

# State Synthesis Using PRS.

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## Abstract

We studies the complexity of synthesis quantum states using PRS, our reasch continues the work by [Ira+22], [Ros23], [RY21], [MY23], [Del+23].

## 1 Pseudorandomness.

**Definition 1.1** (Pseudorandom Quantum states). *Let  $\mathcal{H}, \mathcal{K}$  be the Hilbert and the key spaces, their diminsions depeand on a security paramter  $n$ . A state famliiy  $\{|\psi_k\rangle\}_{k \in \mathcal{K}}$  is a pseudiorandom, if the following hold:*

1. *Efficient generation. There is a polynomial-time quantum algorithm  $G$  that generates state  $|\psi_k\rangle$  on input  $k$ .*
2. *Pseudorandomness. Any polynomially many copies of  $|\phi_k\rangle$  with the same random  $k \in K$  is computationally indistinguishable from the same number of copies of the Haar random state.*

**Definition 1.2** (Pseudorandom Unitary Operators). *A famliiy of unitary operators  $\{U_k \in U(\mathcal{H})\}_{k \in \mathcal{K}}$  is pseudorandom, if two conditions hold:*

1. *Efficient computation. There is an efficient quantum algorithm  $Q$ , such that for all  $k$  and any  $|\psi\rangle \in \mathcal{H}$   $Q(k, |\psi\rangle) = U_k |\psi\rangle$ .*
2. *Pseudorandomness. The uniform random distribution on  $U_k$  is computationally in distinguishable from a Haar random unitary operator.*

**Definition 1.3** (The keeping setting). *Let  $R^A \otimes R^B$  be a general two registers domain. We define the **keeping setting** to let one construct quntum/classical circuits<sup>1</sup>  $G : R^A \otimes R^B \rightarrow R^A \otimes R^B$  such that it is gurnted that the register  $R^B$  can't be accsed after the computation.*

**Claim 1.1.** *Let  $G$  be a PRS generator, than under the the keeping setting one can assume that  $G$  takes as input two register, the first contains  $n$  ancille qubits initiliaized to  $|0\rangle$  and the seconed contain a classic string initiliezied to be the seed  $k$ .*

*Proof.* Given a PRS  $G : R^A \rightarrow R^A$  define  $\tilde{G} : R^A \otimes R^B \rightarrow R^A \otimes R^B$  as follow, first  $\tilde{G}$  copy the calscial state in  $R^B$  (the  $k$ -length seed) to  $R^A$  and then appaly  $G$  on  $R^A$ , Hence on sampled seed  $k \in R^B$  results the output  $|\psi_k\rangle \otimes |k\rangle$ . Under the keeping setting any polynomial distinguishier-canidate  $D$  has accses only for  $|\psi_k\rangle$ , So if  $D$  distinguish between the distrubition generated by  $\tilde{G}$  and the Haar measure then it also distinguish between  $G$  and Haar measure.  $\square$

**Claim 1.2.** *Let  $G : |0\rangle^n \otimes \mathbb{F}_2^k \rightarrow \{|\psi_k\rangle\}_{k \in \mathcal{K}}$  be a PRS generator uses  $n$ - ancilles and  $k$  classicl bits. Then for any unitery  $V : \mathcal{H}_n \rightarrow \mathcal{H}_n$  it holds that  $(V \otimes I^{\otimes k})G$  is also a PRS.*

*Proof.*  $\square$

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<sup>1</sup>On which we think as a canidate for PRS/PRF/PRG generator.

**Claim 1.3** (Levi's Lemma for PRS). *Let  $f : \mathcal{H} \rightarrow \mathbb{R}$  be a **BQP**-computable function on the  $n$ -qubits Hilbert space, and let  $g : (0, 1) \rightarrow \mathbb{R}$  be a function such that:*

$$\Pr_{|\psi\rangle \sim U} [f(|\psi\rangle) > \varepsilon] < g(\varepsilon)$$

*Then, a similar inequality also holds for states sampled by the PRS, when the probability for the measure  $f$ -value greater than  $\varepsilon$  is bounded by  $g(2\varepsilon)$ . Namely,*

$$\Pr_{|\psi\rangle \sim |\psi_k\rangle} [f(|\psi\rangle) > \varepsilon] < g(2\varepsilon)$$

