Searchable Encryption

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Summer Internship in Cryptology
R. C. Bose Centre for Cryptology and Security

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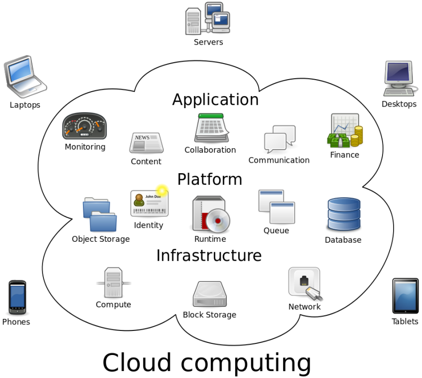
Cloud Services



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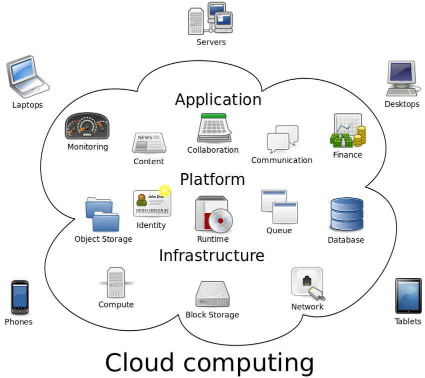

Cloud Computing Services

- Amazon Web Services (AWS)
- Microsoft Azure
- Google Cloud Platform
- IBM Cloud

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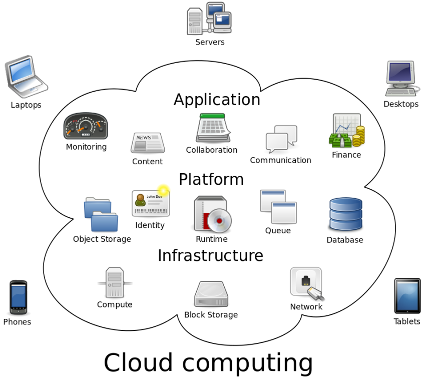

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Cloud Storage Services

- Google Drive
- Dropbox
- Microsoft Onedrive

Can we trust Remote Storage Service Providers?

Cloud Computing and Storage

- Email service providers- Gmail, outlook.com, Yahoo! Mail etc.
- Stoarge service providers- Google Drive, Dropbox etc.
- Institutional Server

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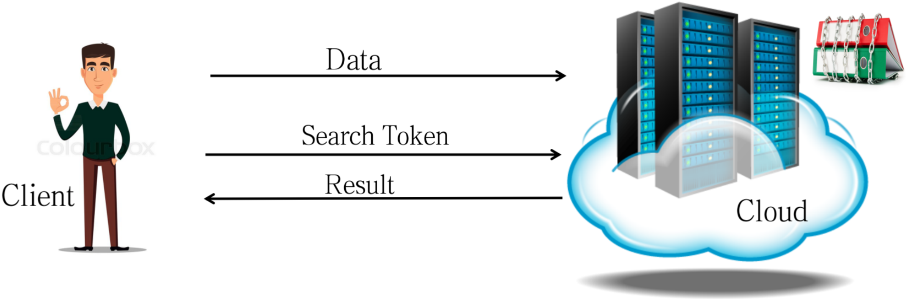
No!

Privacy-Preserving Computation



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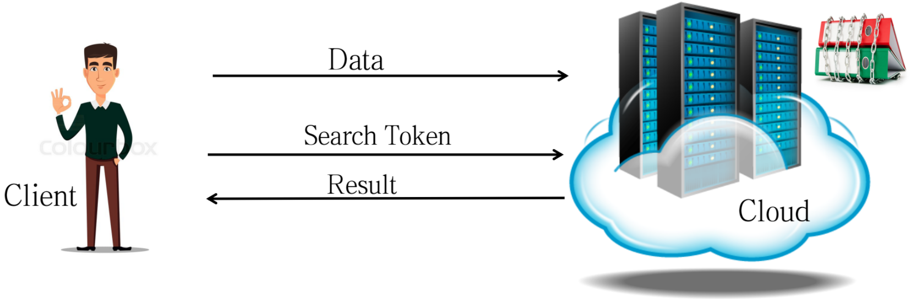

- Preserve search privacy $\rightarrow$ Private Information Retrieval

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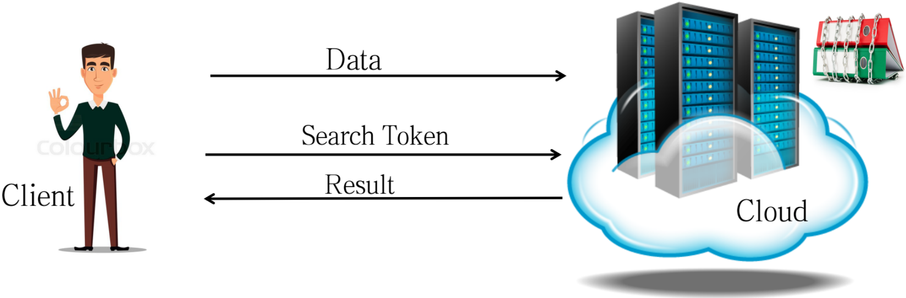

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- Data repository is huge → Privacy-preserving data mining

