A new exponential separation between quantum and classical one-way communication complexity

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EPSRC Engineering and Physical Sciences Research Council

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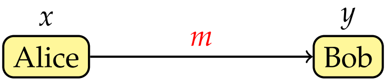

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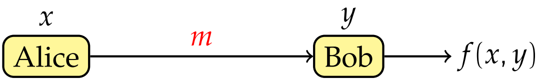

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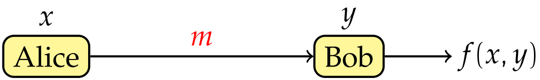

- The classical one-way communication complexity (1WCC) of a boolean function f is the length of the shortest message m sent from Alice to Bob that allows Bob to compute $f(x, y)$ with constant probability of success $> 1/2$.

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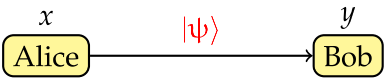

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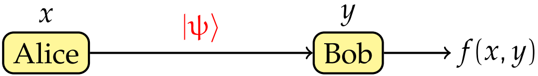

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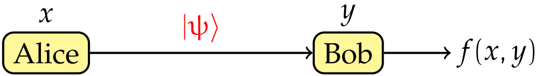

- The quantum 1WCC of f is the smallest number of qubits sent from Alice to Bob that allows Bob to compute $f(x, y)$ with constant probability of success $> 1/2$.

- We don't allow Alice and Bob to share any prior entanglement or randomness.

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- In fact, for partial functions, quantum one-way communication is exponentially stronger than even two-way classical communication [Klartag and Regev '10].

- If $f(x, y)$ is a total function, the best separation we have is a factor of 2 for equality testing [Winter '04].

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Subgroup Membership

The Subgroup Membership problem is defined in terms of a group G, as follows.

- Alice gets a subgroup $H \leqslant G$.
- Bob gets an element $g \in G$.
- Bob has to output 1 if $g \in H$, and 0 otherwise.

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For any group G, there's an $O(\log^2 |G|)$ bit classical protocol: Alice just sends Bob the identity of her subgroup.

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- Alice prepares two copies of the $O(\log |G|)$ qubit state $|H\rangle := \sum_{h \in H} |h\rangle$ and sends them to Bob.
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- Bob can distinguish these two cases with constant probability of success using the swap test.

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- The complexity of the general problem has been an open problem for some time [Aaronson et al '09]... now it's even considered to be a "semi-grand challenge" for quantum computation: [http://scottaaronson.com/blog/?p=471]

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- Idea: can we prove any separation between quantum and classical 1WCC for a more general version of this problem?

The problem

Perm-Invariance

- Alice gets an n-bit string x.
- Bob gets an $n \times n$ permutation matrix M.
- Bob has to output $\begin{cases} 1 & \text{if } Mx = x \\ 0 & \text{if } d(Mx, x) \geqslant \beta|x| \\ \text{anything} & \text{otherwise,} \end{cases}$

where β is a constant, $|x|$ is the Hamming weight of x and $d(x, y)$ is the Hamming distance between x and y.

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Note that Subgroup Membership is the special case where x is a $|G|$ bit string such that $x_i = 1 \Leftrightarrow i \in H$, and M is the group action corresponding to g (and we set $\beta = 2$).

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- Any one-way classical protocol that solves Perm-Invariance with a constant success probability strictly greater than 1/2 must communicate at least $\Omega(n^{7/16})$ bits (for $\beta = 1/8$).

Therefore, there is an exponential separation between quantum and classical one-way communication complexity for this problem.

The quantum protocol

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- By the promise that either $|\psi_{Mx}\rangle = |\psi_x\rangle$, or $\langle\psi_{Mx}|\psi_x\rangle \leqslant 1/8$, these two cases can be distinguished with a constant number of repetitions.

The classical lower bound

We prove a lower bound for a special case of PERM-INVARIANCE.

PM-Invariance

- Alice gets a $2n$-bit string x such that $|x| = n$.
- Bob gets a $2n \times 2n$ permutation matrix M, where the permutation entirely consists of disjoint transpositions (i.e. corresponds to a perfect matching on the complete graph on $2n$ vertices).
- Bob has to output $\begin{cases} 1 & \text{if } Mx = x \\ 0 & \text{if } d(Mx, x) \geqslant n/8 \\ \text{anything} & \text{otherwise.} \end{cases}$

Relation to previous work

This is equivalent to the following problem.

