Order-Revealing Encryption:
How to Search on Encrypted Data

Kevin Lewi and David J. Wu
Stanford University

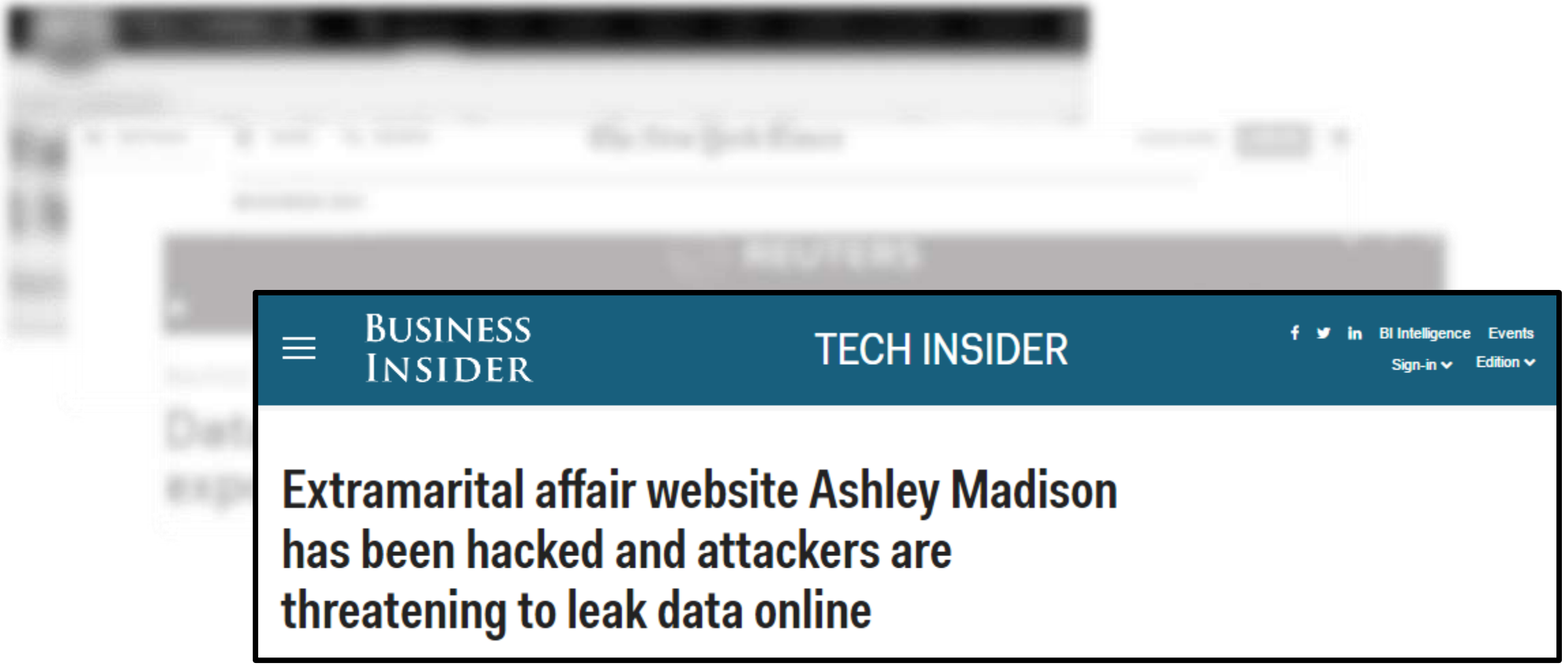
Searching on Encrypted Data

The information accessed from potentially exposed accounts "may have included names, email addresses, telephone numbers, dates of birth, hashed passwords (using MD5) and, in some cases, encrypted or unencrypted security questions and answers…"

