Exploiting Update Leakage In Searchable Symmetric Encryption

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Motivation

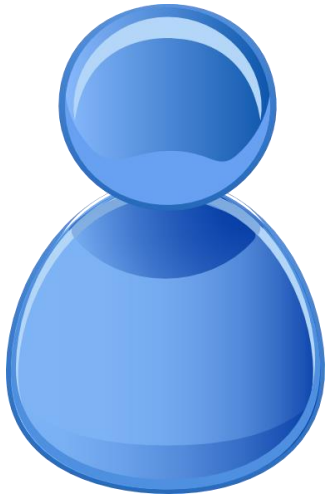
- Cloud computing offers popular and useful applications:
- Remote storage
- Scalable databases
- Email platforms

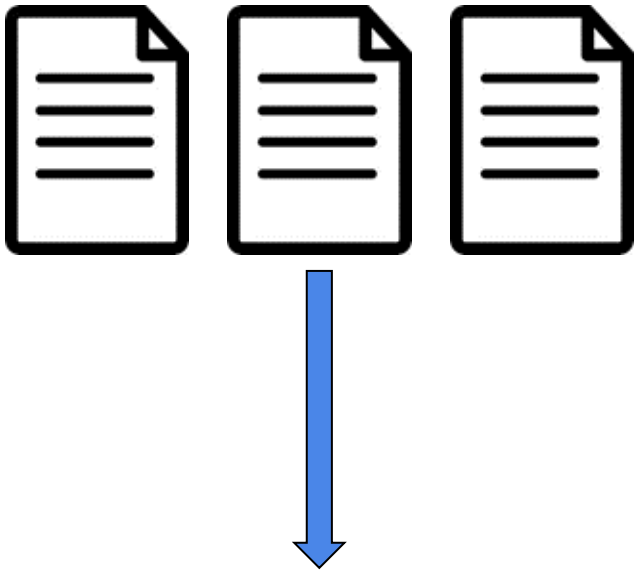
Motivation

How can a client search over private data on an untrusted remote server?

