TRUSTWORTHY, PRIVACY-PRESERVING AND FUNCTIONAL DATA OUTSOURCING SYSTEMS

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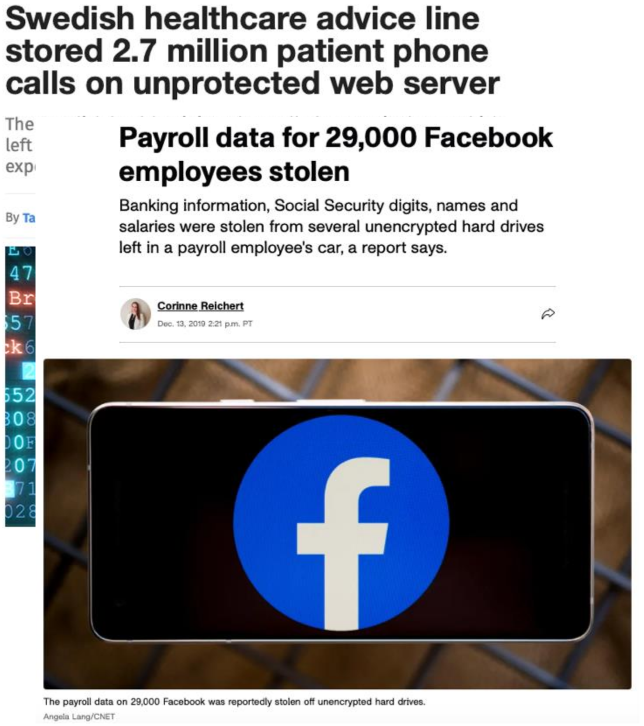
Overview


Swedish healthcare advice line stored 2.7 million patient phone calls on unprotected web server

Payroll data for 29,000 Facebook employees stolen

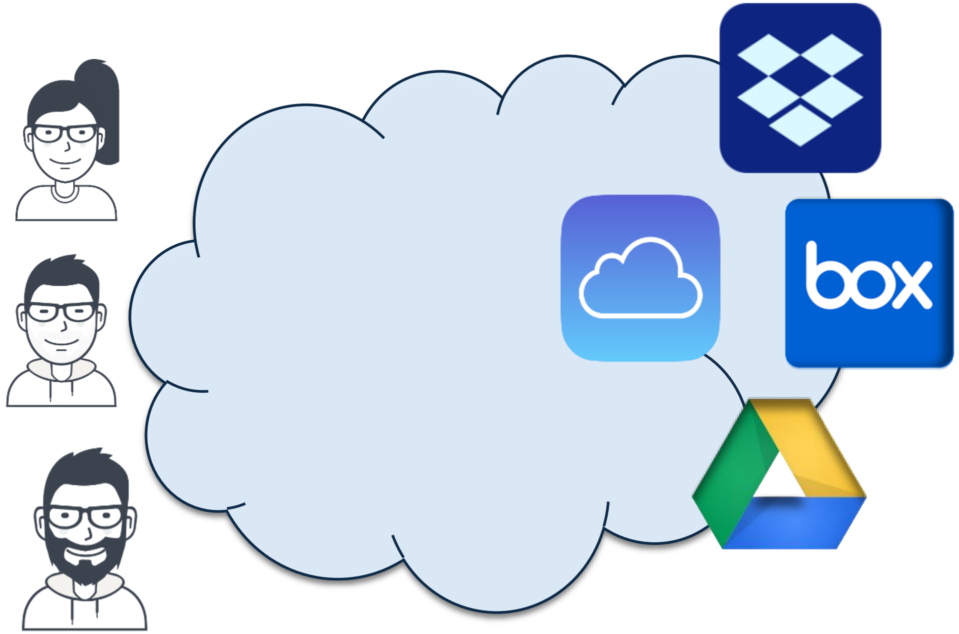
Banking information, Social Security digits, names and salaries were stolen from several unencrypted hard drives left in a payroll employee's car, a report says.

Corinne Reichert

Dec. 13, 2019 2:21 p.m. PT

The payroll data on 29,000 Facebook was reportedly stolen off unencrypted hard drives.

Angela Lang/CNET



Storage-as-a service (STaaS)


Fortune 500 company leaked 264GB in client, payment data

Updated: The data leak impacted Tech Data's client servers,

Russian Government Hackers Penetrated DNC, Stole Opposition Research on Trump

By Ellen Nakashima, Washington Post

- **Misuse** of personal sensitive data (Facebook/Cambridge Analytica)
- Data **breaches** of large enterprises (Yahoo!, Sony PSN, Equifax)

The need for encrypted storage platforms

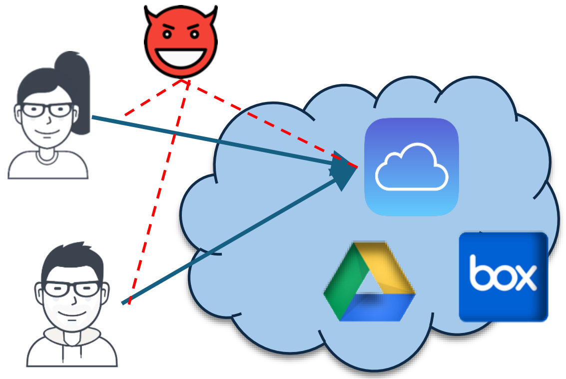
Is Data Confidentiality Enough?

End-to-end encrypted systems are increasingly popular

Keybase PREVEIL SpiderOak sync.com tresorit

Data is always kept encrypted, however:

- Data integrity and soundness are still concerns
- Sensitive information can still be inferred from **metadata**



(e.g., query/access pattern and frequency, side-channel information)

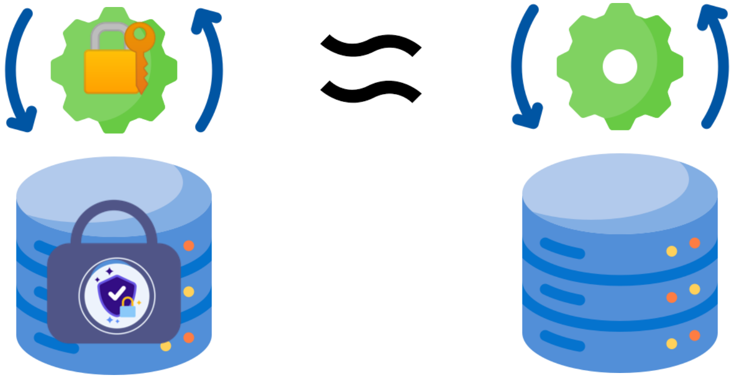
"Metadata absolutely tells you everything about somebody's life. If you have enough metadata, you don't really need content" –

A former NSA General Counsel

- Inefficient and insecure operations that leak user data and queries

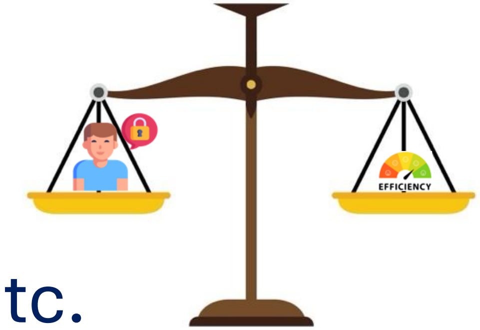
Desirable Properties

Trustworthy data outsourcing services are expected to:

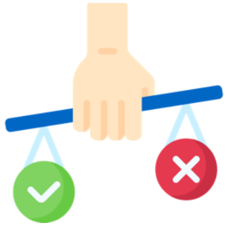


1. **Keep** user **data intact**

2. **Ensure** data and user **privacy**



3. **Provide** essential **functionalities**: querying, analytics, etc.