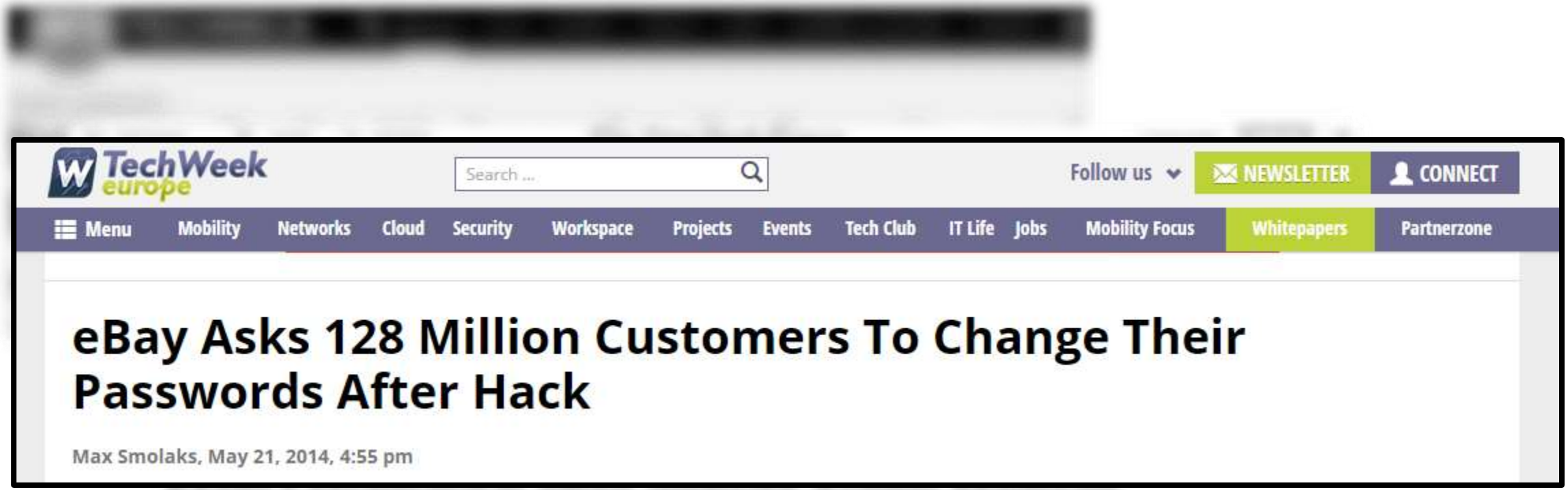
Searching on Encrypted Data

Searching on Encrypted Data

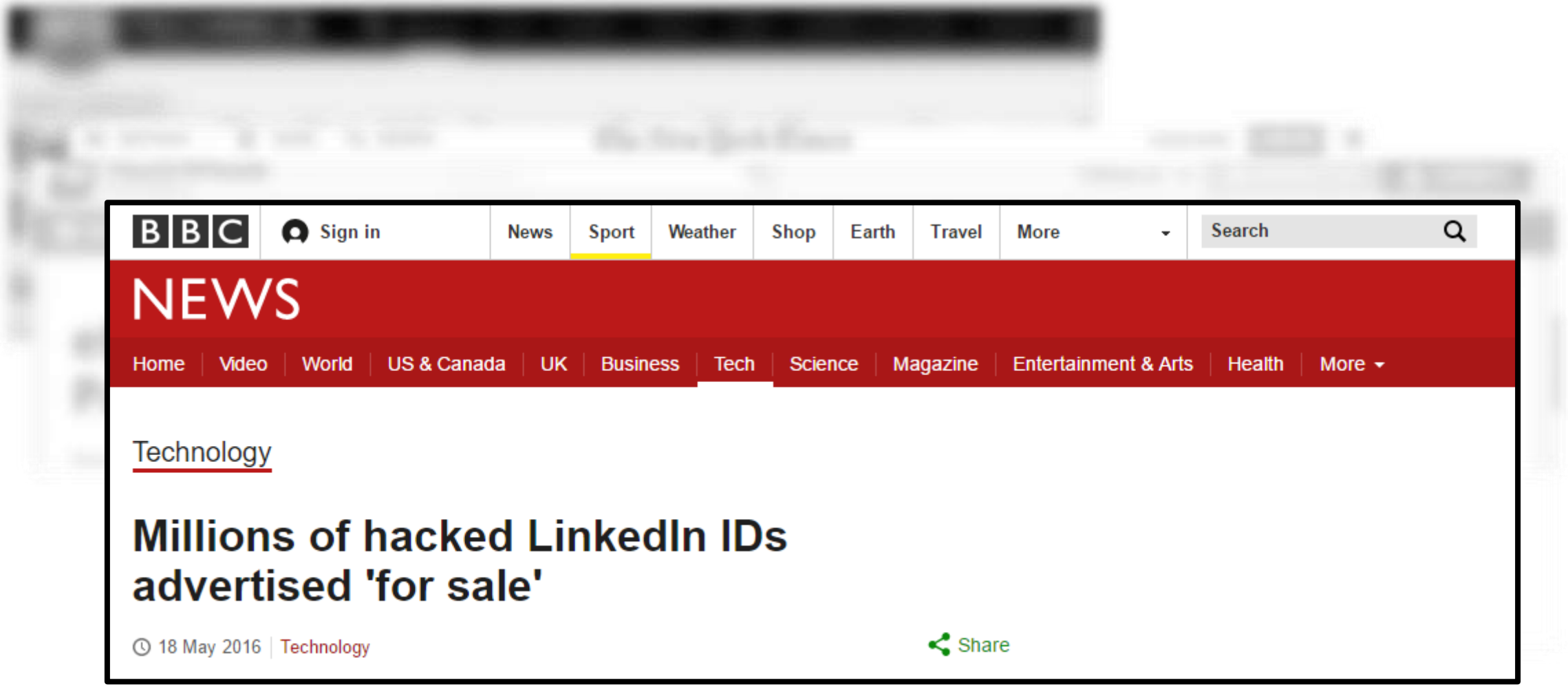
Searching on Encrypted Data



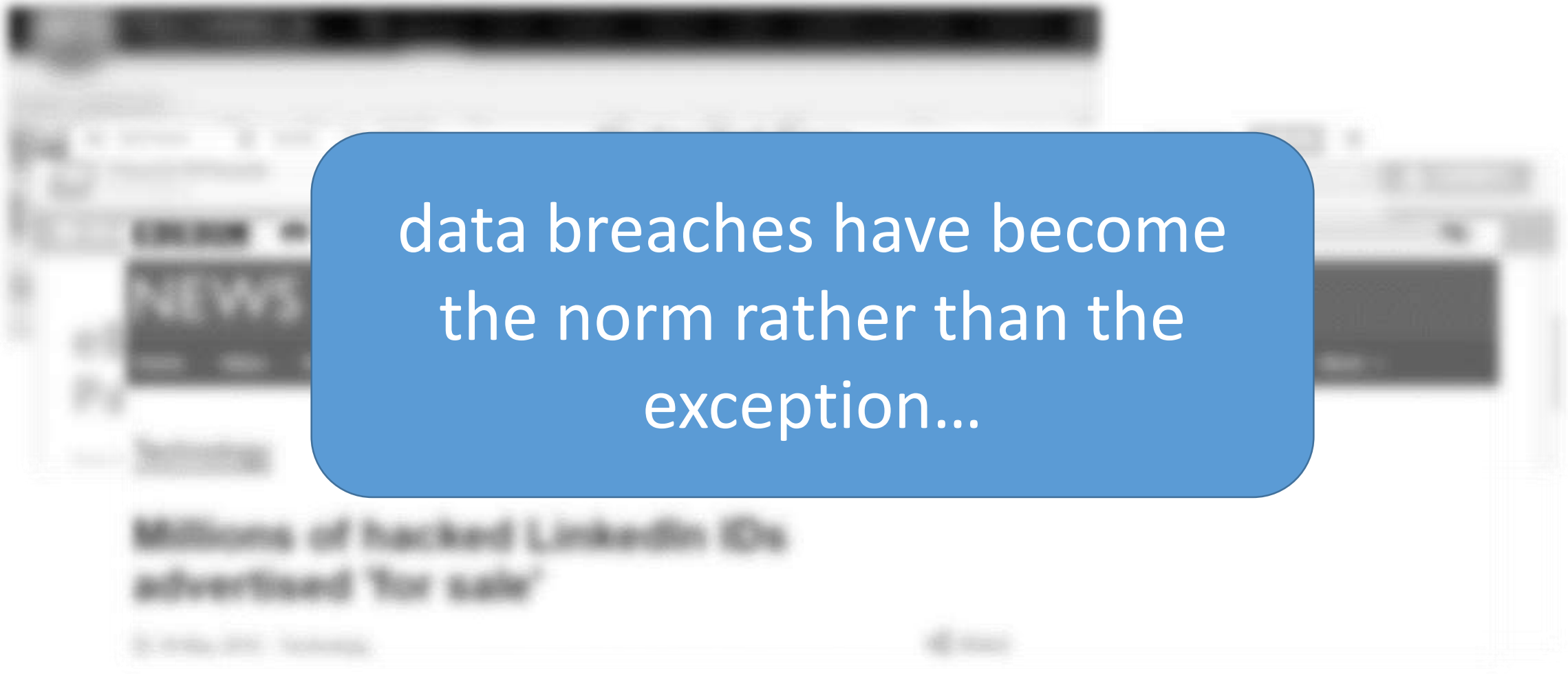
Searching on Encrypted Data



Searching on Encrypted Data

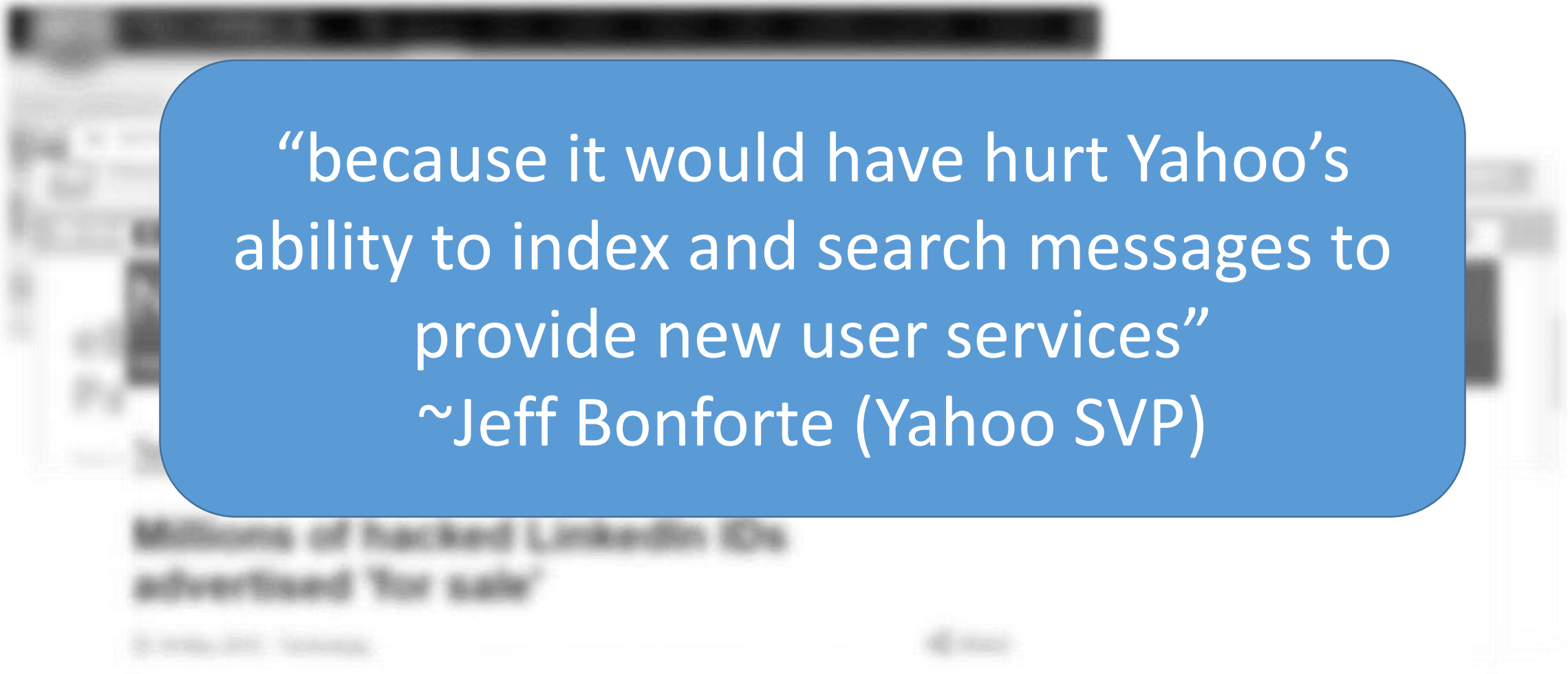


Searching on Encrypted Data



data breaches have become the norm rather than the exception…

Why Not Encrypt?