*In particular, Levi's lemma has a version that captures concentration of states sampled by PRS generator, states the following: Assume there exists  $K$  such that for any  $|\psi\rangle, |\phi\rangle \in \mathcal{S}(\mathbb{C}^d)$   $|f(|\psi\rangle) - f(|\phi\rangle)| < K||\psi\rangle - |\phi\rangle|$ . Then there exists a universal constant  $C > 0$  such:*

$$\Pr_{|\psi\rangle \sim |\psi_k\rangle} [|f(|\psi\rangle) - \mathbf{E}_{|\phi\rangle \sim U} [f(|\phi\rangle)]| > \varepsilon] < \exp\left(-\frac{Cd}{K^2}4\varepsilon^2\right)$$

*Proof.* □

**Claim 1.4.** *Probabilistic counting argument and  $\varepsilon$ -net over PRS.*

**Claim 1.5.** *existence of  $\text{poly}(n)$  gates  $G_1, G_2, \dots$  such that, any  $G_i$  has a polynomial depth,  $\langle p(G_i) | \tau \rangle > a$  and  $\langle \tau^\perp | p(G_j) \rangle \langle p(G_i) | \tau^\perp \rangle < b$  for any  $i \neq j$ .*

*Proof.* □

**Claim 1.6.** *bla bla bla*

**Definition 1.4.**  $\varepsilon$ -biased test 2-degree for testing RPU/RPS.  $f(\langle x_j | G_s | \theta \rangle) = 1$  For example ask if  $\langle \psi_j, \tau^\perp \rangle \langle \tau^\perp | \psi_j \rangle$  what I can say about that quantity as polynomial?

## 2 What We Need for Synthesis.

**Definition 2.1** (Pseudorandom Unitary for Synthesis). *A family of unitary operators  $\{U_k \in U(\mathcal{H})\}_{k \in \mathcal{K}}$  is pseudorandom for synthesis, if two conditions hold:*

1. *Efficient computation.* There is an efficient quantum algorithm  $Q$ , such that for all  $k$  and any  $|\psi\rangle \in \mathcal{H}$   $Q(k, |\psi\rangle) = U_k |\psi\rangle$ .
2. *Pseudorandomness for synthesis.* Given a state  $|\tau\rangle$  and polynomial number of samples  $U_1, U_2, \dots, U_m$ . Then:

$$(a) \quad |\langle \Phi(\tau, U_k) | U_k \tau \rangle|^2 > a$$

$$(b) \quad |\langle \Phi(\tau, U_k) | U_k \tau^\perp \rangle \langle \tau^\perp | U_j^\dagger | \Phi(\tau, U_j) \rangle|^2 < b$$

*The uniform random distribution on  $U_k$  is computationally indistinguishable from a Haar random unitary operator.*

What about, Assume that  $U$  is a quantum circuit such that  $\log n$  qubits are initialized to some state and instead ancilla, we have noisy ancilla, can we show that circuit is equivalent to  $\log n$  circuit? That will enable us to prove a quantum version for Nisan Wigderson PRG ( $\text{BPP} = \text{P}$ ).

**Problem.** Let  $U$  be a quantum circuit which get  $\log n$  stable qubits and  $\text{poly}(n)$  more random qubits obtained from the random Haar measure, can we simulate the circuit in  $\log n$  time?

approximate the absolute value function, For example, you can consider the binomial expansion of  $\sqrt{1-y}$  on  $[0, 1]$ . Namely, setting  $y = 1 - x^2$ , we have  $|x| = \sqrt{1-y} = \sum_{m=0}^{\infty} \binom{1/2}{m} (-y)^m$ ,  $x \in [-1, 1]$ . That will allow me to bound the  $k$ -design.

