A framework for searching encrypted databases

Pedro Geraldo M. R. Alves,
Diego F. Aranha

Laboratory of Security and Applied Cryptography
Instituto de Computação, Universidade Estadual de Campinas

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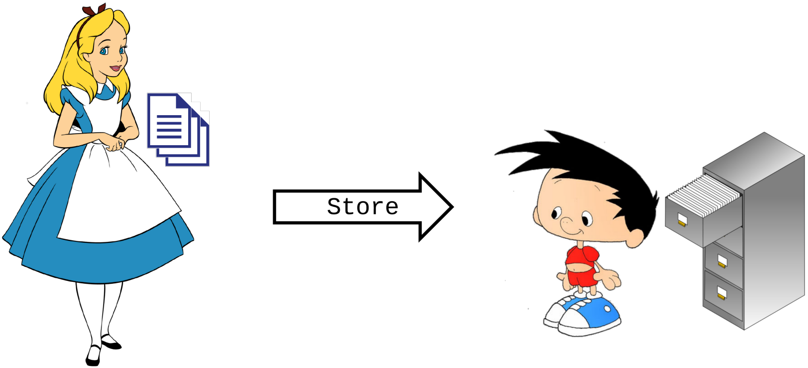
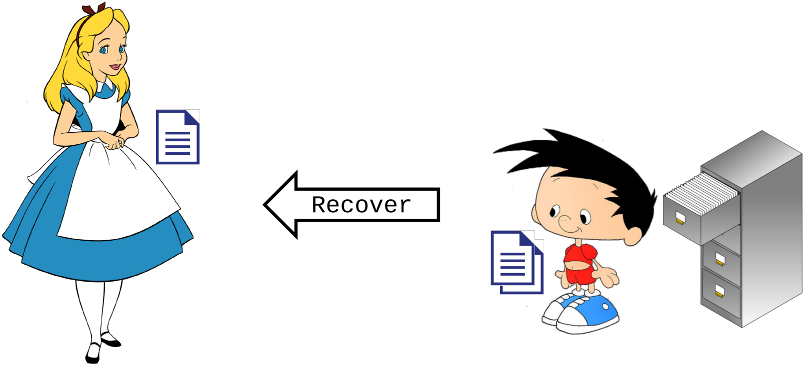
The unstrusted storage

Storing



The unstrusted storage

Recovering



Searching on encrypted datasets

Security requirements

1. Bob is not trustworthy.
   - Confidentiality must be preserved.
   - Secure storage.
2. Alice would like to occasionally retrieve subsets of documents according to predicates.
   - Communication is constrained.
   - Secure searching.

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PRISM, Yahoo, Ashley Madison,...

Searching on encrypted datasets – **CryptDB**

- SQL-only.
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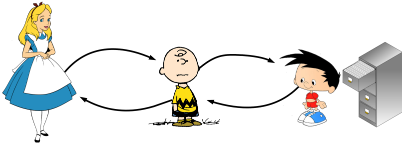
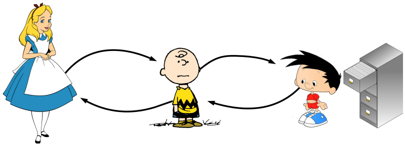
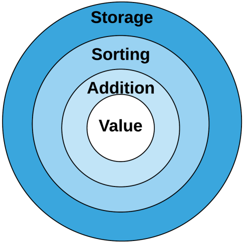
  - Logged-in users are vulnerable.



Searching on encrypted datasets – **CryptDB**

- SQL-only.
- Open-source.
- User – Aplication – Database.
  - Logged-in users are vulnerable.
- Onions.
- *Selection* overhead of 6 times.





Searching on encrypted datasets – **Arx**

- Implemented on top of **MongoDB**.
- **Not** open-source (but plans to be).
- Application – Database.
- Rather than onions, data structures.
  - Requires the **previously knowledge** about what operations will be executed on each field.
- Arx-Range and Arx-Eq built over **AES** or a *deterministic* scheme.
- Arx-Eq overhead of 2 times.
- Arx-Range takes 6 *ms* in the worst case scenario for a **1M-records database** (30 times slower ?).
- Slower but more secure ?

Building blocks

Building blocks

Homomorphic encryption (HE)

Let

- **E** and **D** be a pair of **encryption and decryption** functions,
- m_1 and m_2 be plaintexts.