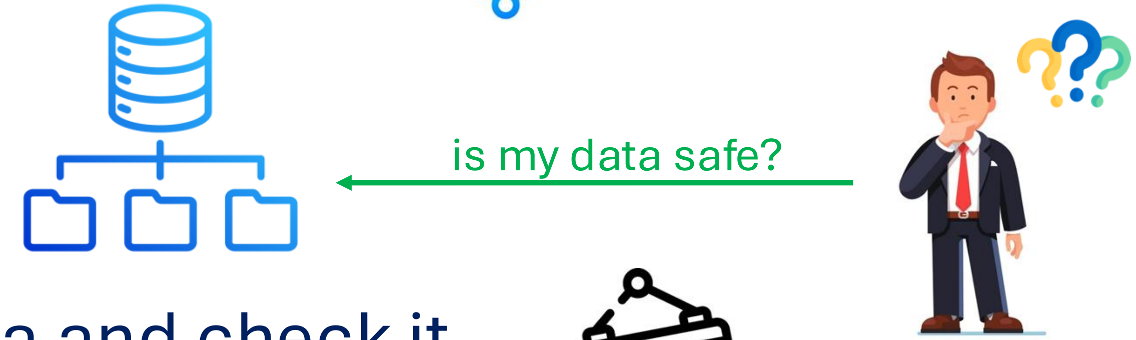


1. Data Intactness

- Data loss can happen due to unwanted accidents or adversarial behaviors

- A data owner/user expects the following guarantees:

  - Authenticated storage
  - Retrievability



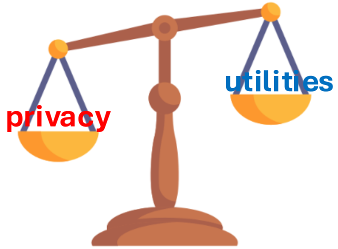
- The user can download the whole data and check it

 High communication cost and significant overhead

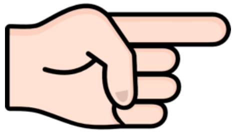
- **Proof of Retrievability** can offer the above guarantees with small user and/or server overhead

2. User/Data Privacy and Utilization Dilemma

- There is a dilemma between user/data privacy and utilization



- Data is encrypted 

 How to execute queries as on plaintext data, for example: 

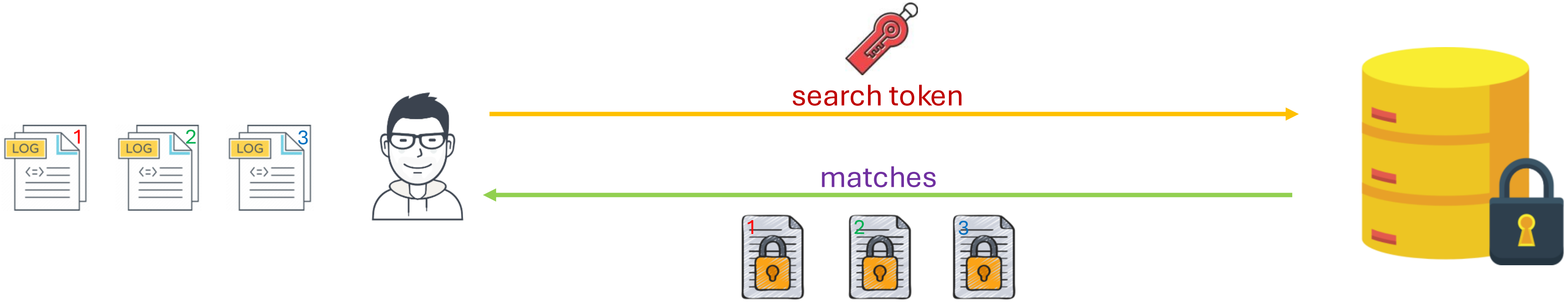
  - **Search query**: obtain documents matching a specific keyword
  - **Data analytics**: obtain statistical information 

- There are encrypted systems with these built-in capabilities 
  - Costly crypto tools (e.g., Multiparty Computation, Homomorphic Encryption)
  - **Metadata** leakage

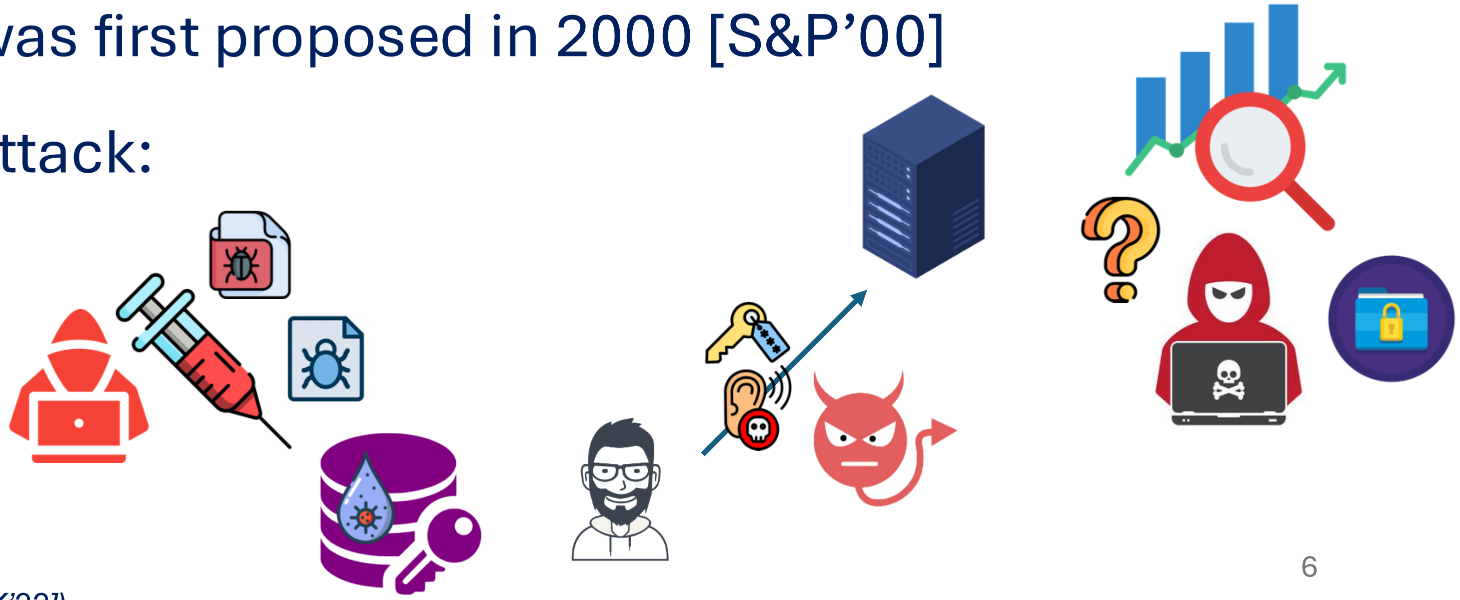
  

2. User/Data Privacy and Utilization Dilemma

- How to support encrypted search securely and efficiently?



