Solving k-SAT on quantum machines

Alain Sarlette — QUANTIC — inria Paris

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Outline

I. Optimization / classical problem

II. Quantum annealing methods

III. Harnessing quantum dissipation

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I. Optimization / classical problem

k-SAT : computational approach

II. Quantum annealing methods

standard quantum annealing

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new quantum annealing

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quantum Zeno dragging

Tutorial

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Main result

k-SAT combinatorial optimization paradigm

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$$F(x) = (x_1 \text{ or } x_2 \text{ or } x_3) \text{ and}$$
$$(\overline{x}_1 \text{ or } x_4 \text{ or } x_5) \text{ and}$$
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Example: yes, take e.g.
$x_1=x_2=\text{false}$
$x_3=\text{true}$

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NP – complete : Hard to solve for some instances $(\sim 2^{\alpha n})$

Equivalent to whole class of (practical) problems

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(best current guarantee)

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- **backtracking trees:** Grover-inspired quantum walk procedure → $\mathrm{T}_{new} \sim \sqrt{T}$

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k-SAT cost functions could have more **structure**

e.g. $\mathrm{G(x)}$ = number of unsatisfied clauses

Open question: quantum algebraic acceleration exploiting this?

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Hidden in this procedure: rising cost of uncomputing

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The Quantum Annealing method

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   where $H(t)$ slowly varies from H_1 to H_0 ;
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Adiabatic propagation theorem:

$|\psi(t)>$ remains guaranteed close to the ground state of $H(t)$ if

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→ runtime $T \sim \|H'\| / \Delta^2$

H_1 induces avoided crossings

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  ! moreover, building this $G(x)$ from local interactions may be hard

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  ! also more natural implementation, local couplings

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- Gap amplification (details later): 1 ancilla level per clause gives $\Delta_{new} \sim \sqrt{\Delta_{old}}$ but now with only guarantee $T \sim \frac{1}{\Delta_{new}^2} \sim 1/\Delta_{old}$

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A different take on H(t) in Quantum Annealing

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H(0) : trivial Hamiltonian,
highly degenerate

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{ $|x(0)> = |{+}{+}\ldots{+}>$ for all x }

$|x(s)> = \cos(s\pi/4)\ |+> \pm \sin(s\pi/4)\ |->$

on each qubit

$|0_{logic}>$

$|1_{logic}>$

almost degenerate for $s \ll 1$

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Start analysis of $|\psi(t)>$ by jumping (= quenching) to $s_1 \ll 1$

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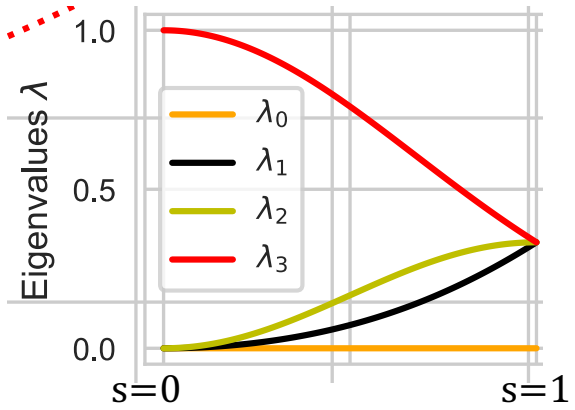

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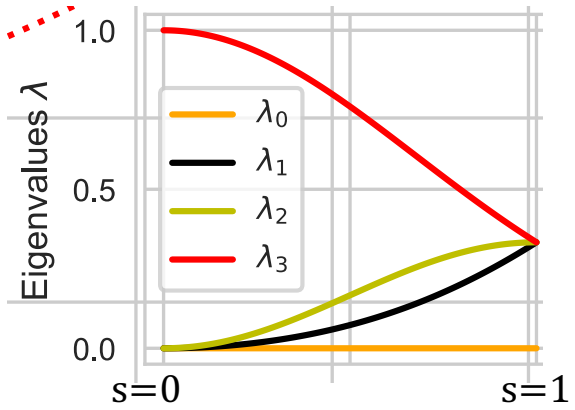

