Order-Revealing Encryption:
How to Search on Encrypted Data

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Stanford University

Searching on Encrypted Data

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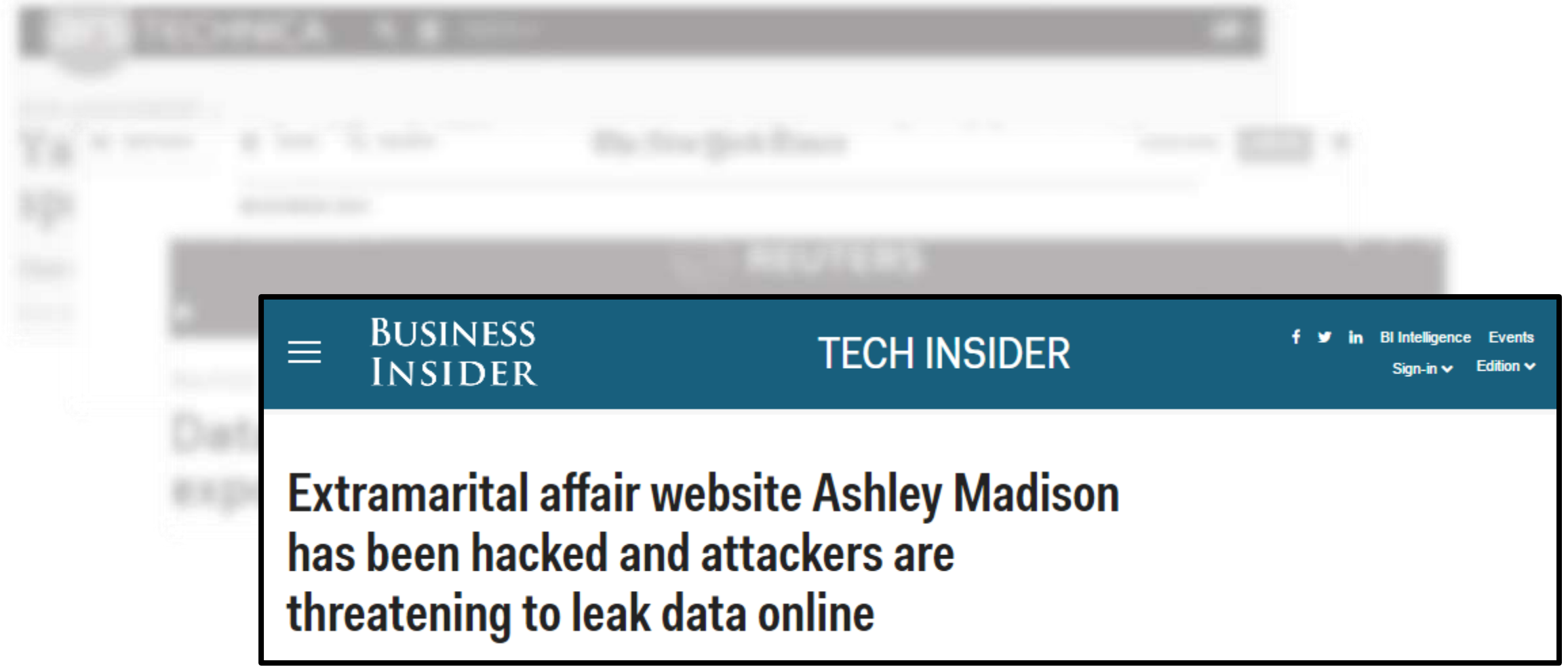
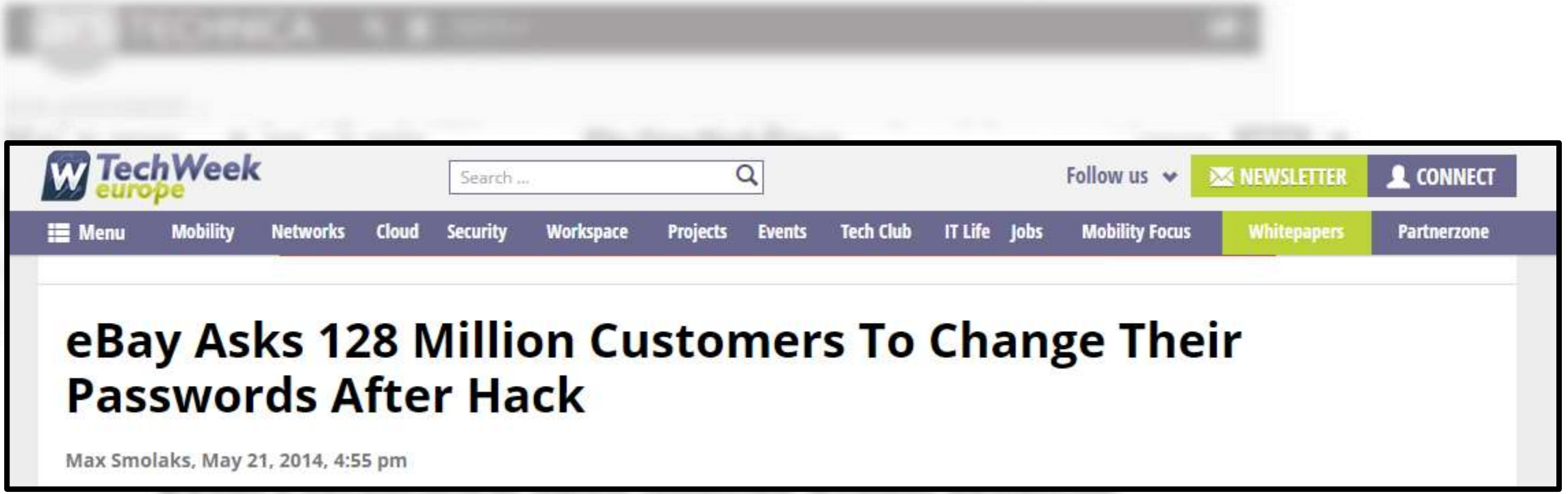


Searching on Encrypted Data



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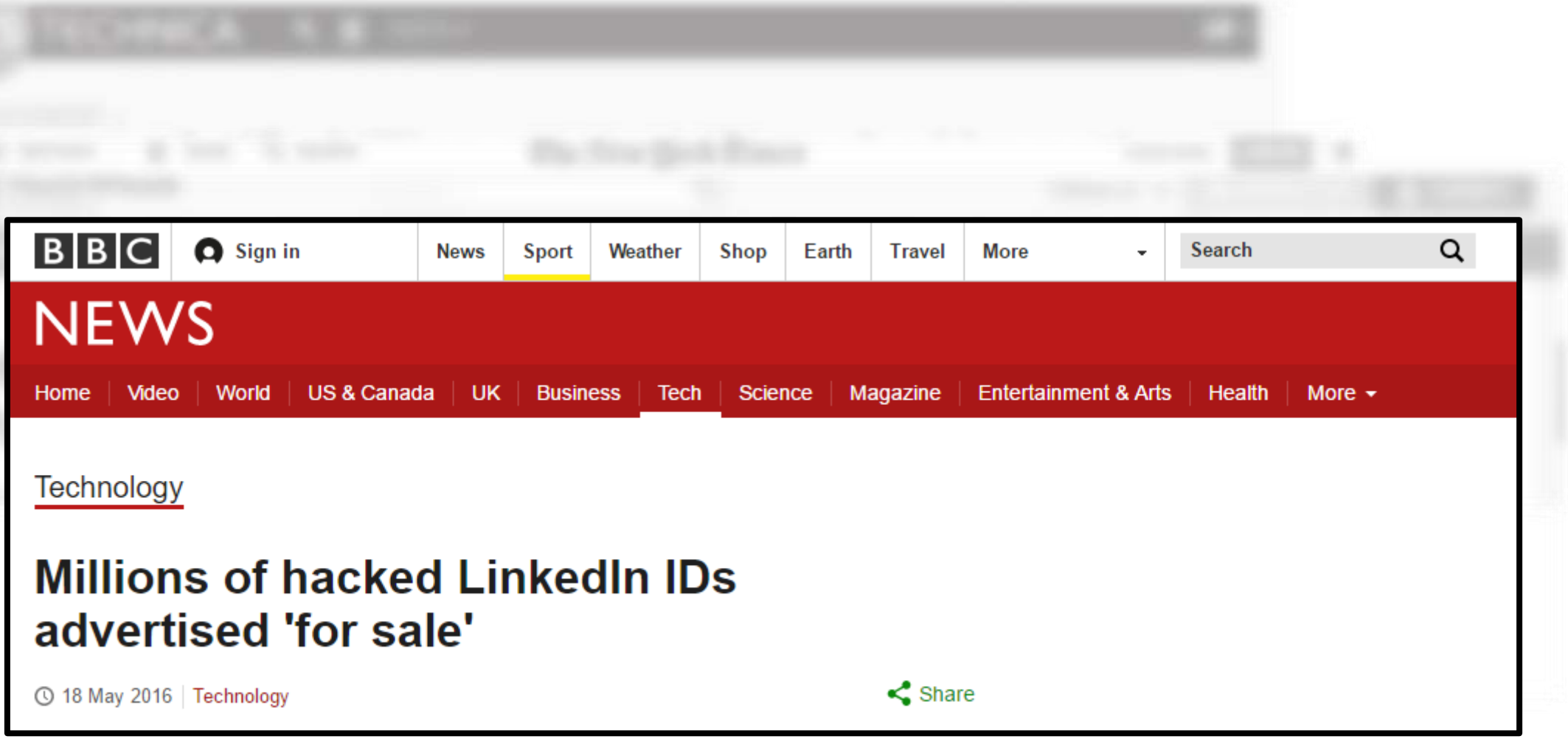