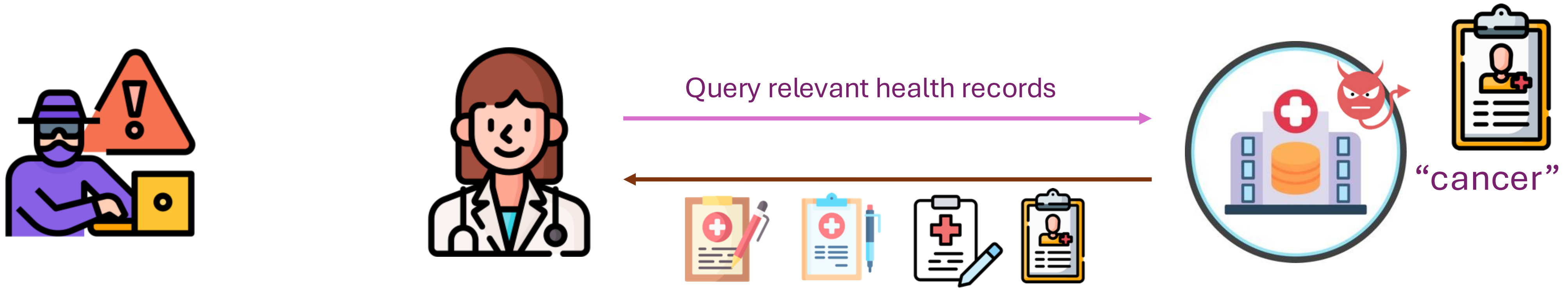
- **Searchable Encryption** (SE) was first proposed in 2000 [S&P'00]
- **Vulnerable** to many types of attack:
  - File-injection attacks
  - Keyword-guessing attacks*
  - Leakage-abuse attacks



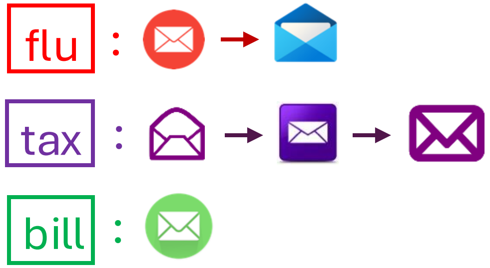
* *For public-key SE only (e.g., [EUROCRYPT'04, USENIX'22])*

Examples of Metadata Leakage Attacks

- There are potential attacks exploiting **metadata**. For example:



Access Pattern Leakage Attack



File-Injection Attack

Data intactness

Data and query confidentiality

The goal of my dissertation is to efficiently resolve **security**, **privacy**, and **functionalities** issues simultaneously in data outsourcing systems

Data/Query Searchability

Authenticated Storage

Data loss can happen due to:

- Hardware failures 
- Adversarial behaviors 

Two Decades of Proof of Retrievability (PoR)

First proposal

Proof of Retrievability [CCS'07]: Error Correcting Code (ECC), Static

Provable Data Possession [CCS'07]: Integrity of *most* data

2007

2009 — **[CCSW'09]** ECC; ↑ Error rate; Static

2011 — **[CRYPTO'11]** Verifiable Computation; Static; Audit: $O(N)$

2012 — **[ACSAC'12]** Dynamic; Update: $O(\log\log N)$; Audit: $O(\sqrt{N})$

2013 — **[CCS'13]** Dynamic; Incrementally Constructible Code (ICC); Update/Audit: $O(\log N)$; Proof size: $O(\beta + \lambda^2 \log N)$

2017 — **[JoC'17]** Dynamic, ECC; Efficient update; Update/Audit: $O(\log^2 N)$

2021 — **[USENIX'21]** Dynamic; Low server storage cost; Audit: $O(N)$

2023 — **[NDSS'23] (Ours)** Dynamic; ICC; Update/Audit: $O(\log N)$; Proof size: $O(\log \beta)/O(1)$

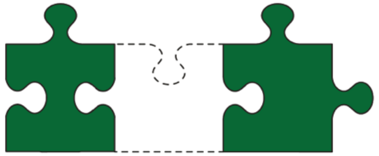
N: # blocks

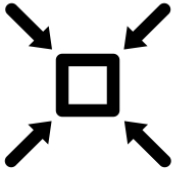
β: block size

λ: security parameter

Efficient Dynamic PoR for Cold Storage

- **Research Gap:**





  - Minimal audit cost: audit proof size and end-to-end audit latency

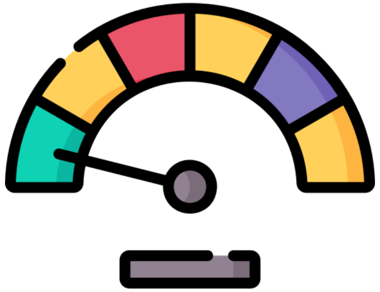
- Our **Porla** [NDSS'23]:

  - *Minimize* audit cost:
    - ✓ Audit bandwidth: $O(\log\beta)$ or $O(1)$, where:
    - ✓ Server/Client: $O(\lambda\log N)$

N: #data blocks

β: data block size

λ: security parameter

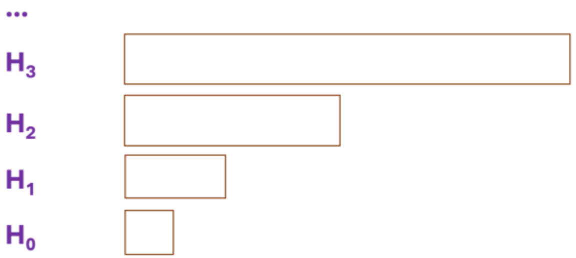


  - Maintain a reasonable update performance:
    - ✓ Server: $O(\log N)$
    - ✓ Client/Bandwidth: $O(\beta)$

[NDSS'23] **Tung Le**, Pengzhi Huang, Attila A. Yavuz, Elaine Shi, and Thang Hoang. "Efficient Dynamic Proof of Retrievability for Cold Storage." In *2023 Annual Network and Distributed System Security Symposium (ISOC NDSS 2023)*, San Diego, CA, March 2023.

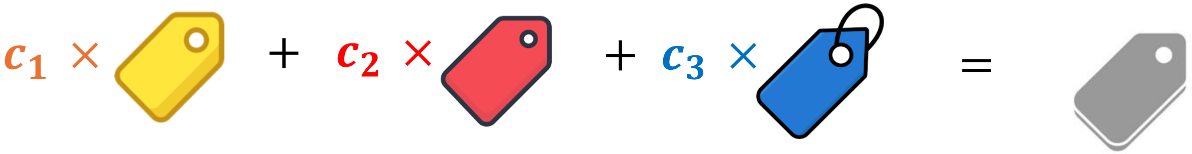
Our Porla [NDSS'23]

Main Techniques:

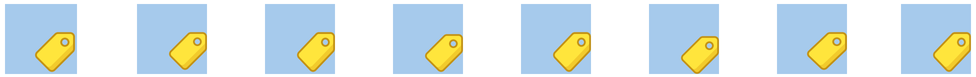


- Incrementally Constructible Code

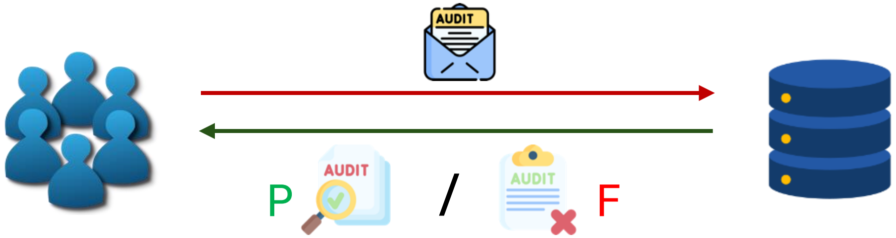
- Homomorphic MAC



- Verifiable Computation Techniques

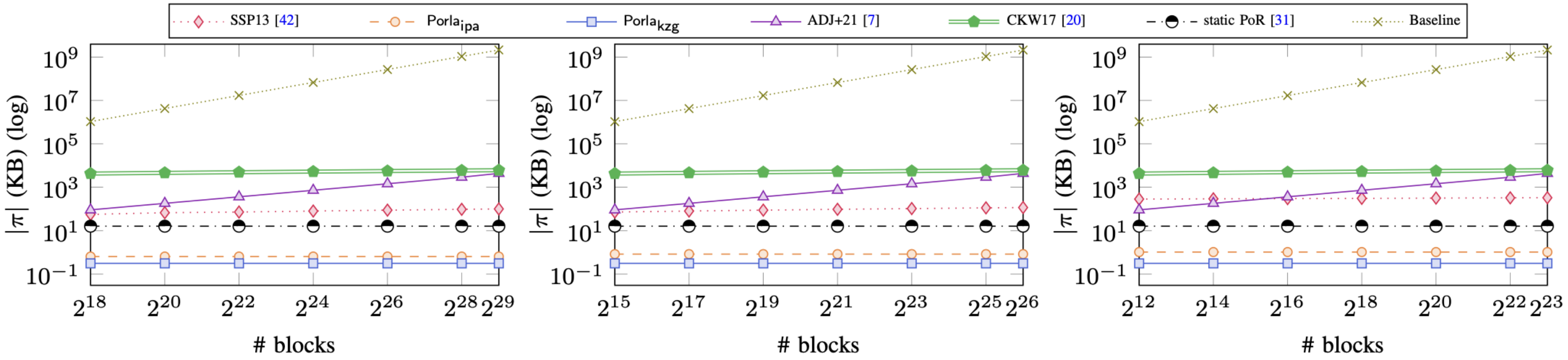


- Support Public Audit



Porla Achievements

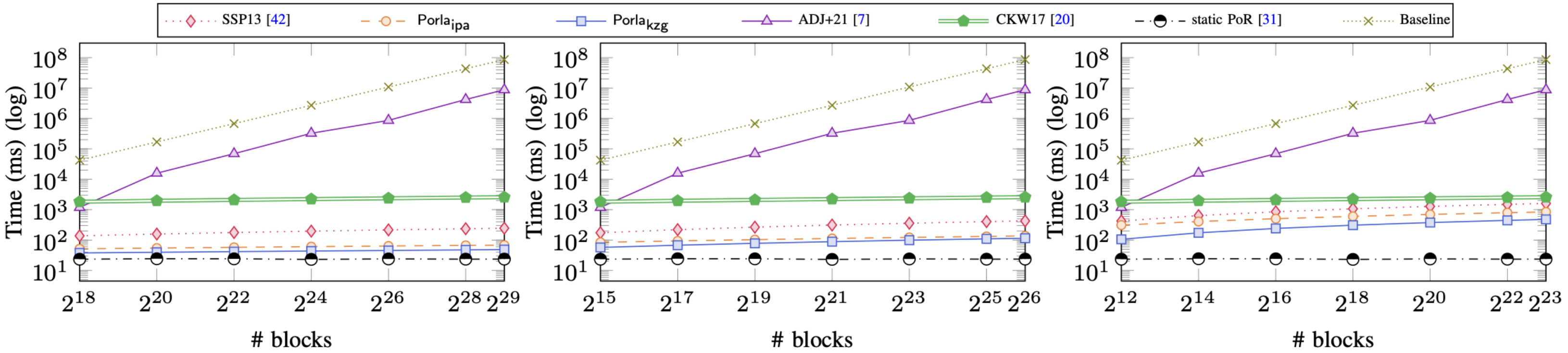
- 87 × –14,012 × smaller proof size than previous DPoR schemes



(a) $\beta = 4$ KB **(b)** $\beta = 32$ KB **(c)** $\beta = 256$ KB

Fig. 6: Audit proof size of Porla and its counterparts.

- 4 × –18,000 × faster audit time than prior approaches



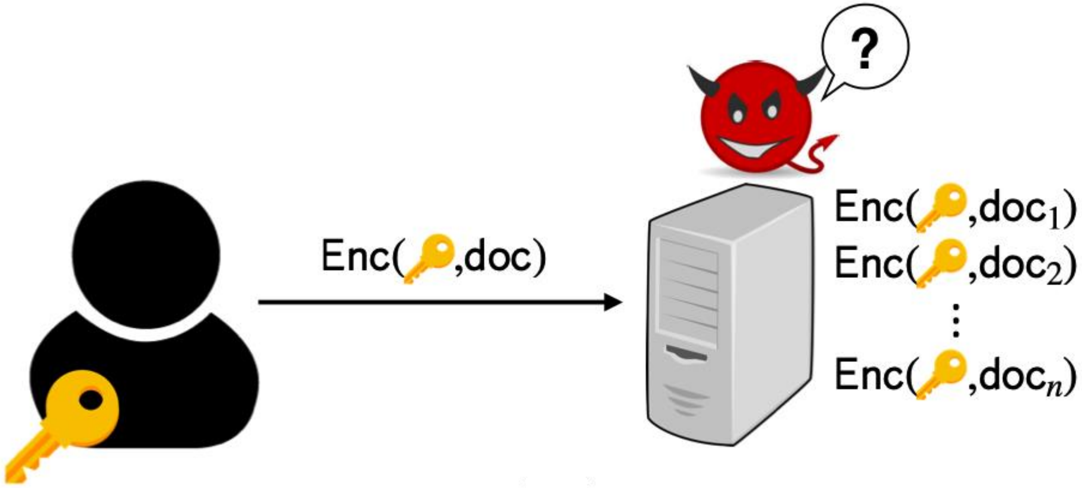
(a) $\beta = 4$ KB **(b)** $\beta = 32$ KB **(c)** $\beta = 256$ KB

Fig. 7: End-to-end audit delay of Porla and its counterparts.

Searchable Encryption: Motivation

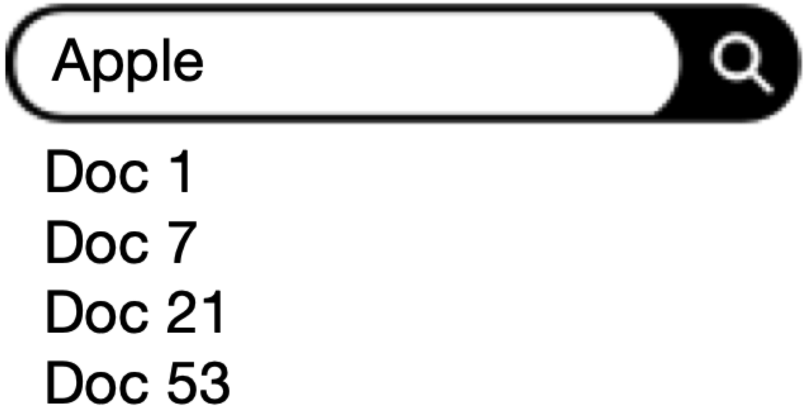
End-to-End Encryption (E2EE)