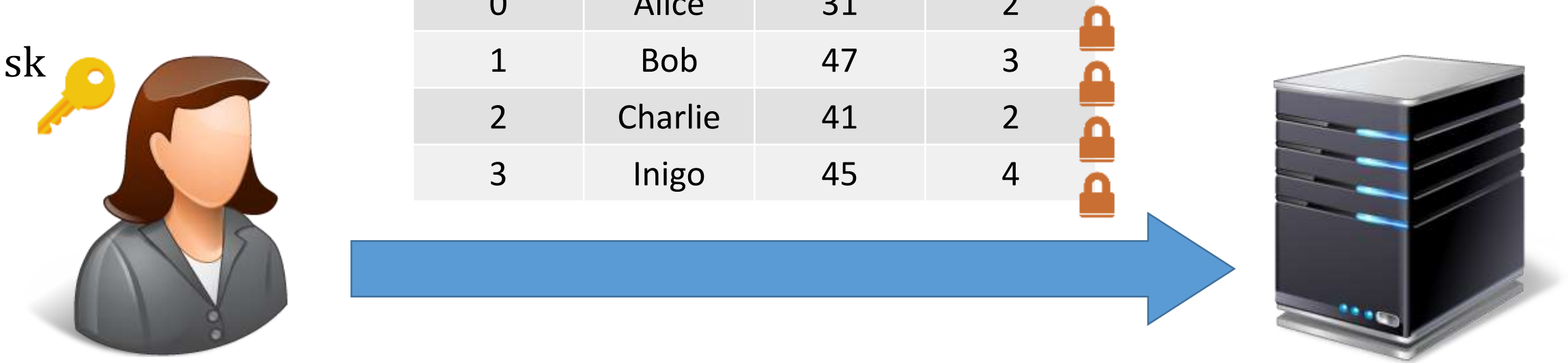


"because it would have hurt Yahoo's ability to index and search messages to provide new user services"
~Jeff Bonforte (Yahoo SVP)

Searching on Encrypted Data

database

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



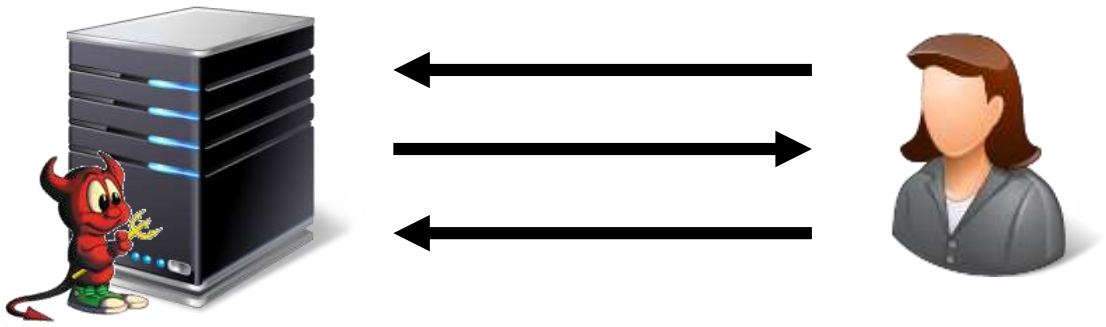
client

client holds a secret key
(needed to encrypt +
query the server)

server stores
encrypted database

server

Security for Encrypted Search



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

active adversary

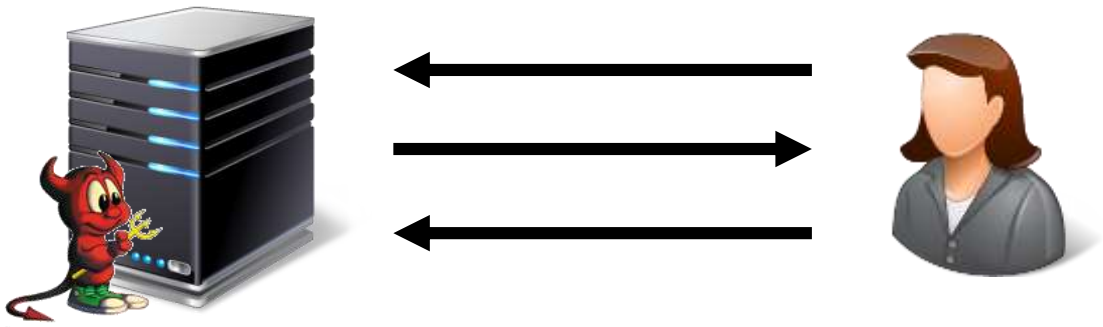
online attacks (e.g., active corruption)

offline attacks (e.g., passive snapshots)

adversary only sees contents
of encrypted database

snapshot adversary

Security for Encrypted Search



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

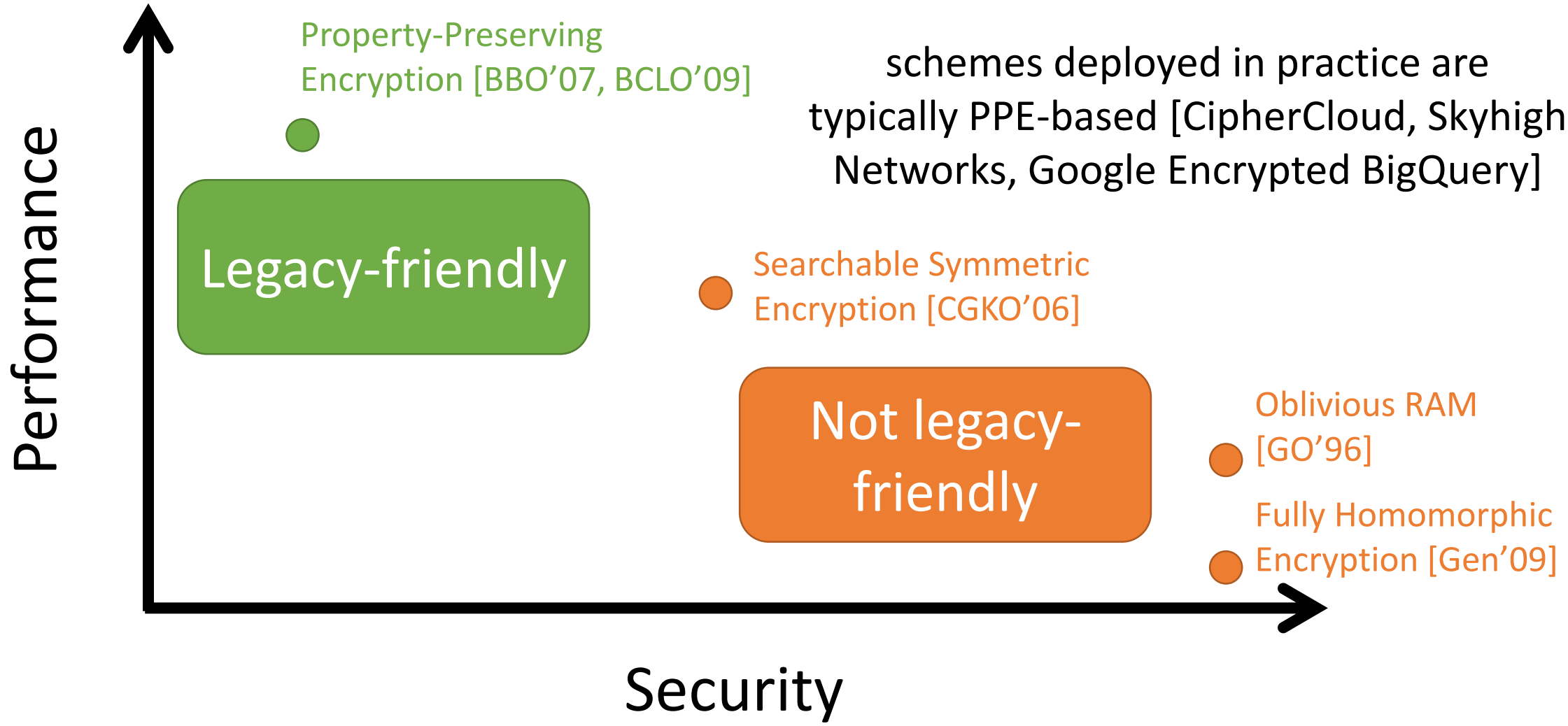
online attacks (e.g., active corruption)