Searchable Symmetric Encryption: Keyword Extraction

Client

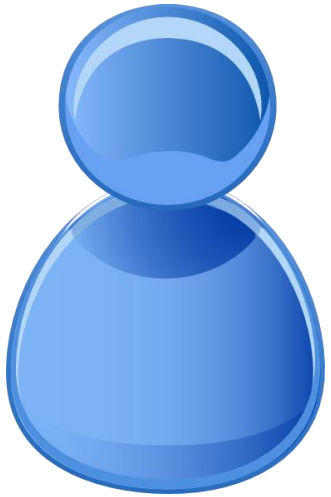




Apple: File 1, File 2, File 3
Banana: File 2
Carrot: File 9, File 22
…

Tokenizing the Index

Client



Inverted Index

Apple: File 1, File 2, File 3
Banana: File 2
Carrot: File 9, File 22
…

Apple
Banana
Carrot
…

One-Way Trapdoor

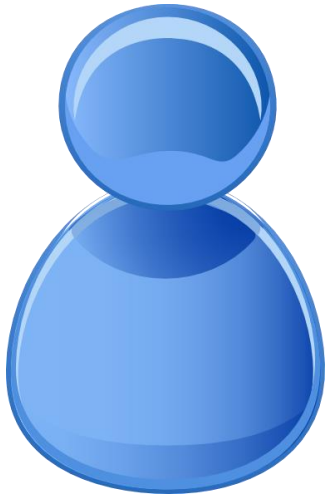
τ_1
τ_2
τ_3
…

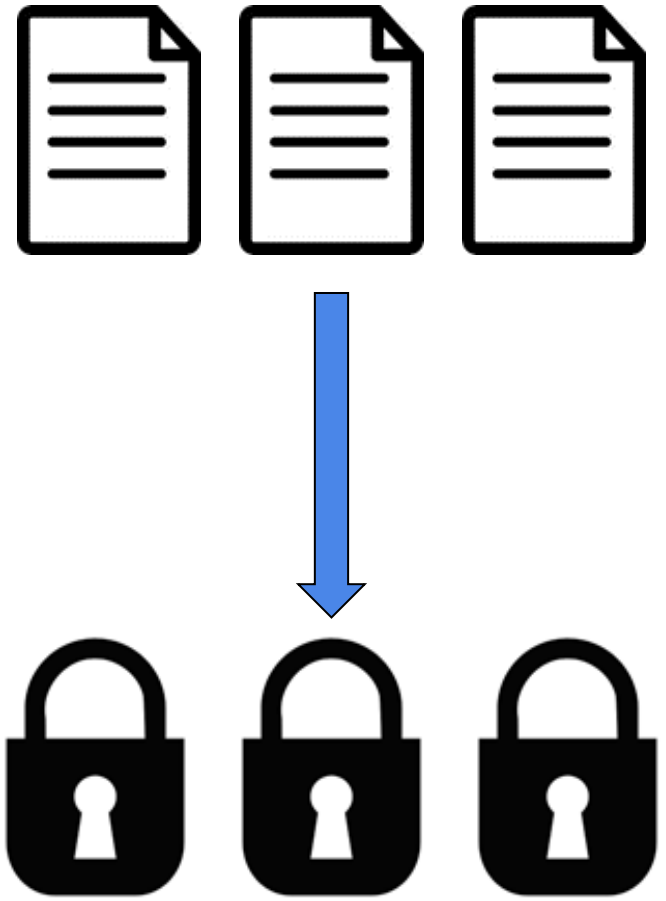
Encrypted Search Index

τ_1: File 1, File 2, File 3
τ_2: File 2
τ_3: File 9, File 22
…

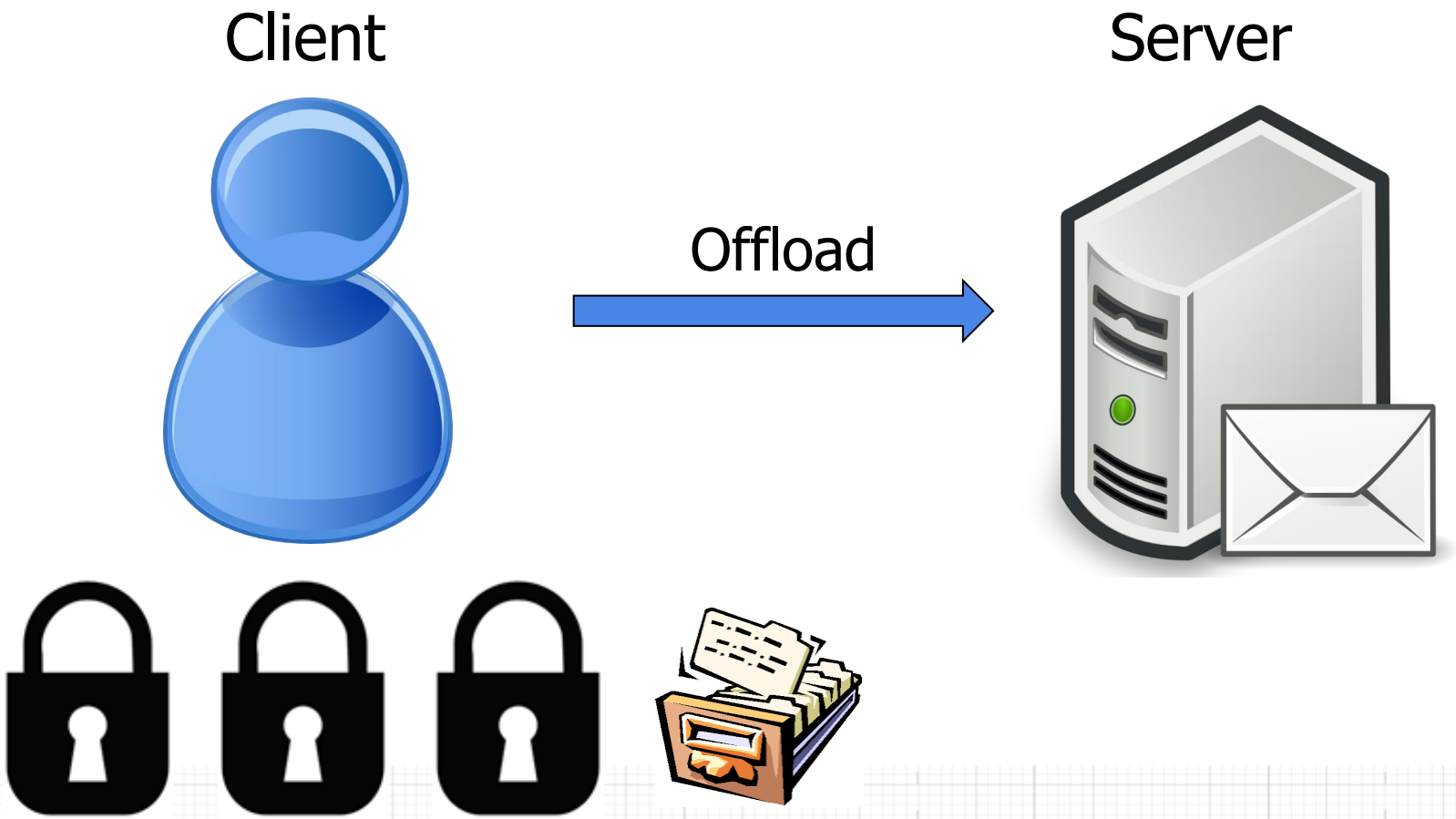
Encrypting the Files

Client



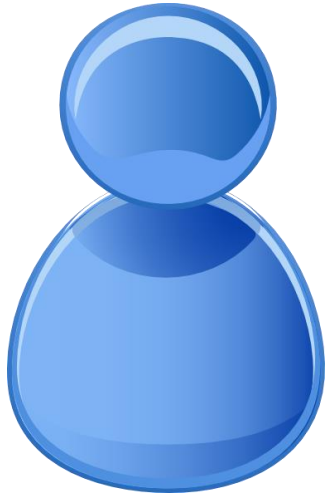


Completing the Setup Phase



Completing the Setup Phase

Client

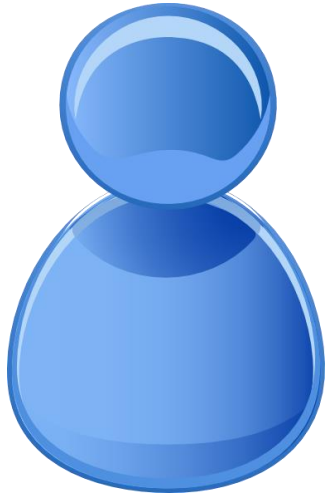


Server

τ_1: File 1, File 2, File 3
τ_2: File 2
τ_3: File 9, File 22
…

Searching the Encrypted Database

Client



One-Way Trapdoor

Banana → τ_2

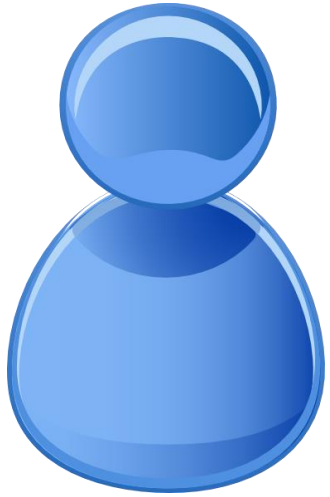
Server

τ_1: File 1, File 2, File 3
τ_2: File 2
τ_3: File 9, File 22
…

Searching the Encrypted Database

Client

Server



Client sends τ_2

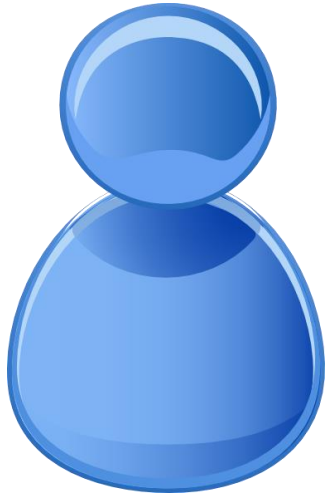
τ_1: File 1, File 2, File 3
τ_2: File 2
τ_3: File 9, File 22
…