Denote by  $q_d(x)$  the  $d$ -order approximation of  $|x|$ , Namely

$$q_d(x) = \sum_{m=0}^d \binom{1/2}{m} (-1)^m (1-x^2)^m$$

and as the series converges to any  $x \in (-1, 1)$  we have that  $|x| = q_d(x) + O(\binom{1/2}{d}(1-x^2)^d)$  which by the fact that  $1-x^2 \in (-1, 1)$  can be simplified to  $|x| = q_d(x) + O(\binom{1/2}{d}) = q_d(x) + O(1/d^{1+1/2})$ .

$$\begin{aligned} \mathbf{E}_{U \sim D} [(\langle \Phi(\tau, U) | \text{Re } U\tau \rangle)^2] &= \mathbf{E}_{U \sim D} \left[ \frac{1}{2^{n/2}} \sum_x (-1)^{\text{sign}(\text{Re} \langle x | U\tau \rangle)} \text{Re} \langle x | x \rangle \langle x | U\tau \rangle \right] \\ &= \mathbf{E}_{U \sim D} \left[ \frac{1}{2^{n/2}} \sum_x |\text{Re} \langle x | U\tau \rangle| \right] \\ &= \mathbf{E}_{U \sim D} \left[ \sum_x |\text{Re} \langle x | U\tau \rangle| / 2^{n/2} \right] \\ &\geq \mathbf{E}_{U \sim D} \left[ \sum_x q_d \left( |\text{Im} \langle x | U\tau \rangle| / 2^{n/2} \right) - \binom{1/2}{d} \left( \frac{|\text{Im} \langle x | U\tau \rangle|}{2^{n/2}} \right)^d \right] \\ &\geq \mathbf{E}_{U \sim \text{Haar}} \left[ \sum_x q_d \left( |\text{Im} \langle x | U\tau \rangle| / 2^{n/2} \right) - \binom{1/2}{d} \left( \frac{|\text{Im} \langle x | U\tau \rangle|}{2^{n/2}} \right)^d \right] - \delta \cdot 2^n \\ &\geq \mathbf{E}_{U \sim \text{Haar}} \left[ \sum_x |\text{Re} \langle x | U\tau \rangle| / 2^{n/2} - 2 \cdot \binom{1/2}{d} \left( \frac{|\text{Im} \langle x | U\tau \rangle|}{2^{n/2}} \right)^d \right] - \delta \cdot 2^n \\ &\sim \mathbf{E}_{U \sim \text{Haar}} \left[ \sum_x |\text{Re} \langle x | U\tau \rangle| / 2^{n/2} \right] - \delta \cdot 2^n \\ \mathbf{E}_{U, U_2 \sim D} [\langle \Phi(\tau, U) | U\tau^\perp \rangle \langle \tau^\perp U_2^\dagger | \Phi(\tau, U_2) \rangle] &= \end{aligned}$$

**Claim 2.1.** fix a state  $|\tau\rangle$ . Let  $U$  be a unitary sampled from  $k$ -design distribution  $D$  and denote by  $|s\rangle$  the vector which  $U$  sends  $|\tau\rangle$  to. Now, observe that  $U$  can be written as  $U = |s\rangle \langle \tau| + V$  when  $V$  act on space orthogonal to  $|\tau\rangle$  denote it by  $|\tau^\perp\rangle$ . Then the distribution over  $V$  is also a  $k$ -design relative to the Haar measure on  $|\tau^\perp\rangle$ .

*Proof.* □

**Definition 2.2.** Denote by

$$\begin{aligned} M(\tau, U)(x) &= \max \{ |\text{Re} \langle x | U\tau \rangle|, |\text{Im} \langle x | U\tau \rangle| \} \\ \bar{M}(\tau, U)(x) &= \min \{ |\text{Re} \langle x | U\tau \rangle|, |\text{Im} \langle x | U\tau \rangle| \} \end{aligned}$$

When it will be clear from the context we omit  $\tau, U$  and use only  $M(x), \bar{M}(x)$ .