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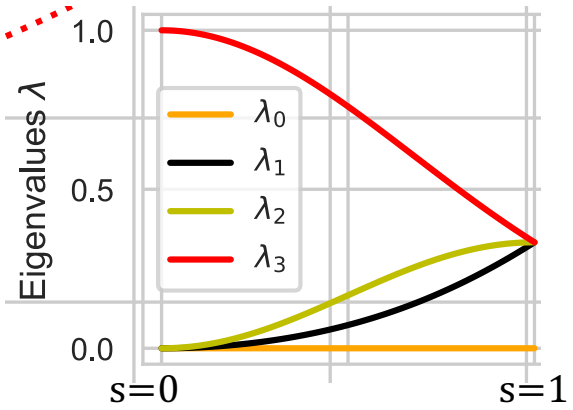
  $= |$ <011 … 101 $_{\text{logic}}(s_1) \,|$ --…-> $|$ $\sim \cos(s_1)^n$

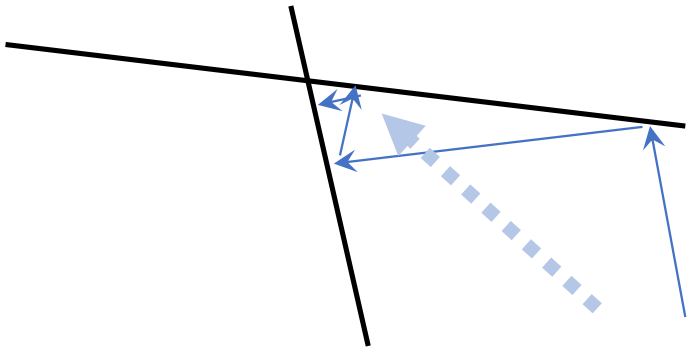
Runtime T follows this tradeoff in the choice of s_1

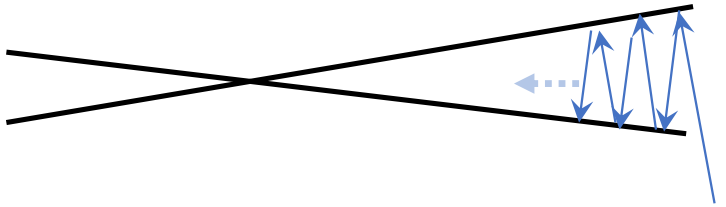


(weak) relation to alternated projections method

To find intersection between subspaces: project alternatively onto each

- Almost parallel subspaces imply slow convergence





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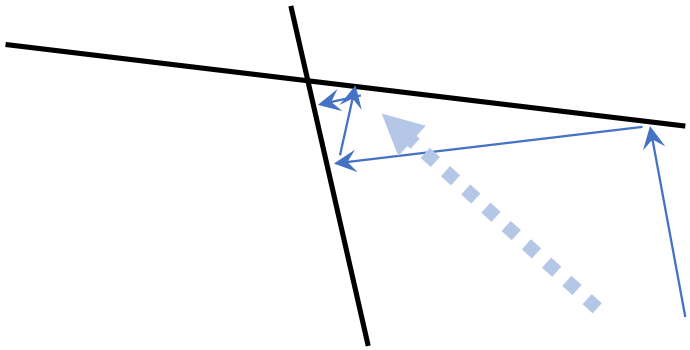
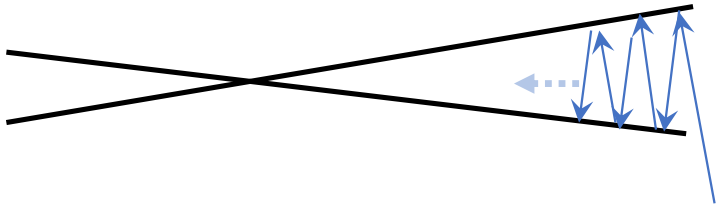
- Here, track slowly opening intersection, until it encodes k-SAT solution

