

# Cryptography meets algorithms (15893) Lecture Notes

## Lecture 1: Private Information Retrieval

Scribe: Justin Zhang

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The Private Information Retrieval problem was first introduced by CGKS 98. In this setting, we will have a client and server(s). The server(s) are connected to a public database indexed from 1 to  $n$ , which could represent DNS, webpage, leaked password database, etc.

A client wants to fetch an entry from this database  $i \in [n]$  but does not want to leak their query to the server(s). More formally,

**Definition 1** (PIR - Single Server Scheme). *A protocol between a client  $c$  and server  $s$  where,*

- *Client has desired index  $i \in [n]$ , and server(s) have  $DB \in \{0, 1\}^n$*
- *At the end of the protocol, client outputs bit  $b \in \{0, 1\}$*

*with properties,*

- **Correctness:**  $\forall n : DB \in \{0, 1\}^n, i \in [n]$ , under honest execution,

$$\Pr[b = DB[i]] \geq 1 - \mu(n) \quad (\text{negligible } \mu)$$

- **Privacy:**  $\forall i, j \in [n], DB \in \{0, 1\}^n$ , and function  $view_s$  representing the view of server  $s$ :

$$view_s(n, DB, i) \cong view_s(n, DB, j)$$

*where  $\cong$  stands for identically distributed, statistically, or computationally indistinguishable.*

**Remark 1** (Honest-server vs. malicious-server privacy). *The above privacy definition assumes an honest server. It is also possible to define privacy against a malicious server. In today's lecture, all the PIR constructions will only have a single round-trip — in this special case, honest-server privacy and malicious-server privacy are equivalent. So we will simply define honest-server privacy here.*

This definition is naturally extended to a two (and any  $n \geq 2$ ) server definition, where the two servers do not communicate.

**Definition 2** (PIR - Two Server Scheme). *A protocol between a client  $c$  and servers  $s_1, s_2$  where,*

- *Client has desired index  $i \in [n]$ , and server(s) have  $DB \in \{0, 1\}^n$*
- *At the end of the protocol, client outputs bit  $b \in \{0, 1\}$*

*with properties,*

- **Correctness:**  $\forall n : DB \in \{0, 1\}^n, i \in [n]$ , under honest execution,

$$\Pr[b = DB[i]] \geq 1 - \mu(n) \quad (\text{negligible } \mu)$$

- **Privacy:**  $\forall i, j \in [n], \text{DB} \in \{0, 1\}^n$ , and function  $\text{view}_s$  representing the view of server  $s$ :

$$\text{view}_{s_1}(n, \text{DB}, i) \cong \text{view}_{s_1}(n, \text{DB}, j)$$

$$\text{view}_{s_2}(n, \text{DB}, i) \cong \text{view}_{s_2}(n, \text{DB}, j)$$

Note that PIR schemes can additionally be extended to retrieve blocks of data by querying the database bit-by-bit.

## 1 Single Server PIR constructions

Naively, the client can just download the entire database, which is perfect correctness and privacy, but this has linear bandwidth, client computation, and server computation with respect to the database size.

### 1.1 FHE PIR

For a smarter and overall more efficient scheme, we assume we have an FHE scheme ( $\text{Gen}$ ,  $\text{Enc}$ ,  $\text{Dec}$ ). An FHE scheme allows us to perform addition and multiplication operations on the ciphers which propagate to their underlying plain-texts.<sup>1</sup>

The scheme is as follows:

1. The client samples  $(pk, sk) \leftarrow \text{FHE.Gen}(1^\lambda)$ , and encrypts their query as  $m \leftarrow \text{FHE.Enc}(i)$ . The client then sends  $m$  to the server.
2. The server homomorphically evaluates the selection circuit  $S$  and let  $c = \text{Eval}(S, m)$  ( $S(i)$  selects the  $i$ -th bit from  $\text{DB}$  and the circuit is  $\tilde{O}(n)^2$  in size), and sends it to the client.
3. The client decrypts  $\text{FHE.Dec}(sk, c)$ .

The correctness of the scheme is clear. The scheme has  $\tilde{O}(1)$  bandwidth and client computation and  $\tilde{O}(n)$  server computation. Some notable PIR schemes include Spiral [MW22] and SimplePIR [HHCG<sup>+</sup>22].

**Question:** Can we get sub-linear bandwidth without any cryptographic (hardness) assumptions? In fact, this is possible in the two server setting (we will see this next), and we can prove that this is impossible in the one server case.

## 2 Two Server PIR Constructions

### 2.1 $\sqrt{n}$ -BW 2-Server-Scheme with Information-theoretic (IT) security

Note that IT security implies no harness assumptions, so this is perfect and statistically private.