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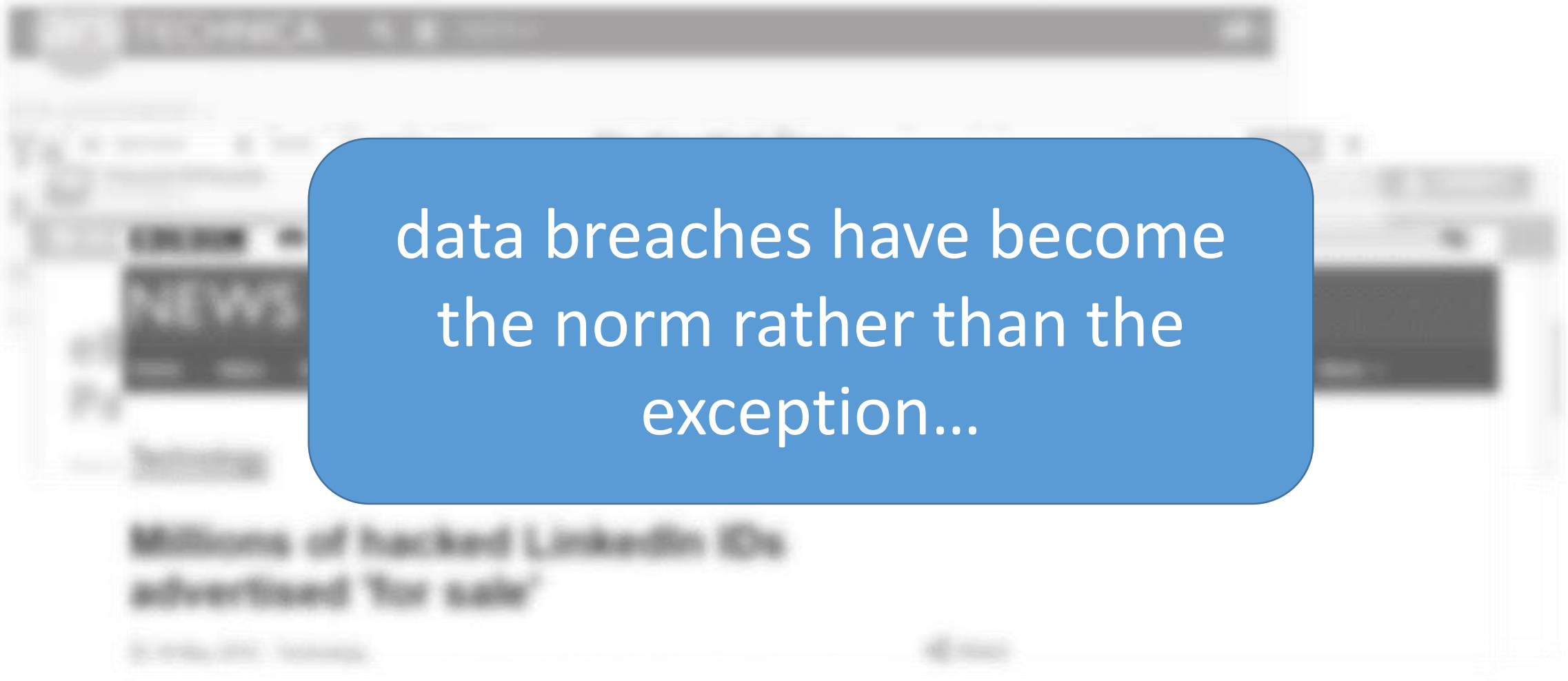
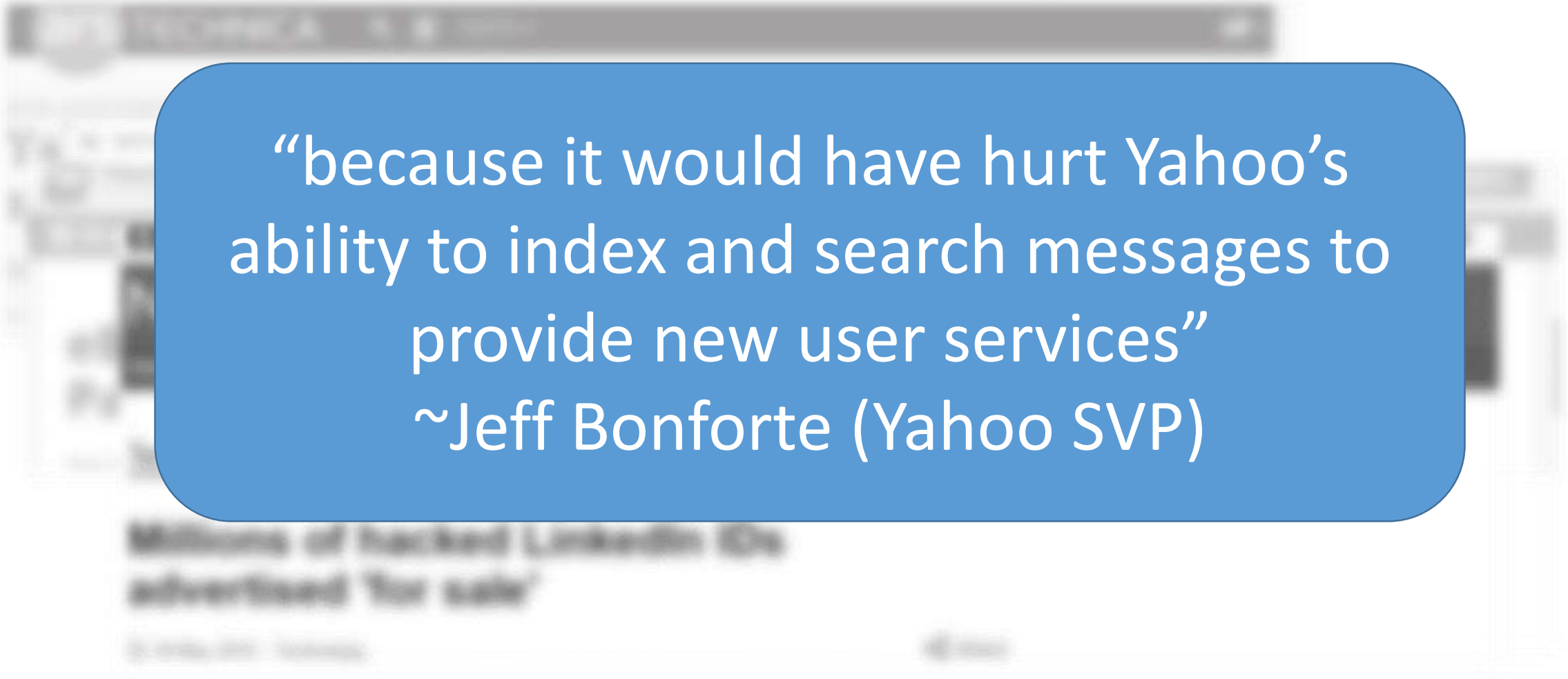


Why Not Encrypt?



"because it would have hurt Yahoo's ability to index and search messages to provide new user services"
~Jeff Bonforte (Yahoo SVP)

Order-Revealing Encryption [BLRSZZ'15]

secret-key encryption scheme

client

$$\begin{aligned} \mathrm{ct}_1 &= \mathrm{Enc}(\mathrm{sk}, 123) \\ \mathrm{ct}_2 &= \mathrm{Enc}(\mathrm{sk}, 512) \\ \mathrm{ct}_3 &= \mathrm{Enc}(\mathrm{sk}, 273) \end{aligned}$$

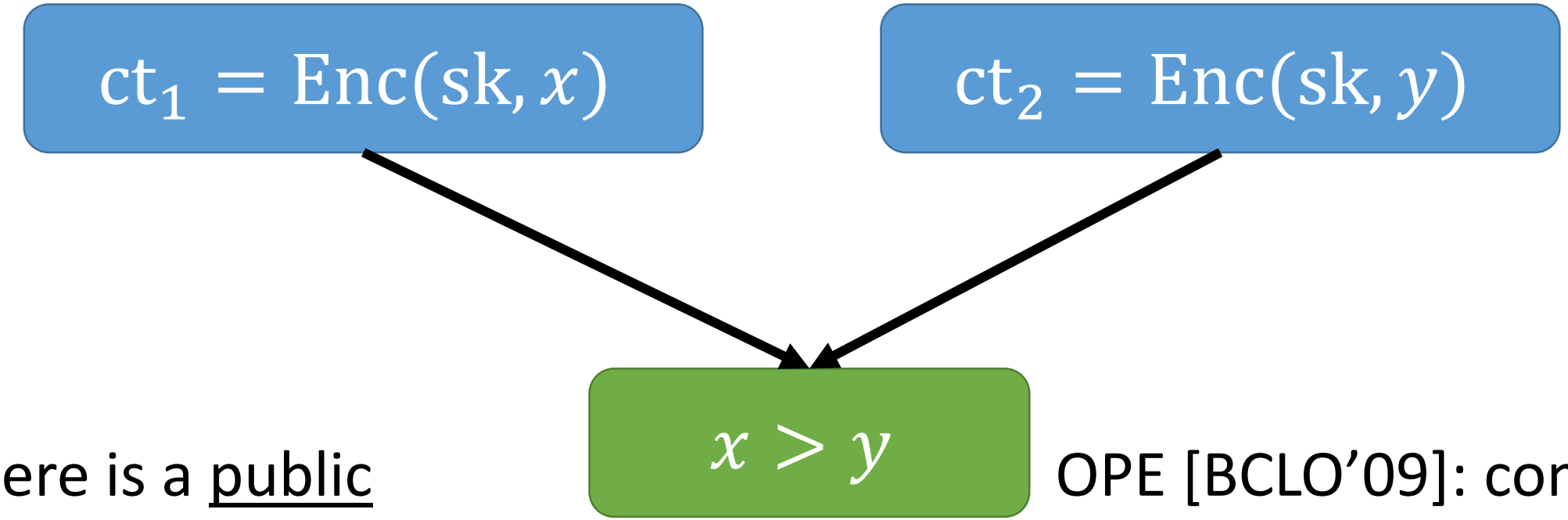
server

Which is greater: the value encrypted by ct_1 or the value encrypted by ct_2?

(legacy-friendly) range queries on encrypted data

Order-Revealing Encryption [BLRSZZ'15]

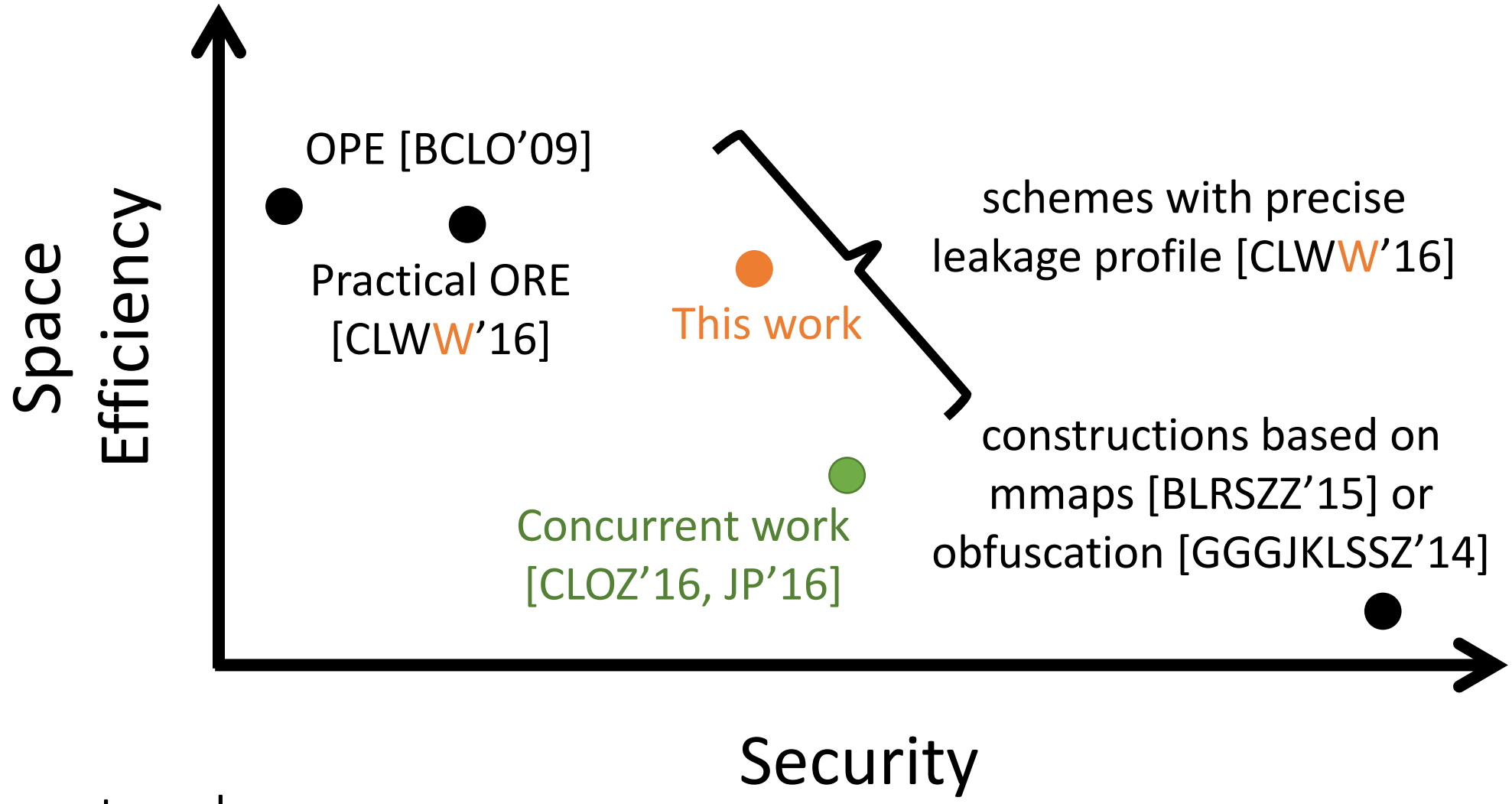
given any two ciphertexts



there is a public function for performing comparisons

OPE [BCLO'09]: comparison function is numeric comparison on ciphertexts

The Landscape of ORE



not drawn to scale

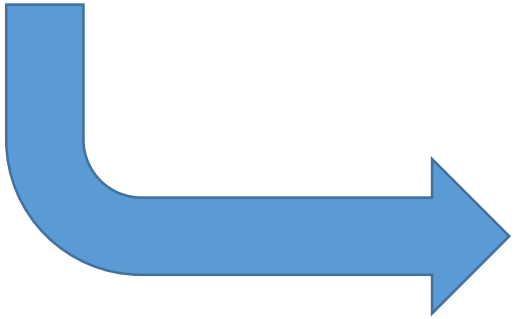
Inference Attacks [NKW'15, DDC'16, GSBNR'16]