PM-Invariance

- Alice gets a $2n$-bit string x.
- Bob gets an $n \times 2n$ matrix M over $\mathbb{F}_2$, where each row contains exactly two 1s, and each column contains at most one 1.
- Bob has to output $\begin{cases} 0 & \text{if } Mx = 0 \\ 1 & \text{if } |Mx| \geqslant n/16 \\ \text{anything} & \text{otherwise.} \end{cases}$

Relation to previous work

A similar problem was used by [Gavinsky et al '08] to separate quantum and classical 1WCC.

α-Partial Matching

- Alice gets an n-bit string x.
- Bob gets an $\alpha n \times n$ matrix M over $\mathbb{F}_2$, where each row contains exactly two 1s, and each column contains at most one 1, and a string $w \in \{0,1\}^{\alpha n}$.
- Bob has to output $\begin{cases} 0 & \text{if } Mx = w \\ 1 & \text{if } Mx = \bar{w} \\ \text{anything} & \text{otherwise.} \end{cases}$

So the main difference is the relaxation of the promise by removing this second string from Bob's input.

Stop press

- Following the completion of this work, Verbin and Wu seem to have improved the lower bound on PM-Invariance to the optimal $\Omega(\sqrt{n})$.
- See "The Streaming Complexity of Cycle Counting, Sorting By Reversals, and Other Problems", Proc. SODA'11.

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- Show that the induced distributions on Bob's inputs are close to uniform whenever Alice's subset is large.

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- Fix two "hard" distributions: one on Alice & Bob's zero-valued inputs, and one on their one-valued inputs.
- Show that the induced distributions on Bob's inputs are close to uniform whenever Alice's subset is large.
- This means they're hard for Bob to distinguish.

More formally

For any distribution $\mathcal{D}$ on Alice and Bob's inputs, let $\mathcal{D}^S$ be the induced distribution on Bob's inputs, given that Alice's input was in set S.

Lemma (e.g. [Gavinsky et al '08])

- Let $f : \{0,1\}^m \times \{0,1\}^n \rightarrow \{0,1\}$ be a function of Alice and Bob's distributed inputs.

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- Assume there is a one-way classical protocol that computes f with success probability $1 - \epsilon$, for some $\epsilon < 1/3$, and uses c bits of communication.
- Then there exists $S \subseteq \{0,1\}^m$ such that $|S| \geqslant \epsilon\, 2^{m-c}$, and $\|\mathcal{D}_0^S - \mathcal{D}_1^S\|_1 \geqslant 2(1 - 3\epsilon)$.

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- Let p_M be the probability under $\mathcal{D}_1$ that Bob gets M, given that Alice's input was in A, for an arbitrary set A.
- Let N_{2n} be the number of partitions of $\{1, \ldots, 2n\}$ into pairs. Then

$$p_M = \frac{\binom{2n}{n}}{N_{2n}\binom{n}{n/2}} \Pr_{x \in A}[Mx = x].$$

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- We can now calculate

$$N_{2n} \sum_M p_M^2 = \frac{\binom{2n}{n}^2}{N_{2n} \binom{n}{n/2}^2 |A|^2} \left(\sum_{x,y \in A} \sum_M [Mx = x, My = y] \right).$$

Proof idea

- It turns out that the sum over M only depends on the Hamming distance $d(x, y)$:

$$\sum_M [Mx = x, My = y] = h(x + y)$$

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- So

$$N_{2n} \sum_M p_M^2 = \frac{\binom{2n}{n}^2}{N_{2n} \binom{n}{n/2}^2 |A|^2} \left(\sum_{x,y} f(x) f(y) h(x + y) \right),$$

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where f is the characteristic function of A.

- This means that it's convenient to upper bound $N_{2n} \sum_M p_M^2$ using Fourier analysis over the group $\mathbb{Z}_2^{2n}$.