The pair (E, D) forms an **encryption scheme** with the **homomorphic property** for some operator $\diamond$ if and only if the following holds :

$$E(m_1) \circ E(m_2) \equiv E(m_1 \diamond m_2).$$

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For example, in **ElGamal's proposal**, $\circ =$ multiplication and $\diamond =$ addition.

Building blocks

Order-revealing encryption (ORE)

Let

- **E** be an **encryption** function,
- **C** be a **comparison** function,
- m_1 and m_2 be plaintexts.

The pair (E, C) is defined as an **encryption scheme** with the **order-revealing property** if and only if :

$$C(E(m_1), E(m_2)) = \begin{cases} \text{LOWER}, & \text{if } m_1 < m_2, \\ \text{EQUAL}, & \text{if } m_1 = m_2, \\ \text{GREATER}, & \text{otherwise.} \end{cases}$$

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For example, **[Chenette *et al.* 2015]** and **[Lewi and Wu 2016]** work.

The framework

Objective : Develop **a model** for databases capable of **storing** and **searching** on encrypted records **without any cryptographic key**.

The framework

Classes of attributes

- **Records** in a database **are composed by attributes**. These consist of a **name** and a **value** and may be **classified** according to their **purpose**.

static An *immutable* value only used for storage.

index Enables *comparison* between *index* attributes. Used for building a searchable index.

computable A mutable value. It supports the *evaluation* by a mathematical function.

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static	An *immutable* value only used for storage.
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computable	A mutable value. It supports the *evaluation* by a mathematical function.

- **ORE** and **HE** schemes are natural candidates for *index* and *computable* attributes.

The framework

Building an index

In order to build a **secure and efficient** *index* we need a **Secure ORE**. This is **defined as** an ORE scheme such that $E(m) = (c_L, c_R)$ and $C\left(c_{L1}, c_{R2}\right)$.

The framework

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Encrypted search framework

Let **S** be a set of words, **(E,C)** the encryption and comparison functions of a **secure ORE** scheme and **(sk, pk)** secret and public keys.

$\textsc{BuildIndex}_{sk}(S)$: Output the set
$$S^* = \{c_R \ \mid (c_L, c_R) = \mathrm{E}_{sk}(w), \forall w \in S\}.$$

$\textsc{Trapdoor}_{sk}(w)$: Output the trapdoor $T_w = (c_L \mid (c_L, c_R) = \mathrm{E}_{sk}(w))$.

$\textsc{Search}_{S^*,\ r}(T_w)$: It iterates through $\mathcal{I}$ and outputs **every record such that** $C\left(T_w, w^*\right) = r$.

The framework

Database operations

- The relational algebra proposed by **[Codd 1983]** must be revisited for building a functional database.

Selection (σ) : Uses $\textsc{Search}$ to select records with the relationship $\mathbf{r} \in \{\text{LOWER}, \text{EQUAL}, \text{GREATER}\}$ when compared to **w**.

Projection (π) : In a collection of records, **selects** a subset of attributes A according to their **names**.

encrypted : Deterministic encryption or treated as *index* values.

deterministic : Selection by $(Enc_{deterministic}(a) \mid a \in A)$.

index : Selection by $\textsc{Search}$ using $(Trapdoor(a) \mid a \in A)$.

unencrypted : Standard algorithm.

The framework

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Difference ($-$) : $A - B = \sigma_{\text{not in B}}(A)$.

Union ($\cup$) : $A \cup B = A + (B - A)$.

Intersect ($\cap$) : $A \cap B = \sigma_{\text{in B}}(A)$.

The framework

Database operations

Insert : Standard algorithm (**but records are inserted encrypted by the data owner**).

Cartesian product ($\times$) : Standard algorithm.

Update : Standard algorithm (**but only for *computable* attributes**).

Rename (ρ) : Applied on $\pi_A(\sigma_r)$.

- encrypted: Deterministic encryption or treated as *index* values.
  - *deterministic*: Replaces by $(a = Enc_{deterministic}(b) \mid a \in A)$.
  - *index*: Replaces by $(a = \textsc{Trapdoor}(b) \mid a \in A)$.
- unencrypted: Standard algorithm.