E2EE provides strong security guarantees if attacker compromises server

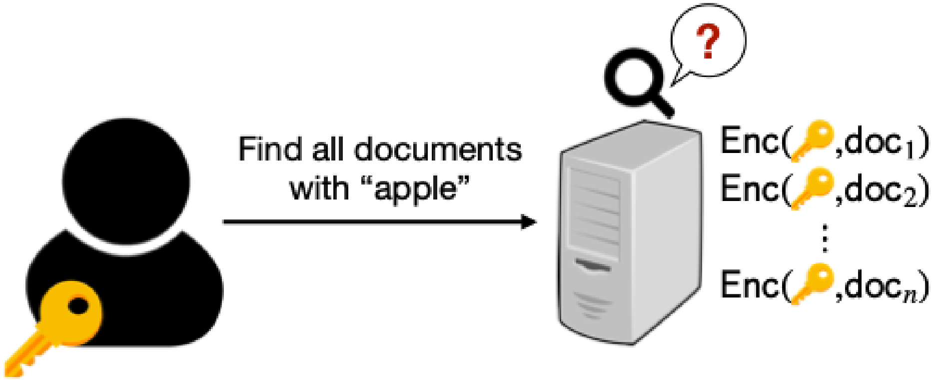


Searchable Encryption: Motivation

Users expect the ability to execute search



Challenge: server cannot decrypt data to search



20 Years+ of Searchable Encryption (SE)

VIRGINIA TECH

First proposal

2000 — **SSE [S&P'00]**
Search: $O(|DB|)$

2004 — **PKSE [EUROCRYPT'04]**
Support multi-writer
Search: $O(|DB|)$

2006 — **SSE [CCS'06]**
Search Comp.: $O(|r_w|)$
Search Comm.: $O(|r_w|)$
Static

2012 — **IKK (Access Pattern) Attack [NDSS'12]**
Known prior knowledge

2014 — **SSE [NDSS'14]**
Search Comp.: $O(|r_w|)$
Search Comm.: $O(|r_w|)$
Dynamic
No forward privacy

2016 — **Σοφος [CCS'16]**
Forward privacy
Search: $O(|r_w|)$
Leak patterns
File-injection Attack [USENIX'16]

2019 — **POSUP [PETS'19]**
Hide patterns
High overhead (ORAM)
Secure SGX hardware

2020 — **DORY [OSDI'20]**
Hide patterns (DPF)
Malicious security
Search Comp.: $O(N.m)$
Search Comm.: $O(N)$

2022 — **HSE [USENIX'22]**
Support multi-writer
Forward privacy
Keyword-guessing attacks
Search Comp.: $O(|W|)$
IHOP Attack [USENIX'22]
Similar prior knowledge

2023 — **MAPLE (Ours) [PETS'23]**
Hide patterns
Search Comp.: $O(N.\log m)$
Search Comm.: $O(N)$

2024 — **MUSES (Ours) [USENIX'24]**
Hide patterns
Search Comm.: $O(n_s)$

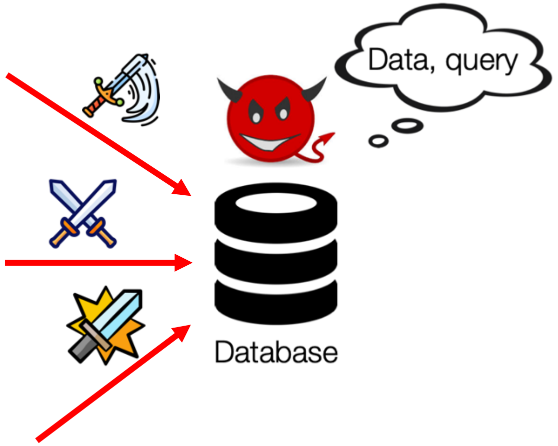
Improve communication, computation efficiency, and security

DB: database N: #documents W: keyword universe set m: keyword representation size n_s: search result size r_w: #matches

Pattern-Leakage Attacks

Numerous Leakage-Abuse Attacks in Searchable Encryption:

- **Search Pattern:** Repetition in search queries [USENIX’21, USENIX’22, CCS’23, USENIX’24]



- **Result Pattern:** Repetition in matching documents [NDSS’12, CCS’15, CCS’16, NDSS’20, CCS’21, NDSS’22, USENIX’22]

- **Volume Pattern:** Repetition in the number of matching documents [CCS’15, USENIX’21, CCS’23, USENIX’24]

Our MAPLE [PETS'23]

Research Gap:

- Hide search result pattern with search complexity $O(N.m)$, where N is the number of documents and m is the keyword representation size
- Limited multi-user support: assume all users are trusted or control access policies based on access level

Our **MAPLE** [PETS'23]:

- Server search complexity: $O(N.\log m)$
- Hide *all* metadata: search, result and volume patterns
- Multi-user with fine-grained access control

[PETS'23] **Tung Le**, and Thang Hoang. "MAPLE: A Metadata-Hiding Policy-Controllable Encrypted Search Platform with Minimal Trust." In 2023 Privacy Enhancing Technologies Symposium *(PETS 2023)*, Lausanne, Switzerland, July 2023.

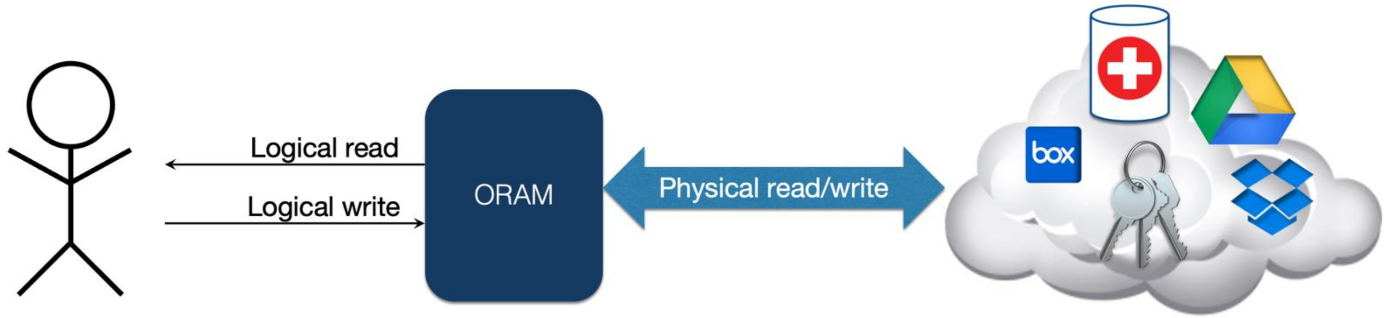
Main techniques:

- Bloom Filter to compress search index

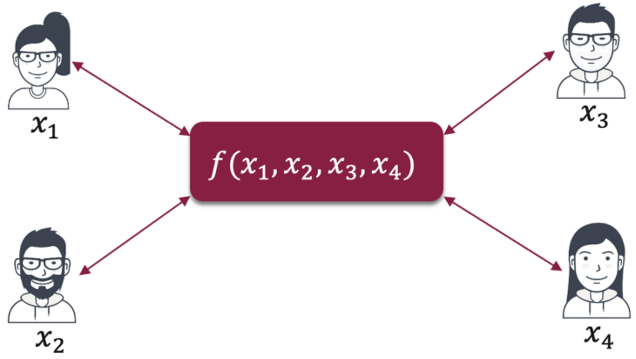
	"amazon"	"google"	"netflix"	...	"apple"
doc 1	1	0	1	0	1
doc 2	0	1	1	0	0
doc 3	1	1	0	0	0
...	0	1	0	1	1
doc N	1	0	0	1	1

Bitmap for keywords in doc 2

- Oblivious Random Access Machine (ORAM)
  - Circuit ORAM
  - Oblivious Table



- Multiparty Computation



MAPLE Achievements

- MAPLE is $2.6\times - 10.7\times$ slower than DORY with BF size $\leq 2^{14}$, and starts to outperform when BF size $\geq 2^{16}$

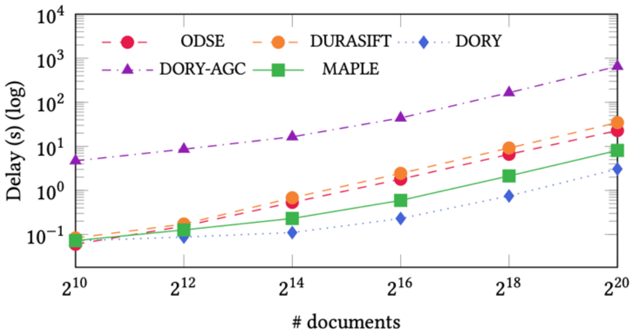


Figure 5: Search delay of MAPLE and its counterparts.