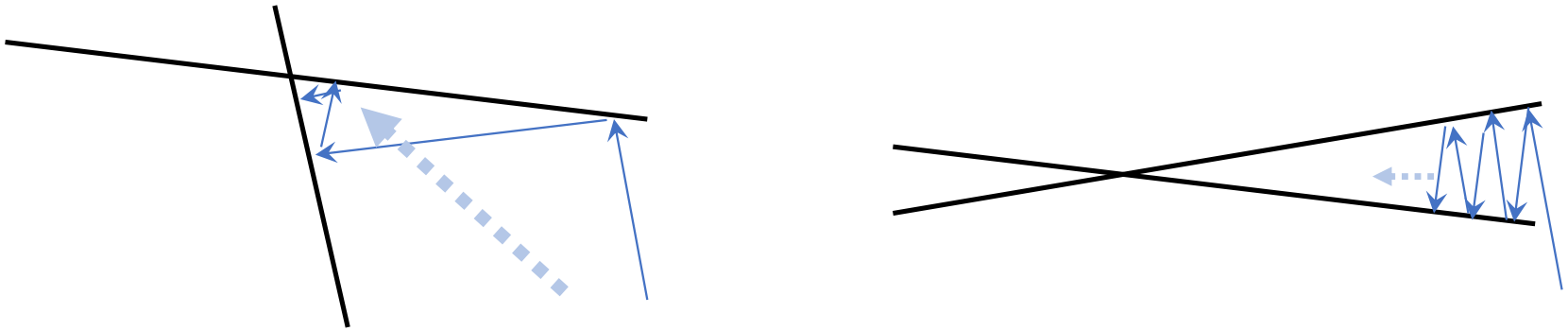




(weak) relation to alternated projections method

Detectability Lemma: Let $P_1, P_2, \ldots, P_m$ quasi-local with $\leq g$ pairwise overlaps

then $\| \prod_k (I - P_k) |\psi_\perp\rangle \|^2 \leq 1 / (1 + \Delta/g^2)$



Recap: k-SAT annealing with t-dependent basis

$$|x(t)> = \cos(s_t\,\pi/4)\,|+> \pm \sin(s_t\,\pi/4)\,|->$$ on each qubit

true

false

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- **Initial loss of fidelity**: sub-exponential with $t_1 \sim 1/\sqrt{n}$
- **With gap amplification**: runtime $T \sim 1/\sqrt{\Delta(s_1)}^2 \sim 1/\Delta(s_1)$
- **Bound on $\Delta(s_1)$**: still work in progress…

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= measure in slowly varying basis (quantum Zeno effect)

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fast in random order

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Equivalent Lindbladian:

$$\frac{d}{dt}\rho = \frac{1}{\mathrm{m}} \sum_{\mathrm{m}} \mathrm{P}_{\mathrm{m}}\, \rho\, \mathrm{P}_{\mathrm{m}} - \frac{1}{2}\mathrm{P}_{\mathrm{m}}\, \rho - \frac{1}{2}\, \rho\, \mathrm{P}_{\mathrm{m}}$$

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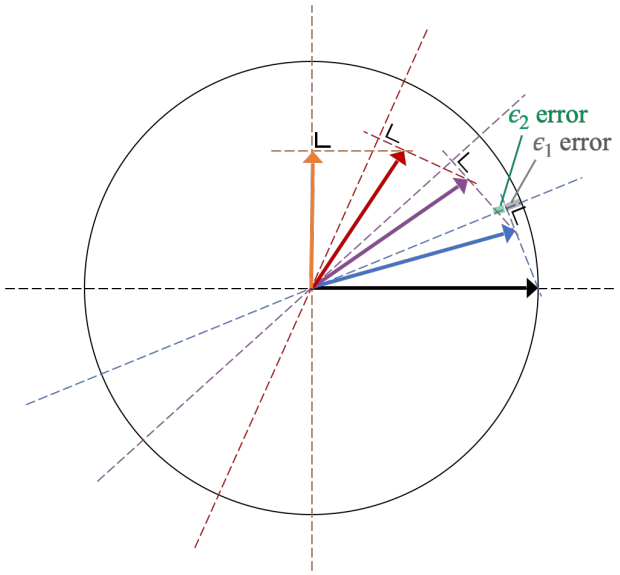
  - incomplete projection onto basis