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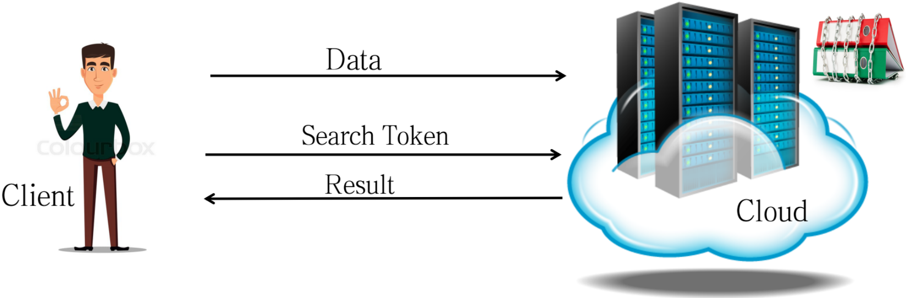

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- Data are encrypted → Searchable Encryption

Trivial Solution

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- Does NOT solve the purpose of using cloud

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  - Search Results

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- What about channel?
  - Secure?
  - Can it be aborted?

Cryptographic Tools

Pseudo Random Function (PRF)

Definition

$F : \{0,1\}^k \times \{0,1\}^n \rightarrow \{0,1\}^m$

- $\forall$ key $K \in \{0,1\}^k$, and $\forall x \in \{0,1\}^n$, $F(K, x)$ or $(F_K(x))$ is Efficiently computable
- F is Indistinguishable from a random Function

Pseudo Random Permutation (PRP)

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- DES
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Note

- a PRP is a PRF

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Deterministic random bit generator

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Properties

- Given a seed (start state), produces a sequences of random numbers/bits
- Efficient: Can produce many numbers/bits in a short time
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Examples

- Stream cipher
- linear congruential generator
- Multiple-recursive generators

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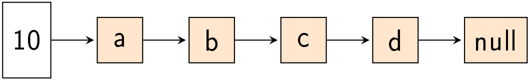
Examples

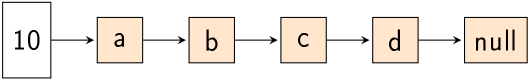
- SHA-0, SHA-1, SHA-2, SHA-3, MD5, SHA256 etc.

Data Type and Structures

Linked List



Linked List



Operations

- Create (Link List)
- Insert (a Node)
- Delete (a Node)

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A collection of (key-value) pairs, such that each possible key appears at most once in the collection.

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Operations

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- Search whether a key exists

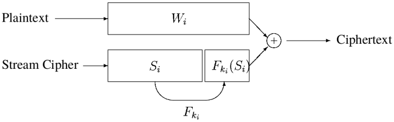
Properties

- Creation: In constant time
- Insertion: In logarithmic time
- Search: In constant time

Song et al. [SWP00] Scheme

Scheme I

Encrypt a document $D = (W_1, W_2, \ldots, W_l)$ as follows



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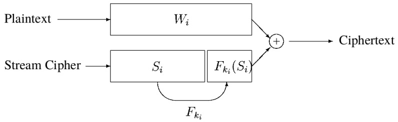

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For each i

- $T_i = S_i || F_{k_i}(S_i)$
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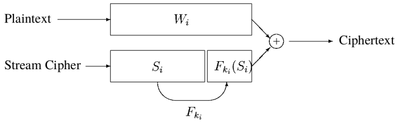

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Finally uploads $Enc(D) = (C_1, C_2, \ldots, C_l)$

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Search

To search for a word W

- Must reveal all the k_i

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Solution

- Alice must know in advance which locations W may appear

Scheme II

- $k_i = f_{k'}(W_i)$, solves problem with keys
- $T_i = S_i || f_{k_i}(S_i)$, f is a PRF
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Scheme II

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Search

To search for a word W

- Only reveals all the $f_{k'}(W)$, Controlled searching.
- Check all positions
- If any decryption matches, returns the Doc

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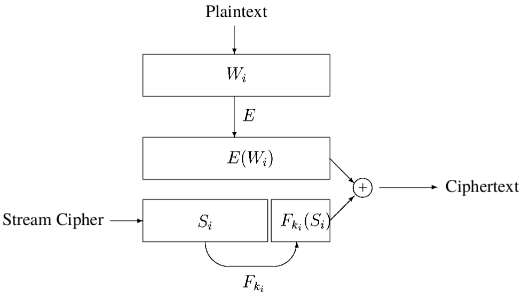
- W is revealed during search

Scheme III



- $Xi = E_{k''}(W_i)$, $E_{k''}$ is a deterministic encryption algorithm
- $k_i = f_{k'}(X_i)$
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To search for a word W

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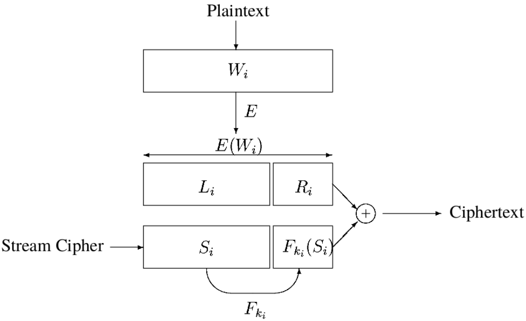
Problems