One-Way Trapdoor

Banana  τ_2

Searching the Encrypted Database

Client

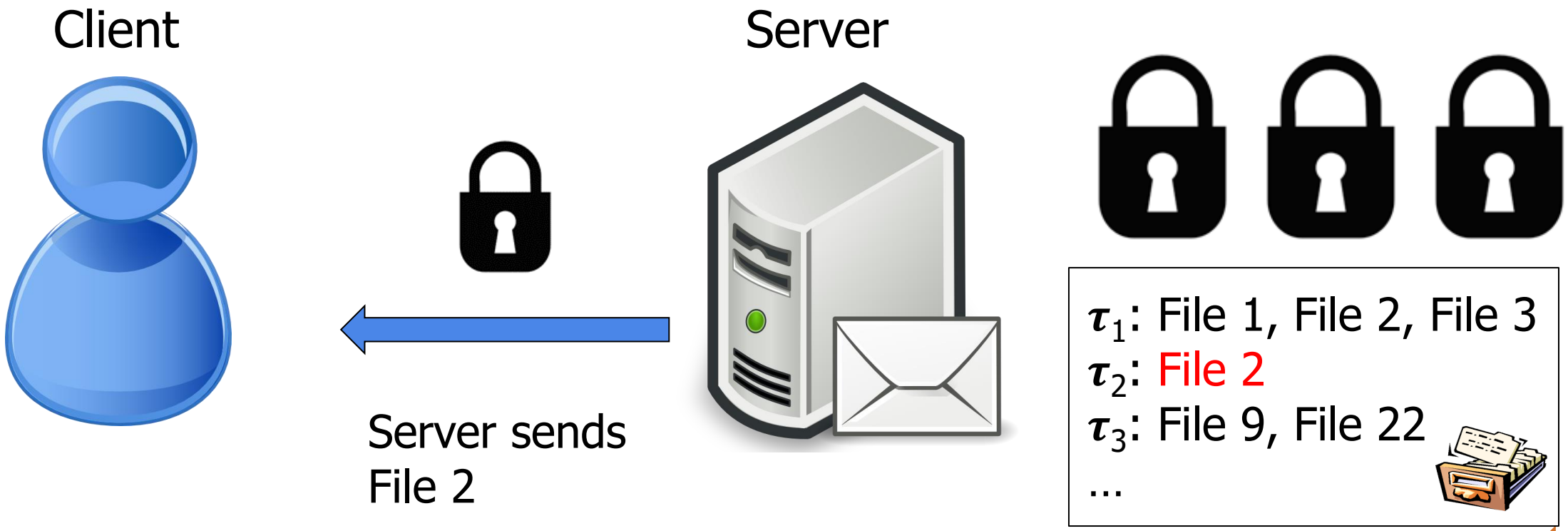


Client sends τ_2

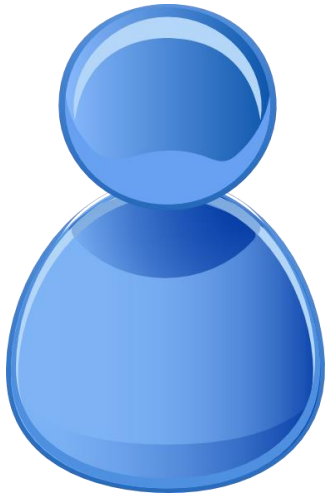
Server

τ_1: File 1, File 2, File 3
τ_2: File 2
τ_3: File 9, File 22
…

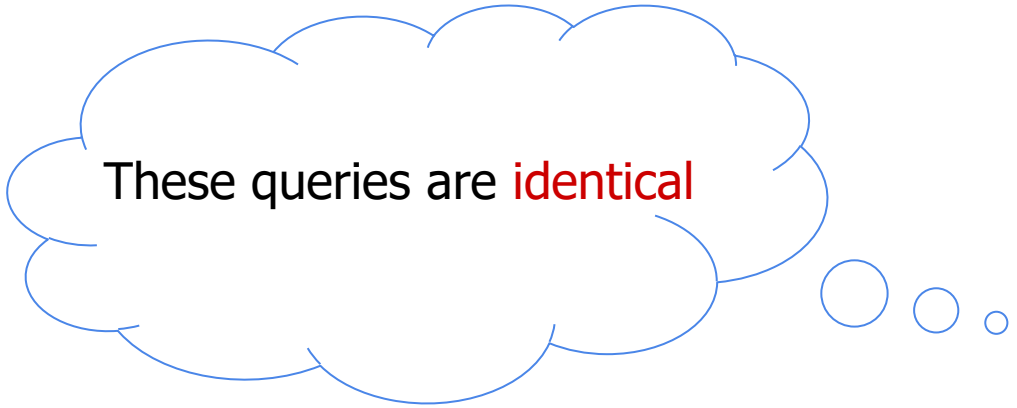
Searching the Encrypted Database



Vulnerability: Search Pattern Leakage



Client



Server

Keyword k → Query token t

One way function

This process is deterministic

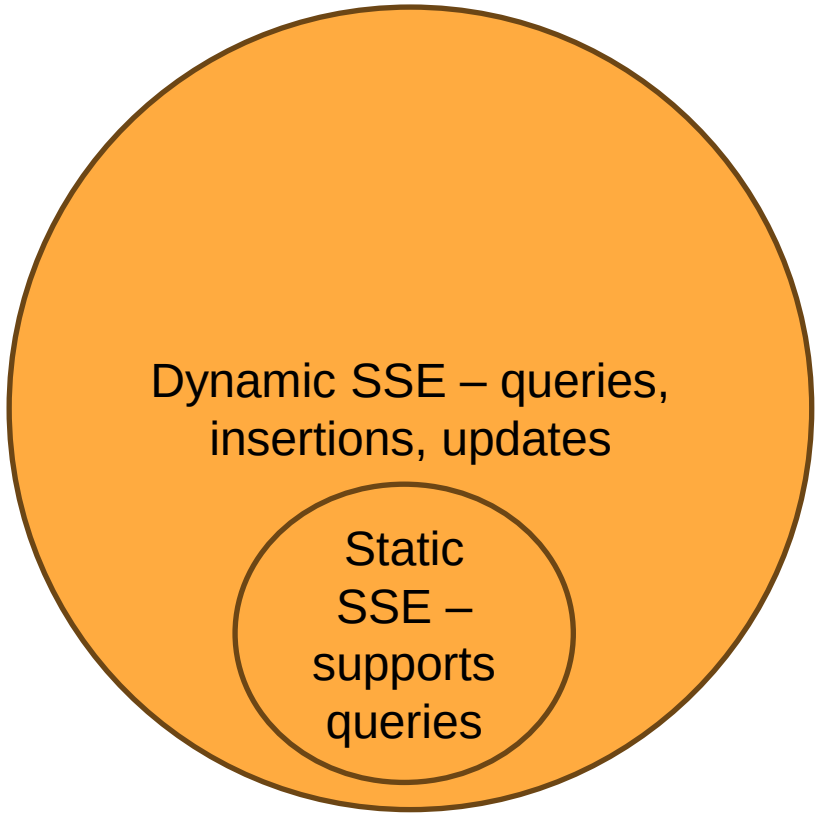
$\{\tau_1, \tau_2, \tau_3, \tau_4, \tau_2, \tau_1, \tau_5\}$