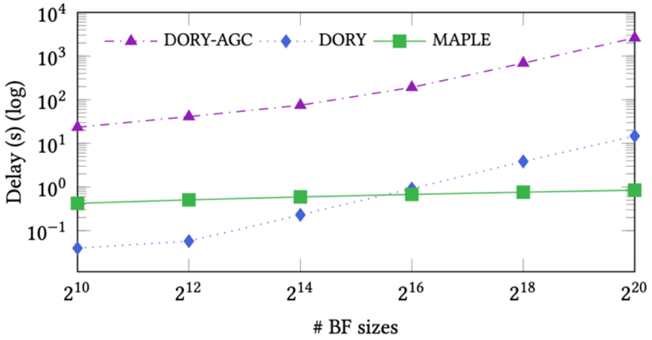
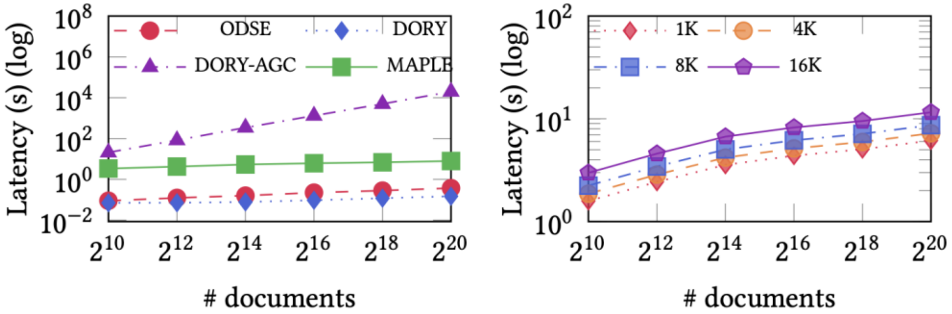


Figure 6: Search delay with varied BF sizes.

- MAPLE is 3.3s – 7.8s slower to achieve oblivious update

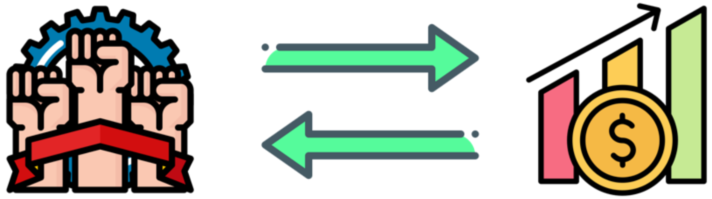


(a) Document update **(b) Permission update**

Figure 8: Update delay of MAPLE and its counterparts.

Our MUSES [USENIX'24]

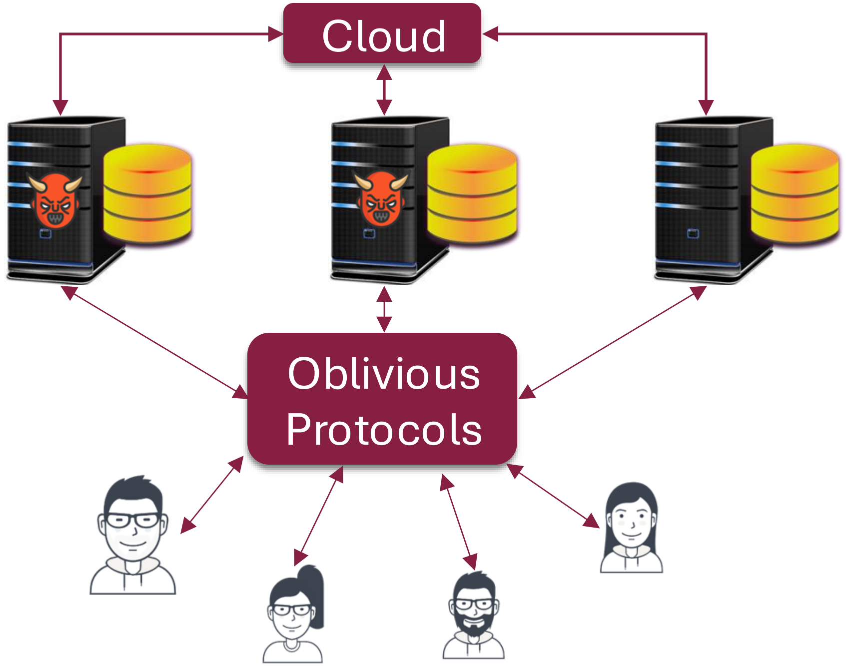
- Generic MPCs are powerful but expensive



- Distributed computations specifically designed for a particular computation task are more efficient

Our **MUSES** [USENIX'24]:

- Hide *all* statistical information: search, result, and volume patterns
- Minimal user overhead for search and permission revocation

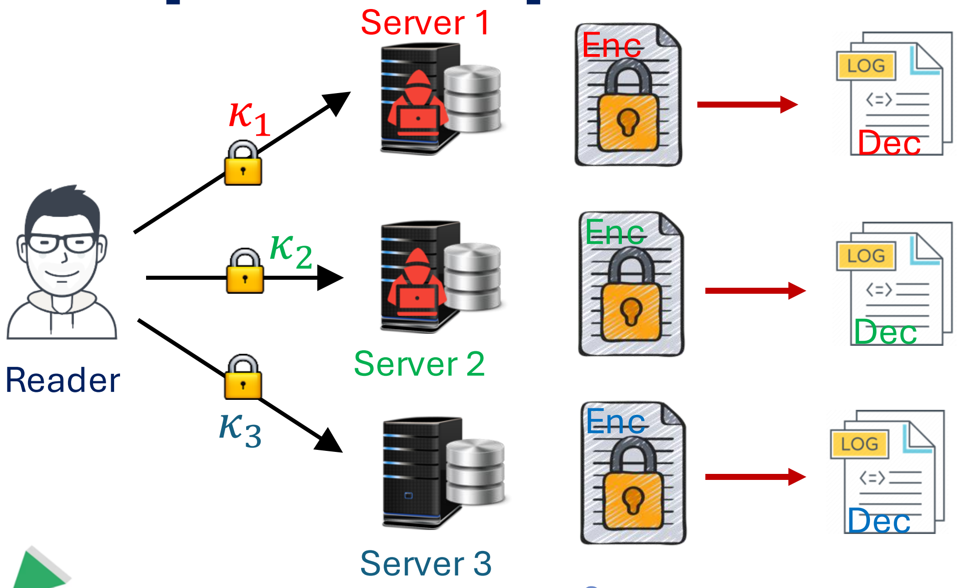


[USENIX'24] **Tung Le**, Rouzbeh Behnia, Jorge Guajardo, and Thang Hoang. "MUSES: Efficient Multi-User Searchable Encrypted Database." In USENIX Security Symposium *(USENIX Security 2024)*, Philadelphia, PA, August 2024.