- Owner can't recover the plaintext as $E_{k''}(W_i)$ is needed for decryption
- Applicable for Scheme II

Scheme IV- Final Scheme



- $X_i = E_{k''}(W_i)$, $E_{k''}$ is a deterministic encryption algorithm
- $X_i =< L_i||R_i >$
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Scheme IV

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- Sends (X, k) computed similarly

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Decryption

To search for a word W

- Generate S_i
- Recover L_i XORing S_i with C_i
- Recover $k_i = f_{k'}(L_i)$,
- Recover X_i
- Get W_i Decrypting X_i

Major Disadvantage

- Every keywords of every files have to be decrypted

Eu-Jin Goh [Goh03] Scheme

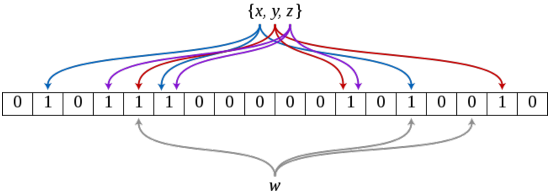
Main Contribution

- Defined Secure index
- Formulated Security Model for indexes

Background

Bloom Filter

- A set $S = s_1, \ldots, s_n$, represented by an array of m bits.
- All array bits are initially set to 0
- The filter uses r independent hash functions $h_1, \ldots, h_r$,
- To determine if an element a belongs to the set S, checks whether all $h_i(a)$ are 1 or not



Scheme Overview

Key Generation

Given Security parameter s

- $f : \{0,1\}^n \times \{0,1\}^s \rightarrow \{0,1\}^s$, pseudo-random function
- $k_1, \ldots, k_r \leftarrow \{0,1\}^s$, keys for hash functions
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Build Index

Given K_{priv} and a document $D = (w_0, \ldots, w_t)$ with identifier D_{id}

- For each unique word wi for $i \in [0, t]$, -
  - Compute trapdoor: $(x_1 = f(w_i, k_1), \ldots, x_r = f(w_i, k_r)) \in \{0,1\}^{sr}$,
  - Compute codeword for w_i in $D_{id} : (y_1 = f(D_{id}, x_1), \ldots, y_r = f(D_{id}, x_r)) \in \{0,1\}^{sr}$
  - Insert $y_1, \ldots, y_r$ into D_{id} 's Bloom filter BF.
- Output $\mathcal{I}_{D_{id}} = (D_{id}, BF)$ as the index for D_{id} .

Scheme Overview

Trapdoor Generation

Given a keyword w

- $T_w = (f(w, k_1), \ldots, f(w, k_r))$

Search

- $(x_1, \ldots, x_r) \leftarrow Tw$
- The index $\mathcal{I}_{D_{id}} = (D_{id}, BF)$ for document D_{id}
- For w Compute
  $D_{id} : (y1 = f(D_{id}, x1), \ldots, yr = f(D_{id}, xr)) \in \{0, 1\}^{sr}$.
- Test if BF contains 1's in all r locations denoted by $y1, \ldots, yr$

Chang and Mitzenmacher [CM05] Scheme

Scheme Description

Privacy Preserving Keyword Searches on Remote Encrypted Data [CM05]

Scheme overview

- Skip Now

Major Issues of Earlier Schemes

- Greater Search Complexity: Linear in number of documents

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- Leaks Search Pattern: Whether two queries were for the same keyword or not
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SSE can be achieved using oblivious RAMs (O-RAM)

- Functionality: can simulate any data structure in a hidden way, and can support conjunctive queries, B-trees etc...
- Privacy: hides everything, even the access pattern
- Efficiency: logarithmic number of rounds per each read/write

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Question?

Can we search over encrypted data in single/constant rounds?

- with privacy,
- with efficiency

Curtmola et al. [CGKO06] Scheme

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Inverted Index

- Index data structure
- Maps content to its locations in a database

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D_1 ← {cryptography, search, symmetric, encryption}

D_2 ← {public, encryption, add}

D_3 ← { add, public, cryptography}

D_4 ← {search, symmetric, encryption, decryption, add}

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$D_2 \leftarrow$ {public, encryption, add}

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$D_4 \leftarrow$ {search, symmetric, encryption, decryption, add}

Content	Locations
encryption	$[D_1, D_2, D_4]$
symmetric	$[D_1, D_4]$
decryption	$[D_4]$
cryptography	$[D_1, D_3]$
add	$[D_3, D_4]$
search	$[D_1, D_4]$
public	$[D_2, D_3]$

Table: Inverted Index corr. to $\mathcal{D}$

Notations

- $D = (D_1, \ldots, D_n)$- Document Collection
- D_i- Document
- T- A Table
- A- An Array
- L_i- The Link list corr. to D_i
- F- A PRP
- G- A PRG
- H- A keyed Hash function

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A tuple of PPT algorithms as follows

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- **Key Generation:**
  - Input: A security parameter k
  - Output: A secret key K

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A tuple of PPT algorithms as follows