Example list of previous queries

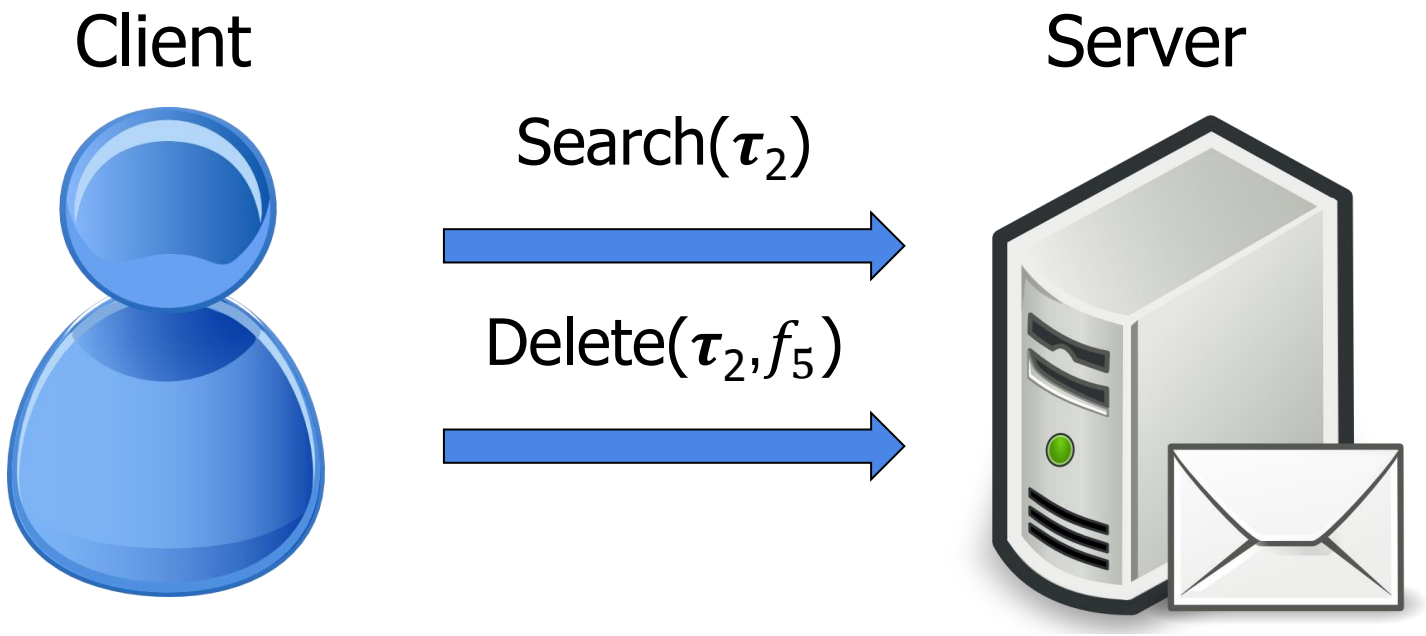
Dynamic SSE

- We focus on **Dynamic** SSE, which enables index updates, ex.
- Insert($\boldsymbol{\tau}_2$, f_5), Delete($\boldsymbol{\tau}_4$, f_1)

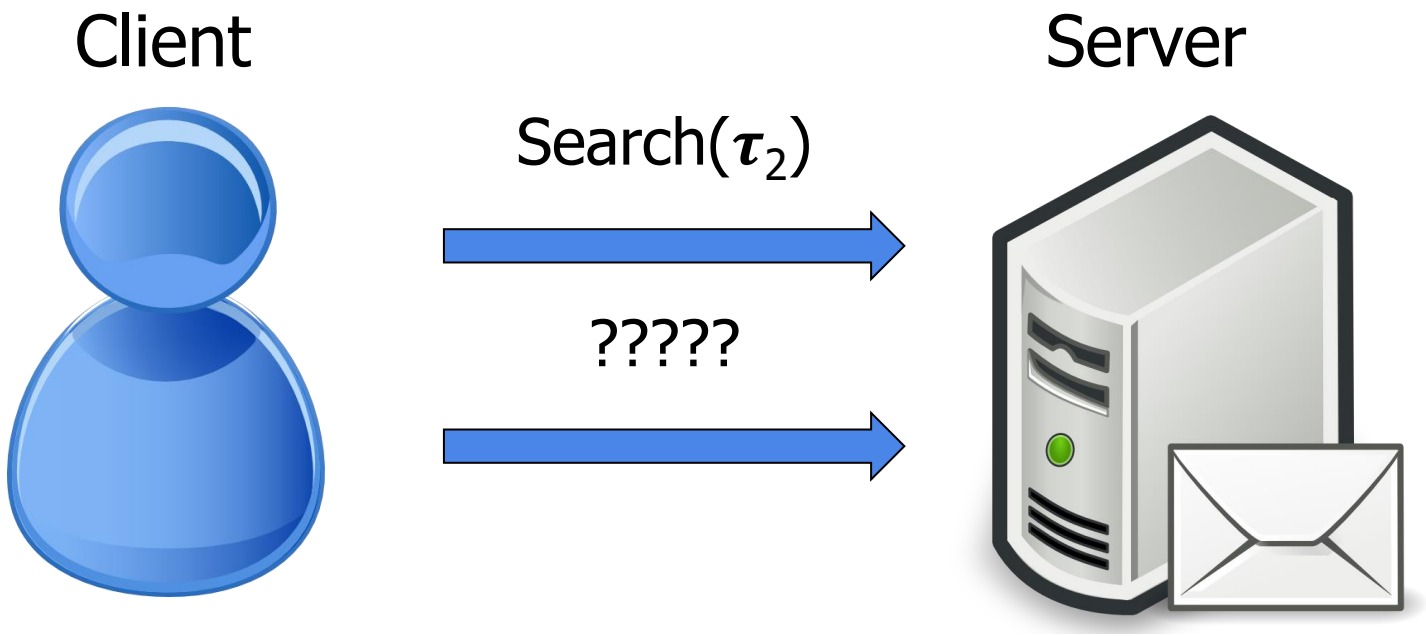
- Forward and Backward Privacy are optional security properties



Forward Privacy



Forward Privacy



Server cannot link future updates to previous queries

Insight

- We can learn info about updates after a search
- For example…

Post-Search Update Leakage

- Assume a client does the following operations:

1. Search($\boldsymbol{\tau}_1$)

The server sees all boxed operations.

