Security of quantum bit string commitment depends on the information measure

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(Dated: July 26, 2018)

Unconditionally secure non-relativistic bit commitment is known to be impossible in both the classical and the quantum world. However, when committing to a string of \( n \) bits at once, how far can we stretch the quantum limits? In this letter, we introduce a framework of quantum schemes where Alice commits a string of \( n \) bits to Bob, in such a way that she can only cheat on \( a \) bits and Bob can learn at most \( b \) bits of information before the reveal phase. Our results are two-fold: we show by an explicit construction that in the traditional approach, where the reveal and guess probabilities form the security criteria, no good schemes can exist: \( a + b \) is at least \( n \). If, however, we use a more liberal criterion of security, the accessible information, we construct schemes where \( a = 4 \log_2 n + O(1) \) and \( b = 4 \), which is impossible classically. Our findings significantly extend known no-go results for quantum bit commitment.

PACS numbers:

Imagine two mutually distrustful parties Alice and Bob at distant locations. They can only communicate over a channel, but want to play the following game: Alice secretly chooses a bit \( x \). Bob wants to be sure that Alice indeed has made her choice. Yet, Alice wants to keep \( x \) hidden from Bob until she decides to reveal \( x \). To convince Bob that she made up her mind, Alice sends Bob a commitment. From the commitment alone, Bob cannot deduce \( x \). At a later time, Alice reveals \( x \) and enables Bob to open the commitment. Bob can now check if Alice is telling the truth. This scenario is known as bit commitment. Commitments play a central role in modern day cryptography. They form an important building block in the construction of larger protocols in, for example, gambling and electronic voting, and other instances of secure two-party computation. In the realm of quantum mechanics, it has been shown that oblivious transfer \( [4] \) can be achieved provided there exists a secure bit commitment scheme \( [2, 3] \). In turn, classical oblivious transfer can be used to perform any secure two-party computation \( [3] \). Commitments are also useful for constructing zero-knowledge proofs \( [5] \) and lead to coin tossing \( [6] \).

Classically, unconditionally secure non-relativistic bit commitment is known to be impossible. Unfortunately, after several quantum schemes were suggested \( [7] \), non-relativistic quantum bit commitment was shown to be impossible, too \( [8, 9] \), even in the presence of superselection rules \( [10] \). In fact, only very limited degrees of concealment and bindingness can be obtained \( [11] \). It has been shown that the quantum no-go theorems do not apply to protocols which use two or more sites and take account of relativistic signaling constraints. We work in the non-relativistic quantum mechanical setting, hence all presented results are referring to this setting only. In the face of the negative results regarding this setting, what can we still hope to achieve?

In this letter, we consider the task of committing to a string of \( n \) bits at once when both the honest player and the adversary have unbounded resources. Since perfect bit commitment is impossible, perfect bit string commitment is impossible, too. We thus give both Alice and Bob a limited ability to cheat. First, we introduce a framework for the classification of bit string commitments in terms of the length \( n \) of the string, Alice’s ability to cheat on at most \( a \) bits and Bob’s ability to acquire at most \( b \) bits of information before the reveal phase. We say that Alice can cheat on \( a \) bits if she can reveal up to \( 2^a \) strings successfully. Bob’s security definition is crucial to our investigation: If \( b \) determines a bound on his probability to guess Alice’s string, then we prove that \( a + b \) is at least \( n \). This implies that the trivial protocol, where Alice’s commitment consists of sending \( b \) bits of her string to Bob, is optimal. If, however, \( b \) is a bound on the accessible information that the quantum states contain about Alice’s string, then we show that non-trivial schemes exist. More precisely, we construct schemes with \( a = 4 \log_2 n + O(1) \) and \( b = 4 \). This is impossible classically.

Quantum commitments of strings have previously been considered by Kent \( [12] \), who pointed out that in the quantum world useful bit string commitments could be possible despite the no-go theorem for bit commitment. His scenario differs significantly from ours and imposes an additional constraint, which is not present in our work: Alice does not commit to a superposition of strings.

Framework.

Definition 1 An \((n, a, b)\)-Quantum Bit String Commit-
ment (QBSC) is a quantum communication protocol between two parties, Alice (the committer) and Bob (the receiver), which consists of two phases and two security requirements.

- (Commit Phase) Assume that both parties are honest. Alice chooses a string \( x \in \{0,1\}^n \) with probability \( p_x \). Alice and Bob communicate and at the end Bob holds state \( \rho_x \).

- (Reveal Phase) If both parties are honest, Alice and Bob communicate and at the end Bob learns \( x \). Bob accepts.