The key idea is the view of database  $\text{DB} \in \{0, 1\}^n$  as a  $S \in \{0, 1\}^{\sqrt{n} \times \sqrt{n}}$  matrix. Say the client wants to query the  $(i, j)$ 'th entry. To do this, the server can simply return the entire column  $j$ , which we can afford to do via the square-root bandwidth. To provide security, the client also supplies a one-hot-vector  $q_j$ , split into two random shares  $v_1, v_2$  via a 2-share secret sharing scheme (that is, sample random  $v_1, v_2$  conditioned on  $v_1 \oplus v_2 = q_j$ ).

The scheme is as follows:

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<sup>1</sup>TA: Arithmetic circuit (including addition and multiplication gates) is Turing-complete. Thus, FHE allows the server to evaluate arbitrary computation given the encrypted input. However, we have to be careful about its efficiency – we usually discuss the time complexity of an algorithm in the RAM model, whereas FHE only works in the circuit model (in general).

<sup>2</sup> $\tilde{O}$  hides the polylogarithmic factors.

1. The client creates  $v_1, v_2$  as described above. The client sends these shares to servers  $s_1, s_2$  respectively.
2. Each server  $s_i$ , on receiving  $v_i$  computes the matrix-vector product,

$$r_i \leftarrow S v_i \bmod 2$$

and sends the  $\sqrt{n}$ -size vector  $r_i$  to the client.

3. The client computes and outputs  $r_1 \oplus r_2$ .

It is straightforward to verify correctness by seeing that

$$r_1 \oplus r_2 = S r_1 \oplus S r_2 \bmod 2 = S(r_1 \oplus r_2) \bmod 2$$

Lastly, this scheme is private, since  $v_1, v_2$  are uniformly random in each server's view, respectively.

## 2.2 $n^{\frac{1}{3}}$ -BW 2-server Scheme (CGKS '98)

We will first motivate this construction with a two server scheme with expected  $\frac{n}{2}$  bandwidth and a eight server scheme with  $n^{\frac{1}{3}}$  bandwidth.

### 1. $\mathbb{E}[\frac{n}{2}]$ -BW 2-server Scheme

The client samples  $S_1 \subseteq [n]$  uniformly as follows: for each  $i \in [n]$ , add  $i$  to  $S_1$  with probability  $\frac{1}{2}$ . Then, the client computes

$$S_2 = S_1 \Delta \{i\}$$

where  $\Delta$  is the symmetric difference operator. That is, if  $i$  is included in  $S_1$ , we remove it from the set, otherwise we add it to the set.  $S_1, S_2$  are sent to each server respectively, where server  $i$  computes and sends back,

$$r_i \leftarrow \bigoplus_{j \in S_i} \text{DB}[j]$$

The client on receiving  $r_1, r_2$  outputs  $r_1 \oplus r_2$ .

**Correctness** follows from the fact that  $i$  is the only database index that appears once, with every other index appearing twice (hence XOR'ing to 0).

**Privacy:** First,  $S_1$  is uniformly random. Second, to see why  $S_2$  is uniformly random to server 2, just consider the following distribution – “tossing  $n$  random coins, and flip the  $i$ -th coin afterwards, regardless of the original result”. This distribution is uniformly random even when  $i$  is known.

**Remark 2.** Note that if we run the above  $n/2$ -BW scheme not on bits, but on blocks of  $\sqrt{n}$  size (i.e., treat the  $n$ -bit database as  $\sqrt{n}$  blocks each of size  $\sqrt{n}$ ), the scheme is equivalent to the earlier  $\sqrt{n}$ -BW scheme.

### 2. $n^{\frac{1}{3}}$ -BW 8-server Scheme

The idea is to view the database as a  $n^{\frac{1}{3}} \times n^{\frac{1}{3}} \times n^{\frac{1}{3}}$  cube. Then, each index  $i \in \{0, 1, \dots, n-1\}$  can be expressed as a thruple  $(x^*, y^*, z^*)$  (note we start at 0 for natural base 3 representation).

The client samples  $X, Y, Z \subseteq \{0, \dots, n^{\frac{1}{3}}-1\}$  independently as follows: for each  $x \in \{0, \dots, n^{\frac{1}{3}}\}$  add it to  $X$  with probability  $\frac{1}{2}$ . Do the same for  $Y, Z$ .