Post-Search Update Leakage

- Assume a client does the following operations:

1. Search($\boldsymbol{\tau}_1$)
2. Add($\boldsymbol{\tau}_1, f_1$)

The server sees all boxed operations.

Post-Search Update Leakage

- Assume a client does the following operations:

1. Search($\boldsymbol{\tau}_1$)
2. Add($\boldsymbol{\tau}_1, f_1$)
3. Delete($\boldsymbol{\tau}_2, f_1$)

The server sees all boxed operations.

Post-Search Update Leakage

- Assume a client does the following operations:

1. Search($\boldsymbol{\tau}_1$)
2. Add($\boldsymbol{\tau}_1, f_1$)
3. Delete($\boldsymbol{\tau}_2, f_1$)
4. Search($\boldsymbol{\tau}_1$)

The server sees all boxed operations.

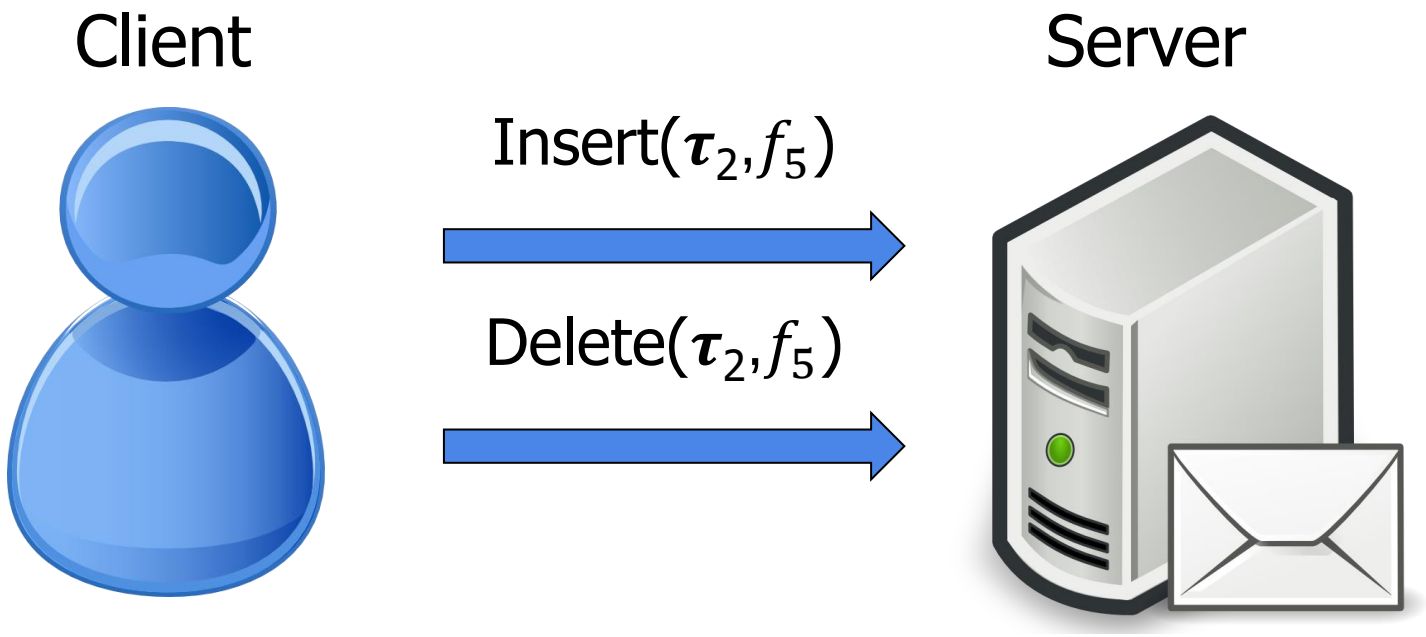
Post-Search Update Leakage

- Assume a client does the following operations:

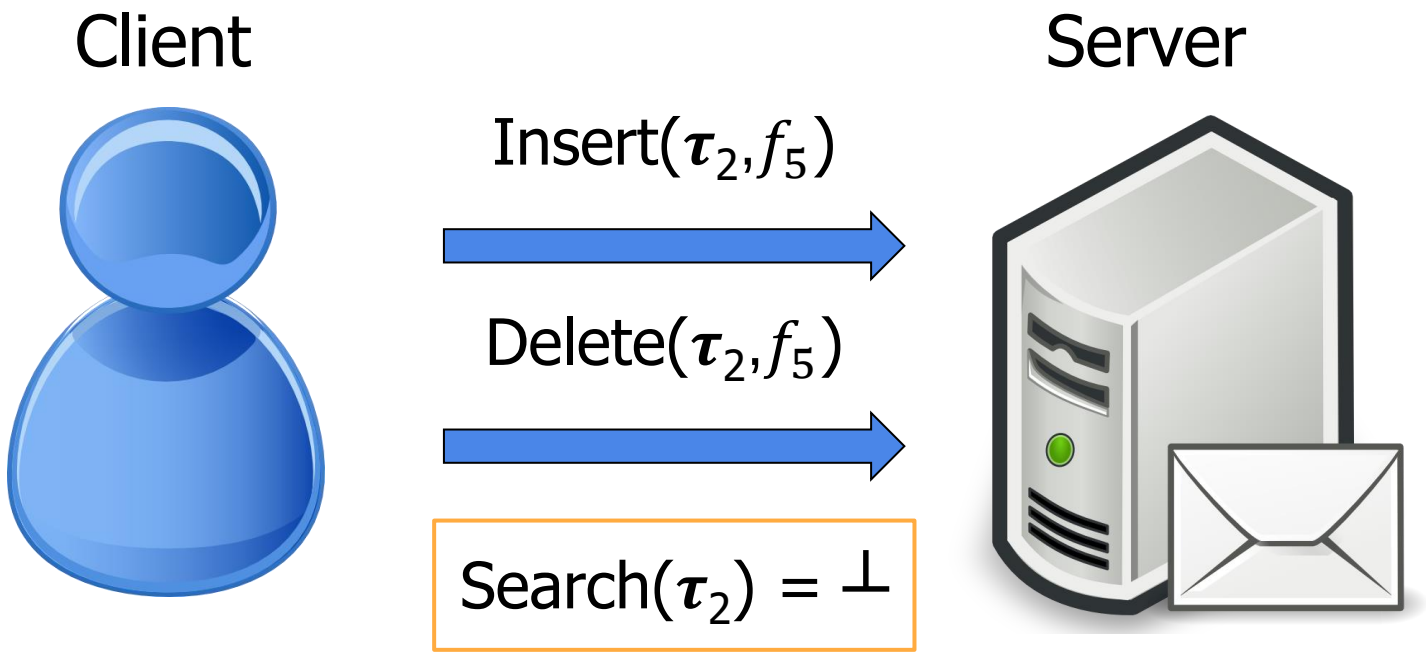
1. Search($\boldsymbol{\tau}_1$)
2. Add($\boldsymbol{\tau}_1, f_1$)
3. Delete($\boldsymbol{\tau}_2, f_1$)
4. Search($\boldsymbol{\tau}_1$)
5. Search($\boldsymbol{\tau}_2$)

The server sees all boxed operations.