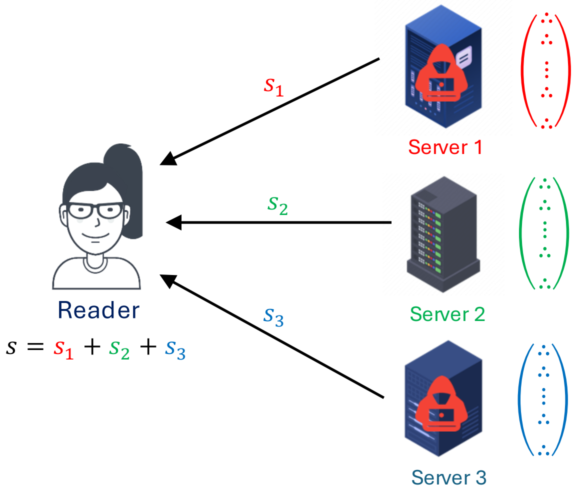
Main techniques:

- Key-Homomorphic Pseudorandom Function [CRYPTO'13]

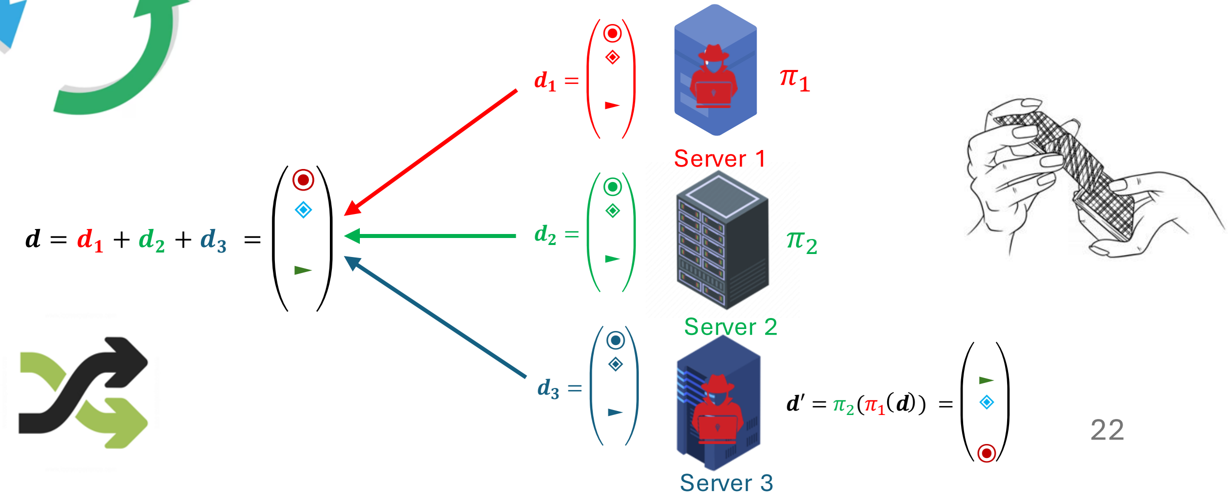
Delegating Decryption



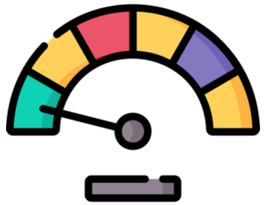
- Our Multiparty Oblivious Counting



- Our Multiparty Oblivious Shuffling



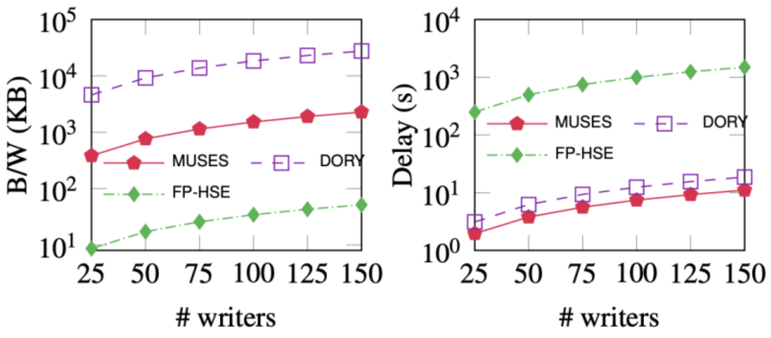
Reader's bandwidth:



12 × −97 × smaller than DORY (hide patterns), 6 × larger than FP-HSE (leak patterns)

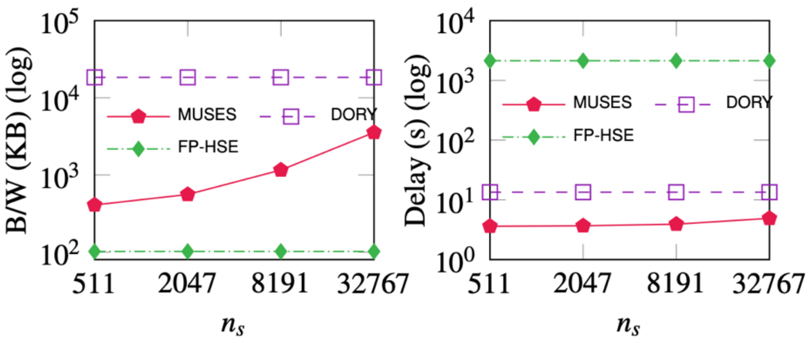
End-to-end latency:

2 × −4 × faster than DORY, 127 × −632 × faster than FP-HSE



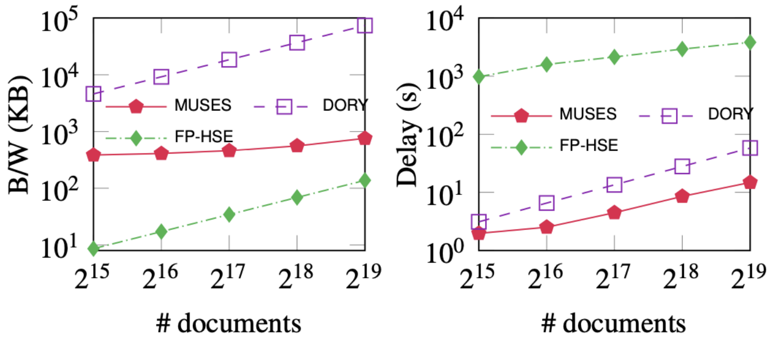
(a) Reader's bandwidth (b) E2E delay

Figure 6: Keyword search performance (log scale on y-axis).



(a) Reader's bandwidth (b) E2E delay

Figure 10: Keyword search performance with varying n_s.



(a) Reader's bandwidth (b) E2E delay

Figure 11: Keyword search performance w/ varying database sizes.