Fourier analysis in 2 lines

Informally:

- The Fourier transform of a function $f : \{0,1\}^n \to \mathbb{R}$ is the function $\hat{f} : \{0,1\}^n \to \mathbb{R}$ defined by

$$\hat{f}(x) = \frac{1}{2^n} \sum_{y \in \{0,1\}^n} (-1)^{x \cdot y} f(y).$$

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- For any functions $f, g : \{0,1\}^n \to \mathbb{R}$,

$$\sum_{x,y \in \{0,1\}^n} f(x) f(y) g(x+y) = 2^{2n} \sum_{x \in \{0,1\}^n} \hat{g}(x) \hat{f}(x)^2.$$

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- This allows us to write

$$N_{2n} \sum_M p_M^2 = \frac{\binom{2n}{n}^2 2^{4n}}{N_{2n} \binom{n}{n/2}^2} \frac{1}{|A|^2} \sum_{x \in \{0,1\}^{2n}} \hat{h}(x) \hat{f}(x)^2,$$

  where f is the characteristic function of A, and h is as on the previous slide.

Upper bounding this sum

We can upper bound this sum using the following crucial inequality.

Lemma

Let A be a subset of $\{0,1\}^n$, let f be the characteristic function of A, and set $2^{-\alpha} = |A|/2^n$. Then, for any $1 \leqslant k \leqslant (\ln 2)\alpha$,

$$\sum_{x,|x|=k} \hat{f}(x)^2 \leqslant 2^{-2\alpha} \left(\frac{(2e \ln 2)\alpha}{k} \right)^k,$$

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and the same holds if we replace k with $n-k$ in the sum.

- This inequality is based on a result of Kahn, Kalai and Linial (the KKL Lemma), which in turn is based on a "hypercontractive" inequality of Bonami, Gross and Beckner.

Differences between this and previous work

The previous work [Gavinsky et al '08] uses similar techniques. But we seem to need to deal with some additional technical complications:

- They show that the induced distribution on vectors Mx is close to uniform, whereas we seem to need to work directly with the distribution on M.
- They show that $\sum_{x,|x|=k} \hat{f}(x)^2$ is low when k is small, whereas we seem to need to also work with high k.
- We seem to need to put some (fairly) tight bounds on Krawtchouk polynomials and other functions of binomial coefficients.

Finishing up

To summarise:

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- We upper bound the "Fourier weight at the k'th level" of f, $\sum_{x,|x|=k} \hat{f}(x)^2$, using the previous lemma.
- Combining the two upper bounds, we end up with something that's smaller than a constant unless $|A| \leqslant 2^{2n-\Omega(n^{7/16})}$.
- Thus, unless Alice sends at least $\Omega(n^{7/16})$ bits to Bob, he can't distinguish the distribution $\mathcal{D}_1^A$ from uniform with probability better than a fixed constant.

Finishing up

To summarise:

- We calculate and upper bound the Fourier transform $\hat{h}(x)$, which turns out to be exponentially decreasing as $|x| \to n$.
- We upper bound the "Fourier weight at the k'th level" of f, $\sum_{x,|x|=k} \hat{f}(x)^2$, using the previous lemma.
- Combining the two upper bounds, we end up with something that's smaller than a constant unless $|A| \leqslant 2^{2n-\Omega(n^{7/16})}$.
- Thus, unless Alice sends at least $\Omega(n^{7/16})$ bits to Bob, he can't distinguish the distribution $\mathcal{D}_1^A$ from uniform with probability better than a fixed constant.
- So the classical 1WCC of PM-INVARIANCE is $\Omega(n^{7/16})$.

Conclusions

- We've found an $\Omega(n^{7/16})$ lower bound on the classical 1WCC of the PM-Invariance problem, implying an exponential separation between quantum and classical 1WCC.

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Conclusions

- We've found an $\Omega(n^{7/16})$ lower bound on the classical 1WCC of the PM-INVARIANCE problem, implying an exponential separation between quantum and classical 1WCC.

- The original question still remains: can we get a quadratic separation between quantum and classical 1WCC for SUBGROUP MEMBERSHIP?

- Or indeed any asymptotic separation for any total function?

Thanks!

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