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

Security / Performance Tradeoffs



not drawn to scale

Order-Revealing Encryption [BLRSZZ'15]

secret-key encryption scheme

client

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

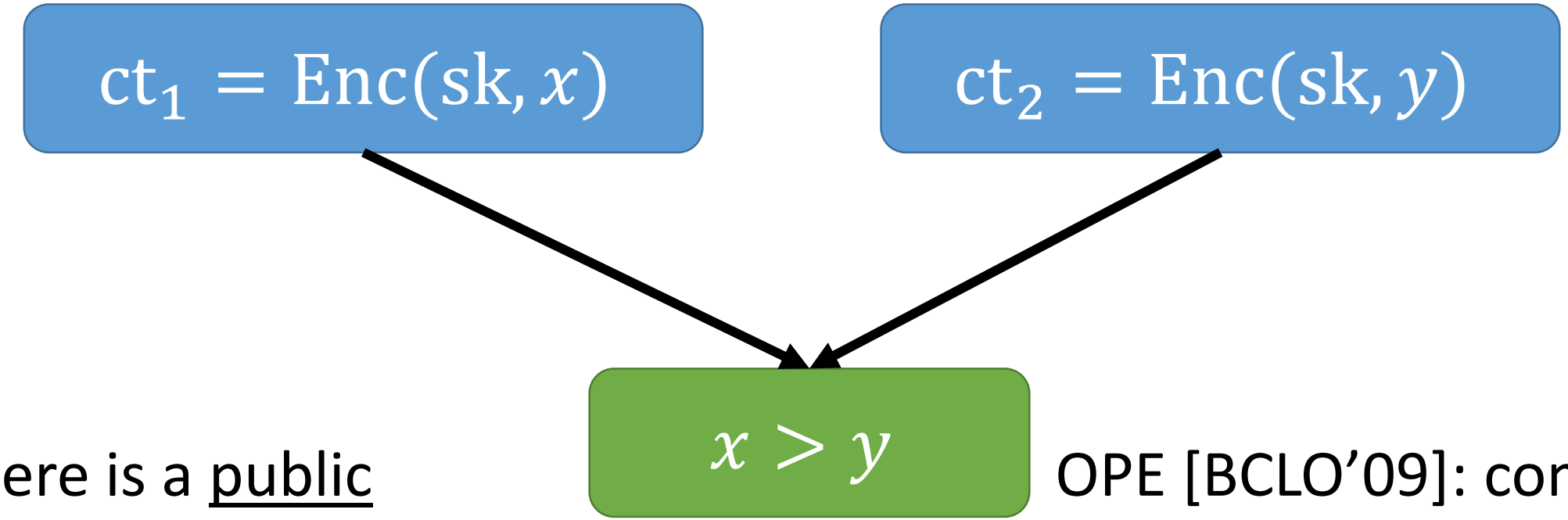
server

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]

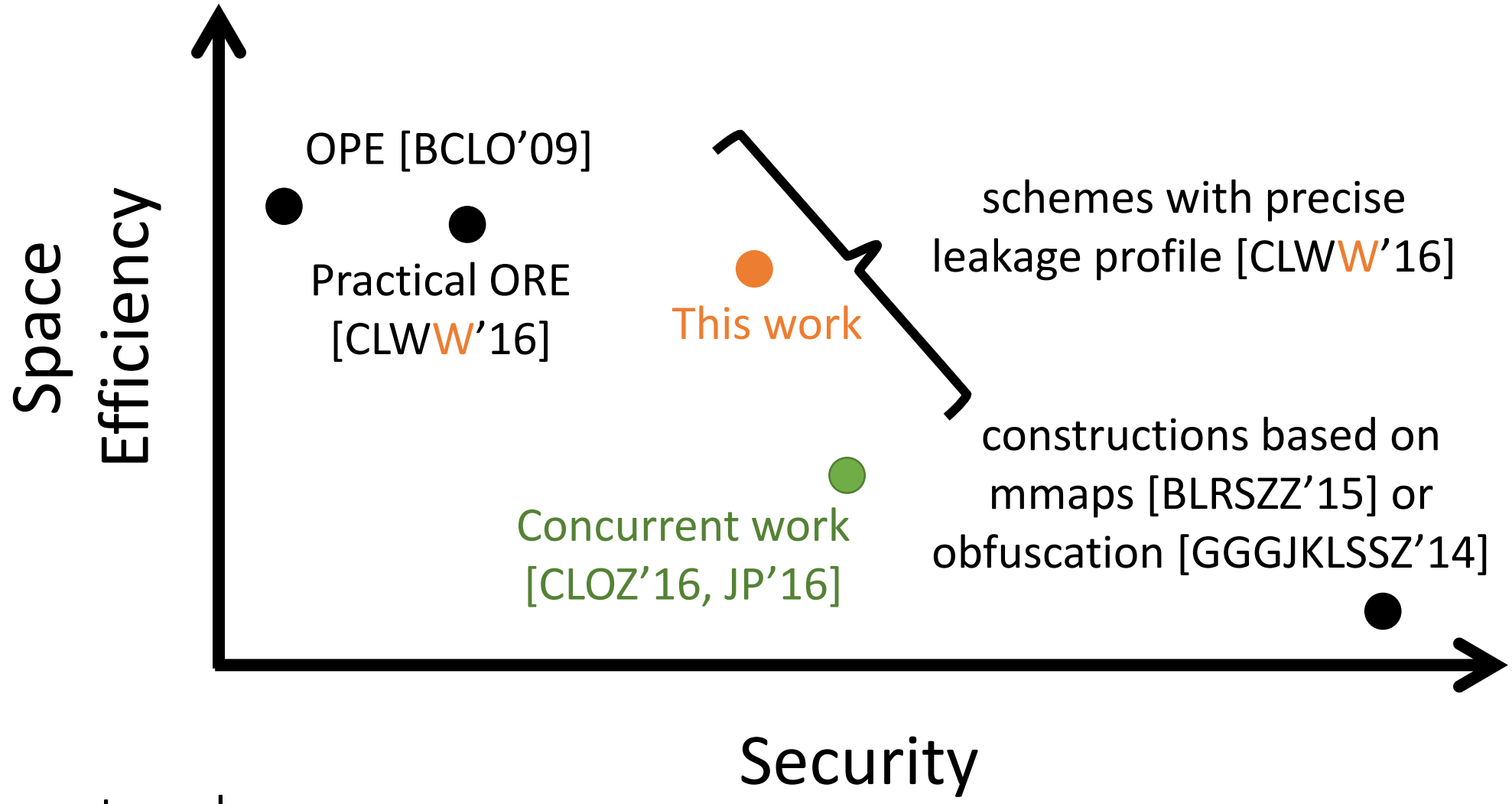
given any two ciphertexts



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]

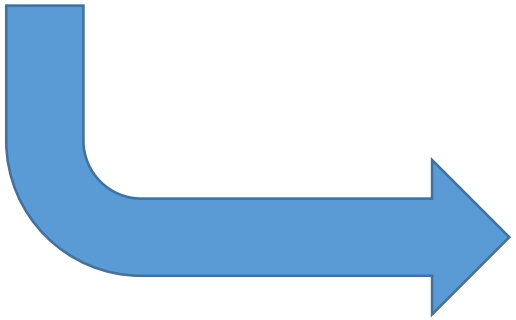
ID	Name	Age	Diagnosis
wpjOos	2wzXW8	SqX9l9	KqLUXE
XdXdg8	y9GFpS	gwilE3	MJ23b7
P6vKhW	EgN0Jn	S0pRJe	aTaeJk
orJRe6	KQWy9U	tPWF3M	4FBEO0