- **Key Generation:**
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- **Encryption:** a document collection D
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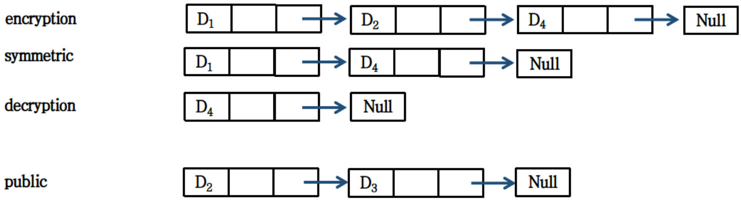
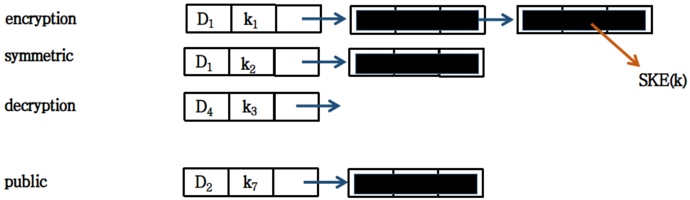
- **Decryption:** for an encrypted document D_i
  - Input: A secret key K and a ciphertext ci
  - Output: A document D_i

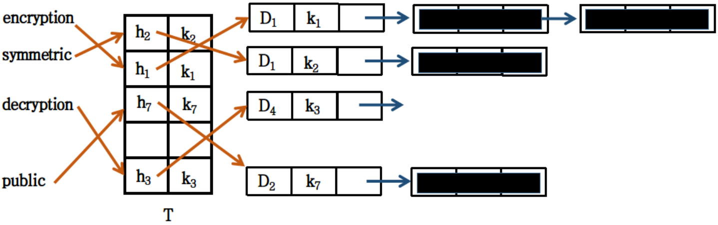
Build Inverted Index



Encrypt List Entries



Make Search Table



Encrypt 1st Node

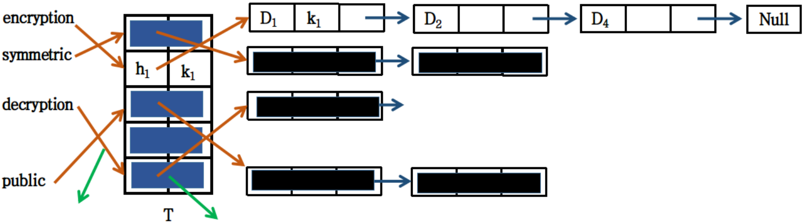
Encrypt Table

Search: Generate Trapdoor

Trapdoor = $<\mathrm{PRP}(k'', w_2),\ \mathrm{PRG}(k', w_2)>$

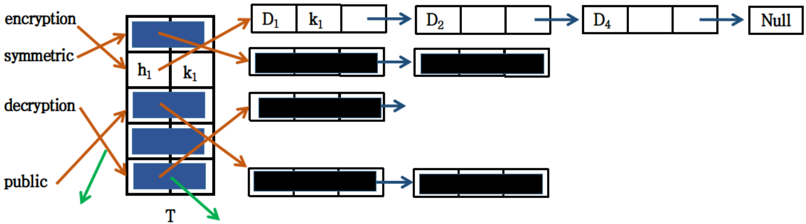
Search: Decrypt List

Trapdoor = < PRP (k'',w_2), PRG (k',w_2) >



Search: Return Result

Trapdoor = < PRP (k'', w_2), PRG (k', w_2) >



Returns = { D_1, D_2, D_4 }

Advantages

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Search Complexities

- # decryption $\leftarrow$ O(Search Result)

Advantages

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- # decryption $\leftarrow$ O(Search Result)

Communication Complexities

- # rounds $\leftarrow$ constant

Advantages

Search Complexities

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- # rounds $\leftarrow$ constant

Privacy

- Yes

Issues

Previous Schemes are STATIC

- One encrypted index is generated, Can't be changed
- Does not support Addition of document
- Does not support Deletion of document
- Does not support Addition of word in a document
- Does not support Deletion of word from a document

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In Practical

- Database should support word of file updates

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In Practical

- Database should support word of file updates

Dynamic SSE

- SSE that Supports updates

Definition of Dynamic SSE

Definition of Dynamic SSE

Skip Now :)

Few Remarkable works on Dynamic SSE

Kamara et al. [KPR12] Scheme

Scheme Overview

- 1st ever work on Dynamic SSE

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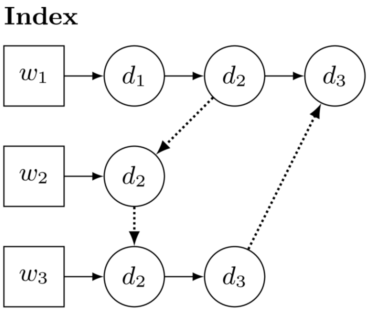
- Inverted Index Based
- Instead of one, used TWO indexes-
  - Search index - Inverted index
  - Deletion Index - General index