$$|\langle \Phi(\tau, U) | U\phi \rangle|^2 = |\langle \Phi(\tau, U) | \text{Re } U\phi \rangle|^2 + |\langle \Phi(\tau, U) | \text{Im } U\phi \rangle|^2$$

$$\begin{aligned}
\langle \Phi(\tau, U_k) | MU_k \phi \rangle &= \sum_x (-1)^{\text{sign } M(\langle x | U \tau \rangle)} \frac{1}{2^{n/2}} \langle x | U \phi \rangle \\
&= \sum_{\tau, \phi \text{ agree on } x} \left| \frac{1}{2^{n/2}} M(\langle x | U \phi \rangle) \right| - \sum_{\tau, \phi \text{ disagree on } x} \left| \frac{1}{2^{n/2}} M(\langle x | U \phi \rangle) \right| \\
&\approx \sum_{\tau, \phi \text{ agree on } x} q_d \left( \frac{1}{2^{n/2}} \bar{M}(\langle x | U \phi \rangle) \right) - \sum_{\tau, \phi \text{ disagree on } x} q_d \left( \frac{1}{2^{n/2}} \bar{M}(\langle x | U \phi \rangle) \right) \pm 2^n \zeta_d \left( \frac{1}{2^{n/2}} \right)
\end{aligned}$$

noitce that we obtained a  $d$ -degree polinomial, denote it by  $T_\phi$ .

$$\begin{aligned}
|\langle \Phi(\tau, U) | MU \phi \rangle| &\approx q_{d'}(\langle \Phi(\tau, U) | U \phi \rangle) + \zeta_{d'}(\langle \Phi(\tau, U) | U \phi \rangle) \\
&\approx q_{d'}(\langle \Phi(\tau, U) | U \phi \rangle) + \zeta_{d'}(\langle \Phi(\tau, U) | U \phi \rangle) \\
&\approx q_{d'}(T_\phi) + \zeta_{d'}(T_\phi) \\
&\approx q_{d'}(T_\phi) + \zeta_{d'}(T_\phi)
\end{aligned}$$

Assume that our  $k$ -design collection is defined such that for any  $|\varphi\rangle$  it holds that:

$$\Pr_{U_1, U_2 \sim D} [\text{sign}(\text{Re} \langle x | U_1 \varphi \rangle) = \text{sign}(\text{Re} \langle x' | U_2 \varphi \rangle)] = \frac{1}{2}$$

**Claim 2.2.** *left  $f : N \rightarrow \{\pm\}$  then the set  $(-1)^{f(x)} |x\rangle \langle x| U$  is a  $k$ -design.*

*Proof.*

$$\begin{aligned}
\text{tr}(U' V'^{\dagger}) &= \text{tr} \left( (-1)^{f(x)} |x\rangle \langle x| U V^{\dagger} (-1)^{f(x)} |x\rangle \langle x| \right) \\
&= \text{tr} \left( (-1)^{f(y)} |y\rangle \langle y| (-1)^{f(x)} |x\rangle \langle x| U V^{\dagger} \right) = \text{tr}(U V^{\dagger})
\end{aligned}$$

So, we get that:

$$\begin{aligned}
\frac{1}{|X|^{t,2}} \sum_{U, V \in X'} |\text{tr}(U V^{\dagger})|^{2t} &= \frac{1}{|X|^2} \sum_{U, V \in X} |\text{tr}(U V^{\dagger})|^{2t} \\
&= \int |\text{tr}(U)|^{2t} dU
\end{aligned}$$

□

Ok the tactics is going to be the follow, we need the  $k$ -design property only for the first stage. When we want to show that  $|\Phi\rangle$  has an overlap with  $|\tau\rangle$  after that, we can give up on that assumption and by using  $f, g$  universal we can ensure a small overlapp between pair of diffenet  $U, V$ .

**Claim 2.3.** *Assume  $f$  above sampled from a universal family hash functions. Then we have that :*

$$\mathbf{E}_{U, V \sim X, f \sim \mathcal{H}} [|\langle \Phi(\tau, V) V^{\dagger} | \psi \rangle \langle \psi | U \Phi(\tau, U) \rangle|^2] \approx_{\delta} \mathbf{E}_{U, V \sim Haar} [|\langle \Phi(\tau, V) V^{\dagger} | \psi \rangle \langle \psi | U \Phi(\tau, U) \rangle|^2]$$