ID	Name	Age	Diagnosis
wpjOos	2wzXW8	SqX9l9	KqLUXE
XdXdg8	y9GFpS	gwilE3	MJ23b7
P6vKhW	EgN0Jn	S0pRJe	aTaeJk
orJRe6	KQWy9U	tPWF3M	4FBEO0

encrypted database

+

public information

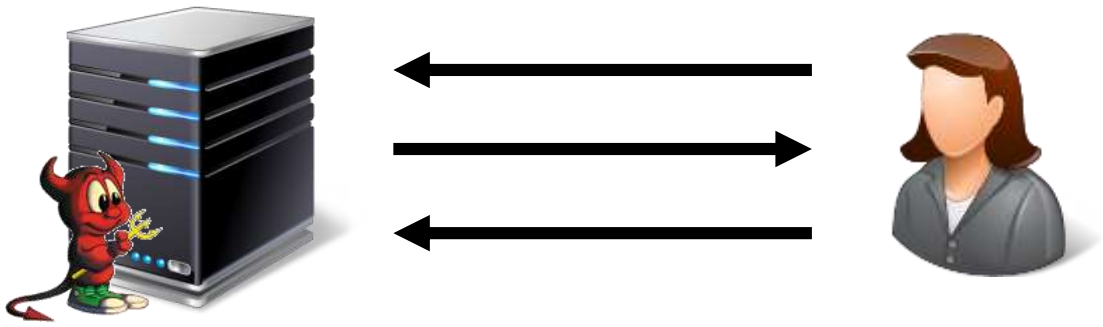


frequency and statistical analysis

ID	Name	Age	Diagnosis
???	Alice	30-35	2
???	Bob	45-50	3
???	Charlie	40-45	2
???	???	40-45	4

plaintext recovery

Online vs. Offline Security



adversary sees encrypted database +
queries and can interact with the database

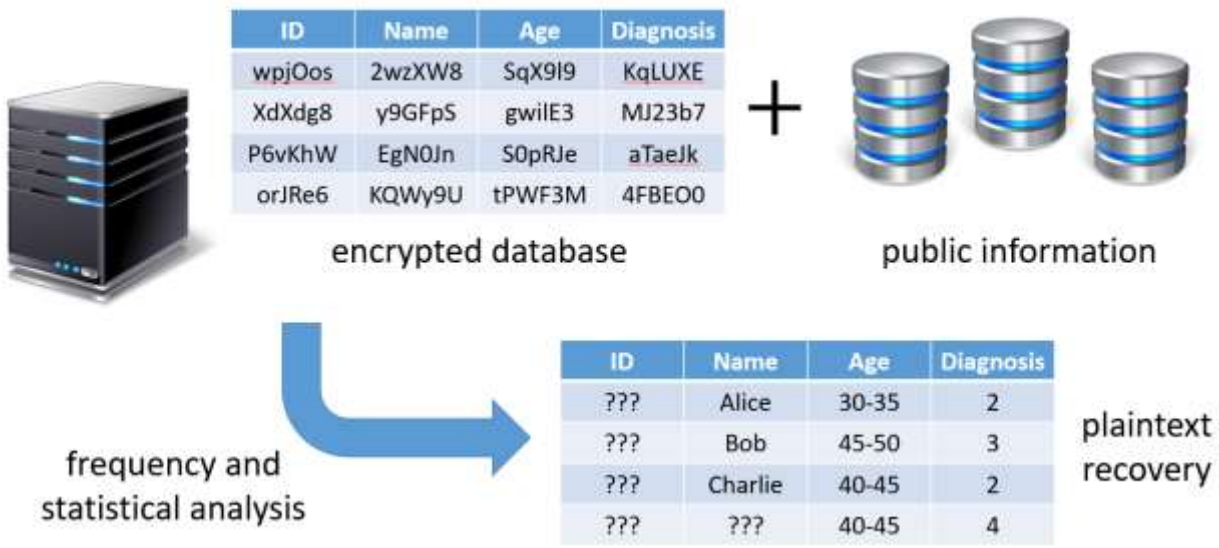
online attacks (e.g., active corruption)

offline attacks (e.g., passive snapshots)

adversary only sees contents
of encrypted database

typical database breach:
contents of database are stolen
and dumped onto the web

Inference Attacks [NKW'15, DDC'16, GSBNR'16]



PPE schemes <u>always</u> reveal certain properties (e.g., equality, order) on ciphertexts and thus, are vulnerable to offline inference attacks

Can we <u>fully</u> defend against offline inference attacks while remaining legacy-friendly?

This Work

Can we fully defend against offline inference attacks while remaining legacy-friendly?

Trivial solution: encrypt the entire database, and have client provide decryption key at query time

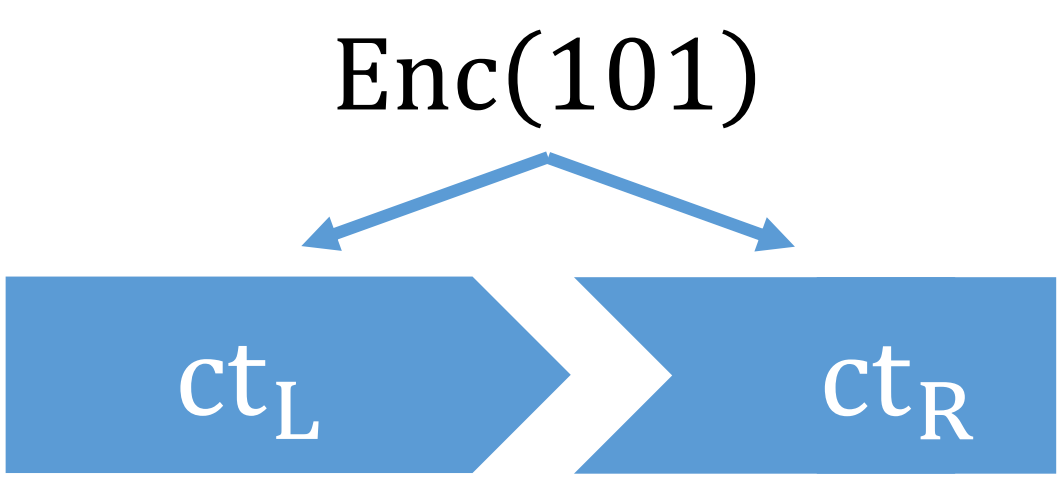
Desiderata: an ORE scheme that enables:

- perfect offline security
- limited leakage in the online setting

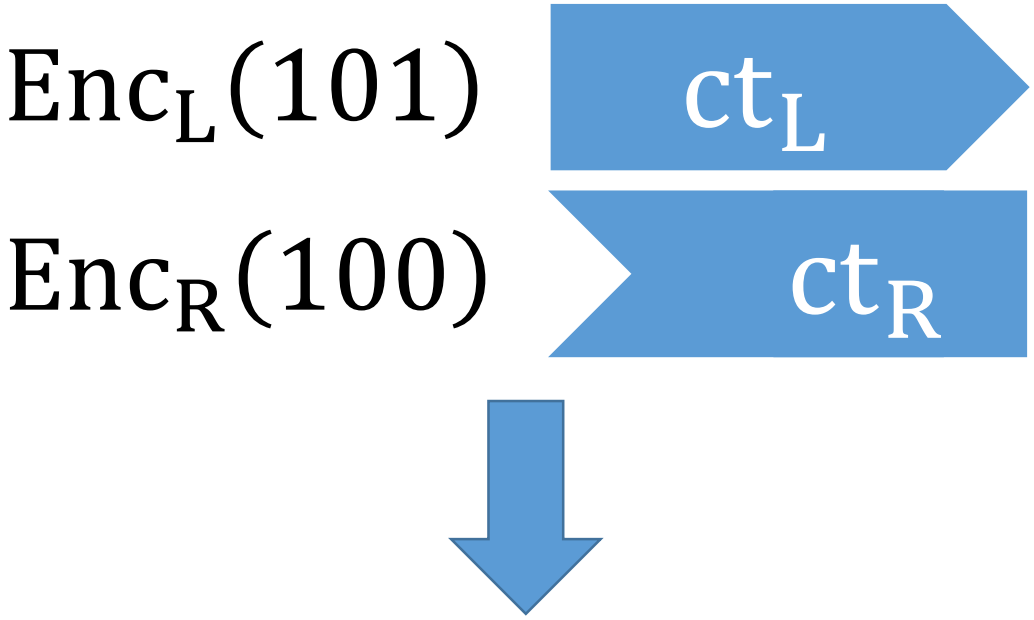
ORE with Additional Structure

Focus of this work: performing range queries on encrypted data

Key primitive: order-revealing encryption scheme where ciphertexts have a “decomposable” structure



ciphertexts naturally split into two components



greater than

ORE with Additional Structure

$\mathrm{Enc}_{\mathrm{L}}(101)$ → ct_{L}

$\mathrm{Enc}_{\mathrm{R}}(100)$ → ct_{R}

comparison can be performed between left ciphertext and right ciphertext

right ciphertexts provide **semantic security**!

robustness against offline inference attacks!

Encrypted Range Queries

ID	Name	Age	Diagnosis
0	Alice	31	2
1	Bob	47	3
2	Charlie	41	2
3	Inigo	45	4

build encrypted index

Age	ID
$\mathrm{Enc}_R(31)$	$\mathrm{Enc}(0)$
$\mathrm{Enc}_R(41)$	$\mathrm{Enc}(2)$
$\mathrm{Enc}_R(45)$	$\mathrm{Enc}(3)$
$\mathrm{Enc}_R(47)$	$\mathrm{Enc}(1)$

store right ciphertexts in sorted order

record IDs encrypted under independent key

Name	ID
$\mathrm{Enc}_R(\mathrm{Alice})$	$\mathrm{Enc}(0)$

Age	ID
$\mathrm{Enc}_R(31)$	$\mathrm{Enc}(0)$

Diagnosis	ID
$\mathrm{Enc}_R(2)$	$\mathrm{Enc}(2)$
$\mathrm{Enc}_R(2)$	$\mathrm{Enc}(0)$
$\mathrm{Enc}_R(3)$	$\mathrm{Enc}(1)$
$\mathrm{Enc}_R(4)$	$\mathrm{Enc}(3)$

separate index for each searchable column, and using independent ORE keys

Encrypted Range Queries

Encrypted database:

ID	Name	Age	Diagnosis
0	Alice	31	2
1	Bob	47	3
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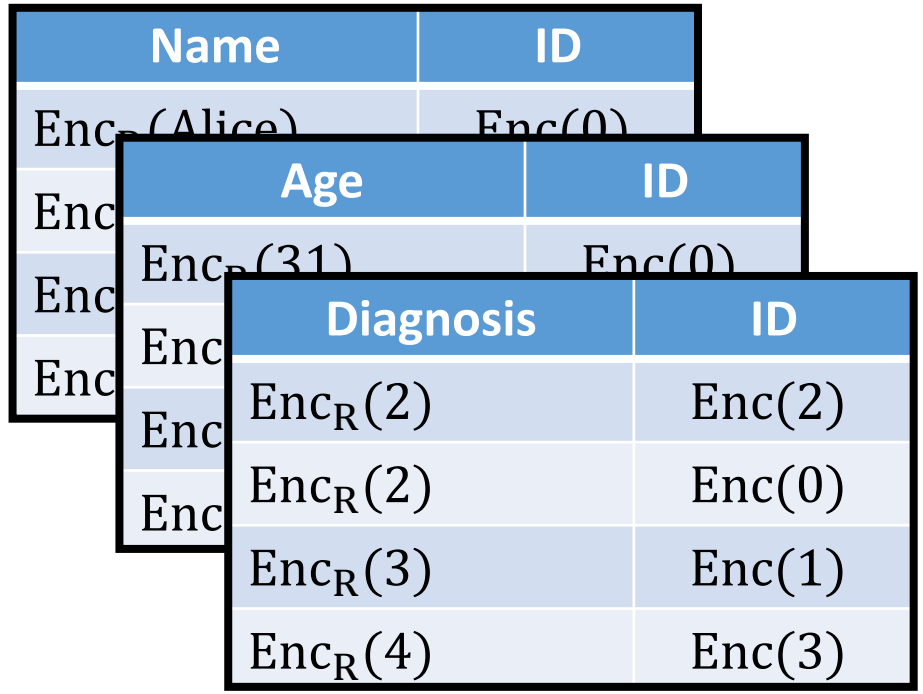
3	Inigo	45	4

columns (other than ID) are encrypted using a semantically-secure encryption scheme