Example



Main Index M

$f_{k_c}(w_1) \longrightarrow (4 \,||\, 1) \oplus f_{k_b}(w_1)$

$f_{k_c}(w_2) \longrightarrow (0 \,||\, 2) \oplus f_{k_b}(w_2)$

$f_{k_c}(w_3) \longrightarrow (5 \,||\, 0) \oplus f_{k_b}(w_3)$

$f_{k_c}(\text{free}) \longrightarrow 6 \oplus f_{k_b}(\text{free})$

Deletion Index I

$f_{k_c}(d_1) \longrightarrow 1 \oplus f_{k_b}(d_1)$

$f_{k_c}(d_2) \longrightarrow 5 \oplus f_{k_b}(d_2)$

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Example

Main Index M

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Main List L

0	1	2	3	4	5	6	7
w_2	w_3	free	w_1	w_1	w_3	free	w_1
d_2	d_3	D_7	d_3	d_1	d_1	D_3	d_2

Deletion List D

d_2	d_1	d_2	r	d_3	d_2	d_3	r'
w_3	w_1	w_2		w_3	w_1	w_1	

Issues

- Complex Scheme- Difficult To Implement
- Nodes were at Random location- Sequential operation

Kamara et al. [KP13] Scheme

Scheme Overview

- Search or update can be done in Parallel

Kamara et al. [KP13] Scheme

Scheme Overview

- Search or update can be done in Parallel
- Extra: do not leak information about the keywords contained in a newly added or deleted document

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Scheme Overview

- Search or update can be done in Parallel
- Extra: do not leak information about the keywords contained in a newly added or deleted document
- Used *tree-based multi-map data structure*- keyword red-black (KRB) tree

Background

(k, m) Hash Table

- A table of $(key, value)$ pairs
- $key \in \{0,1\}^k$
- at most m entries

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KRB-Based Dynamic SSE

Scheme Overview

- On White-Board

Remarkable Works Till Today

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- Practical Dynamic Searchable Encryption with Small Leakage

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Kamara et al. [KM17] Scheme

- Boolean SSE with Worst-Case Sub-linear Complexity

Attacks on Searchable Encryption Scheme

Islam et al. [IKK12] Attack

Access Pattern disclosure on Searchable Encryption: Ramification, Attack and Mitigation

- 1st to investigate- Access Pattern disclosure on Searchable Encryption
- Attack the existing Schemes with few assumptions
- Provide solution to the problem

Attack Overview

Assumptions

- Attacker observes $Q =< Q_1, \ldots, Q_l >$ and their responses $< R_{Q_1}, \ldots, R_{Q_l} >$
- Attacker knows the underlying keywords for a set of k queries: K_Q
- Attacker has access to a $(m \times m)$ matrix M s.t. $M_{i,j} = Pr[(k_i \in d) \wedge (k_j \in d)]$, here d is sampled uniformly from D.

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Attack Process

- From knowledge of d (sampled uniformly from D)
  - From publicly known large dataset, ex. WikiLeaks
  - Inside Attacker may have access to the sizable subset of the dataset
- From publicly known large dataset
  - Attacker can calculate frequency of keywords i.e., $Pr[(k_i \in d)]$
  - Attacker can calculate $M_{i,j} = Pr[(k_i \in d) \wedge (k_j \in d)]$
- They later considered $Pr[(k_{i_1} \in d) \wedge \ldots \wedge (k_{i_r} \in d)]$

Attack Overview

Attack Result

- Knowing only subset of D significant # queries can be guessed

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$(\alpha, 0)$- secure index

- For each keyword, there are at least $\alpha - 1$ keywords which appear exactly in the same set of documents.
- It's hard for an attacker to distinguish a keyword given the query response of that particular keyword.

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- It's hard for an attacker to distinguish a keyword given the query response of that particular keyword.

Proposed a noise addition technique

- Inject false positive docs so that index remains $(\alpha, 0)$- secure
- User can later decrypt the document and reject if the keywords is not present

Inference Attacks on Property-Preserving EDB (Naveed et al. [NKW15])

- SKIP NOW

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Property Preserving Encryption (PPE)

Leaks a certain property of the plaintext

- Order Preserving Encryption (PPE): Reveals the order of the messages (i.e., the order property).
- Deterministic Encryption (PPE): Reveals whether they are equal or not (i.e., the equality property).

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Where is it Applicable?

- Searchable encryption that supports Range queries
- PPE Based database CryptDB and its variants

Inference Attacks on Property-Preserving EDB (Naveed et al. [NKW15])

Attack Techniques

- Frequency analysis: DTE
- l_p-optimization: DTE
- Sorting attack: OPE
- Cumulative attack: OPE

Leakage-Abuse Attacks (Cash et al. [CGPR15])

Leakage-Abuse Attacks Against Searchable Encryption

- Query recovery attack: Determining the plaintext of queries that have been issued by the client
- Partial plaintext recovery attack: Reconstruct indexed documents as much as possible

Query recovery attack

Attack Model

- Count Attack:
- Server knows $count(w) \forall w \in W$
- Fully document knowledge

Query recovery attack

Attack Model

- Count Attack:
- Server knows $count(w) \forall w \in W$
- Fully document knowledge

Solution?