encrypted database

+

public information

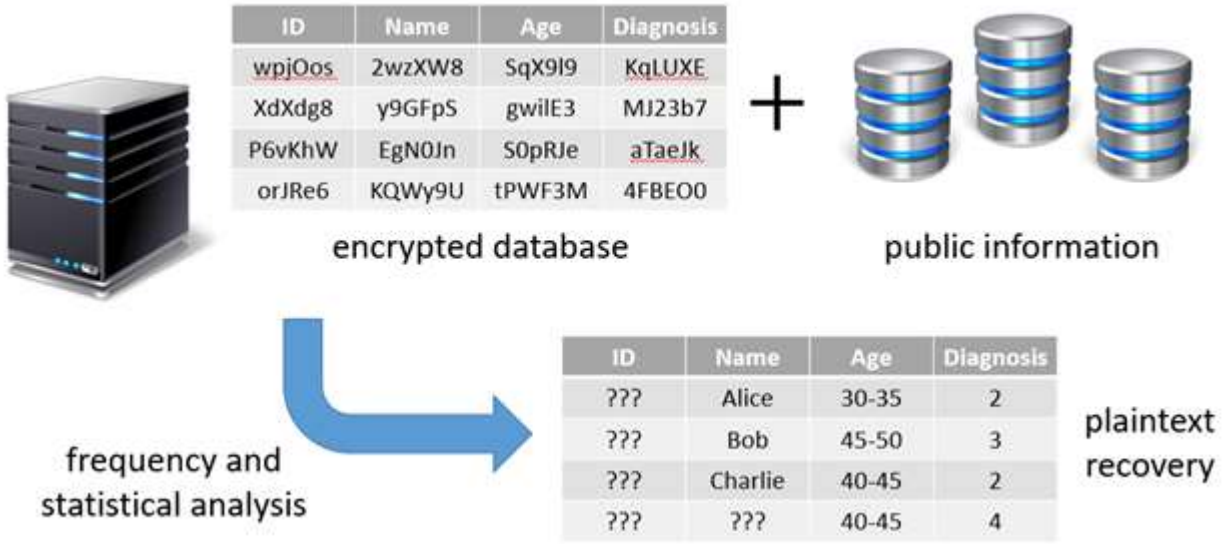
frequency and statistical analysis



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

plaintext recovery

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 <u>offline inference attacks</u>

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

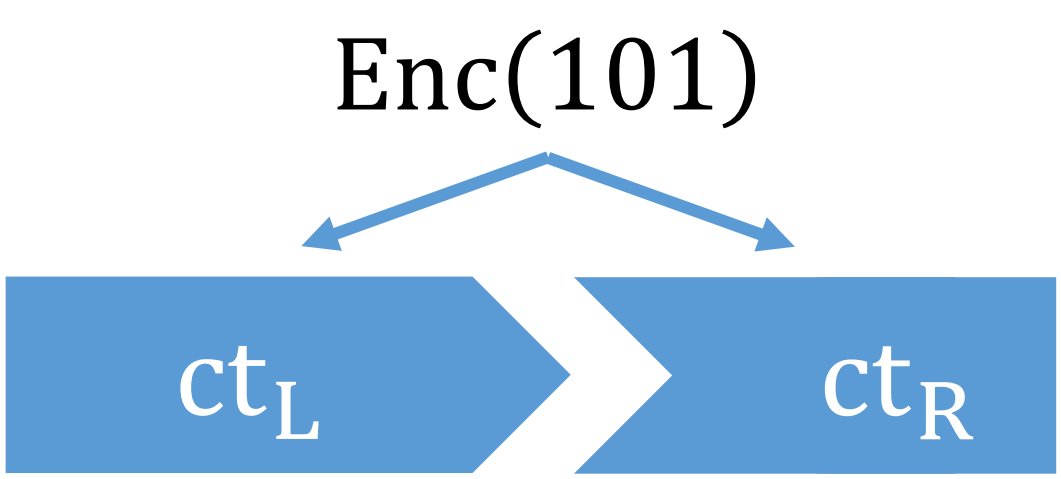
Desiderata: an ORE scheme that enables:

- perfect offline security
- limited leakage in the online setting

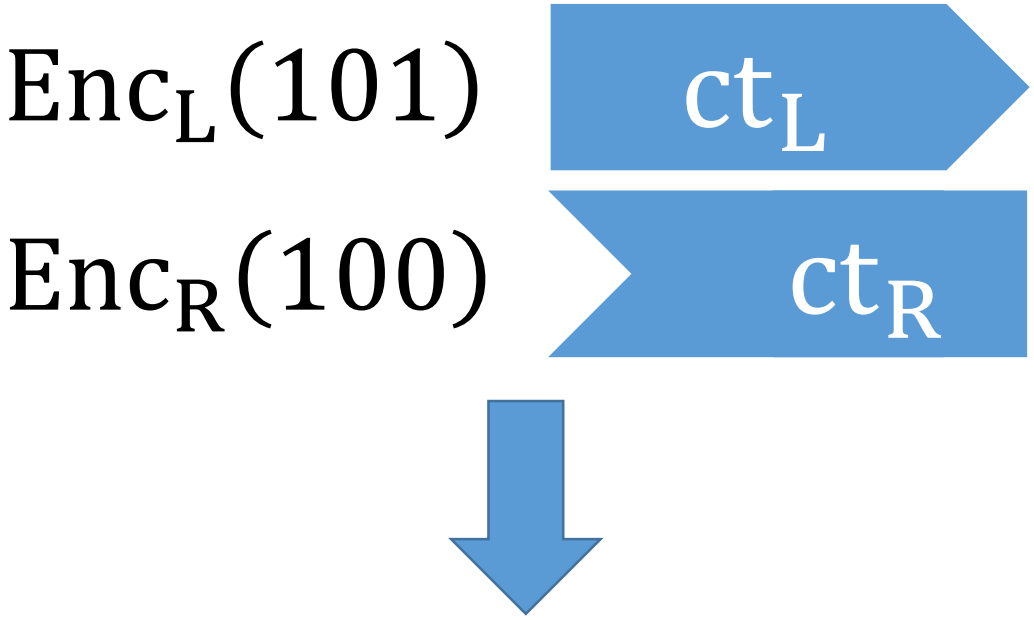
ORE with Additional Structure

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
Enc(Alice)	Enc(0)

Age	ID
Enc(31)	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

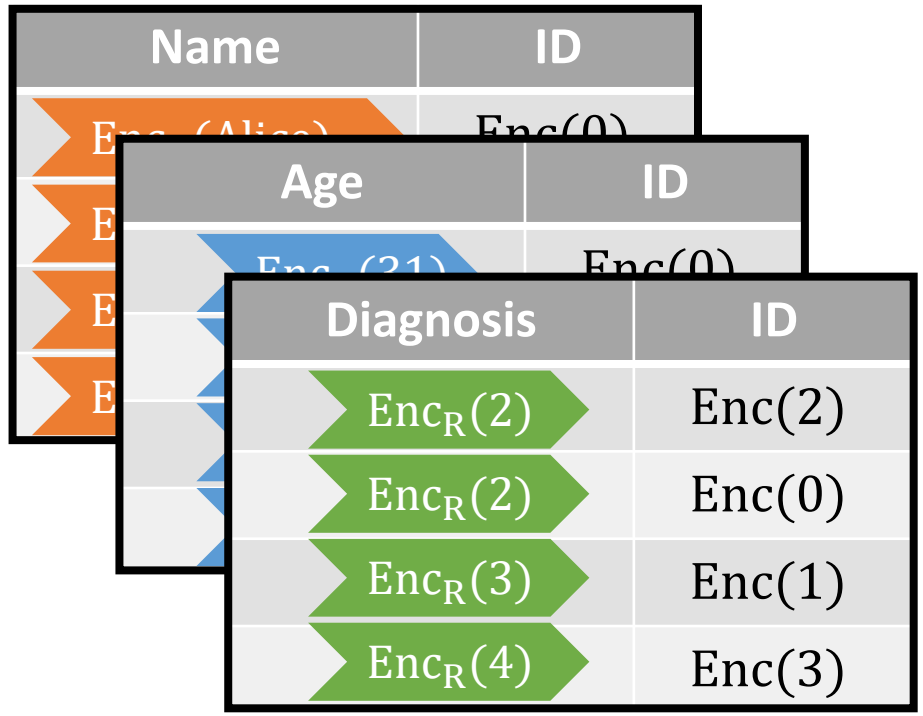
Encrypted Range Queries

Encrypted database:

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

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

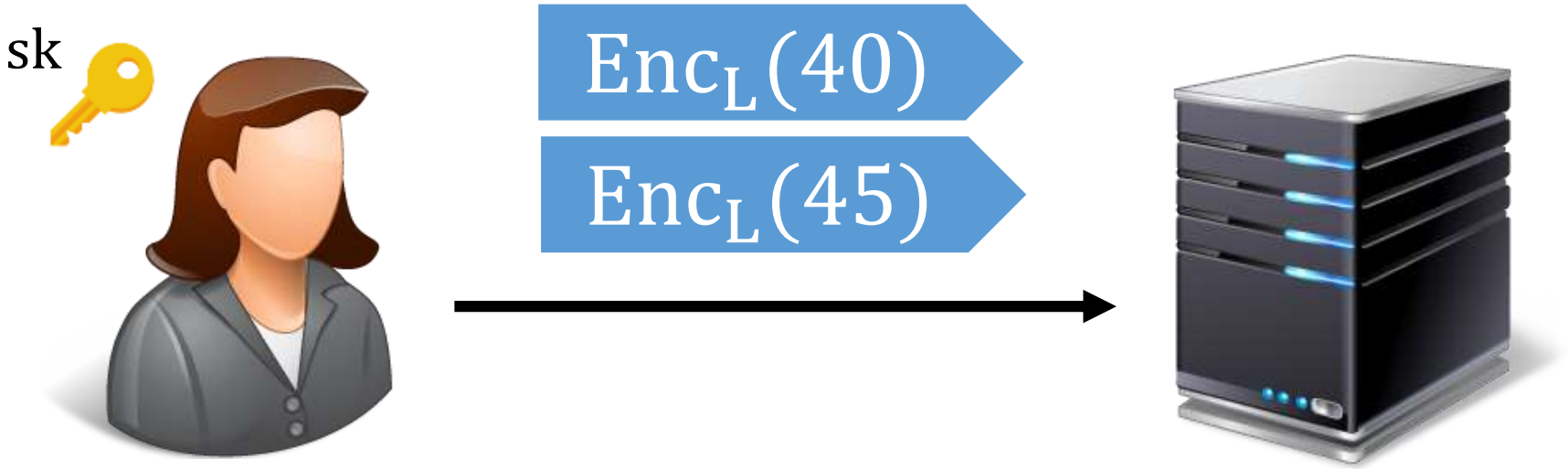
clients hold (secret) keys needed to decrypt and query database



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

Encrypted Range Queries

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

$\text{Enc}_L(40)$

$\text{Enc}_L(45)$

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

use binary search to determine endpoints (comparison via ORE)

Encrypted Range Queries

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

$\text{Enc}_L(40)$

$\text{Enc}_L(45)$

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

use binary search to determine endpoints (comparison via ORE)

Encrypted Range Queries

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

$\text{Enc}_L(40)$

$\text{Enc}_L(45)$

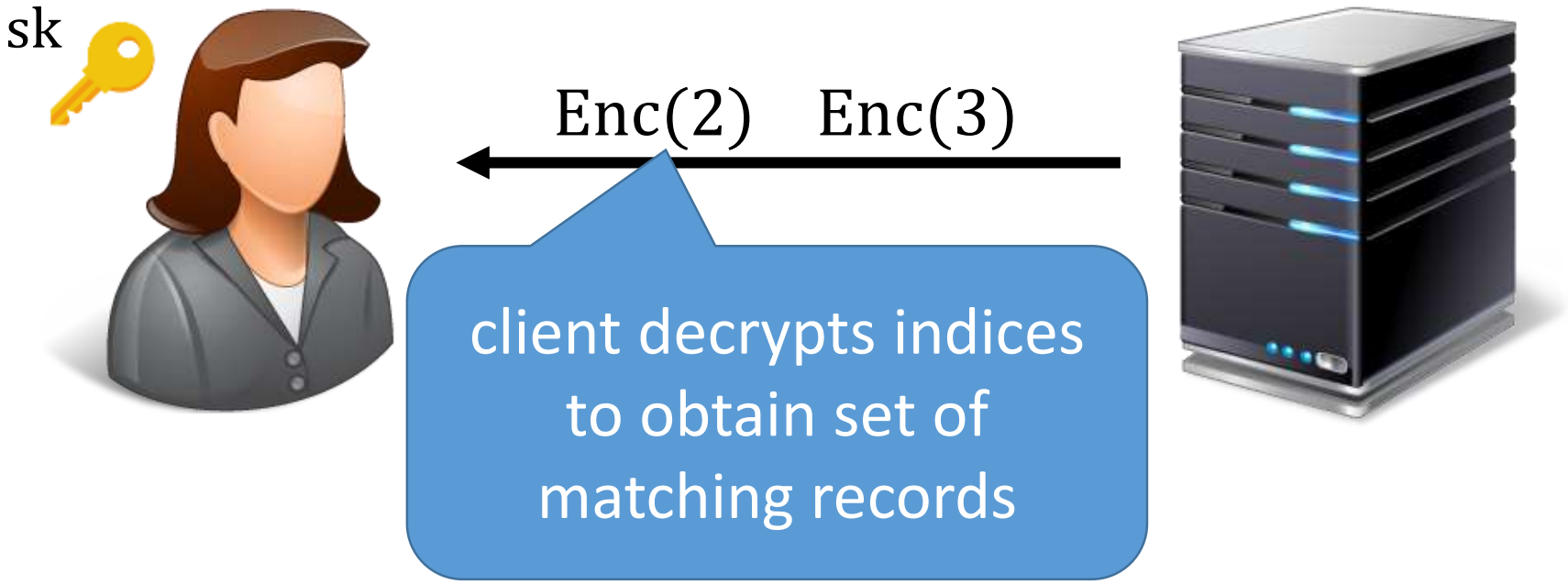
Age	ID
$\text{Enc}_R(31)$	$\text{Enc}(0)$
$\text{Enc}_R(41)$	$\text{Enc}(2)$
$\text{Enc}_R(45)$	$\text{Enc}(3)$
$\text{Enc}_R(47)$	$\text{Enc}(1)$

use binary search to determine endpoints (comparison via ORE)