*Proof.*

$$\begin{aligned}
\langle \Phi(\tau, V) V^{\dagger} | \psi \rangle &= \frac{1}{2^{n/2}} \sum_x (-1)^{\text{sign}(\text{Re} \langle x | V | \tau \rangle)} \langle x | V \psi \rangle \\
&= \frac{1}{2^{n/2}} \sum_x (-1)^{f(x) + \text{sign}(\text{Re} \langle x | V | \tau \rangle)} \langle x | V' \psi \rangle \\
&= \frac{1}{2^{n/2}} \sum_x (-1)^{f(x) + f(x) \cdot \text{sign}(\text{Re} \langle x | V' | \tau \rangle)} \langle x | V' \psi \rangle \\
&= \frac{1}{2^{n/2}} \sum_x (-1)^{f(x)(1 + \text{sign}(\text{Re} \langle x | V' | \tau \rangle))} \langle x | V' \psi \rangle \\
&= \frac{1}{2^{n/2}} \sum_x (-1)^{f(x)(1 + \text{sign}(\text{Re} \langle x | V' | \tau \rangle))} \langle x | V' \psi \rangle
\end{aligned}$$

$$\begin{aligned}
&\Rightarrow \langle \Phi(\tau, V) V^\dagger | \psi \rangle \langle \psi | U \Phi(\tau, U) \rangle \\
&= \frac{1}{2^n} \sum_{x, x'} (-1)^{g(x') + f(x) + \text{sign}(\text{Re}\langle x | V | \tau \rangle) + \text{sign}(\text{Re}\langle x' | U | \tau \rangle)} \\
&\quad \cdot \langle x | V' \psi \rangle \langle x' | U' \psi \rangle \\
&\Rightarrow | \langle \Phi(\tau, V) V^\dagger | \psi \rangle \langle \psi | U \Phi(\tau, U) \rangle |^2 \\
&= \frac{1}{2^{2n}} \sum_{y, y', x, x'} (-1)^{g(x') + f(x) + \text{sign}(\text{Re}\langle x | V | \tau \rangle) + \text{sign}(\text{Re}\langle x' | U | \tau \rangle)} \\
&\quad \cdot \langle y | V' \psi \rangle \langle y' | U' \psi \rangle \cdot \\
&\quad \cdot (-1)^{g(y') + f(y) + \text{sign}(\text{Re}\langle y | V | \tau \rangle) + \text{sign}(\text{Re}\langle y' | U | \tau \rangle)} \\
&\quad \cdot \langle y | V' \psi \rangle^* \langle y' | U' \psi \rangle^* \\
&\mathbf{E}_{U, V \sim X, f, g \sim \mathcal{H}^2} [ | \langle \Phi(\tau, V) V^\dagger | \psi \rangle \langle \psi | U \Phi(\tau, U) \rangle |^2 ] \\
&\mathbf{E}_{U, V \sim X, f, g \sim \mathcal{H}^2} [ | \langle \varphi V'^\dagger | x \rangle \langle x | U' \varphi \rangle |^2 ] \\
&= \mathbf{E}_{U^{prime}, V^{\dagger, '}, \sim X, f, g \sim \mathcal{H}^2} [ \langle y | U' | \phi \rangle^* \langle y' | V^{\dagger, '}, | \phi \rangle^* \langle x | U' | \phi \rangle \langle x' | V^{\dagger, '}, | \phi \rangle ] \\
&= \mathbf{E}_{U, V \sim X, f, g \sim \mathcal{H}^2} [ (-1)^{f(x) + g(x') + f(y) + g(y')} \langle y | U | \phi \rangle^* \langle y' | V | \phi \rangle^* \langle x | U | \phi \rangle \langle x' | V | \phi \rangle ] \\
&= \mathbf{E}_{U, V \sim X, f, g \sim \mathcal{H}^2} [ \mathbf{1}_{x=x'=y=y'} \langle y | U | \phi \rangle^* \langle y' | V | \phi \rangle^* \langle x | U | \phi \rangle \langle x' | V | \phi \rangle ] \\
&\leq \frac{2^n}{2^{2n}} = \frac{1}{2^n}
\end{aligned}$$

□

**Claim 2.4.**  $| \langle \Phi(\tau, U_k) | U_k \tau^\perp \rangle \langle \tau^\perp U_j^\dagger | \Phi(\tau, U_j) \rangle |^2 < b$