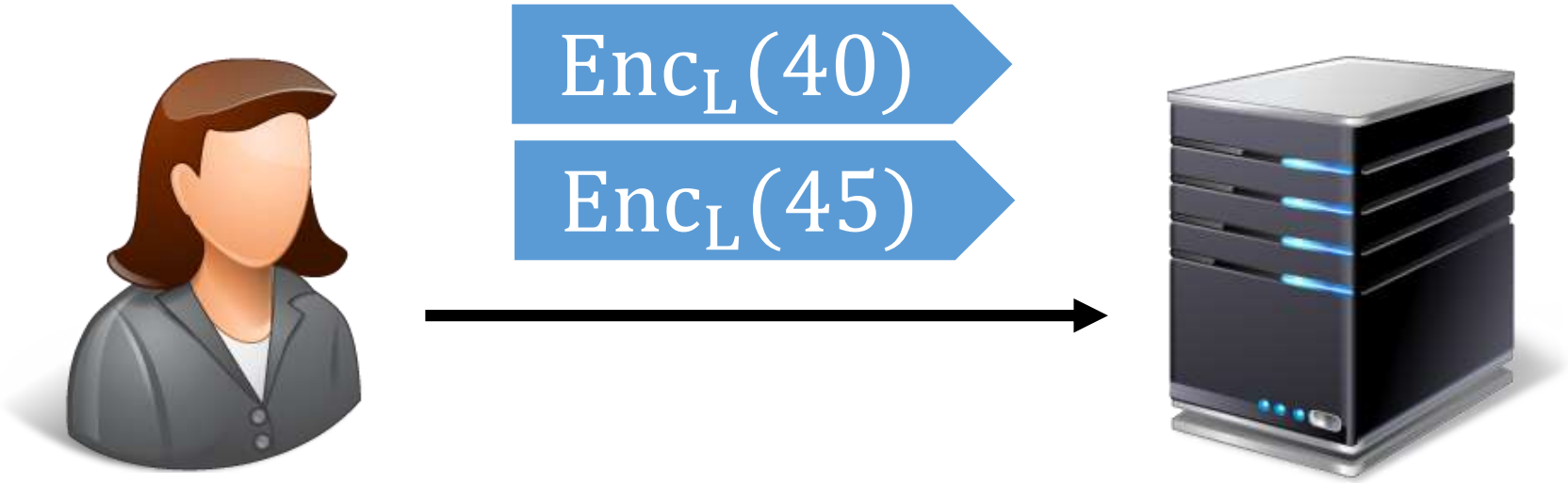
clients hold (secret) keys needed to decrypt and query database



encrypted search indices

Encrypted Range Queries

Query for all records where $40 \geq \text{age} \geq 45$:



Encrypted Range Queries

Query for all records where $40 \geq \text{age} \geq 45$:

$\text{Enc}_L(40)$

$\text{Enc}_L(45)$

Age	ID
$\text{Enc}_R(31)$	$\text{Enc}(0)$
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$\text{Enc}_R(45)$	$\text{Enc}(3)$
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use binary search to determine endpoints (comparison via ORE)

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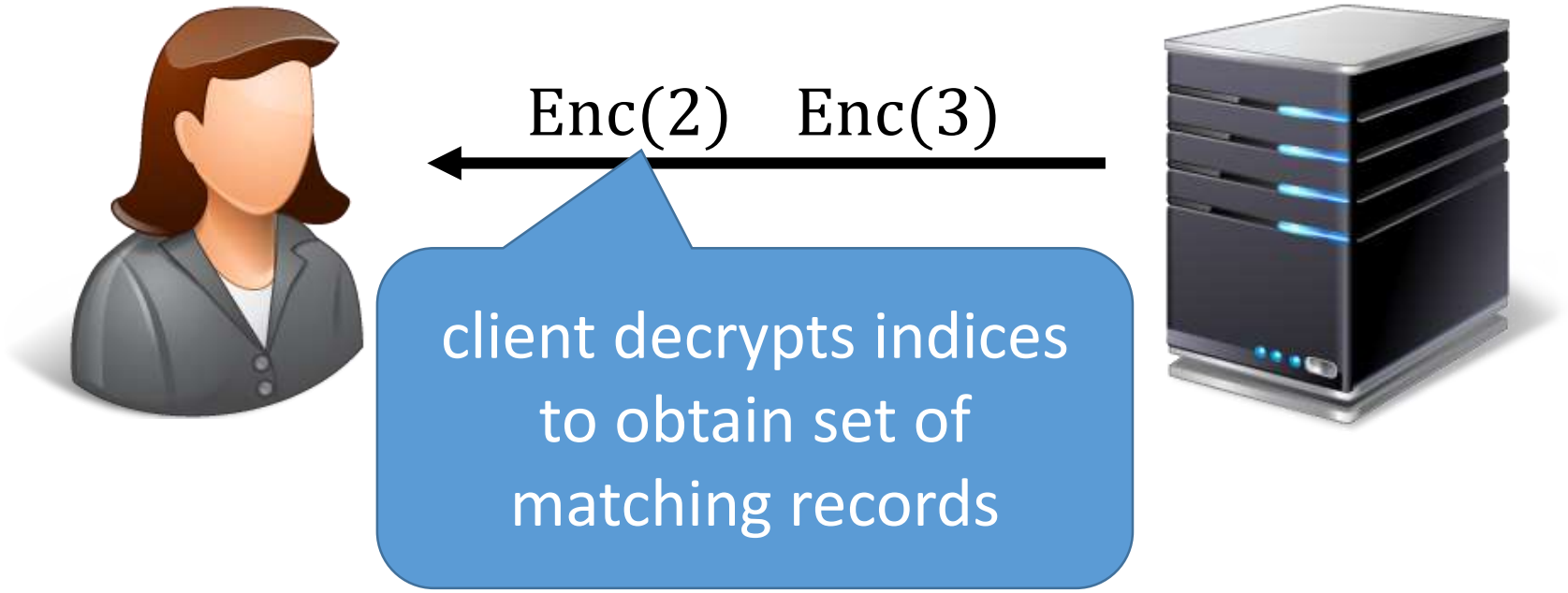
$\text{Enc}_R(45)$	$\text{Enc}(3)$
$\text{Enc}_R(47)$	$\text{Enc}(1)$

use binary search to determine endpoints (comparison via ORE)

return encrypted indices that match query

Encrypted Range Queries

Query for all records where $40 \geq \text{age} \geq 45$:



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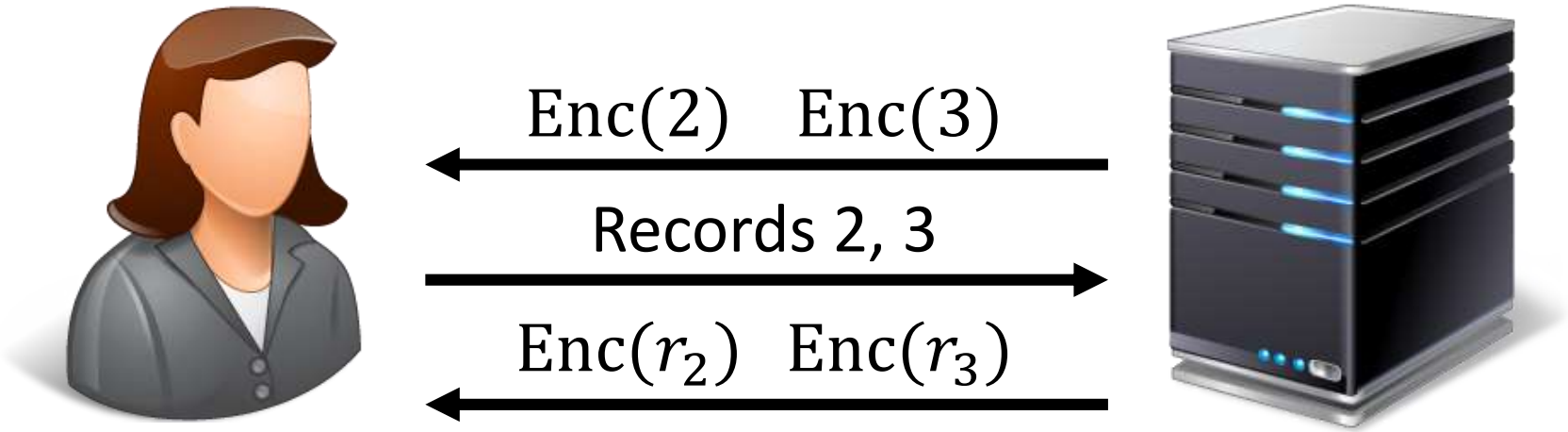

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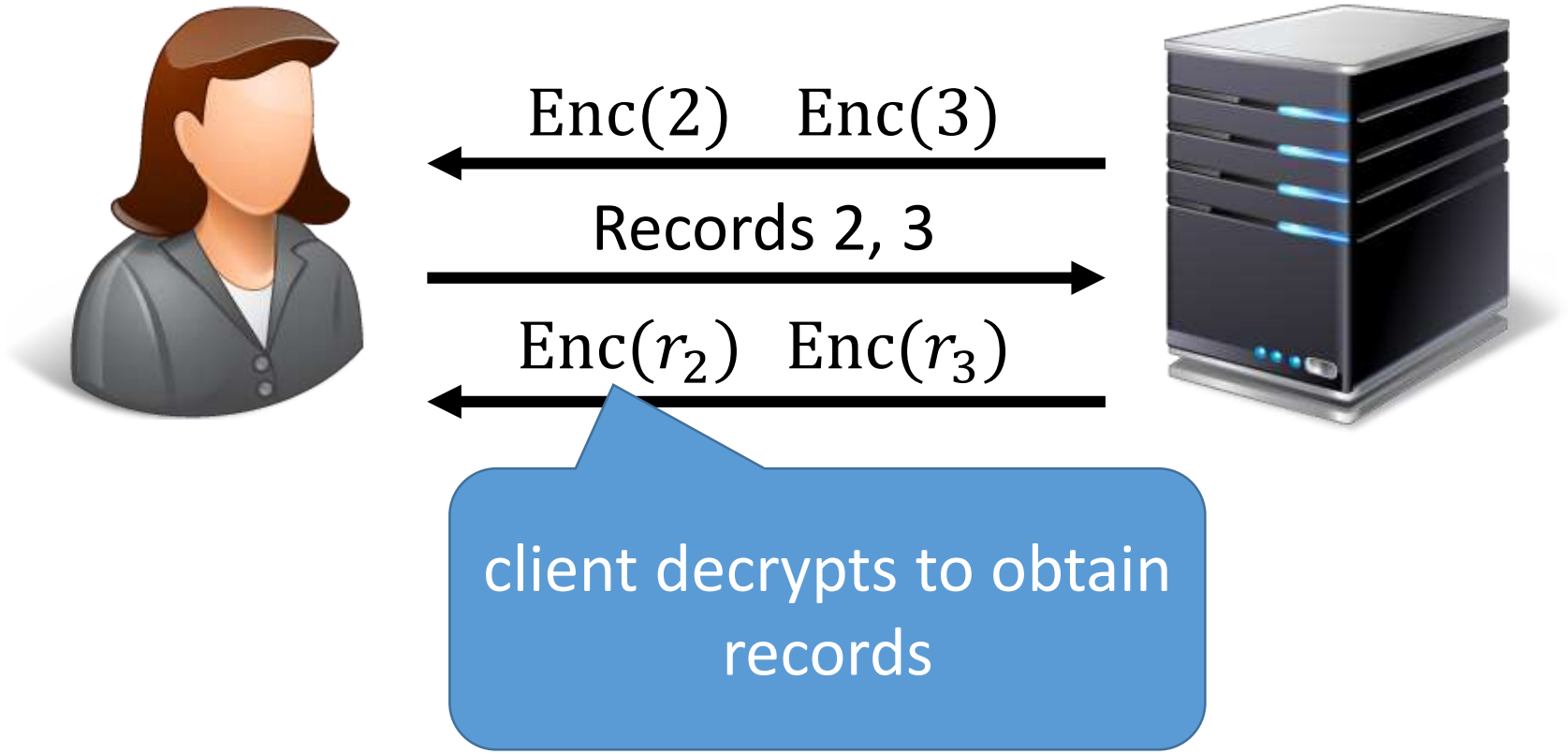