The framework

Security analysis

Pros

- Operates over an encrypted database **without the cryptographic keys**. The data owner has exclusive possession of cryptographic keys.
- Preservation of privacy **while the user is not compromised**.
- The **comparison** function may have its use **limited**.

The framework

Security analysis

Pros

- Operates over an encrypted database **without the cryptographic keys**. The data owner has exclusive possession of cryptographic keys.
- Preservation of privacy **while the user is not compromised**.
- The **comparison** function may have its use **limited**.

Cons

- Unable to **hide repeated queries**.
- Each query **reveals** the **other half** of the ciphertext.

The framework

Performance analysis

Pros

- SEARCH may be implemented with **logarithmic complexity**.
- State-of-the-art ORE proposals are built over **symmetric primitives**.

Cons

- Speed overhead.
- Space overhead.
- Does **not** support selection by **regular expressions**.

Conceptual implementation

- A proof-of-concept implementation for MongoDB was developed and **is available** to the community – `github.com/pdroalves/encrypted-mongodb`.
- Wrapper for the Python's driver.
- Implements :
  - **AES** for *static*.
  - **Lewi-Wu** for *index*.
  - **Paillier** and **ElGamal** for *computable*.
- BUILDINDEX generates an **AVL tree**.
- MongoDB **is not friendly** to custom index structures and comparators, so walking through the tree depends on a **database-external operation** at Python-side.

Conceptual implementation

Benchmark

TABLE – Attribute structure of elements in the synthetic dataset.

Name	Value type	Class
e-mail	string	*static*
firstname	string	*static*
surname	string	*static*
country	string	*static*
age	integer	*index*
text	string	*static*

Conceptual implementation

Benchmark

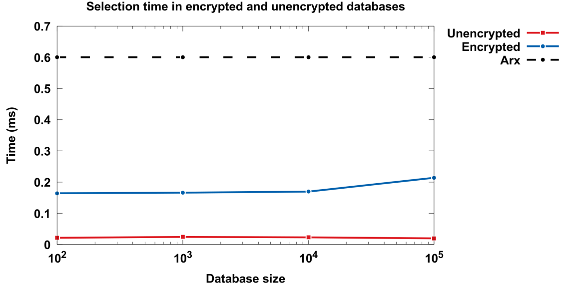

FIGURE – Time required to perform **a selection query in the worst case scenario** for an **AVL tree-based index** and 128 bits security level. The measures are the average of 100 independent executions [1].

- Space consumption increased 36%.
- Speed overhead **overhead** goes **from 7 to 11 times**.

1. Machine : Intel Xeon E5-2630 CPU at 2.60GHz, 32GB of RAM and a Seagate Barracuda SATA3-HD at 7200rpm.

Conclusion and future work

Conclusion

- We propose a framework for building **functional-encrypted databases**.
- Codd's **relational algebra was revisited** for encrypted-databases and it keeps former computational complexity.
- Privacy is **preserved** even if the database or application gets compromised.
- A proof-of-concept **implementation for MongoDB** was presented.

Future work

- Pursue a **more efficient** implementation.
- Apply the framework in a **real-world** application.

Conclusion and future work

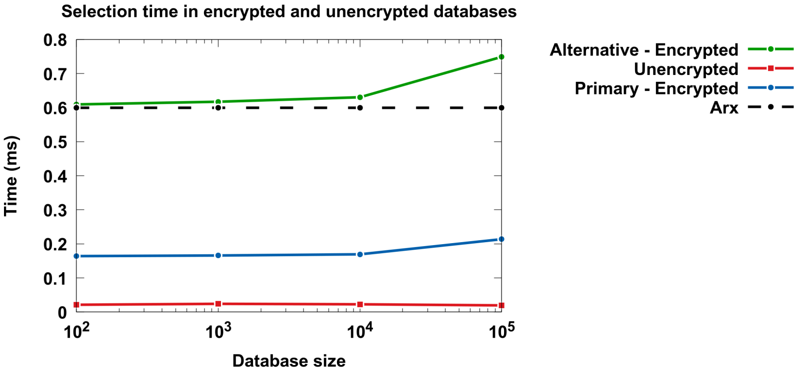

FIGURE – **Time required** to perform **a selection query in the worst case scenario** for an **AVL tree index**. Two approaches for encrypted databases are presented. The measures are the average of 100 independent executions.

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Bibliography

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- **Codd**, 1983. *A relational model of data for large shared data banks*.
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