*Proof.*

$$\begin{aligned}
&\mathbf{E}_{U \sim D} [ | \langle \Phi(\tau, U_k) | U_k \tau^\perp \rangle \langle \tau^\perp U_j^\dagger | \Phi(\tau, U_j) \rangle |^2 ] \\
&\leq \mathbf{E}_{U \sim D} [ | \langle \Phi(\tau, U_k) | U_k \tau^\perp \rangle |^2 \cdot | \langle \tau^\perp U_j^\dagger | \Phi(\tau, U_j) \rangle |^2 ] \\
&= \mathbf{E}_{U \sim D} [ | \langle \Phi(\tau, U_k) | U_k \tau^\perp \rangle |^2 ]^2 \\
&= \mathbf{E}_{U \sim D} \left[ \left| \sum_x \langle x | U_k \tau^\perp \rangle \right|^2 \right]^2 \\
&= \mathbf{E}_{U \sim D} \left[ \sum_x | \langle x | U_k \tau^\perp \rangle |^2 \right]^2
\end{aligned}$$

□

### 3 The Distillation.

suppose that for any  $|\psi_i^{(k)}\rangle, |\psi_j^{(k)}\rangle$  it holds that:  $| \langle \psi_i^{(k)} | \psi_j^{(k)} \rangle | < \exp(-n)$ . After conditionl swap the normlaized state has the form:

$$|\psi_i^{(k)}\rangle |\psi_j^{(k)}\rangle + |\psi_j^{(k)}\rangle |\psi_i^{(k)}\rangle \mapsto \frac{|\psi_i^{(k)}\rangle |\psi_j^{(k)}\rangle + |\psi_j^{(k)}\rangle |\psi_i^{(k)}\rangle}{\sqrt{2 + 2| \langle \psi_i^{(k)} | \psi_j^{(k)} \rangle |^2}}$$

So

$$\begin{aligned}
|\langle \psi_i^{(k+1)} | \psi_t^{(k+1)} \rangle| &= \frac{|\langle \psi_i^{(k)} | \langle \psi_j^{(k)} | + \langle \psi_j^{(k)} | \langle \psi_i^{(k)} | \cdot |\psi_t^{(k)}\rangle | \psi_s^{(k)}\rangle + |\psi_s^{(k)}\rangle | \psi_t^{(k)}\rangle|}{\sqrt{2+2|\langle \psi_i^{(k)} | \psi_j^{(k)} \rangle|^2} \sqrt{2+2|\langle \psi_t^{(k)} | \psi_s^{(k)} \rangle|^2}} \\
&\leq \frac{1}{2+2\exp(-2n)} \cdot \sum_{\{v,u\}=\{i,j\}, \{v',u'\}=\{t,s\}} |\langle \psi_v^{(k)} | \psi_{v'}^{(k)} \rangle \langle \psi_u^{(k)} | \psi_{u'}^{(k)} \rangle| \\
&\leq \frac{1}{2+2\exp(-2n)} \cdot 4\exp(-2n) \\
&= \frac{1+|\langle \psi_j^{(k)} | \psi_i^{(k)} \rangle|^2}{\sqrt{2+2|\langle \psi_i^{(k)} | \psi_j^{(k)} \rangle|^2}} |\psi_i^{(k)}\rangle \cdot \frac{1+|\langle \psi_s^{(k)} | \psi_t^{(k)} \rangle|^2}{\sqrt{2+2|\langle \psi_t^{(k)} | \psi_s^{(k)} \rangle|^2}} |\psi_t^{(k)}\rangle| \\
&\leq \frac{1}{2} \sqrt{1+|\langle \psi_j^{(k)} | \psi_i^{(k)} \rangle|^2} \sqrt{1+|\langle \psi_s^{(k)} | \psi_t^{(k)} \rangle|^2} \cdot |\langle \psi_i^{(k)} | \psi_t^{(k)} \rangle| \\
&\leq \frac{1}{2} (1+\exp(-2n)) |\langle \psi_i^{(k)} | \psi_t^{(k)} \rangle| \leq \frac{1}{2} (\exp(-n) + \exp(-3n))
\end{aligned}$$