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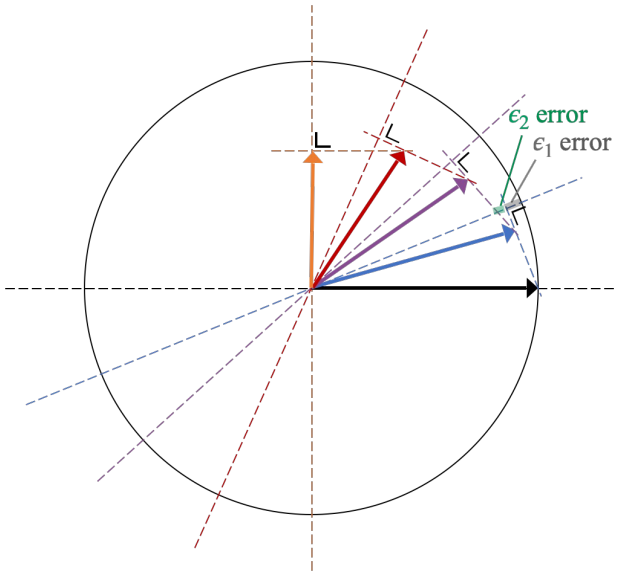
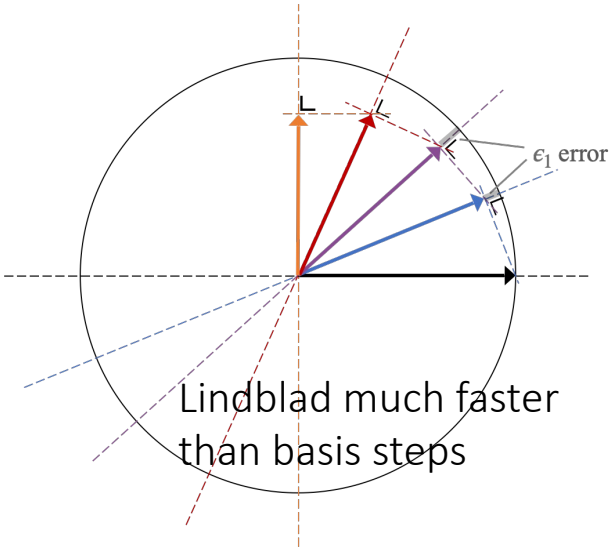
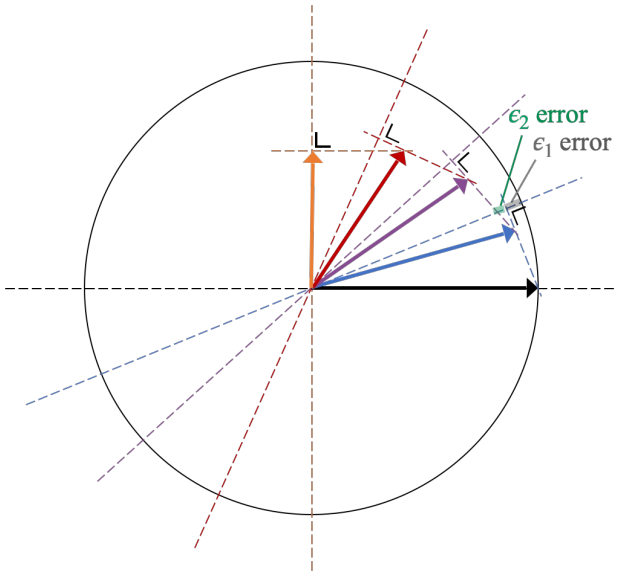
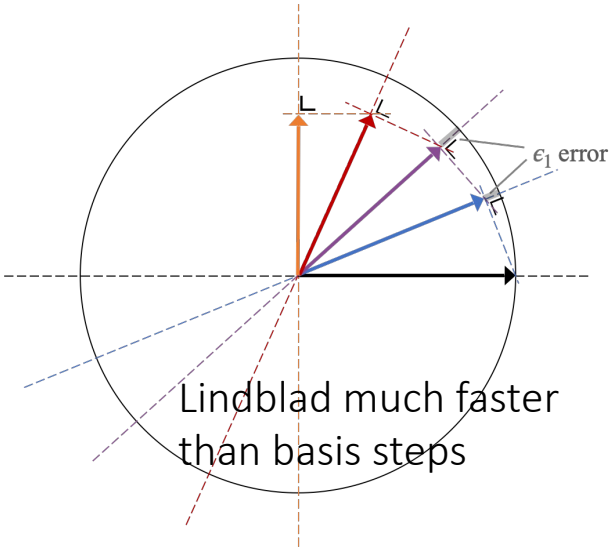