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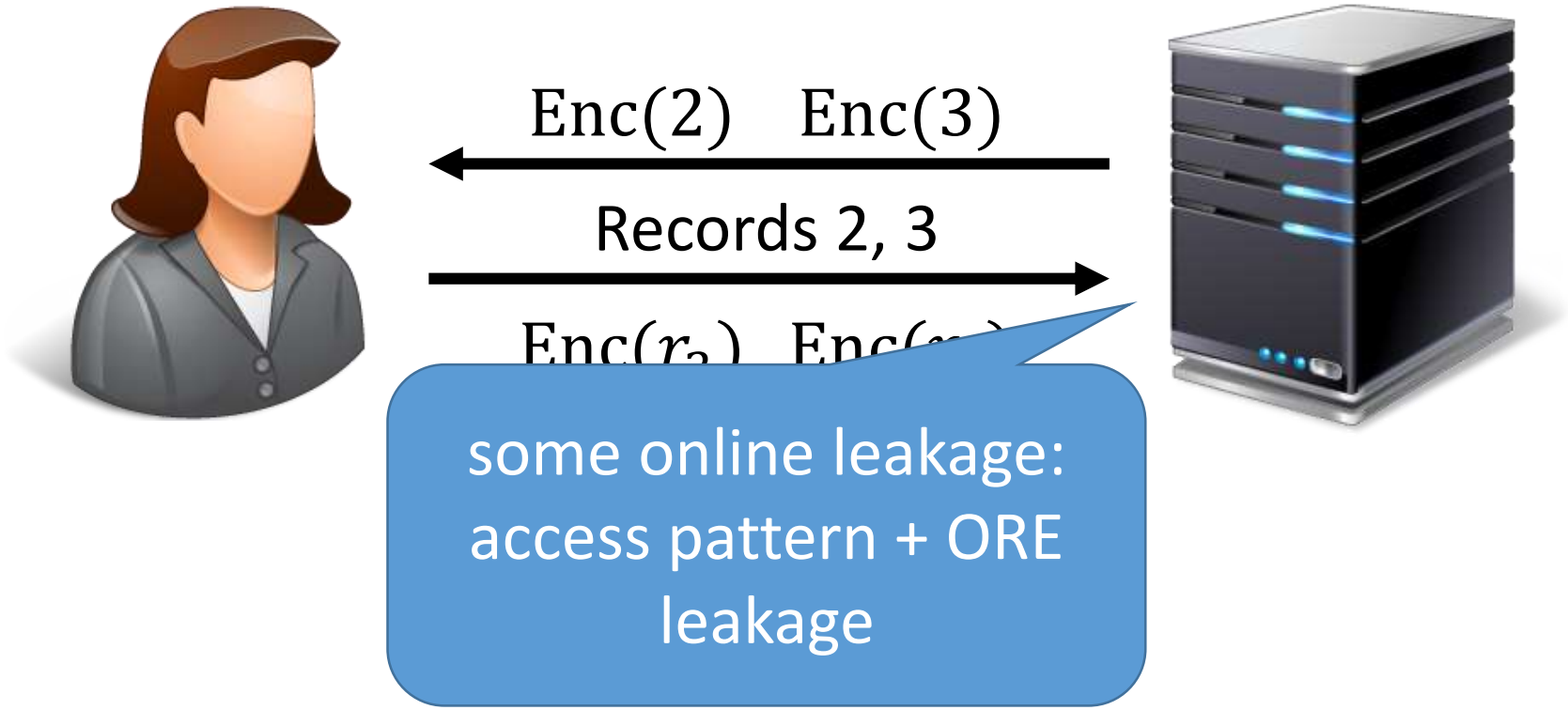

Encrypted Range Queries

Encrypted database:

ID	Name	Age	Diagnosis
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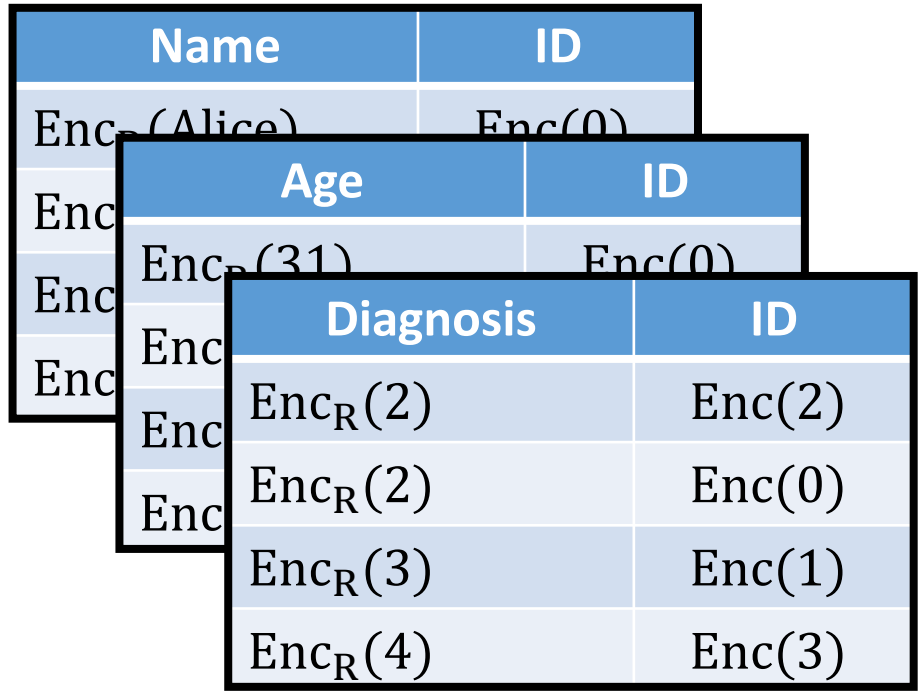
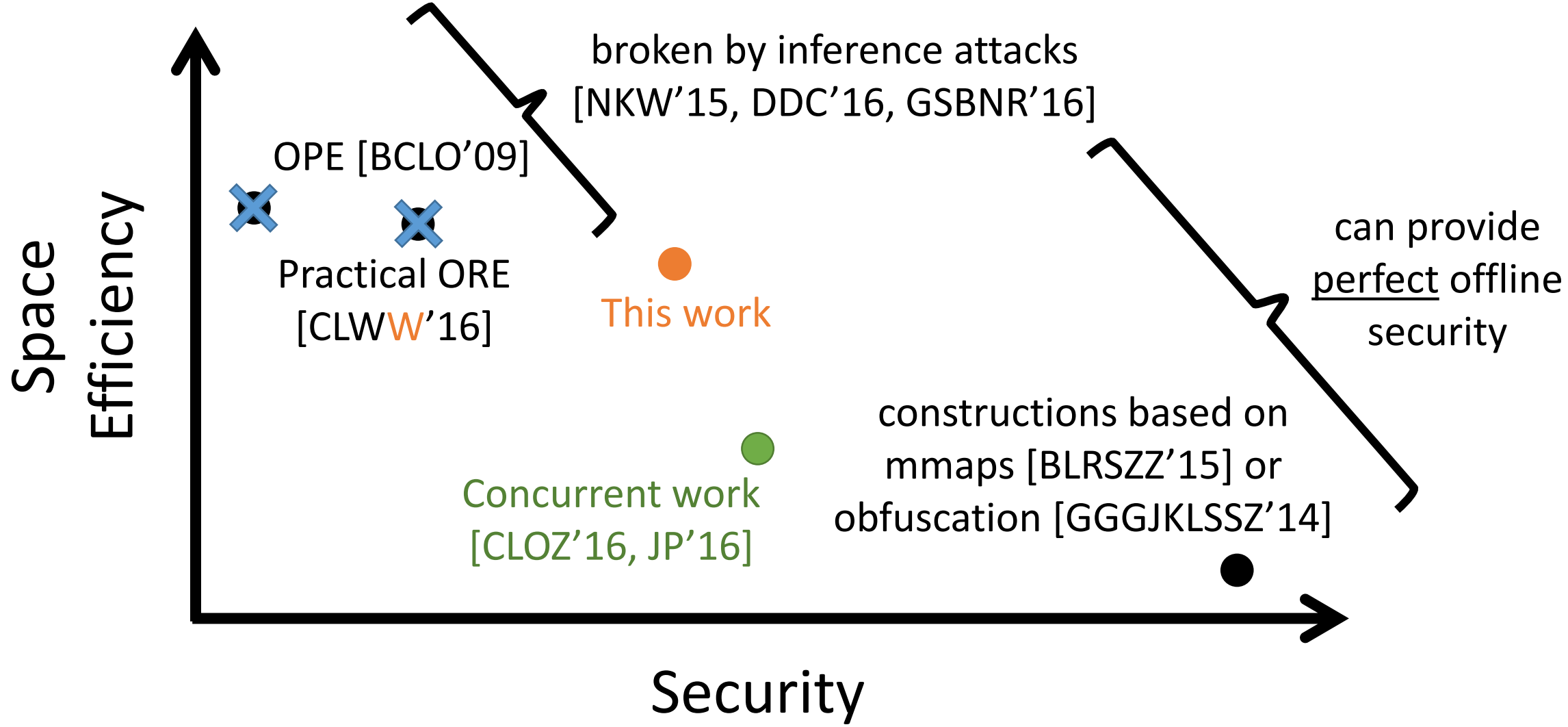
encrypted database is semantically secure!

