridging the gap to experiment:
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QDYN
quantum dynamics and control
www.qnet-library.net

QNET
github.com/mabuchilab/QNET

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Thank you!