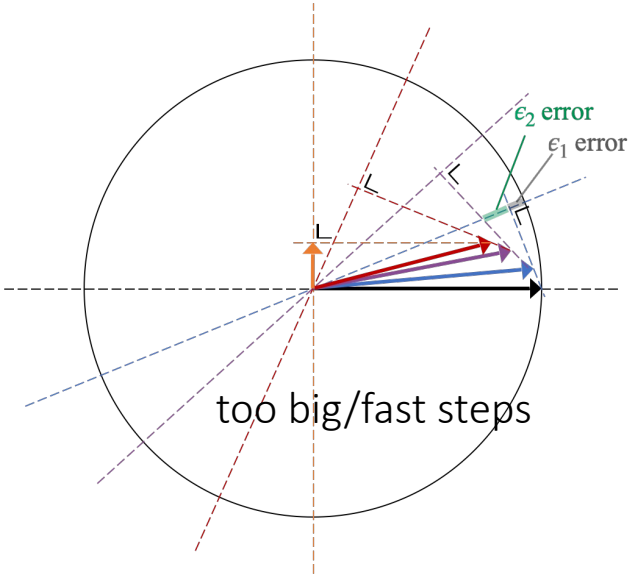


Straightforward analysis with discrete steps $\mathbf{x(t)}$

- Two types of error: - fidelity between old and new basis
  - incomplete projection onto basis



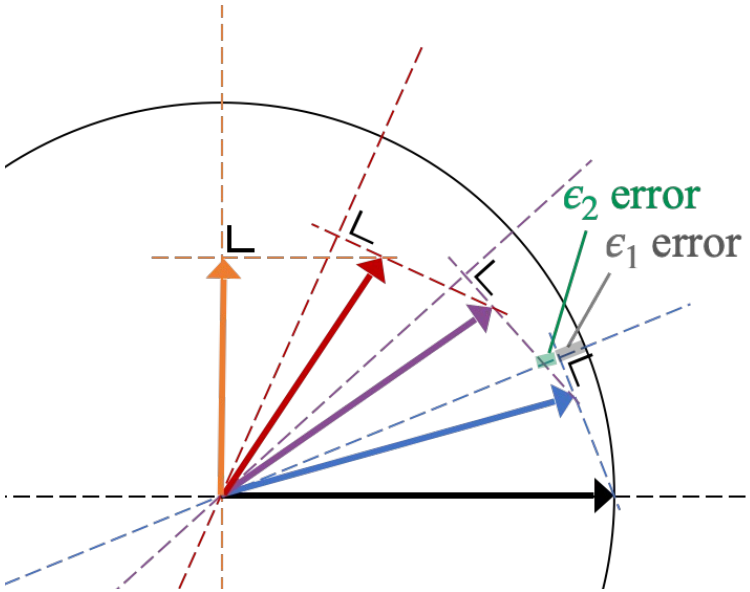




Bottleneck: still spectral gap of H_0

Lindbladian convergence properties at fixed x(s) :