- (Concealing) If Alice is honest, \( \sum_{x \in \{0,1\}^n} p_x B \leq 2^b \), where \( p_x \) is the probability that Bob correctly guesses \( x \) before the reveal phase given \( \rho_x \).

- (Binding) If Bob is honest, then for all commitments of Alice: \( \sum_{x \in \{0,1\}^n} p^A_x \leq 2^c \), where \( p^A_x \) is the probability that Alice successfully reveals \( x \).

We say that Alice successfully reveals a string \( x \) if Bob accepts the opening of \( x \), i.e., he performs a test depending on the individual protocol to check Alice’s honesty and concludes that she was indeed honest. Note that quantumly, Alice can always commit to a superposition of different strings without being detected. Thus even for a perfectly binding bit string commitment (i.e., \( n,a,b \) also an (\( n,a,b \))-QBSC), interacting through a quantum channel. Consider the product of three Hilbert spaces \( \mathcal{H}_A, \mathcal{H}_B \) and \( \mathcal{H}_C \) of bounded dimensions representing the Hilbert spaces of Alice’s and Bob’s machines and the channel, respectively. Without loss of generality, we assume that each machine is initially in a specified pure state. Alice and Bob perform a number of rounds of communication over the channel. Each such round can be modeled as a unitary transformation on \( \mathcal{H}_A \otimes \mathcal{H}_C \) and \( \mathcal{H}_B \otimes \mathcal{H}_C \) respectively. Since the protocol is known to both Alice and Bob, they know the set of possible unitary transformations used in the protocol. We assume that Alice and Bob are in possession of both a quantum computer and a quantum storage device. This enables them to add ancillae to the quantum machine and use reversible unitary operations to replace measurements. By doing so, Alice and Bob can delay measurements and thus we can limit ourselves to protocols where both parties only measure at the very end. Moreover, any classical computation or communication that may occur can be simulated by a quantum computer.

We now show that every \((n,a,b)\)-QBSC is an \((n,a,b)\)-QBSC\( _\xi \). The security measure \( \xi(\mathcal{E}) \) is defined by

\[
\xi(\mathcal{E}) \equiv n - H_2(\rho_{AB}|\rho),
\]

where \( \rho_{AB} = \sum_x p_x |x\rangle \otimes \rho_x \) and \( \rho = \sum_x p_x \rho_x \) are only dependent on the ensemble \( \mathcal{E} = \{p_x, \rho_x\} \). \( H_2(\cdot) \) is an entropic quantity defined in [13] \( H_2(\rho^{AB}|\rho) \equiv -\log \text{Tr}(\rho^{AB} | \rho) \). This quantity is directly connected to Bob’s maximal average probability of successful guessing the string:

**Lemma 1** Bob’s maximal average probability of successfully guessing the committed string, i.e.,

\[
\sup_M \sum_x p_x p^{BM}_{x|\xi} \text{ where } M \text{ ranges over all measurements and } p^{BM}_{x|\xi} \text{ is the conditional probability of guessing } y \text{ given } \rho_x, \text{ is larger or equal to } 2^{-H_2(\rho_{AB}|\rho)}.
\]

**Proof:** By definition the maximum average guessing probability is lower bounded by the average guessing probability for a particular measurement strategy. We choose the square-root measurement which has operators

\[
M_x = p_x \rho_x - \frac{1}{2} \rho_x + \frac{1}{2}, \quad p^{BM}_{x|\xi} = \text{Tr}(M_x \rho_x) \text{ is the probability}
\]
that Bob guesses $x$ given $\rho_x$, hence
\[
\log_2 \sum_x p_x p_{x|x}^{B,\text{max}} \geq \log_2 \sum_x p_x^2 \text{Tr}(\rho_x^{-\frac{1}{2}} \rho_x \rho_x^2) \\
= \log_2 \text{Tr} \left( \left( (I \otimes \rho_{\frac{1}{2}}) \rho_{AB} \right)^2 \right) \\
= -H_2(\rho_{AB}|\rho).
\]
Related estimates were derived in [14]. For the uniform distribution $p_x = 2^{-n}$ we have from the concealing condition that $\sum_x p_{x|x} \leq 2^b$ which by Lemma 1 implies $\xi(\mathcal{E}) \leq b$. Thus, every $(n, a, b)$-QBSC is error-free if both parties are honest.

Now, we can prove our impossibility result.

**Theorem 2** $(n, a, b)$-QBSC$_\xi$ schemes, and thus also $(n, a, b)$-QBSC schemes, with $a + b + c < n$ do not exist. $c$ is a constant equal to $5 \log_2 5 - 4 \approx 7.61$.