Backward Privacy



Backward Privacy



Server cannot learn about contents of deleted entries

Backward Privacy

- After client searches for τ, they learn the following about previous updates on τ:
- **No BP: Full update history (operation, file identifiers, timestamps of all updates)**
- Level 3 BP: Which deletions cancelled which additions, timestamps of all updates
- **Level 2 BP: Timestamps of all updates**
- Level 1 BP: Total number of updates

Backward Privacy

- After client searches for τ, they learn the following about previous updates on τ:
- **No BP: Full update history (operation, file identifiers, timestamps of all updates)**
- Level 3 BP: Which deletions cancelled which additions, timestamps of all updates
- **Level 2 BP: Timestamps of all updates**
- Level 1 BP: Total number of updates

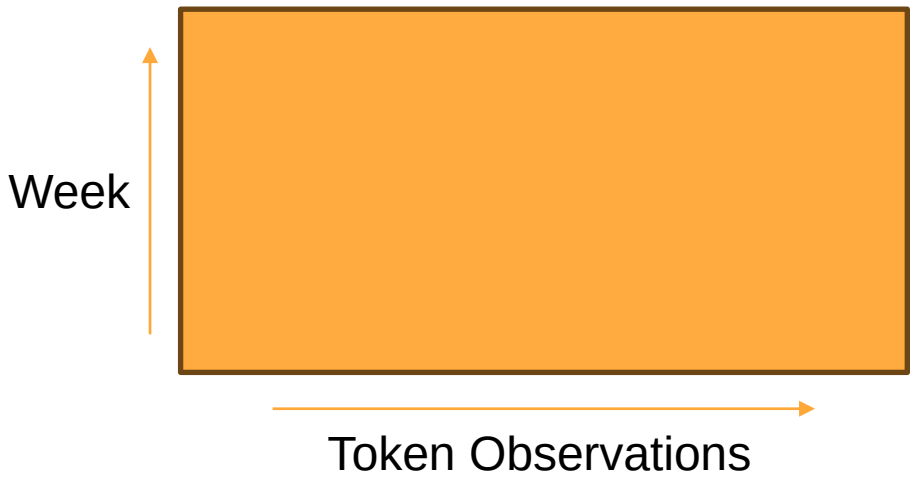
Consensus has been that less leakage must be better, but…
BP reduces performance, so a concrete understanding of the tradeoff is desirable

Insights

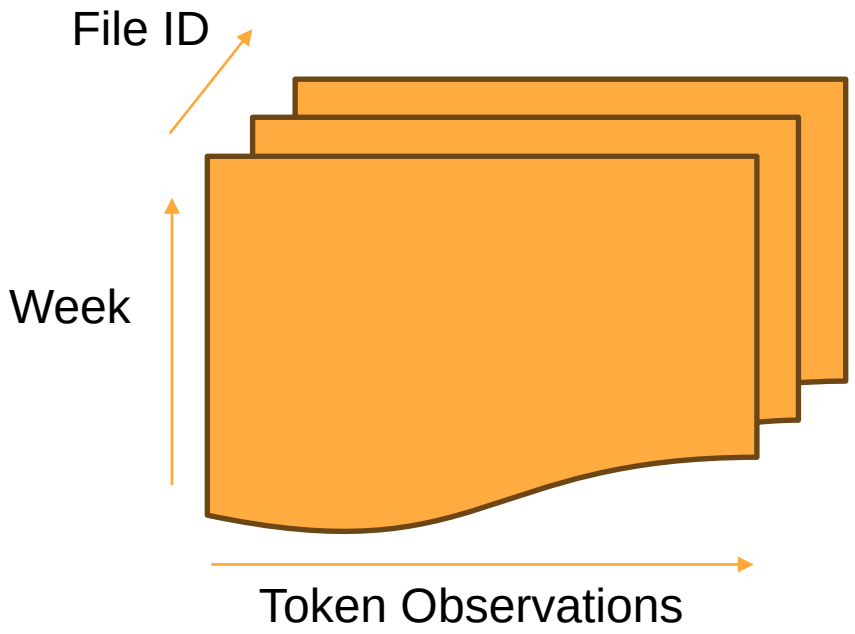
- Level 2 BP and worse: we can use update **timestamps** for a frequency attack
- No BP: we can also exploit the **file identifier**

Approach

UF Attack
(Update Frequency)



UFID Attack
(Update Frequency with File IDs)



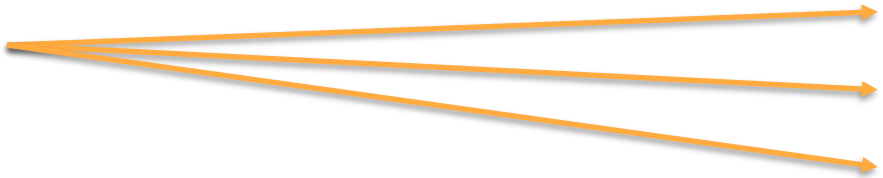
Cross-reference with auxiliary info!