MUSES Achievements: Permission Revocation

Writer’s bandwidth:

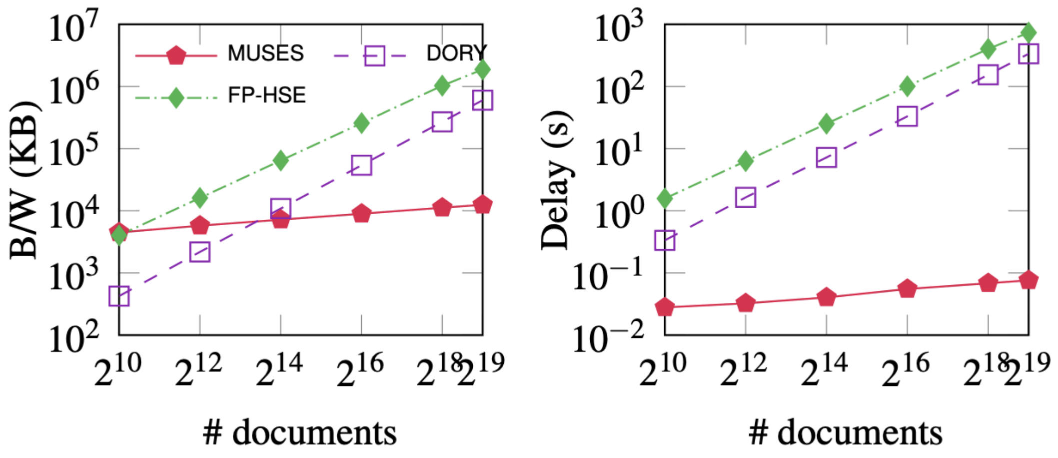
$2\times - 150\times$ smaller than DORY/FP-HSE

End-to-end latency:

$2\times - 6\times$ faster than DORY/FP-HSE

Writer’s latency:

$12\times - 9600\times$ faster than DORY/FP-HSE



(a) Writer’s bandwidth (b) Writer’s latency

Figure 7: Permission revocation performance (log scale on y-axis).

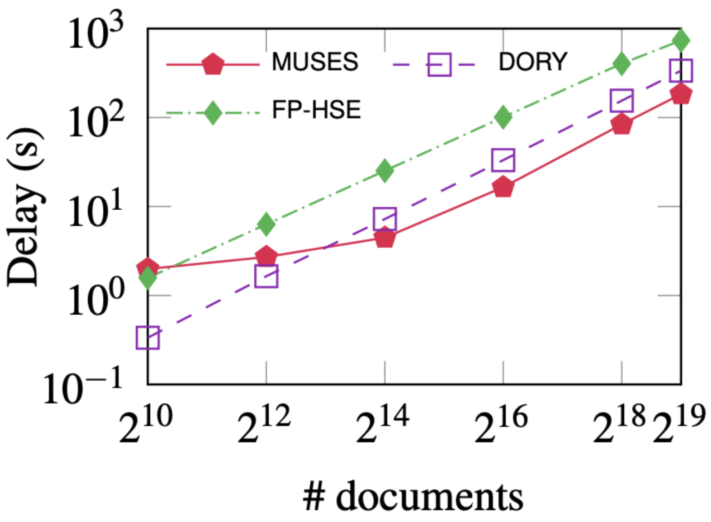
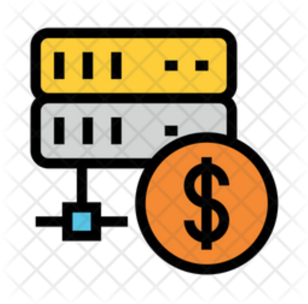


Figure 8: E2E permission revocation delay (log scale on y-axis).

Ongoing Work

- Our prior work relies on distributed computation for secure search
  - Expensive deployment and maintenance cost
- PKSE [EUROCRYPT’04, USENIX’22] can support multi-user more naturally in practical settings (e.g., email, messaging)

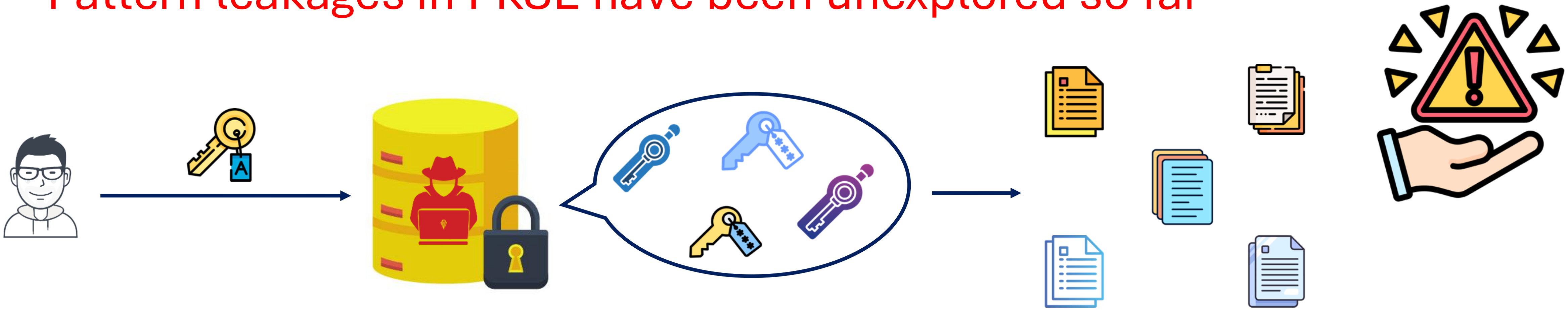
- Many open problems:
  - Keyword-guessing attacks
  - Inefficient forward privacy
  - High server computation cost for search



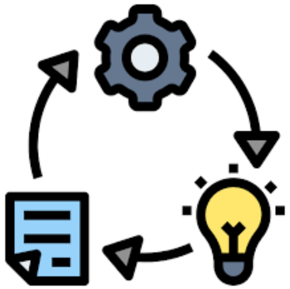
- This work addresses the above fundamental security and performance issues

Future Work

- Pattern leakages in PKSE have been unexplored so far



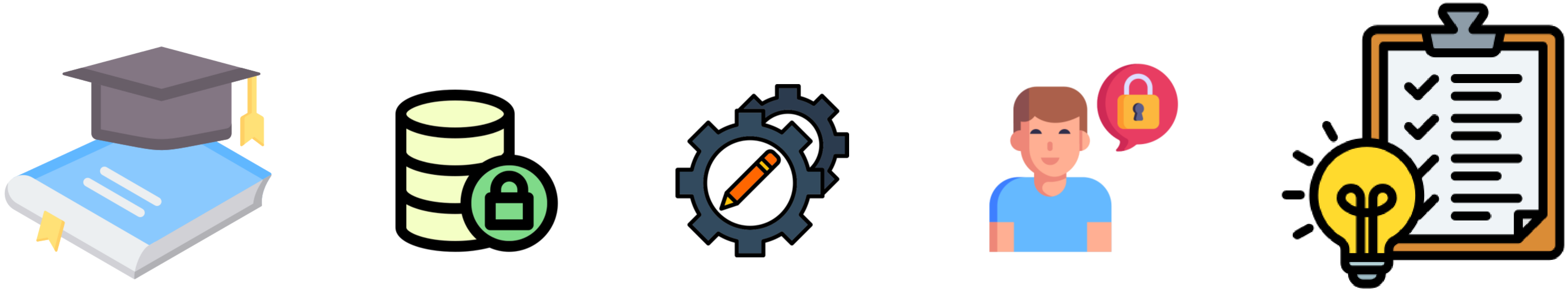
- We aim to resolve pattern-leakage attacks in public-key settings while maintaining/improving efficiency



Conclusion

- My dissertation aims to: 
  - Design an authenticated and retrievable data storage system
  - Address user/data privacy and utilization dilemma: provide efficient search functionality while preventing information leakage

 All are essential to build practical encrypted data outsourcing systems providing high performance and security guarantees



THANK YOU FOR YOUR ATTENTION

Q&A

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