Perfect offline security



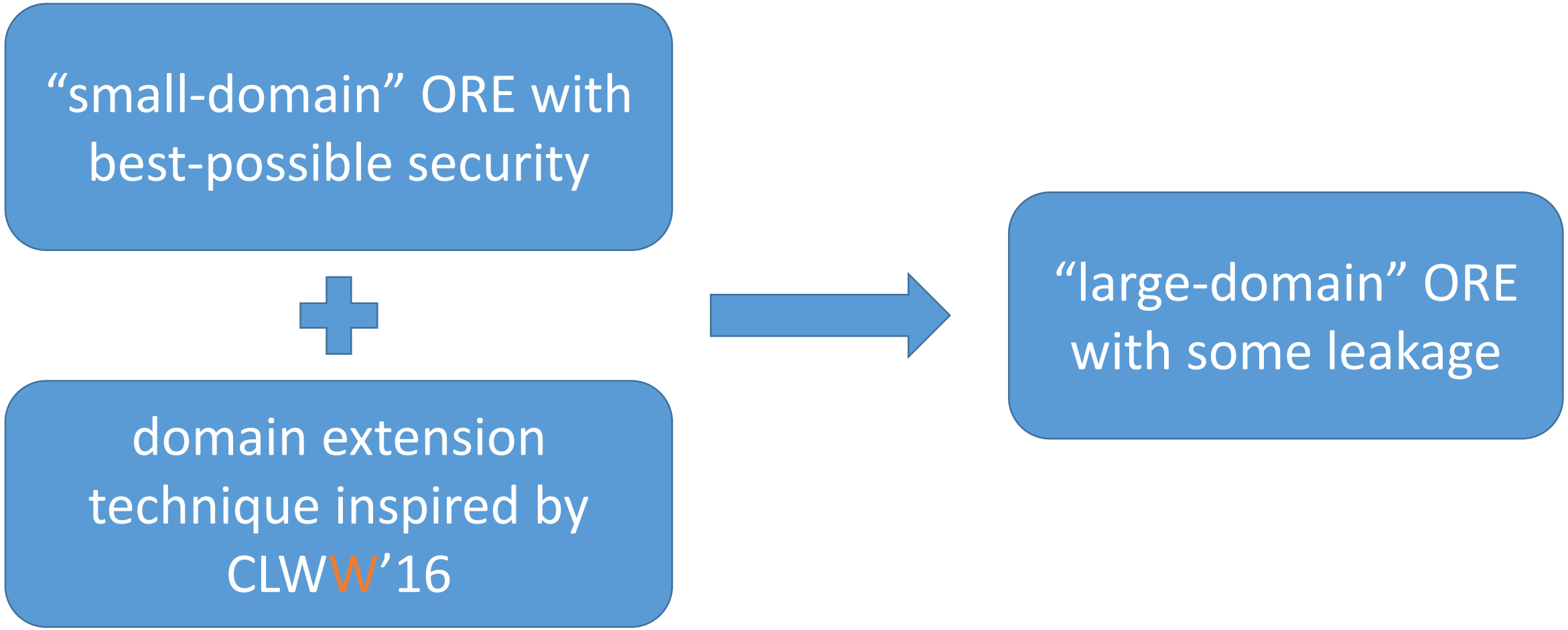
encrypted search indices

The Landscape of ORE



Not drawn to scale

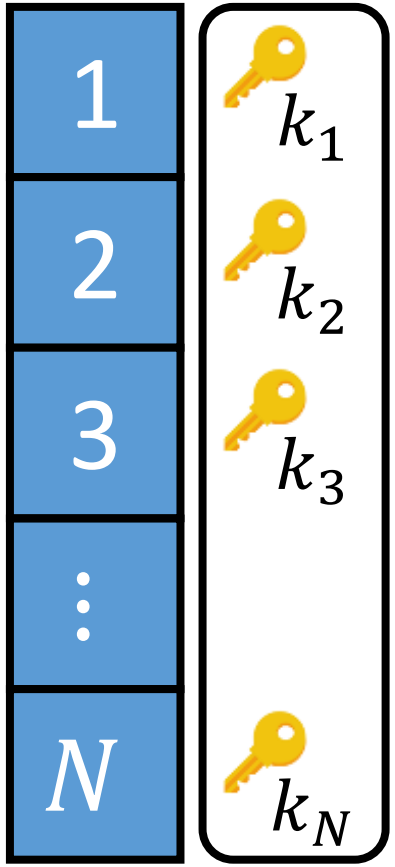
Our New ORE Scheme



Small-Domain ORE with Best-Possible Security

Suppose plaintext space is small: $\{1,2, \ldots, N\}$

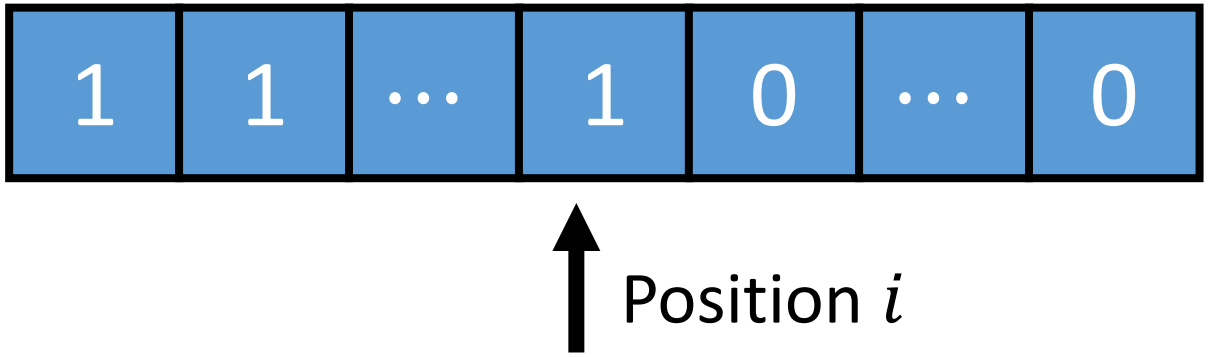
associate a key with each value



$(k_1, \ldots, k_N)$ is the secret key (can be derived from a PRF)

Small-Domain ORE with Best-Possible Security

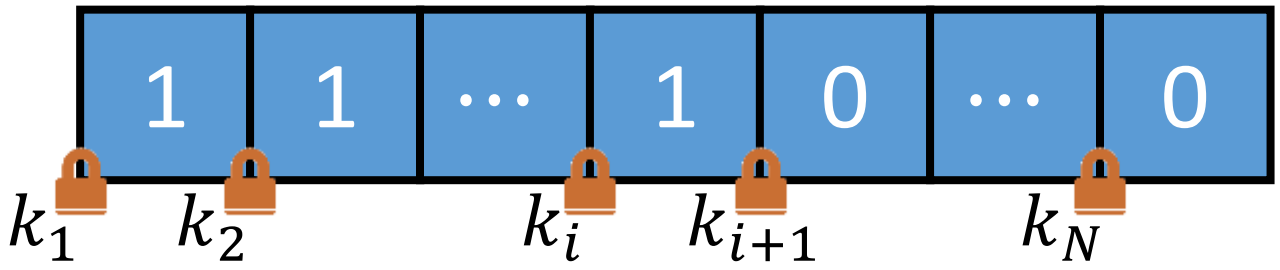
Encrypting a value i



Invariant: all positions $\leq i$ have value 1 while all positions $> i$ have value 0

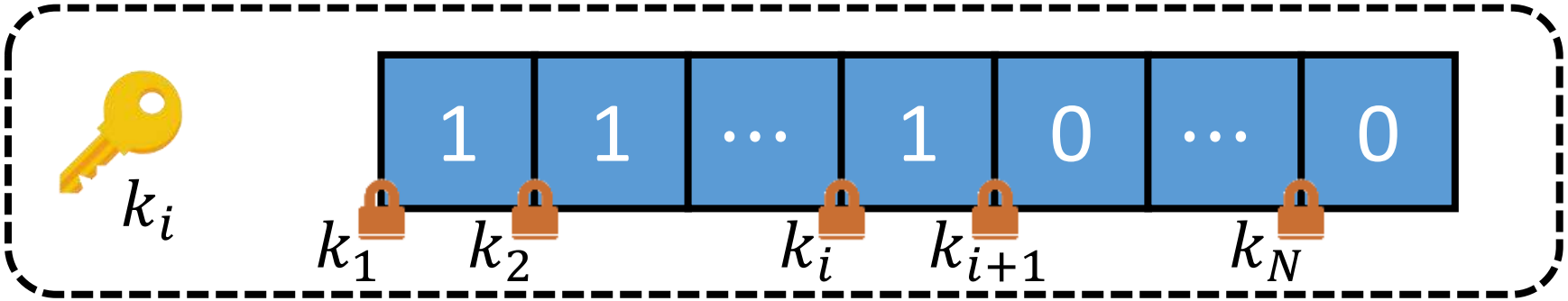
Small-Domain ORE with Best-Possible Security

Encrypting a value i



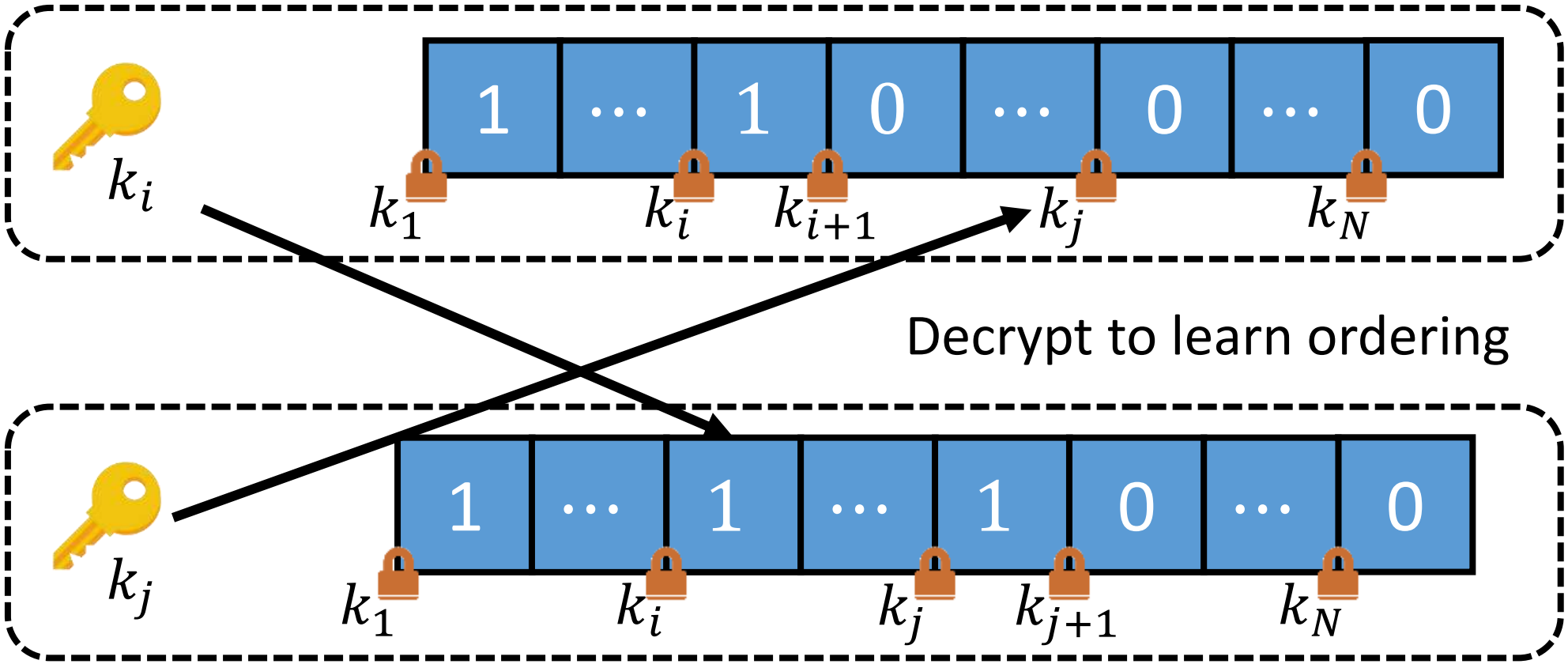
encrypt each slot with key for that slot

To allow comparisons, also give out key for slot i



Small-Domain ORE with Best-Possible Security

Given two ciphertexts



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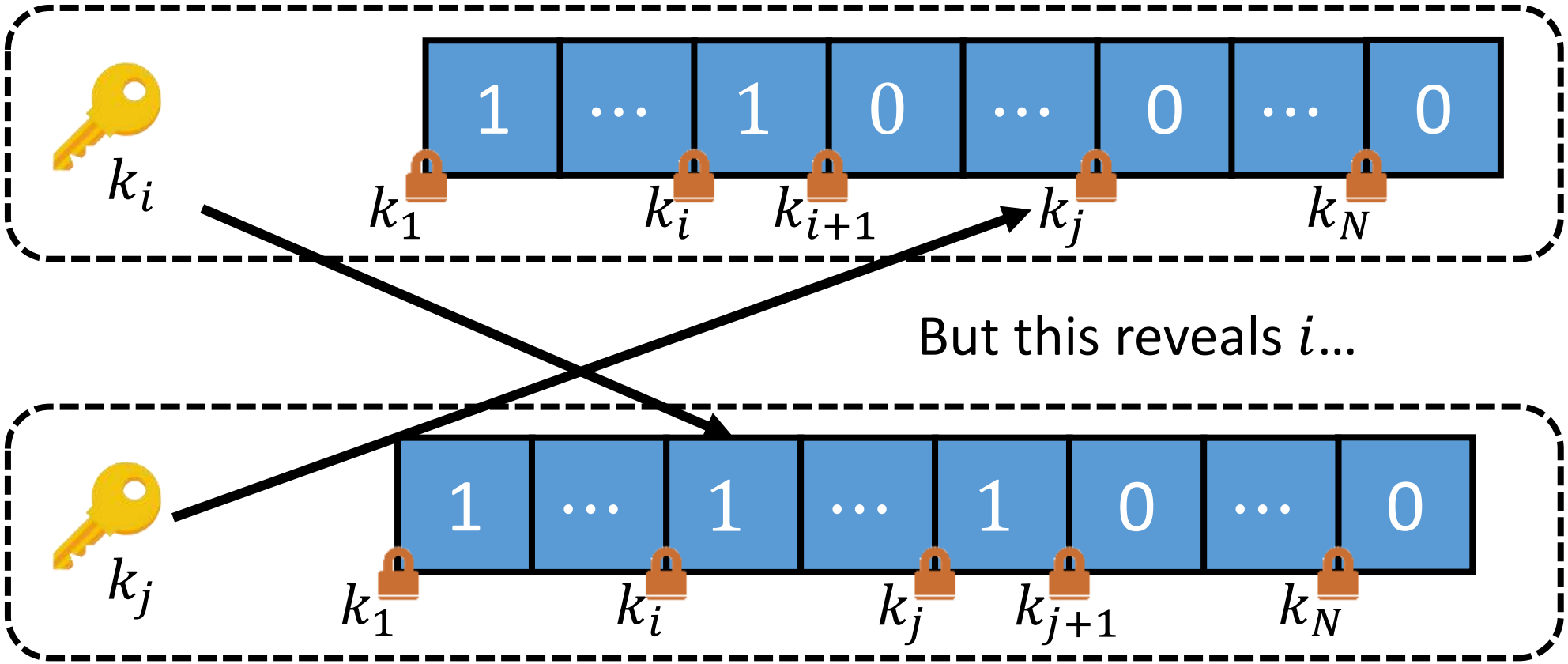
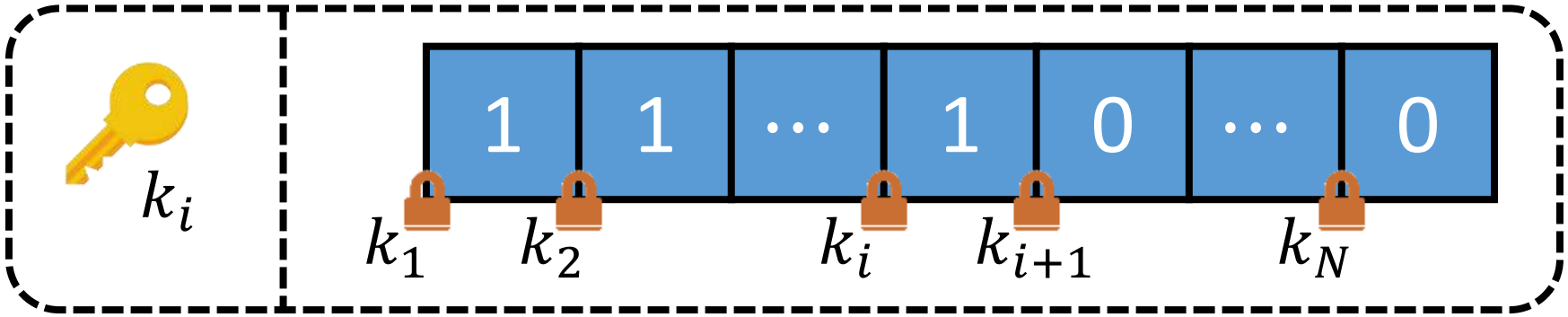


