

Lecture 7: Preprocessing PIR Lower Bounds

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This is our final lecture on private information retrieval. We will prove a lower bound about the client space and server computation trade-off for preprocessing PIR schemes. For the proof, we will use techniques from complexity theory literature.

PIANO PIANO[ZPSZ23] is a preprocessing 1-server PIR scheme covered in lecture 5. It uses the client-specific preprocessing model, meaning that each client has a subscription phase with the server, during which it will perform preprocessing. The scheme has the following specs:

- Client Space: $\tilde{O}(\sqrt{n})$
- Communication Bandwidth per Query: $O(\sqrt{n})$
- Server/Client Compute per Query: $\tilde{O}(\sqrt{n})$

Consider the server computation and client space trade-off. For PIANO, this trade-off [Client Space: $\tilde{O}(\sqrt{n})$, Compute per Query: $\tilde{O}(\sqrt{n})$] is nearly optimal up to poly-log factors. This is because of the following lower bound.

Space/Computation Lower Bound

Claim 1. *Given a 1-Server Preprocessing PIR, define variables as follows:*

- S : Client Space
- T : Server Compute per Query

Then,

$$(S + 1)(T + 1) \geq N$$

This lower bound holds even for a scheme that supports 1 query, regardless of server space, bandwidth, and amount of preprocessing work. Before proceeding with the proof, we first have to discuss another slightly different problem called Yao's Box Problem [Yao90].

1 Yao's Box Problem

We have a server with N boxes, each covering a bit. Note that this is not a PIR scheme, because it does not provide any privacy guarantees.

Preprocessing Phase Client and server can open all bits, and run arbitrary and unbounded computations. However, we have a constraint that at the end of the preprocessing, client can only store S bits of information.

Query Client wants to know the i -th bit. We allow the client and server to have unbounded communication and work. We have a constraint that the server can open at most T boxes and it cannot open box i .

Upper Bound

1. Divide the N boxes into \sqrt{N} segments.
2. Preprocessing Phase: Have the client store the parity of each segment.
3. Query Phase (i): Server opens every box in i 's segment except i and sends the parity back to the client. As the client knows the parity of each segment, it can easily reconstruct the value of bit i .

Here, $S = \sqrt{N}$ and $T = \sqrt{N} - 1$

Lower Bound

Theorem 2. $S(T + 1) \geq N$

Proof. We will be using an encoding type argument. Consider the following experiment.

1. Run preprocessing
2. Define an empty set called `known` = $\{\}$. In each step i , the client finds the smallest $q_i \notin \text{known}$, queries q_i .

With this step, `known` \leftarrow `known` $\cup \{q_i\} \cup$ all boxes opened during query

3. If `known` $\neq [N]$, break. Otherwise, repeat step 2 again.

Let the “client’s hint” denote whatever information that the client stores after the preprocessing phase. The hint is at most S bits long.

Define the encoding `enc` for this process as follows:

`enc` = client’s hint + all “newly opened” boxes in all queries

We write “newly opened” because we do not want to include values that have already been recorded in the encoding.

By Shannon’s theorem, we will show that $|\text{enc}| \geq N$.

Let t_1, t_2, \dots, t_k be the number of newly opened boxes at each step $i \in [k]$.

Note here that we have the power of **plus one**; if I open t boxes, I end up learning $t + 1$ new bits. This is because I also learn the value of the query without opening its box.

Thus, the `known` set increments with the following pattern.

- We newly open t_1 boxes: `known` increments by $t_1 + 1$
- We newly open t_2 boxes: `known` increments by $t_2 + 1$
- and so on...

Thus, we have that $\sum_{i=1}^k (t_i + 1) \geq N$. Let $t = \frac{\sum_{i=1}^k t_i}{k}$. Note that t is the average number of boxes opened on each iteration so it must be upper bounded by T , the maximum number of boxes that can be opened in an iteration. Since we repeat the steps until `known` = $[N]$, we have that

$$\sum_{i=1}^k (t_i + 1) \geq N \implies (t + 1)k \geq N \implies k \geq \frac{N}{t + 1} \quad (1)$$

The encoding size is $S + \sum_{i=1}^k t_k = S + tk$. By Shannon's we have that $S + tk \geq N$. By (1), we have that

$$\begin{aligned}
S + tk &\geq N \\
\implies S + t \frac{N}{t+1} &\geq N && \text{(By (1))} \\
\implies S(t+1) &\geq N && \text{(Simplification)} \\
\implies S(T+1) &\geq N && \text{(As } t \leq T)
\end{aligned}$$

□

2 PIR Lower Bound

Using our knowledge of Yao's Box Problem, let's now try to prove the PIR lower bound.

Theorem 3. *Suppose we have a 1 server preprocessing PIR with perfect correctness and $\text{negl}(n)$ privacy loss with client space S and server computation T per query. Then,*

$$(S+1)(T+1) \geq N \quad [\text{CGK20}]$$

This lower bound holds even for computationally private schemes. It holds even for a single query, regardless of bandwidth, server space, even when preprocessing can be unbounded. However, we have a restriction that the server stores the original database and nothing else. That is, it does not store any encoding of the database.

For the proof, we will show that a solution to the PIR problem can be used to construct an algorithm to solve a probabilistic version of Yao's Box Problem.