- Fidelity to solution space = constant



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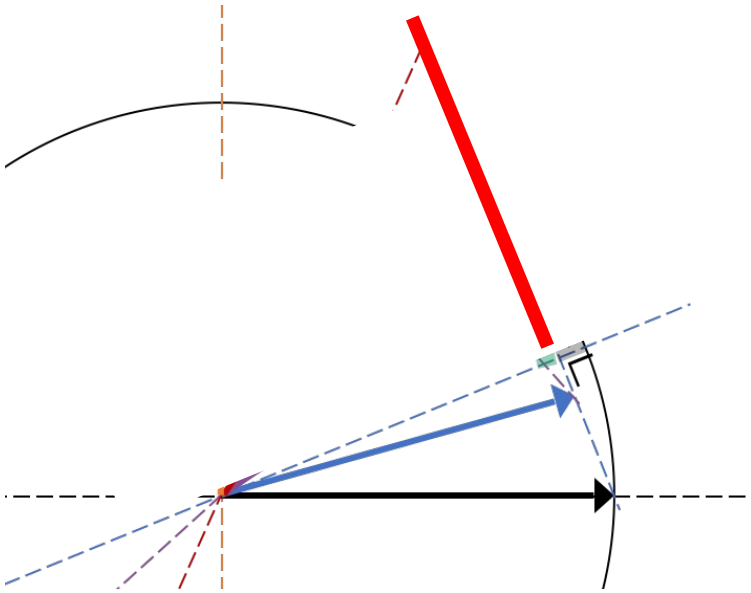

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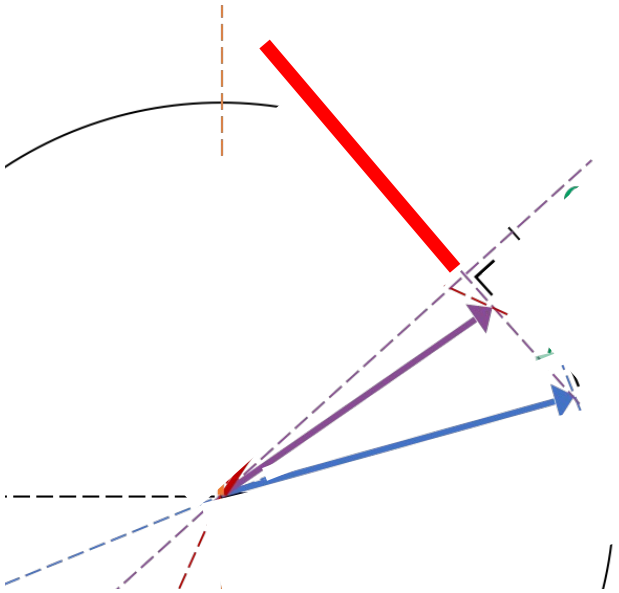

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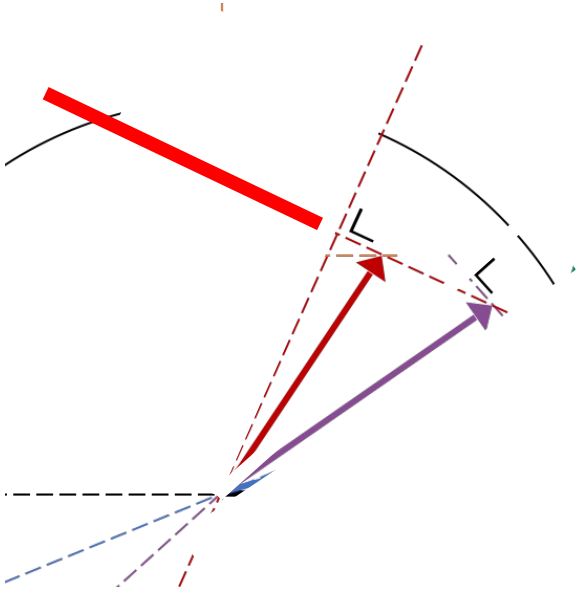