<u>Auxiliary Info</u>

Apple, 7 updates, f_3

Banana, 18 updates, f_1

Coconut, 4 updates, f_3

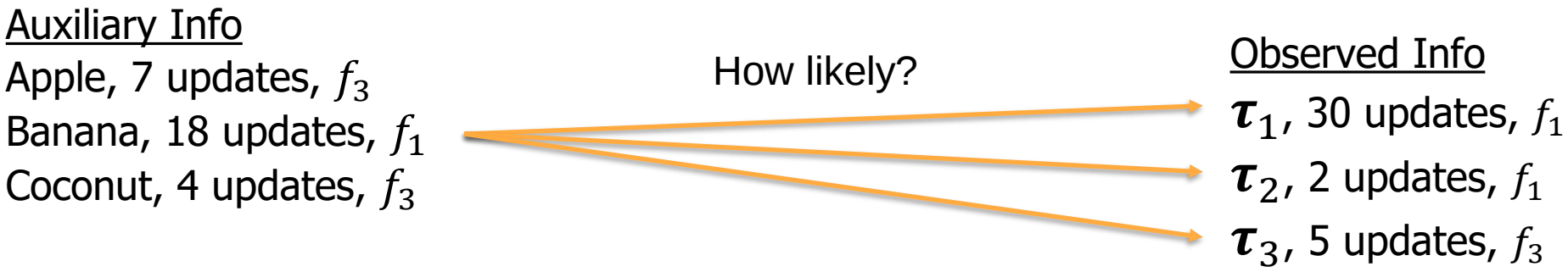


<u>Observed Info</u>

$\boldsymbol{\tau}_1$, 30 updates, f_1

$\boldsymbol{\tau}_2$, 2 updates, f_1

$\boldsymbol{\tau}_3$, 5 updates, f_3



Optimize to find most likely mapping

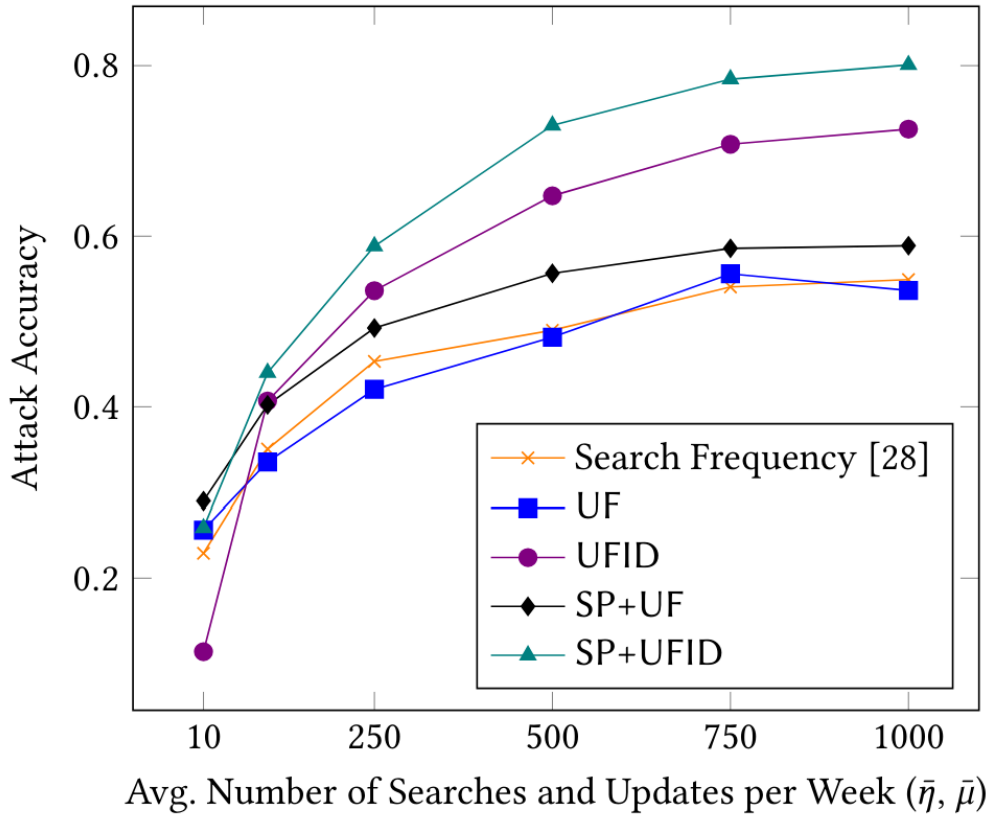
Approach

- Element-by-element multiplication gives joint probability of events occurring
- Can combine with Oya and Kerschbaum's Search Frequency attack to make full use of the search patterns
  - SP+UF Attack (Level II BP)
  - SP+UFID Attack (No BP)

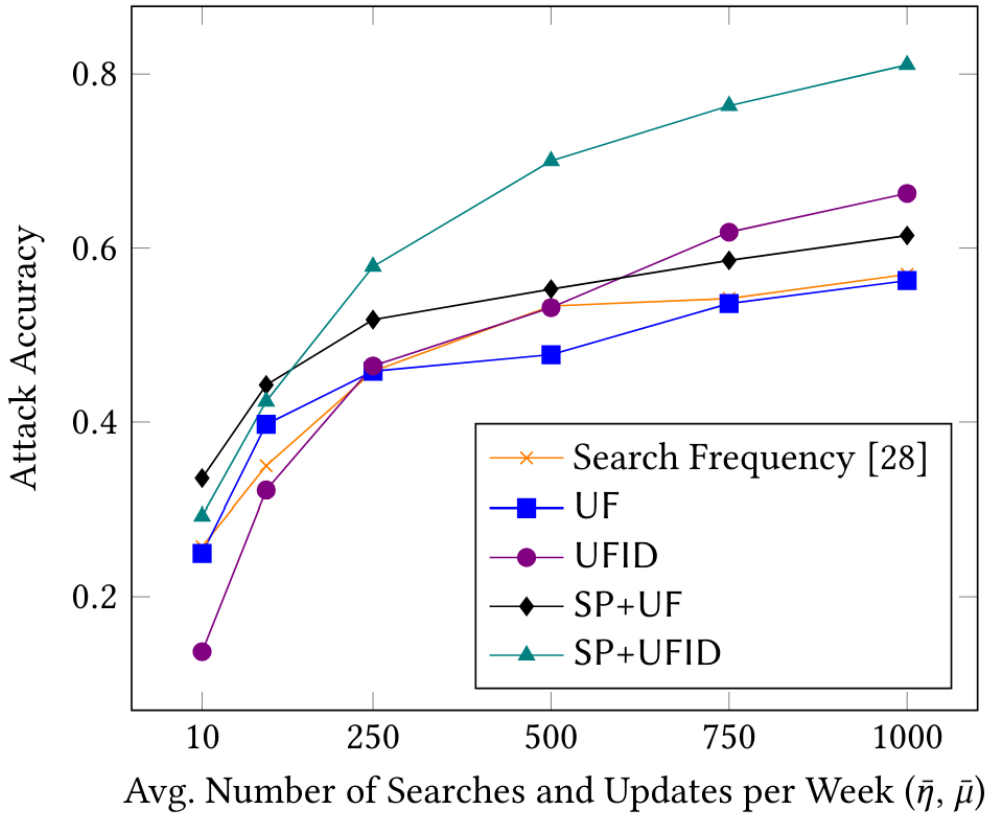
Evaluation

- Extracted keywords from Enron and Lucene datasets
- 100 weeks; first 50 are auxiliary data, adversary tries to guess last 50
- Model searches and updates based on Google Trends probabilities
- Apply forward privacy: updates only revealed if they are searched later
- Apply backward privacy for UF/SP+UF Attacks: hide file ID from update tuples
- Accuracy is number of keywords correctly guessed divided by total keywords seen