- Padding
- Adding Garbage doc id in the index

Query recovery attack from Partially known Docs

- See Islam et al. [IKK12]

Partial plaintext recovery attack

- Known-Document Attack
- Active Attacks

Partial plaintext recovery attack

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Known-Document Attack

- Order of Hashes Known
- Order of Hashes Unknown

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Active Attacks

- Hash order known for chosen document
- Hash order unknown for chosen documents

File Injection Attack (Zhang et al. [ZKP16])

File Injection Attack

All Your Queries Are Belong to Us: The Power of File-Injection Attacks on Searchable Encryption

Attack Overview

- **Focused on Query Recover Attack**

File Injection Attack

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Attack Overview

- **Focused on Query Recover Attack**
- Applicable for Dynamic SSEs
- Attack does not require the server to have any knowledge about the client's files
- Recovers all the keywords being searched by the client with 100% accuracy

Binary search Attack

Process

- Insert $\#\log K$ files.
- ith file contains exactly those keywords whose ith most-significant bit is 1
- If a keyword w is searched and returns then it matches returned files with its injected ones.

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Reduction in # files

- If targeted keyword set $K' \subset K$

Binary search Attack

Hierarchical File Injection

- Considers K' instead of K
- Apply Binary search on K
- # files to be injected $\approx \lceil |K|/2T \rceil . (\lceil \log 2T \rceil + 1)$

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- Forward Privacy: The server cannot tell if a newly inserted file matches previous search queries
- Examples: Stefanov et al. [SPS14], Raphael Bost [Bos16]

Forward Private DSSE

Few Examples of Forward-Secure DSSE

- Stefanov et al. [SPS14]
- $\Sigma o\phi o\varsigma$ (Sophos) Bost [Bos16] in 2016
- Bost et al. [BMO17] in 2017
- Rizomiliotis and Gritzalis [RG15], ORAM Based
- Lai and Chow [LC17] based on Bipartite Graph

We have focused on $\Sigma o\phi o\varsigma$

$\Sigma o\phi o\varsigma$

- Devided into two parts
  - $\Sigma o\phi o\varsigma$-B
  - $\Sigma o\phi o\varsigma$

$\Sigma o\phi o\varsigma$-B -> Idea

$$\begin{tikzcd}[column sep=large, row sep=large]
ST_0(w) \arrow[d, "H_{K_w}"'] \arrow[r, bend left, "\pi_{\mathsf{SK}}^{-1}"] & ST_1(w) \arrow[l, "\pi_{\mathsf{PK}}"] \arrow[d, "H_{K_w}"'] & \cdots & ST_c(w) \arrow[ll, dashed, "\pi_{\mathsf{PK}}^{(c-1)}"] \arrow[d, "H_{K_w}"'] \arrow[r, bend left, "\pi_{\mathsf{SK}}^{-1}"] & ST_{c+1}(w) \arrow[l, "\pi_{\mathsf{PK}}"] \arrow[d, "H_{K_w}"'] \\
UT_0(w) & UT_1(w) & \cdots & UT_c(w) & UT_{c+1}(w)
\end{tikzcd}$$

$\Sigma o\phi o\varsigma$-B -> Setup

<u>Setup()</u>

1: $K_S \xleftarrow{\$} \{0,1\}^\lambda$
2: $(\mathsf{SK}, \mathsf{PK}) \leftarrow \mathsf{KeyGen}(1^\lambda)$
3: $\mathbf{W}, \mathbf{T} \leftarrow \text{empty map}$
4: $\textbf{return } ((\mathbf{T}, \mathsf{PK}), (\mathbf{K_S}, \mathsf{SK}), \mathbf{W})$

$\Sigma o \phi o \varsigma$-$B$ -> Search

$$Search(w, \sigma, EDB)$$

Client:

$K_w \leftarrow F_{K_S}(w)$
$(ST_c, c) \leftarrow \mathbf{W}[w]$
if $(ST_c, c) = \perp$
  return $\emptyset$
Send (K_w, ST_c, c) to the server.

Server:

for $i = c$ **to** 0 **do**
  $UT_i \leftarrow H_1(K_w, ST_i)$
  $e \leftarrow \mathbf{T}[UT_i]$
  $\mathsf{ind} \leftarrow e \oplus H_2(K_w, ST_i)$
  Output each ind
  $ST_{i-1} \leftarrow \pi_{\mathsf{PK}}(ST_i)$
end for

Σοφος-*B* -> Update

Update(add, w, ind, σ; EDB)

Client:

$K_w \leftarrow F(K_S, w)$
$(ST_c, c) \leftarrow \mathbf{W}[w]$
if $(ST_c, c) = \perp$ **then**
  $ST_0 \xleftarrow{\$} \mathcal{M}$, $c \leftarrow -1$
else
  $ST_{c+1} \leftarrow \pi^{-1}_{\mathsf{SK}}(ST_c)$
end if
$\mathbf{W}[w] \leftarrow (ST_{c+1}, c+1)$
$UT_{c+1} \leftarrow H_1(K_w, ST_{c+1})$
$e \leftarrow \mathsf{ind} \oplus H_2(K_w, ST_{c+1})$
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Problem with $\Sigma o\phi o\varsigma$-B

- No Deletion and Huge Client Storage

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Enabling Deletion

- Adding Extra Database for Deletion

Problem with $\Sigma o\phi o\varsigma$-B

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- Adding Extra Database for Deletion
- Searching eliminate the deleted docs

Problem with $\Sigma o \phi o \varsigma$-$B$

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- ST_0 can be generated using PRF

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Security of Searchable Encryption Schemes

Security Definition of SSE

First Formal Definition by Curtmola et al. [CGKO06].