Bottleneck: still spectral gap of H_0

Lindbladian convergence properties at fixed $x(s)$:

- Fidelity to solution space = constant
- Task = suppress coherences {solution} vs. {orthogonal Hilbert subspace}

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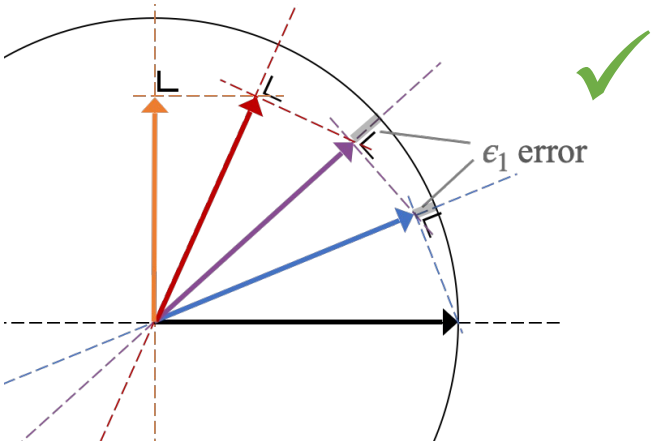

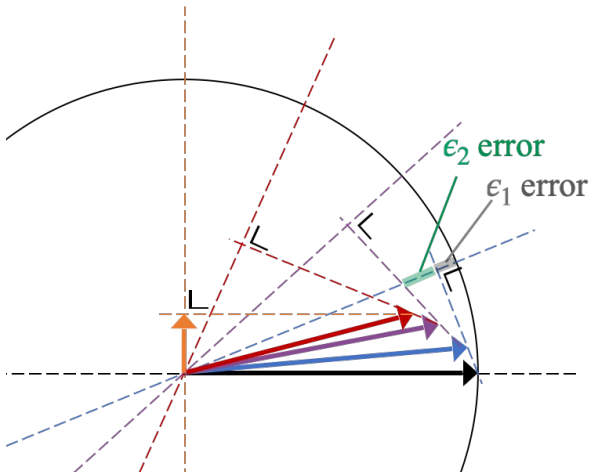

Bottleneck: still spectral gap of H_0

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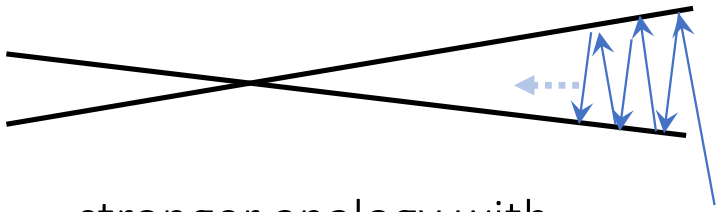
!! decay rate = $\Delta(s_1)$ of H_0



stronger analogy with
alternated projections method

Bottleneck: still spectral gap of H_0

Lindbladian convergence properties at fixed $x(s)$:

- Fidelity to solution space = constant
- Task = suppress coherences {solution} vs. {orthogonal Hilbert subspace}

!! decay rate = $\Delta(s_1)$ of H_0

runtime $T \sim 1/\Delta(t_1)$

« As fast as amplified annealing, but with simpler **open quantum system** »

Outline

I. Optimization / classical problem

II. Quantum annealing methods

Tutorial

New developments

III. Harnessing quantum dissipation

quantum Zeno dragging

[Last part of the talk still unpublished — end of public slides]

Future work

- Spectral gap: estimation per k-SAT instance
  is just a bound: go beyond (with Artem Mamichev)

- Clause-by-clause scheduling

- Introducing feedback: algorithmic (e.g. Schoening)
  for Quantum Error Correction / Fault-tolerance

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