But we have bound for also  $\{i, j\} \times \{s, t\}$  so in general:

$$\begin{aligned}
&\leq 4 \cdot \frac{1}{2} (\exp(-n) + \exp(-3n)) \sim 2\exp(-n) \\
&\leq 2 \cdot (K(k, n) + K(k, n)^3)
\end{aligned}$$

$$\begin{aligned}
&|\left(\sum \sqrt{p_i} \langle \psi_i | \right) |\tau^\perp\rangle \langle \tau^\perp | (q_j | \psi_j) \rangle| \leq \sum_{i,j} \sqrt{p_i q_j} |\langle \psi_i | \tau^\perp \rangle \langle \tau^\perp | \psi_j \rangle| \\
&\leq \sqrt{2^k \cdot 2^k} \max |\langle \psi_i | \tau^\perp \rangle \langle \tau^\perp | \psi_j \rangle| \cdot \sum_{i,j} p_i q_j \leq 2^k \cdot \exp(-n)
\end{aligned}$$

$$\begin{aligned}
&|\tau\rangle \langle \tau| \otimes I \frac{|\psi_i^{(k)}\rangle |\psi_j^{(k)}\rangle + |\psi_j^{(k)}\rangle |\psi_i^{(k)}\rangle}{\sqrt{2+2|\langle \psi_i^{(k)} | \psi_j^{(k)} \rangle|^2}} \\
&\mapsto \frac{\langle \tau | \psi_i^{(k)} \rangle |\tau\rangle |\psi_j^{(k)}\rangle + \langle \tau | \psi_j^{(k)} \rangle |\tau\rangle |\psi_i^{(k)}\rangle}{\sqrt{2+2|\langle \psi_i^{(k)} | \psi_j^{(k)} \rangle|^2}}
\end{aligned}$$

Thus we obtain:

$$\begin{aligned}
|\langle \tau | \star \rangle|^2 &= \left(2+2|\langle \psi_i^{(k)} | \psi_j^{(k)} \rangle|^2\right)^{-1} \cdot \left(|\langle \tau | \psi_i^{(k)} \rangle|^2 + |\langle \tau | \psi_j^{(k)} \rangle|^2 + \langle \tau | \psi_i^{(k)} \rangle \langle \psi_i^{(k)} | \psi_j^{(k)} \rangle \langle \psi_j^{(k)} | \tau \rangle\right) \\
&= \left(2+2|\langle \psi_i^{(k)} | (|\tau\rangle \langle \tau| + |\tau^\perp\rangle \langle \tau^\perp|) | \psi_j^{(k)} \rangle|^2\right)^{-1} \cdot \\
&\quad \cdot \left(|\langle \tau | \psi_i^{(k)} \rangle|^2 + |\langle \tau | \psi_j^{(k)} \rangle|^2 + \langle \tau | \psi_i^{(k)} \rangle \langle \psi_i^{(k)} | (|\tau\rangle \langle \tau| + |\tau^\perp\rangle \langle \tau^\perp|) | \psi_j^{(k)} \rangle \langle \psi_j^{(k)} | \tau \rangle\right)
\end{aligned}$$

Denote  $\xi_k = |\langle \psi_i^{(k)} | \tau^\perp \rangle \langle \tau^\perp | \psi_j^{(k)} \rangle|^2$  so the above simplified into:

$$\begin{aligned}
&\geq \left(2+2|\langle \psi_i^{(k)} | \tau \rangle|^2 |\langle \tau | \psi_j^{(k)} \rangle|^2 + \xi_k\right)^{-1} \cdot \\
&\quad \cdot \left(|\langle \tau | \psi_i^{(k)} \rangle|^2 + |\langle \tau | \psi_j^{(k)} \rangle|^2 + 2|\langle \psi_i^{(k)} | \tau \rangle|^2 |\langle \tau | \psi_j^{(k)} \rangle| - \sqrt{\xi_k}\right) \\
a_{k+1} &\geq \frac{1}{2} \cdot \frac{a_k + b_k + 2a_k b_k - \xi_k}{1 + a_k b_k + \xi_k}
\end{aligned}$$

$$\begin{aligned}
|a\rangle &= \sum a_{xy} |x\rangle |y\rangle \\
|b\rangle &= \sum b_{xy} |x\rangle |y\rangle \\
\langle a^1 | b^1 \rangle &= \sum \frac{1}{n} a_{xy}^* b_{xz} \langle xyz | xyz \rangle = \sum a_x^* b_x
\end{aligned}$$

## References

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