**Proof:** Consider an $(n, a, b)$-QBSC$_\xi$ and the case where both Alice and Bob are honest. Alice committed to $x$. We denote the joint state of the system Alice-Bob-Channel $\mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ after the commit phase by $|\phi_x\rangle$ for input state $|x\rangle$. Let $\rho_x$ be Bob’s reduced density matrix, and let $\mathcal{E} = \{p_x, \rho_x\}$ where $p_x = 2^{-n}$.

Assuming that Bob is honest, we will give a cheating strategy for Alice in the case where $a + b + 5 \log_2 5 - 4 < n$.

The strategy will depend on the two-universal hash function $g : \{0, 1\}^n \rightarrow \mathcal{Y} = \{0, 1\}^{n-m}$, for appropriately chosen $m$. Alice picks a $y \in \mathcal{Y}$ and constructs the state $\sum_{x \in \mathcal{Y}} |x\rangle \langle x| / \sqrt{|g^{-1}(y)|}$. She then gives the second half of this state as input to the protocol and stays honest for the rest of the commit phase. The joint state of Alice and Bob at the end of the commit phase is thus $|\psi_g^y\rangle = \sum_{x \in g^{-1}(y)} |x\rangle \langle x| / \sqrt{|g^{-1}(y)|}$. The reduced states on Bob’s side are $\sigma_g^y = \frac{1}{2} \sum_{x \in g^{-1}(y)} p_x \rho_x$ with probability $q_g^y = \sum_{x \in g^{-1}(y)} p_x$. We denote this ensemble by $\mathcal{E}_g$. Let $\sigma = \sigma_g = \sum_y q_g^y \sigma_g^y$ for all $g$.

We now apply Theorem 1 with $s = n - m$ and $\xi(\mathcal{E}) \leq b$ and obtain $\frac{1}{b} \sum_{g \in \mathcal{G}} d(\mathcal{E}_g) \leq \varepsilon$ where $\varepsilon = \frac{1}{8 m - 4}$. Hence, there is at least one $g$ such that $d(\mathcal{E}_g) \leq \varepsilon$; intuitively, this means that Bob knows only very little about the value of $g(x)$. This $g$ defines Alice’s cheating strategy. It is straightforward to verify that $d(\mathcal{E}_g) \leq \varepsilon$ implies
\[
2^{-n-m} \sum_y \delta(\sigma, \sigma_g^y) \leq 2\varepsilon.
\]
Let us therefore assume without loss of generality that Alice chooses $y_0 \in \mathcal{Y}$ with $\delta(\sigma_{y_0}^g, \sigma) \leq 2\varepsilon$.

Clearly, the probability to successfully reveal some $x$ in $g^{-1}(y)$ given $|\psi_g^y\rangle$ is one [27]. Thus the probability to reveal $y$ (i.e. to reveal an $x$ such that $y = g(x)$) given $|\psi_g^y\rangle$ successfully is one. Let $\tilde{p}_x$ and $\tilde{q}_{y}^g$ denote the probabilities to successfully reveal $x$ and $y$ respectively and $\tilde{p}_{x|y}$ be the conditional probability to successfully reveal $x$, given $y$. We have $\sum_x \tilde{p}_x = \sum_y \tilde{q}_{y}^g \sum_{x \in g^{-1}(y)} \tilde{p}_{x|y} \geq \sum_y \tilde{q}_{y}^g$.

Recall that Alice can transform $|\psi_g^y\rangle$ approximately into $|\psi_{y_0}\rangle$ if $\sigma_{y_0}^g$ is sufficiently close to $\sigma_g^y$ by using only local transformations on her part. It follows from Lemma 2 that we can estimate the probability of revealing $y$, given that the state was really $|\psi_{y_0}\rangle$. Since this reasoning applies to all $y$, on average, we have
\[
\sum_y \tilde{q}_{y}^g \geq \sum_y \left(1 - 2\varepsilon \delta(\sigma_{y_0}^g, \sigma_g^y)\right) \\
\geq 2^{-n-m} \left(1 - 2\varepsilon \left[\sum_y \delta(\sigma_{y_0}^g, \sigma_g^y)\right]\right) \\
\geq 2^{-n-m} \left[2^{-\frac{1}{2}} \left(\sum_y \delta(\sigma_{y_0}^g, \sigma_g^y)\right)^{\frac{1}{2}}\right] \\
\geq 2^{-n-m} \left[1 - 2\varepsilon \left(\sum_y \delta(\sigma_{y_0}^g, \sigma) \right)^{\frac{1}{2}}\right],
\]
where the first inequality follows from Lemma 2 the second from Jensen’s inequality and the concavity of the square root function, the third from the triangle inequality and the fourth from eq. (3) and $\delta(\sigma_{y_0}^g, \sigma) \leq 2\varepsilon$. Recall that to be secure against Alice, we require $2\varepsilon \geq
We insert $\epsilon = \frac{1}{4}2^{-\frac{1}{2}(m-b)}$, define $m = b + \gamma$ and take the logarithm on both sides to get