Probabilistic Yao's Box Problem Suppose we have a working PIR scheme. Now, we will construct a solution to probabilistic Yao's Box Problem as follows:

- Client's Hint: PIR's hint
- Query for $i \in [N]$: Run PIR for query i . If server looks at $\text{DB}[i]$, then output "error".

We want to show the following. Given that $\text{PIRExpt}: i \xleftarrow{\$} [N]$, PIR preprocessing, PIR query on i ,

$$p = \mathbb{P}[\text{PIRExpt opens } i] \leq \frac{T}{N} + \text{negl}(N)$$

That is, we want to show that if we run a PIR query with the a random index i , the probability we open that index is small.

For a fixed i , define the following probability $p_i = \mathbb{P}[\text{PIR on } i \text{ looks at } i]$. Then,

$$p = \frac{1}{N} \sum_i p_i$$

Assume for the sake of contradiction that $p > \frac{T}{N} + \mu$, where μ is non-negligible.

Let $p_{ji} = \mathbb{P}[\text{PIR on } j \text{ opens } i]$. Since our scheme is private, the different indices should be computationally indistinguishable. Thus, this probability should be equally distributed. As a result,

$$p_{ji} = \mathbb{P}[\text{PIR on } j \text{ opens } i] \geq p_i - \text{negl}(N)$$

$$\begin{aligned}
E[\text{server work for PIR on } j] &\geq \sum_{i=1}^N p_{ji} \\
&\geq \sum_{i=1}^N (p_i - \text{negl}(N)) \\
&= Np - \text{negl}(N) && \text{(By def. of } p) \\
&> T + \mu N - \text{negl}(N) && \text{(As } p > \frac{T}{N} + \mu)
\end{aligned}$$

Thus, we have a contradiction because the expected number of locations the server needs to look at is strictly greater than T . Thus, we have shown that

$$\mathbb{P}[\text{PIRExp opens } i] \leq \frac{T}{N} + \text{negl}(N)$$

Shifting our focus back to Yao's Box problem with probabilistic correctness on random index, the probabilistic correctness is

$$\mathbb{P}[i \xleftarrow{\$} \text{correct for } i] \geq 1 - \frac{T}{N} - \text{negl}(N)$$

Encoding Argument Randomness comes from two parts: the preprocessing part (the client's hint), and the query part. With this in mind, we will be using an augmented version of the encoding type argument in 1.

Consider the following experiment.

1. Run preprocessing, and choose a “reasonably good hint.” Initially, let the encoding be just the hint. We will add to this encoding as we go forward.
2. Define an empty set called `known` = {}
3. In each step i , find the smallest $q_i \notin \text{known}$.
 - If \exists online coins such that query q_i will give the correct answer, choose the lexicographically smallest coin. Execute query.

$$\text{known} \leftarrow \cup\{q_i\} \cup \{\text{all newly opened}\}$$

Add “newly opened” to encoding.

- Else add q_i -th bit to the encoding.

4. Repeat until `known` = $[N]$.

A hint is bad for $i \in [N]$ if $\mathbb{P}[\text{query } i \text{ correct} | \text{hint}] = 0$. That is, there does not exist an online coin such that the query is correct.

Claim 4. \exists hint that's bad for at most $T + 1$ location.

Proof. If all hints are bad for more than $T + 1$ locations, then

$$\mathbb{P}[i \in [N], \text{correct on } i] < 1 - \frac{T + 1}{N}$$

We have a contradiction, because it disagrees with our probabilistic correctness result above. \square

Finally, we can reason about the encoding length.

Suppose the worst case where the hint is bad for exactly $T + 1$ locations. Let \mathbf{b}_{bad} be the encoding of the “newly opened” boxes in the bad queries, and \mathbf{b}_{good} be the encoding of the “newly opened boxes in the good queries.

- $|\mathbf{b}_{\text{bad}}| = T + 1$, as each bad iteration adds one bit, and we have $T + 1$ iterations.
- To find $|\mathbf{b}_{\text{good}}|$, we repeat the argument from 1. Let t_1, t_2, \dots, t_k be the number of newly opened boxes at each good step $i \in [k]$.

By the “plus one” argument, we have that $\sum_{i=1}^k (t_i + 1) \geq N - (T + 1)$. We subtract $T + 1$ here because those indices have been handled by the bad iterations.

Let $t = \frac{\sum_{i=1}^k t_i}{k}$. Then as before, we have $k \geq \frac{N}{t+1}$

$$\begin{aligned} \sum_{i=1}^k (t_i + 1) &\geq N - (T + 1) \\ \implies tk + k &\geq N - T - 1 \\ \implies k &\geq \frac{N - T - 1}{t + 1} \end{aligned}$$

Thus, $|\mathbf{b}_{\text{good}}| = tk \geq t \frac{N - T - 1}{t + 1}$

With the information above, we can make the following conclusion.

$$\begin{aligned} |\text{enc}| = S + |\mathbf{b}_{\text{good}}| + |\mathbf{b}_{\text{bad}}| &\geq N \\ \implies S + t \frac{N - T - 1}{t + 1} + T + 1 &\geq N \\ \implies S(t + 1) + T + 1 &\geq N && \text{(By simplification)} \\ \implies (S + 1)(T + 1) &\geq N && \text{(As } t \text{ upper bounded by } T) \end{aligned}$$

□

References

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