Small-Domain ORE with Best-Possible Security

Solution: apply random permutation π (part of the secret key) to the slots



Small-Domain ORE with Best-Possible Security

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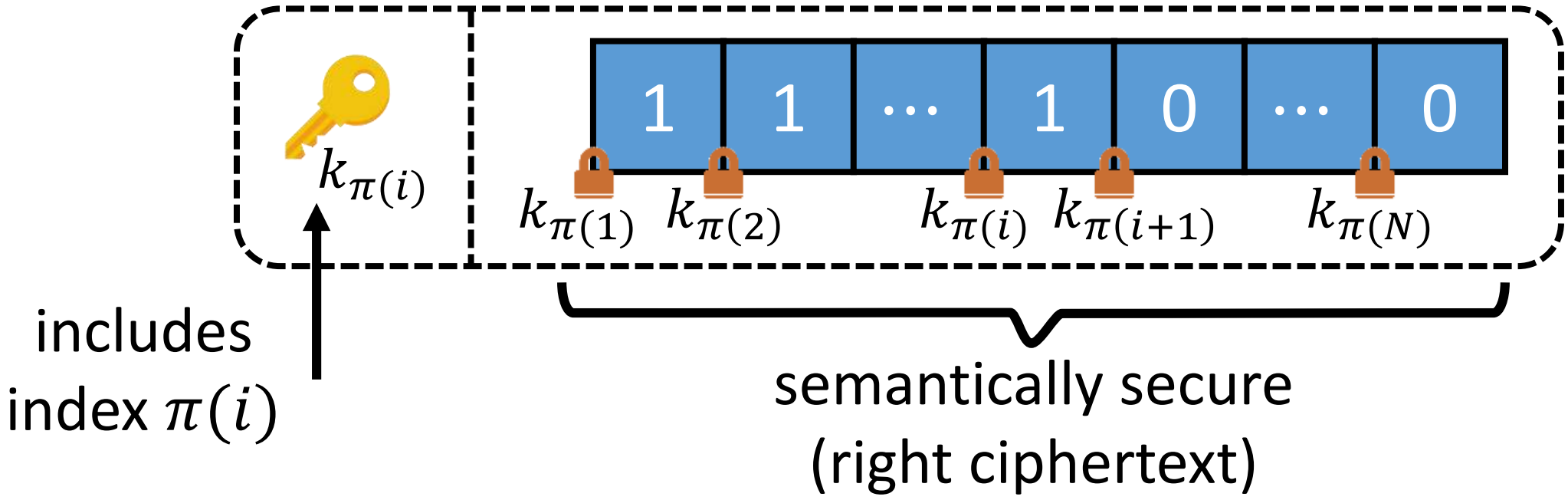
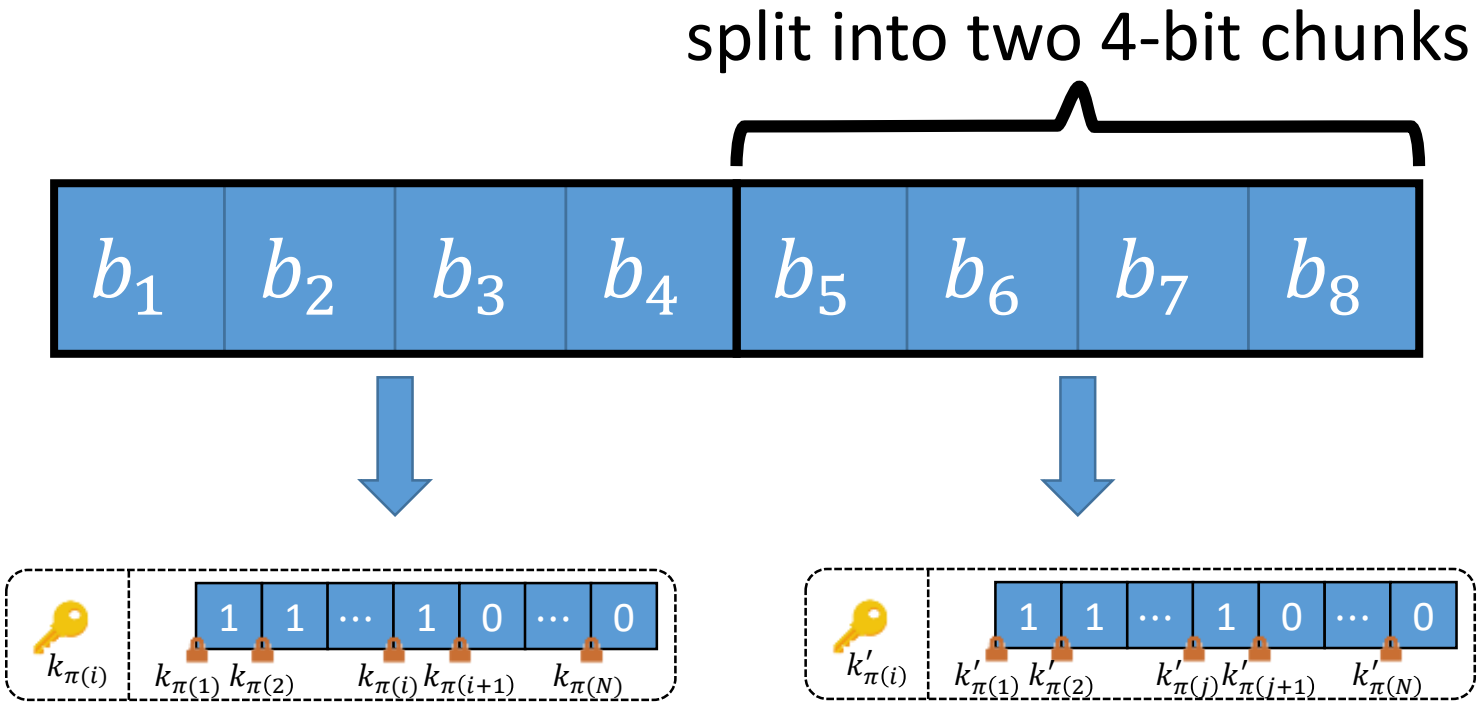


Achieves best-possible security, but ciphertexts are big

Domain Extension for ORE

Key idea: decompose message into smaller blocks and apply small-domain ORE to each block



encrypt each chunk using an ORE instance with a secret key derived from the *prefix*

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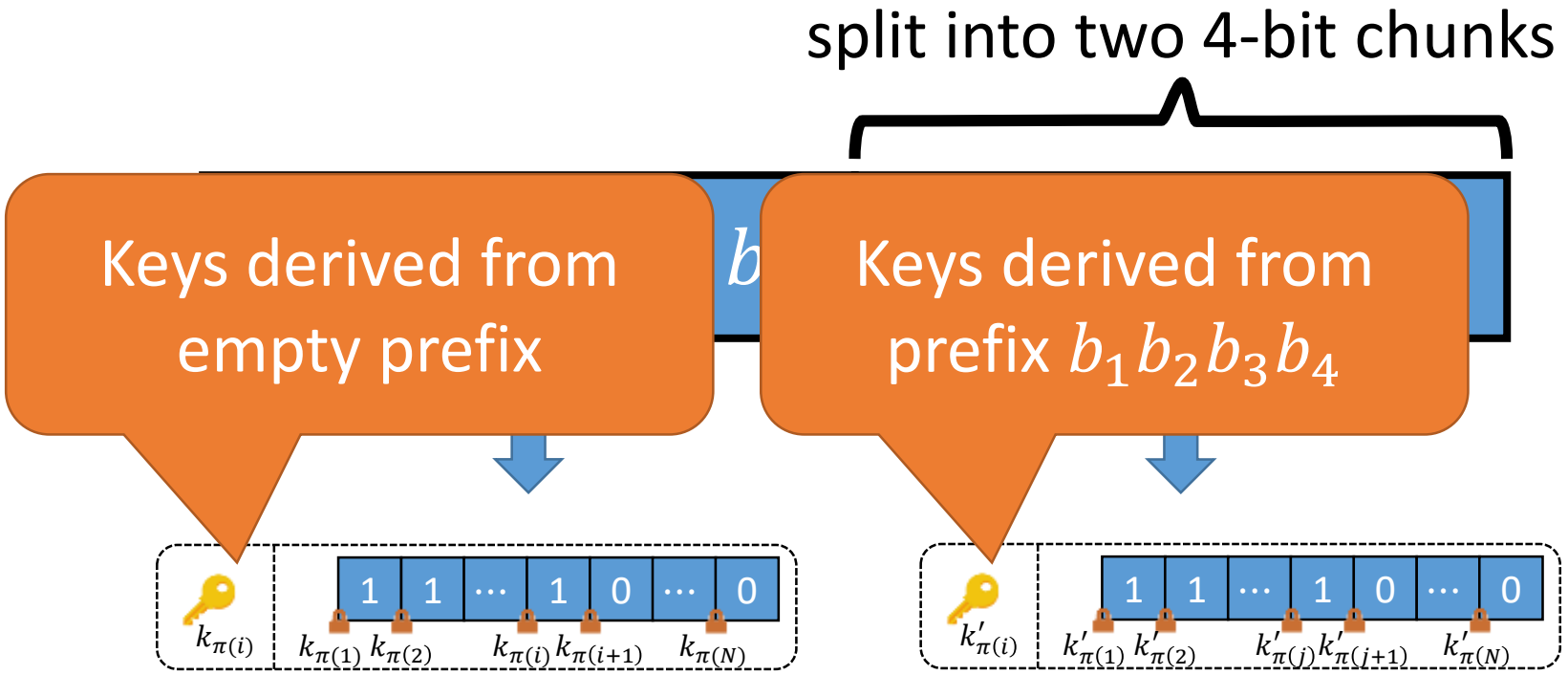