Then, we compute 8 different sets by a 3-wise cartesian products with symmetric differences, enumerated as

$$\begin{aligned}
S_{000} &= X \times Y \times Z \\
S_{001} &= X \times Y \times (Z \Delta \{z^*\}) \\
S_{010} &= X \times (Y \Delta \{y^*\}) \times Z \\
S_{011} &= X \times (Y \Delta \{y^*\}) \times (Z \Delta \{z^*\}) \\
S_{100} &= (X \Delta \{x^*\}) \times Y \times Z \\
S_{101} &= (X \Delta \{x^*\}) \times Y \times (Z \Delta \{z^*\}) \\
S_{110} &= (X \Delta \{x^*\}) \times (Y \Delta \{y^*\}) \times Z \\
S_{111} &= (X \Delta \{x^*\}) \times (Y \Delta \{y^*\}) \times (Z \Delta \{z^*\})
\end{aligned}$$

See that each of these sets have their sizes concentrated around  $\left(\frac{n^{\frac{1}{3}}}{2}\right)^3 = \frac{n}{8}$ . Then, the client sends a succinct description of each set (i.e., sends the three “marginal” vectors instead of the full set) of size  $O(n^{\frac{1}{3}})$  to each server.

Server  $i$  on receiving  $S = X' \times Y' \times Z'$  computes

$$p_i = \bigoplus_{j \in S} \text{DB}[j]$$

Then the client computes  $p_0 \oplus \dots \oplus p_7$ .

We claim that  $p_0 \oplus \dots \oplus p_7 = \text{DB}[i], i = (x^*, y^*, z^*)$ .

*Proof.* For every  $(x, y, z)$  not equal to the query, it will appear an even number times in the summation. We can pair up the sets to see this.

On the other hand,  $(x^*, y^*, z^*)$  only appears once in the summation so we are done.  $\square$

Privacy follows the argument as the previous case.

Now, we finally compress this scheme from eight servers to two servers. To do this, the client sends  $S_{000}$  to server 1 and  $S_{111}$  to server 2.

Each server on receiving  $X' \times Y' \times Z'$  calculates  $3n^{\frac{1}{3}}$  parities to send to the client as follows:

1. For each  $x' \in \{0, \dots, n^{\frac{1}{3}} - 1\}$  we calculate the parity for  $(X' \Delta \{x'\}) \times Y' \times Z'$  as in the previous scheme.
2. For each  $y' \in \{0, \dots, n^{\frac{1}{3}} - 1\}$  we calculate the parity for  $X' \times (Y' \Delta \{y'\}) \times Z'$  as in the previous scheme.
3. For each  $z' \in \{0, \dots, n^{\frac{1}{3}} - 1\}$  we calculate the parity for  $X' \times Y' \times (Z' \Delta \{z'\})$  as in the previous scheme.

Now each server returns  $1 + 3n^{1/3}$  parities to the client. That is, the server 1 will actually compute  $S_{000}$  and  $S_{100}, S_{010}, S_{001}$  will be in those  $3n^{1/3}$  parities. Similarly, the server 2 will compute  $S_{111}$ , and  $S_{011}, S_{101}, S_{110}$  will be in those  $3n^{1/3}$  parities. The client will be able to pick out the correct parities corresponding to its actual query.

Thus, this scheme still has  $n^{\frac{1}{3}}$  bandwidth, and correctness and security still follow.

### 3 State of the Art and Open Problem

For the 2-server setting, the best known lower bound states that  $5 - o(1) \log n$  bandwidth is necessary ([WdW05]), while the best known upper bound requires  $n^{O(\sqrt{\lg \lg n / \lg n})} = n^{o(1)}$ , i.e., sub-polynomial bandwidth ([DG16]). Closing this gap is a long-standing open problem.

### References

- [DG16] Zeev Dvir and Sivakanth Gopi. 2-server pir with subpolynomial communication. *Journal of the ACM (JACM)*, 63(4):1–15, 2016.
- [HHCG<sup>+</sup>22] Alexandra Henzinger, Matthew M. Hong, Henry Corrigan-Gibbs, Sarah Meiklejohn, and Vinod Vaikuntanathan. One server for the price of two: Simple and fast single-server private information retrieval. Cryptology ePrint Archive, Paper 2022/949, 2022. <https://eprint.iacr.org/2022/949>.
- [MW22] Samir Jordan Menon and David J. Wu. SPIRAL: Fast, high-rate single-server PIR via FHE composition. In *IEEE S&P*, 2022.
- [WdW05] Stephanie Wehner and Ronald de Wolf. Improved lower bounds for locally decodable codes and private information retrieval. In Luís Caires, Giuseppe F. Italiano, Luís Monteiro, Catuscia Palamidessi, and Moti Yung, editors, *Automata, Languages and Programming*, pages 1424–1436, Berlin, Heidelberg, 2005. Springer Berlin Heidelberg.