Approaches

- Indistinguishability
- Semantic Security

Security Definition of SSE

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Approaches

- Indistinguishability
- Semantic Security

Adversary Types

- Non-Adaptive: Queries don't depend on previous results
- Adaptive: Queries depend on previous results

Security Definition of SSE

Notations

- $\mathbf{D} \leftarrow$ Collection of documents
- $\mathbf{w} \leftarrow \{w_1, \ldots, w_q\}$, set of keywords for queries
- History $H \leftarrow (\mathbf{D}, \mathbf{w})$

Security Definition of SSE

Notations

- $\mathbf{D} \leftarrow$ Collection of documents
- $\mathbf{w} \leftarrow \{w_1, \ldots, w_q\}$, set of keywords for queries
- History $H \leftarrow (\mathbf{D}, \mathbf{w})$
- Access pattern $\alpha(H) \leftarrow (\mathbf{D}(w_1), \ldots, \mathbf{D}(w_q))$,
- Search pattern $\sigma(H) \leftarrow M(= (m_{ij})_{q \times q}$ where $m_{ij} = 1$ if $w_i = w_j$ else $0)$
- Trace $\tau(H) \leftarrow (|D_1|, \ldots, |D_n|, \alpha(H), \sigma(H))$

.

Non-Adaptive Indistinguishability Game $Ind_{SSE,\mathcal{A}}(k)$

Challenger $\mathcal{C}$ Adversary $\mathcal{A}$

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SSE is secure if $Pr[Ind_{SSE,\mathcal{A}}(k) = 1] \leq \frac{1}{2} + negl(k)$

Adaptive Indistinguishability Game $Ind^{*}_{SSE,\mathcal{A}}(k)$

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Adaptive Indistinguishability Game $Ind^{*}_{SSE,\mathcal{A}}(k)$

Challenger $\mathcal{C}$	Adversary $\mathcal{A}$
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- $(st_{\mathcal{A}}, w_{0,i}, w_{1,i}) \leftarrow \mathcal{A}_i(st_{\mathcal{A}}, I_b, c_b, t_{b,1}, \ldots, t_{b,q-1})$ and Send $(w_{0,i}, w_{1,i})$

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SSE is secure if $Pr[Ind^*_{SSE,\mathcal{A}}(k) = 1] \leq \frac{1}{2} + negl(k)$

Non-Adaptive Semantic Security

$\mathbf{Real}_{\mathsf{SSE},\mathcal{A}}(k)$

$K \leftarrow \mathsf{Gen}(1^k)$

$(st_{\mathcal{A}}, H) \leftarrow \mathcal{A}(1^k)$

$parse\ H\ as\ (\mathbf{D}, \boldsymbol{w})$

$(I, \boldsymbol{c}) \leftarrow \mathsf{Enc}_K(\mathbf{D})$

$for\ 1 \le i \le q,$

$\quad t_i \leftarrow \mathsf{Trpdr}_K(w_i)$

$let\ \boldsymbol{t} = (t_1, \ldots, t_q)$

$output\ \mathrm{v} = (I, \boldsymbol{c}, \boldsymbol{t})\ and\ st_{\mathcal{A}}$

$\mathbf{Sim}_{\mathsf{SSE},\mathcal{A},\mathcal{S}}(k)$

$(H, st_{\mathcal{A}}) \leftarrow \mathcal{A}(1^k)$

$\mathrm{v} \leftarrow \mathcal{S}(\tau(H))$

$output\ \mathrm{v}\ and\ st_{\mathcal{A}}$

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Adaptive Semantic Security

$\mathbf{Real}^{\star}{}_{\mathsf{SSE},\mathcal{A}}(k)$

$K \leftarrow \mathsf{Gen}(1^k)$
$(\mathbf{D}, st_{\mathcal{A}}) \leftarrow \mathcal{A}_0(1^k)$
$(I, \boldsymbol{c}) \leftarrow \mathsf{Enc}_K(\mathbf{D})$
$(w_1, st_{\mathcal{A}}) \leftarrow \mathcal{A}_1(st_{\mathcal{A}}, I, \boldsymbol{c})$
$t_1 \leftarrow \mathsf{Trpdr}_K(w_1)$
for $2 \leq i \leq q,$
  $(w_i, st_{\mathcal{A}}) \leftarrow \mathcal{A}_i(st_{\mathcal{A}}, I, \boldsymbol{c}, t_1, \ldots, t_{i-1})$
  $t_i \leftarrow \mathsf{Trpdr}_K(w_i)$
let $\boldsymbol{t} = (t_1, \ldots, t_q)$
output $\mathrm{v} = (I, \boldsymbol{c}, \boldsymbol{t})$ *and* $st_{\mathcal{A}}$