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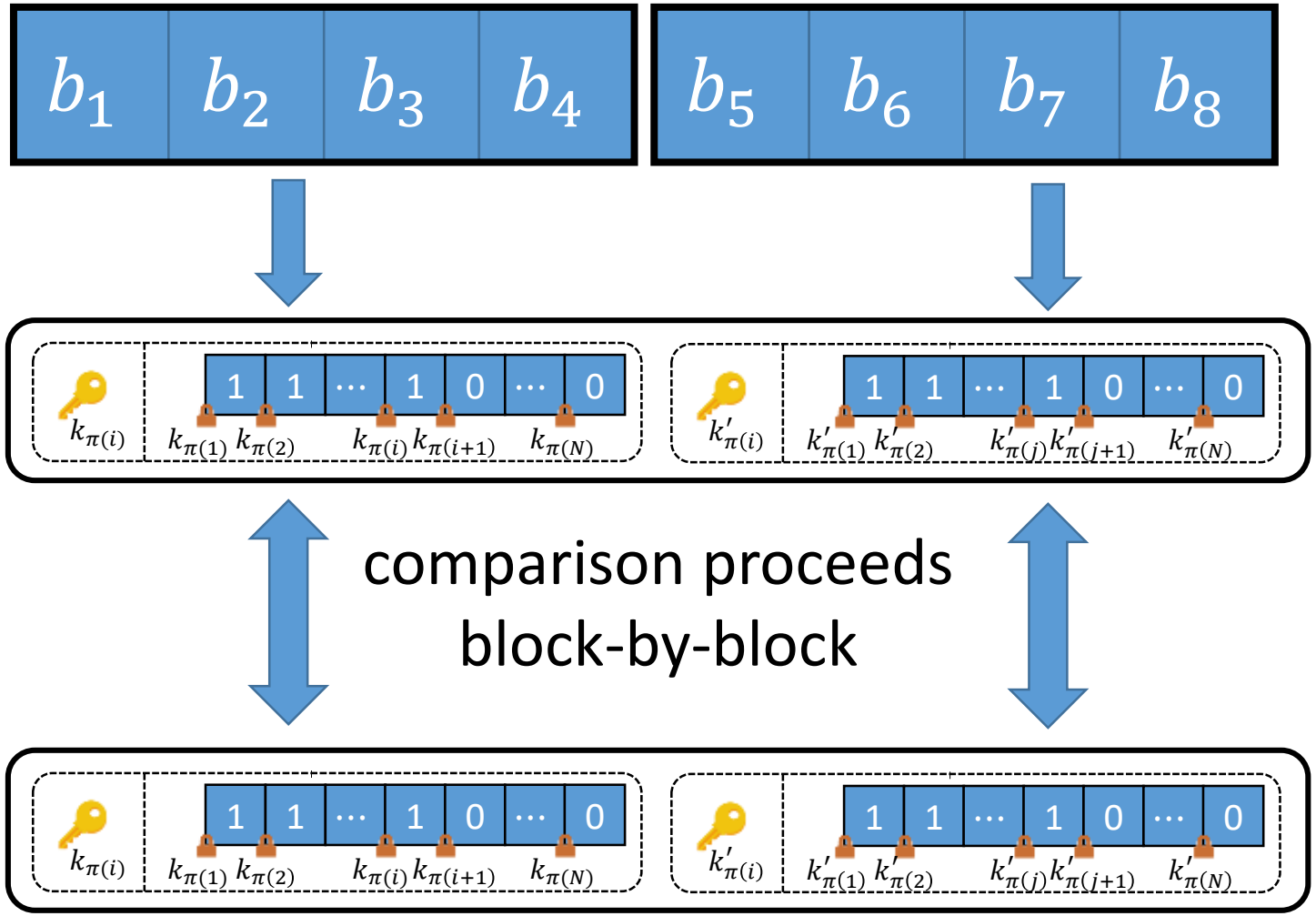
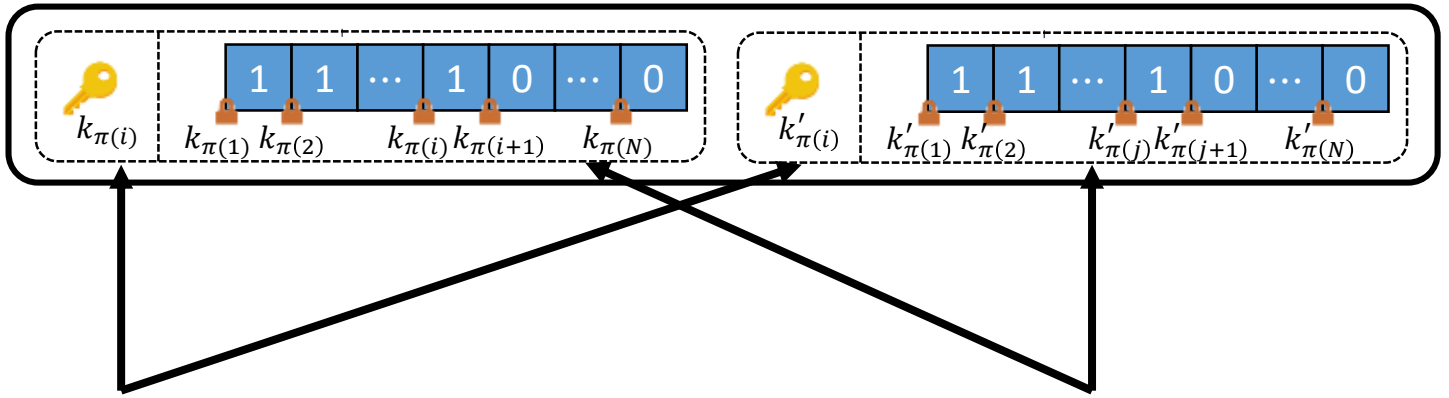


Overall leakage: first **block** that differs

Domain Extension for ORE

Same decomposition into left and right ciphertexts:

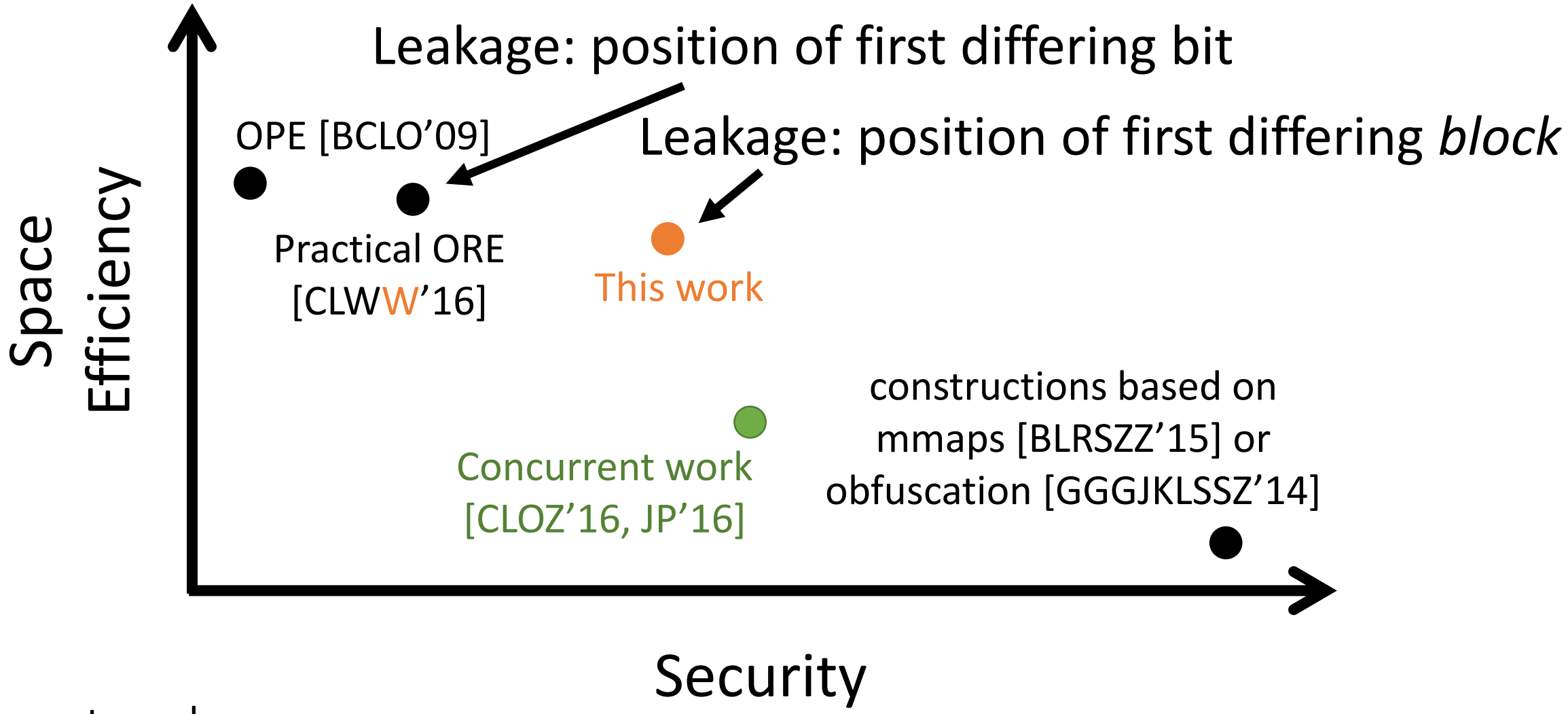


left ciphertext right ciphertext

Right ciphertexts provide semantic security!

Note: optimizations are possible if we apply this technique in a non-black-box way to the small-domain ORE. See paper for details.

The Landscape of ORE



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Performance Evaluation

Scheme	Encrypt (µs)	Compare (µs)	|ct| (bytes)
OPE [BCLO'09]	3601.82	0.36	8
Practical ORE [CLWW'16]	2.06	0.48	8
This work (4-bit blocks)	16.50	0.31	192
This work (8-bit blocks)	54.87	0.63	224
This work (12-bit blocks)	721.37	2.61	1612

Benchmarks taken for C implementation of different schemes (with AES-NI). Measurements for encrypting 32-bit integers.

Performance Evaluation

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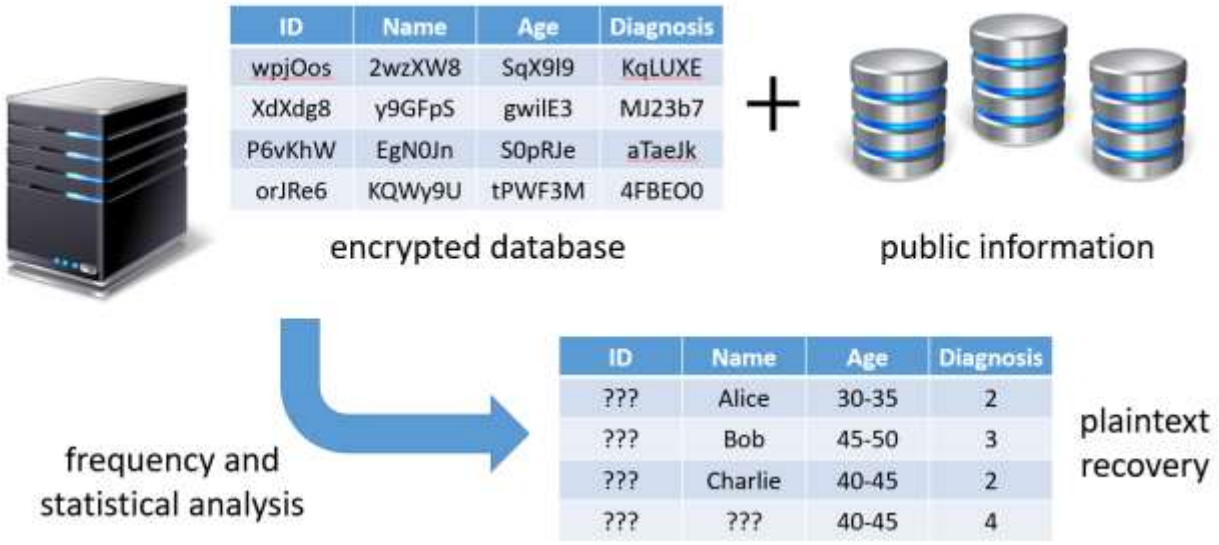
Encrypting byte-size blocks is 65x faster than OPE, but ciphertexts are 30x longer. Security is substantially better.

Conclusions



- Inference attacks render most conventional PPE-based constructions insecure
- However, ORE is still a useful building block for encrypted databases

- Introduced new paradigm for constructing ORE that enables range queries in a way that is mostly legacy-compatible and provides offline semantic security
- New ORE construction that is concretely efficient with strong security
- In paper: new impossibility results for security achievable using OPE

Open Problems

- What kind of inference attacks on possible in the online setting?
  - Indices encrypted separately, so multi-column correlations harder to infer
  - More limited leakage profile (between left and right ciphertexts)
- Can we construct small-domain OREs (with best-possible security) and *sublinear* (in the size of the domain) ciphertext size from PRFs?
- Can we construct left/right ORE (from PRFs) where both left and right ciphertexts are *semantically secure*?

Paper: https://eprint.iacr.org/2016/612
Website: https://crypto.stanford.edu/ore/
Code: https://github.com/kevinlewi/fastore