No Backward Privacy is a Problem…

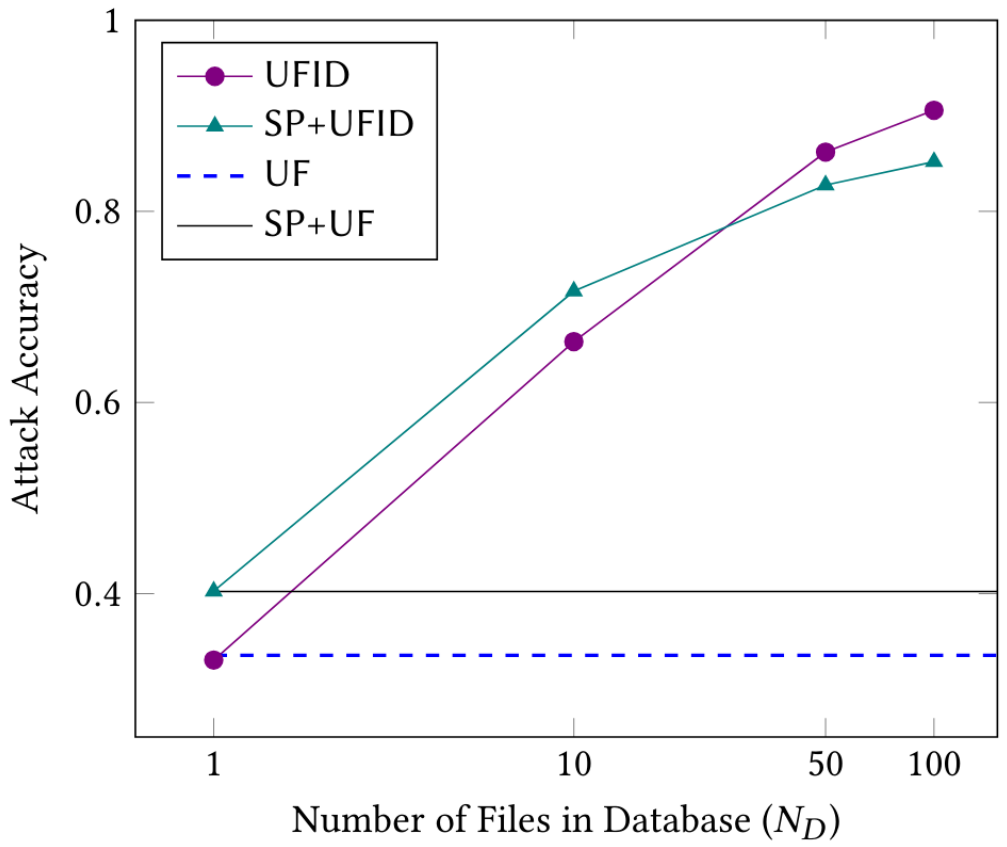


(a) Enron dataset

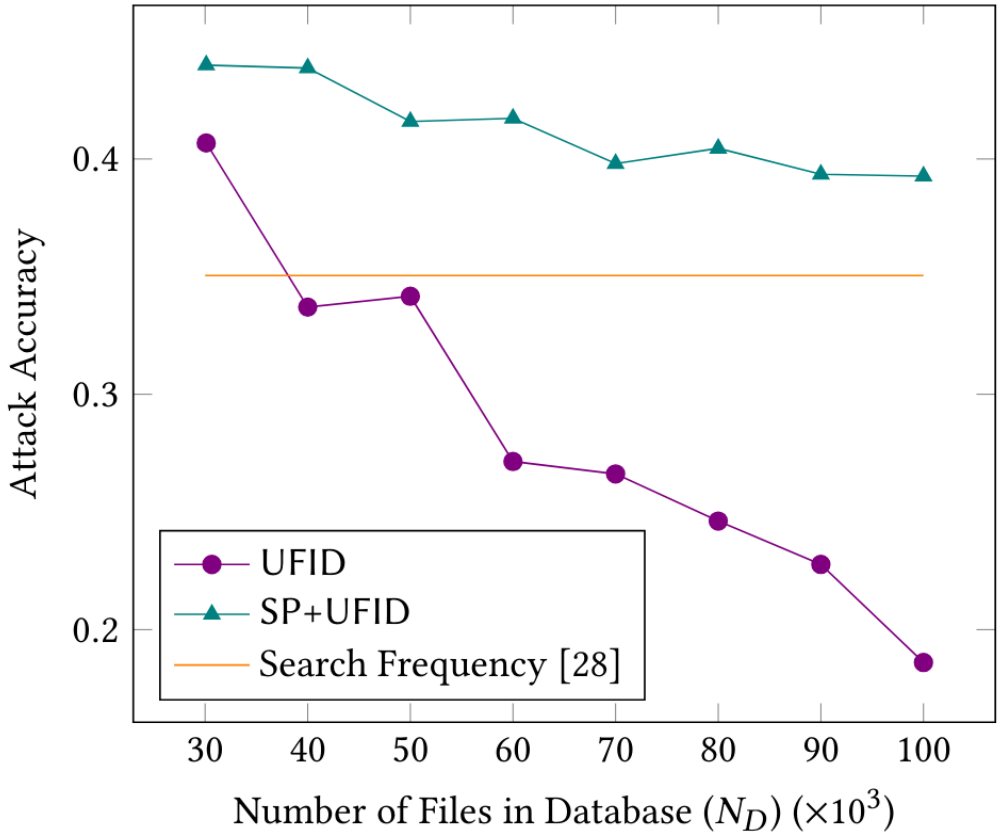


(b) Lucene dataset

Combining Leakage is the Way to Go



(a) Small database



(b) Large database

Limitations

- Obtaining auxiliary info is hard!
- Tracking search patterns in DSSE is non-trivial
- Doesn’t exploit update operation type (add or del)
- Defeated by Level 1 BP or search pattern hiding

Contributions and Conclusion

- We present the first attacks to exploit Post-Search Update Leakage in Forward and Backward-Private DSSE schemes
- Our attacks are the first to empirically validate that BP can reduce attack accuracy by a significant margin
- Improving efficiency of BP is important so users of commercial DSSE applications can enjoy better privacy

Questions?