$$a + b + \delta \geq n,$$  

where $\delta = \gamma - \log(1 - 2^{-\gamma/4+1})$. Keeping in mind that $1 - 2^{-\gamma/4+1} > 0$ (or equivalently $\gamma > 4$), we find that the minimum value of $\delta$ for which eq. (4) is satisfied is $\delta = 5 \log_2 5 - 4$ and arises from $\gamma = 4(\log_2 5 - 1)$. Thus, no $(n,a,b)$-QBSC$_{c}$ with $a + b + 5 \log_2 5 - 4 < n$ exists. □

Since the constant $\epsilon$ does not depend on $a$, $b$ and $n$, multiple parallel executions of the protocol can only be secure if $a + b \geq n$:

**Corollary 1** Let $P$ be an $(n,a,b)$-QBSC with $P^{m}$ an $(mn,ma,mb)$-QBSC. Then $n < a + b + c/m$. In particular, no $(n,a,b)$-QBSC with $a + b < n$ can be executed securely an arbitrary number of times in parallel. The latter statement also applies to $(n, a, b) - \text{QBSC}_{\chi}$, where $\chi$ denotes the Holevo information of the ensemble $E$. [17].

It follows directly from [17] that the results in this section also hold in the presence of superselection rules.

**Possibility.** Surprisingly, if one is willing to measure Bob’s ability to learn $x$ using the accessible information non-trivial protocols become possible. These protocols are based on a discovery known as “locking of classical information in quantum states” [18]. The protocol, which we call LOCKCOM($n, U$), uses this effect and is specified by a set $U = \{U_{1}, \ldots, U_{|U|}\}$ of unitaries.

- Commit phase: Alice has the string $x \in \{0, 1\}^{n}$ and randomly chooses $r \in \{1, \ldots, |U|\}$. She sends the state $U_{r}|x\rangle$ to Bob, where $U_{r} \in U$.

- Reveal phase: Alice announces $r$ and $x$. Bob applies $U_{r}^{\dagger}$ and measures in the computational basis to obtain $x'$. He accepts if and only if $x' = x$.

As a first observation, the number of unitaries $|U|$ limits the number of different ways of revealing a string, i.e. $2^{a} < |U|$. [28]. Furthermore we have adapted the work in [19] in order to show that there exist $O(n^{3})$ unitaries that bring Bob’s accessible information down to a constant: $I_{\text{acc}}(E) \leq 4$ [17, Appendix B.2]. In summary:

**Theorem 3** For $n \geq 3$, there exist $(n, 4 \log_{2} n + O(1), 4)$-QBSC$_{I_{\text{acc}}}$ protocols.

The protocol is as follows: Alice chooses a set of $O(n^{3})$ unitaries independently according to the Haar measure (approximated) and announces the resulting set $U$ to Bob. They then perform LOCKCOM($n, U$). Our analysis shows that this variant is secure against Bob with high probability. Unfortunately, the protocol is inefficient both in terms of computation and communication. It remains open to find an efficient constructive scheme with those parameters.

In contrast, for only two bases, an efficient construction exists and uses the identity and the Hadamard transform as unitaries. From [18] (see also [20]) it then follows that LOCKCOM($n, \{I^{\otimes n}, \frac{1}{\sqrt{2}}(I^{\otimes n} + Z^{\otimes n})\}$) is an $(n, 1, n/2)$-QBSC$_{I_{\text{acc}}}$ protocol. As shown in [21], this protocol can be made cheat sensitive [22] for Bob, i.e. any nonzero information-gain by Bob will be detected by Alice with nonzero probability.

A drawback of weakening the security requirement is that LOCKCOM protocols are not necessarily composable. Therefore, if LOCKCOM is used as a sub-protocol in a larger protocol, the security of the resulting scheme has to be evaluated on a case by case basis. However, LOCKCOM protocols are secure when executed in parallel. This is a consequence of the definition of Alice’s security parameter and the additivity of the accessible information [23], and sufficient for many cryptographic purposes.