$\mathbf{Sim}^{\star}{}_{\mathsf{SSE},\mathcal{A},\mathcal{S}}(k)$

$(\mathbf{D}, st_{\mathcal{A}}) \leftarrow \mathcal{A}_0(1^k)$
$(I, \boldsymbol{c}, st_{\mathcal{S}}) \leftarrow \mathcal{S}_0(\tau(\mathbf{D}))$
$(w_1, st_{\mathcal{A}}) \leftarrow \mathcal{A}_1(st_{\mathcal{A}}, I, \boldsymbol{c})$
$(t_1, st_{\mathcal{S}}) \leftarrow \mathcal{S}_1(st_{\mathcal{S}}, \tau(\mathbf{D}, w_1))$
for $2 \leq i \leq q,$
  $(w_i, st_{\mathcal{A}}) \leftarrow \mathcal{A}_i(st_{\mathcal{A}}, I, \boldsymbol{c}, t_1, \ldots, t_{i-1})$
  $(t_i, st_{\mathcal{S}}) \leftarrow \mathcal{S}_i(st_{\mathcal{S}}, \tau(\mathbf{D}, w_1, \ldots, w_i))$
let $\boldsymbol{t} = (t_1, \ldots, t_q)$
output $\mathrm{v} = (I, \boldsymbol{c}, \boldsymbol{t})$ *and* $st_{\mathcal{A}}$

81

Adaptive Semantic Security for DSSE

Real$_{\mathcal{A}}(\lambda)$:

1. The challenger $\mathcal{C}$ generates a key K by running $Gen(1^{\lambda})$.
2. $\mathcal{A}$ generates a set of files $\mathbf{f}$ and sends it to $\mathcal{C}$.
3. $\mathcal{C}$ computes $(\gamma, \mathbf{c}) \leftarrow Build(K, \mathbf{f})$ and sends $(\gamma, \mathbf{c})$ to $\mathcal{A}$
4. $\mathcal{A}$ makes polynomial number of adaptive queries. In each query $\mathcal{A}$ sends either a search query for a keyword w or an add query for a file f_1 or a delete query for a file f_2 to $\mathcal{C}$.
5. Depending on the query, $\mathcal{C}$ returns either the search token $t_s \leftarrow SearchToken(K, w)$ or the add token $t_a \leftarrow AddToken(K, f_1)$ or the delete token $t_d \leftarrow DelToken(K, f_2)$ to $\mathcal{A}$.
6. Finally $\mathcal{A}$ returns a bit b that is output by the experiment.

Adaptive Semantic Security for DSSE

Ideal$_{\mathcal{A},\mathcal{S}}(\lambda)$:

1. $\mathcal{A}$ generates a set of files $\mathbf{f}$. It gives $\mathbf{f}$ and $\mathcal{L}_{bld}(\mathbf{f})$ to $\mathcal{S}$.
2. On receiving $\mathcal{L}_{bld}(\mathbf{f})$, $\mathcal{S}$ generates $(\gamma, \mathbf{c})$ and sends it to $\mathcal{A}$
3. $\mathcal{A}$ makes polynomial number of adaptive queries $q \in \{w, f_1, f_2\}$. For each query, $\mathcal{S}$ is given either $\mathcal{L}_{srch}(w, \mathbf{f})$ or $\mathcal{L}_{add}(f_1, \mathbf{f})$ or $\mathcal{L}_{del}(f_2, \mathbf{f})$.
4. Depending on the query q, $\mathcal{S}$ returns to $\mathcal{A}$ either search token t_s or add token t_a or delete token t_d.
5. Finally $\mathcal{A}$ returns a bit b that is output by the experiment.

Security

$$|Pr[\mathbf{Real}_{\mathcal{A}}(\lambda) = 1] - Pr[\mathbf{Ideal}_{\mathcal{A},\mathcal{S}}(\lambda) = 1]| \leq \mu(\lambda)$$

Searchable Encryption with Complex Queries

Different type of Queries

Range Queries

- Given two keywords w_1 and w_2, find all keywords between w_1 and w_2.

Different type of Queries

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- Conjunctive Queries:

Different type of Queries

Range Queries

- Given two keywords w_1 and w_2, find all keywords between w_1 and w_2.
- Order should be defined
- Existing schemes: Ishai et al. [IKLO16], Fisch et al. [FVK$^+$15]

- Conjunctive Queries:
- Disjunctive Queries

Different type of Queries

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- Conjunctive Queries:
- Disjunctive Queries
- Boolean Queries:

Different type of Queries

Range Queries

- Given two keywords w_1 and w_2, find all keywords between w_1 and w_2.
- Order should be defined
- Existing schemes: Ishai et al. [IKLO16], Fisch et al. [FVK$^+$15]

- Conjunctive Queries:
- Disjunctive Queries
- Boolean Queries:
- Substring Queries:

Different type of Queries

Range Queries

- Given two keywords w_1 and w_2, find all keywords between w_1 and w_2.
- Order should be defined
- Existing schemes: Ishai et al. [IKLO16], Fisch et al. [FVK$^+$15]

- Conjunctive Queries:
- Disjunctive Queries
- Boolean Queries:
- Substring Queries:
- Phrase Queries:

Generalization of Searchable Encryption

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- More complex queries can be solved if Graph encryption become efficient

Scope of Research

Future Research Directions

- Efficient Forward Secure Scheme Design

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- Efficient Forward Secure Scheme Design
- New techniques can be applied to propose new SSE/DSSE scheme

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- Efficient Forward Secure Scheme Design
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- Provide Solutions of the attacks
- Complex queries on Encrypted Data/DSSE
- Complex queries on Encrypted Graph

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Questions?

Thank You!