**Conclusion** We have introduced a framework for quantum commitments to a string of bits and shown that under strong security requirements (e.g. bounded guessing probability or Holevo information), non-trivial protocols do not exist. A property of quantum states known as locking, however, allowed us to propose meaningful protocols for a weaker security demand: Alice encodes her classical $n$ bit string into a quantum state in such a way that no measurement on Bob’s side will yield high mutual information with the commitment. Alice is genuinely committed, because the quantum states that she sent contain almost the complete commitment, i.e. have high Holevo information.

**Acknowledgments** We thank J. Barrett, I. Damgård, A. Kent, S. Massar, R. Renner and R. Spekkens for discussions and R. de Wolf, A. Broadbent and an anonymous referee for helpful comments. We also thank R. Jain for discussion on his work [24], where, following our preprint [17], he used a different method to prove that $(n,a,b)$-QBSC$_{c}$ with $a + 6b + 31 < n$, do not exist. The attack that he constructs for Alice in order to prove his result, however, aborts with high probably. In the proof of Theorem 2, in contrast, Alice’s cheating is only detected with negligible probability. C. Mochon has pointed out to us that Kitaev’s lower bound for coin flipping can be used to achieve similar no-go result than what we have presented in this letter. However, our no-go leads to an explicit attack by Alice.

M.C. was supported by a DAAD Doktorandenstipendium, the EPSRC and a Magdalene College Neville Research Fellowship. P.H. and H.-K.L. are supported by the Canadian funding agencies CFI, CIAR, CIPI, CRC, NSERC, PREA and OIT. H.B. and S.W. are supported by the NWO vici project 2004-2009. We acknowledge support from EU project RESQ IST-2001-37559, QAP IST 015848 and the FP6-FET Integrated Project SCALA, CT-015714.
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For instance, the class of all functions from \( \{0,1\}^n \) to \( \{0,1\}^k \) is two-universal. For a definition and efficient constructions see [10].

Proof of Lemma 5. \( \delta(\rho_0, \rho_1) \leq \epsilon \) implies \( F(\rho_0, \rho_1) \geq 1 - \epsilon \). \( F(\cdot, \cdot) \) is the fidelity of two quantum states, which, by Uhlmann’s theorem equals \( \max_{U} ||\phi_0 U \otimes \phi_1|| \). Here, \( |\phi_0 \rangle \) and \( |\phi_1 \rangle \) are the joint states after the commit phase and the maximization ranges over all unitaries \( U \) on Alice’s (i.e. the purification) side. Let \( |\psi_0 \rangle = U \otimes |\phi_1 \rangle \) for a \( U \) achieving the maximization. Then \( \delta(|\phi_0 \rangle \langle \phi_0|, |\psi_0 \rangle \langle \psi_0|) = \sqrt{1 - \delta(U, |\phi_0 \rangle \langle \phi_0| U^\dagger)} \leq \sqrt{1 - (1 - \epsilon)^2} \leq \sqrt{2\epsilon} \). If both parties are honest, the reveal phase can be regarded as a measurement resulting in a distribution \( P_Y \) (\( P_Z \)) if \( |\phi_0 \rangle \) (\( |\psi_0 \rangle \)) was the state before the reveal phase. The random variables \( Y \) and \( Z \) carry the opened bit or the value ‘reject \( (r) \)’. Since the trace distance does not increase under measurements, \( \delta(P_Y, P_Z) \leq \delta(|\phi_0 \rangle \langle \phi_0|, |\psi_0 \rangle \langle \psi_0|) \leq \sqrt{2\epsilon} \). Hence \( \frac{1}{2} \left( |P_Y(0) - P_Z(0)| + |P_Y(1) - P_Z(1)| + |P_Y(r) - P_Z(r)| \right) \leq \sqrt{2\epsilon} \). Since \( |\phi_0 \rangle \) corresponds to Alice’s honest commitment to 0 we have \( P_Y(0) = 1, P_Y(1) = P_Z(r) = 0 \) and hence \( P_Z(0) \geq 1 - \sqrt{2\epsilon} \).

Alice learns \( x \), but cannot pick it: she committed to a superposition and \( x \) is chosen randomly by the measurement.

This can be seen as follows. Let \( \tilde{p}_x \) denote the probability that Alice reveals \( x \) successfully. Then, \( \tilde{p}_x \leq \sum_r p_{x,r} \), where \( p_{x,r} \) is the probability that \( x \) is accepted by Bob when the reveal information was \( r \). Let \( \rho \) denote the state of Bob’s system. Summation over \( x \) yields \( \sum_x \tilde{p}_x \leq \sum_{x,r} p_{x,r} \) and \( \sum_{x,r} p_{x,r} = \sum_{x,r} \text{Tr}[x|U_x^\dagger \rho U_r] = \sum_r \text{Tr}\rho = 2^n \).