return encrypted indices that match query

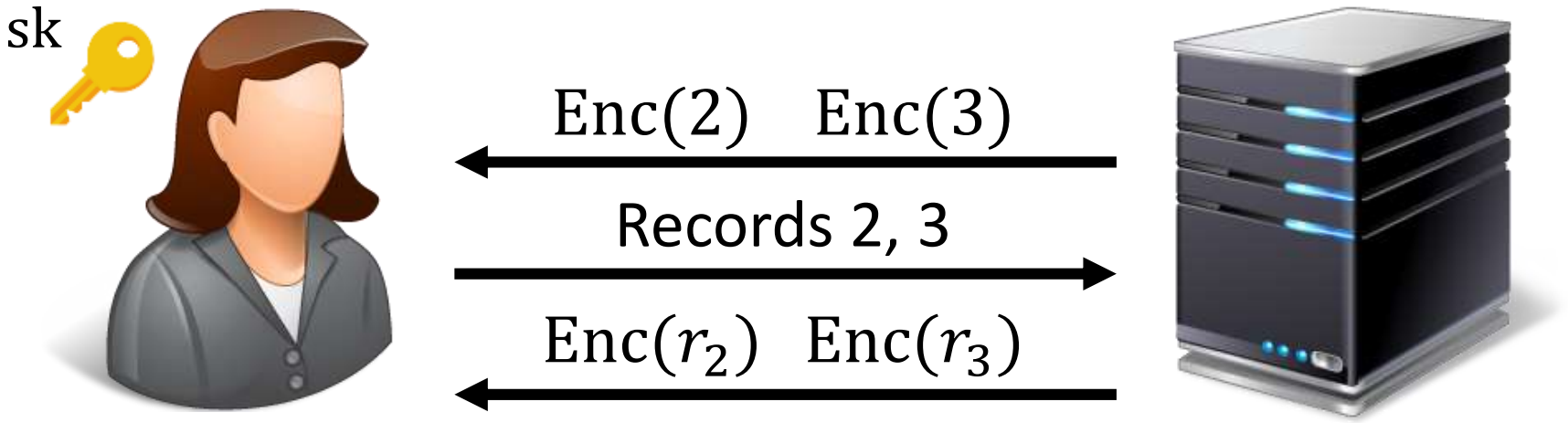
Encrypted Range Queries

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



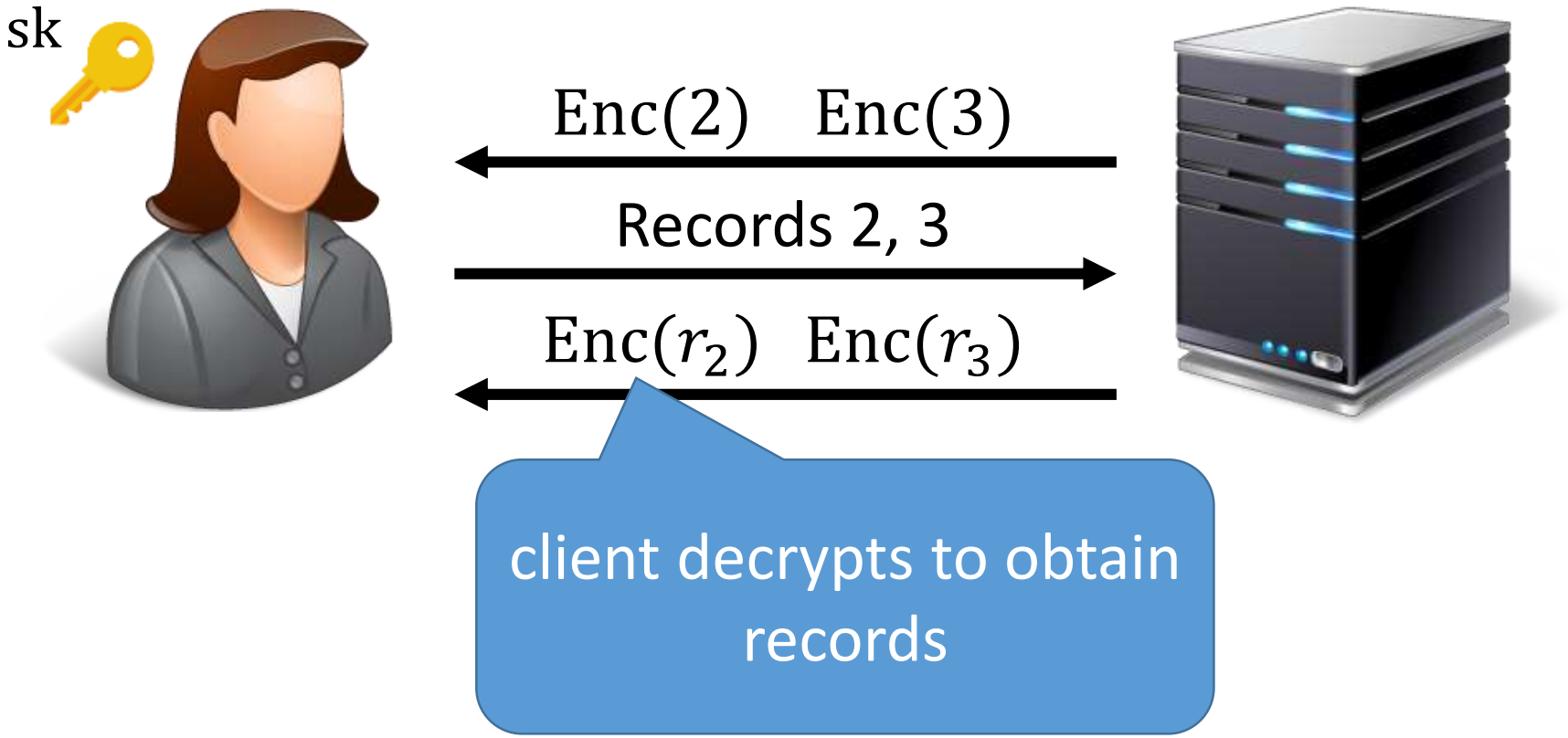
Encrypted Range Queries

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



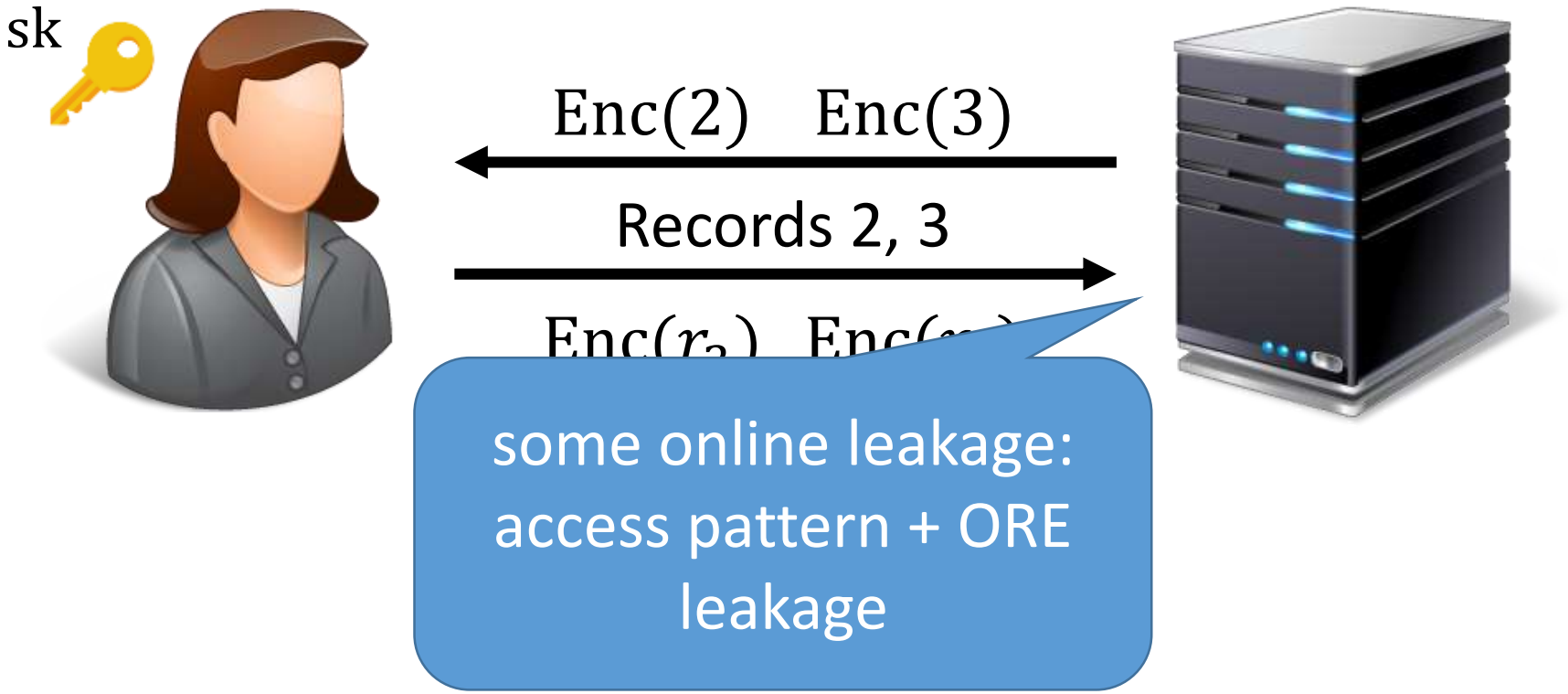
Encrypted Range Queries

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



Encrypted Range Queries

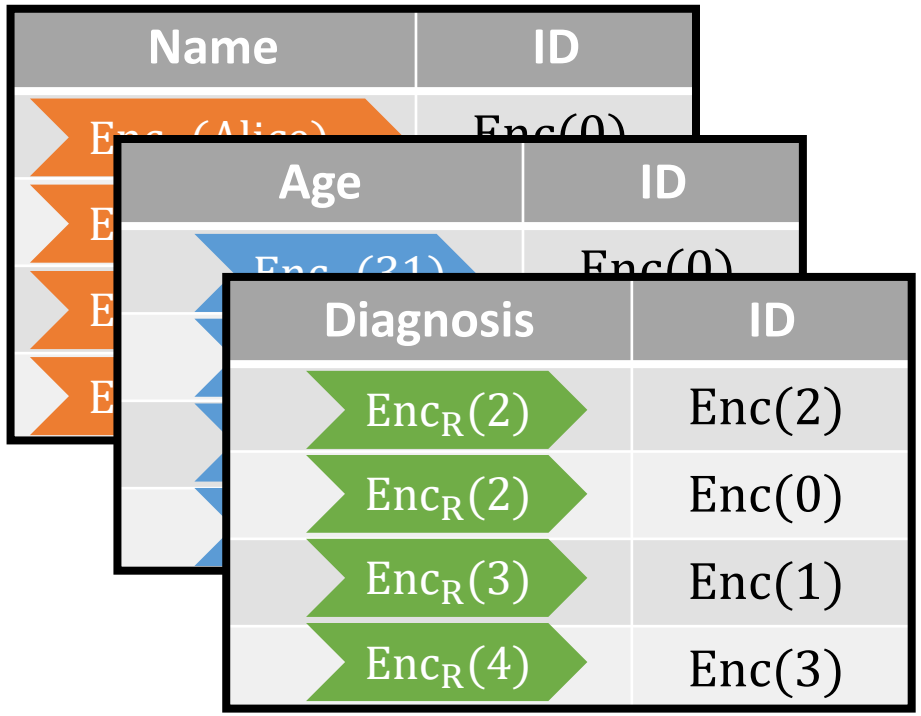
Query for all records where $40 \geq \text{age} \geq 45$:



Encrypted Range Queries

Encrypted database (view of the snapshot adversary):

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

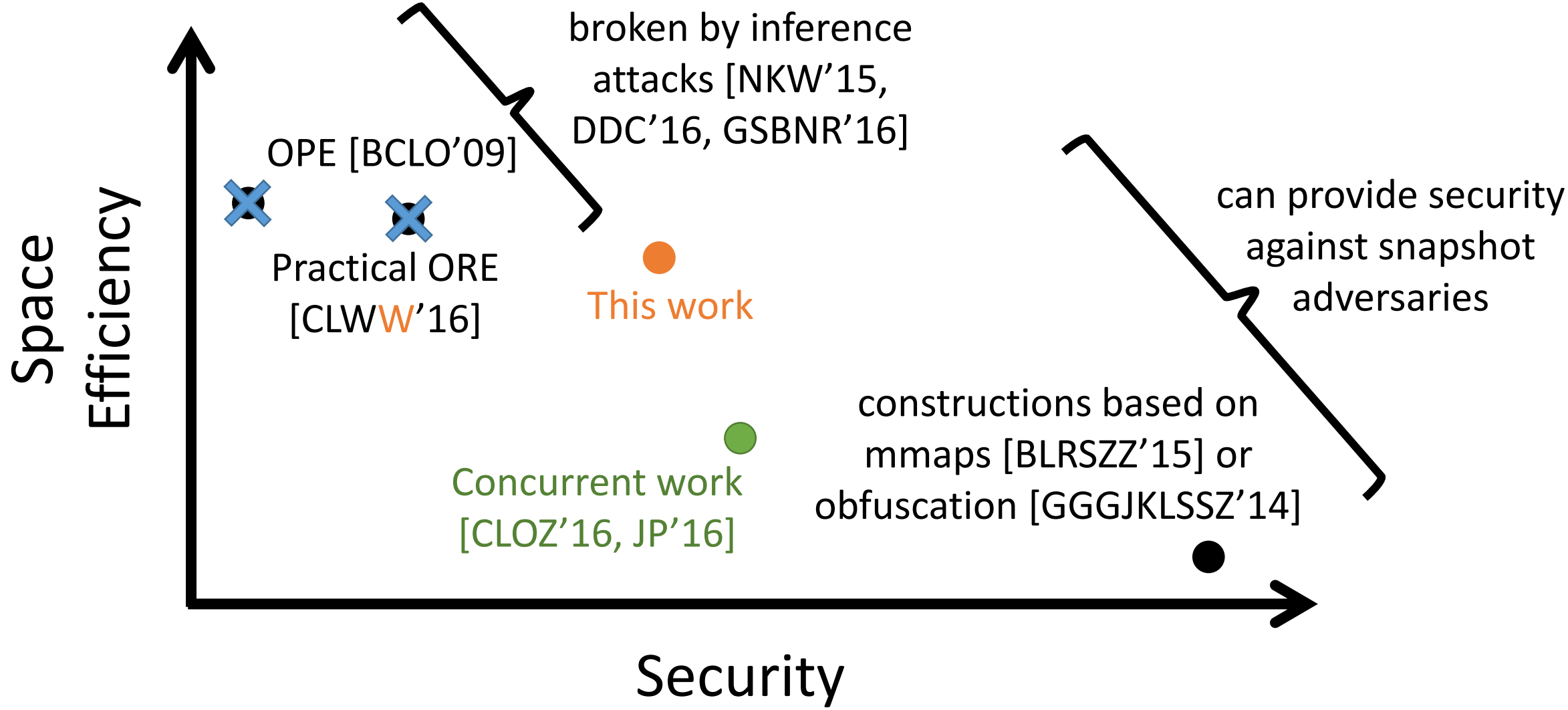


encrypted search indices

encrypted database is semantically secure!

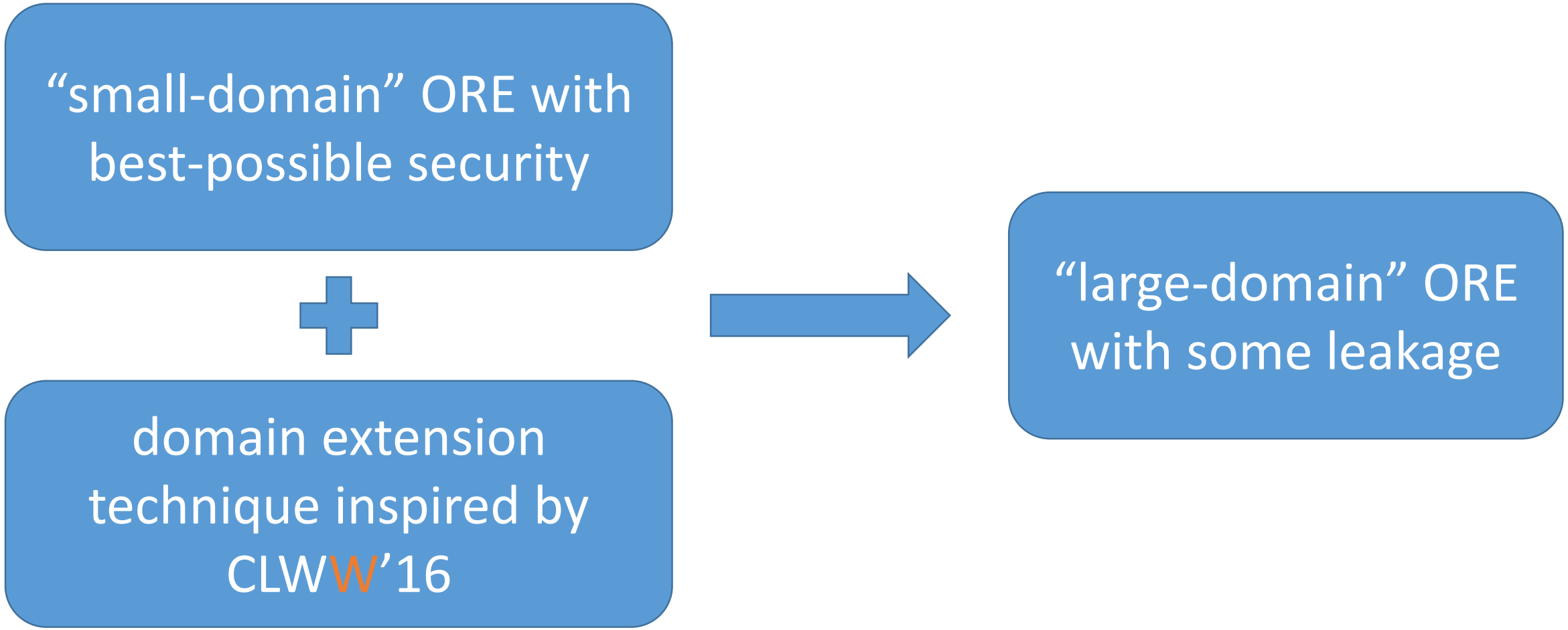
Perfect offline security

The Landscape of ORE



Not drawn to scale

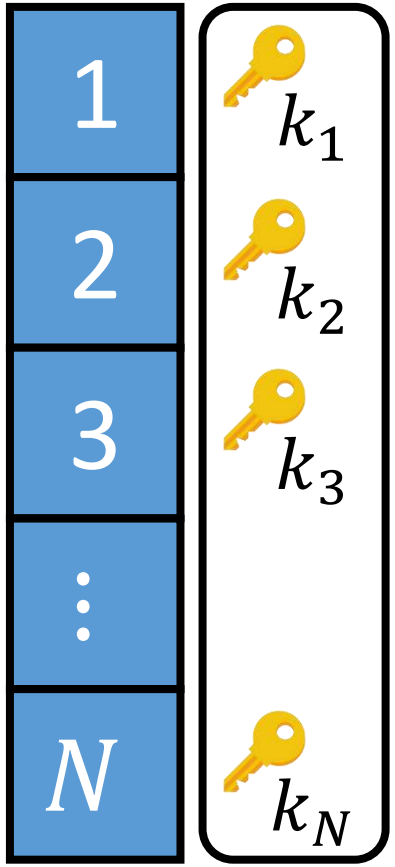
Our New ORE Scheme



Small-Domain ORE with Best-Possible Security

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

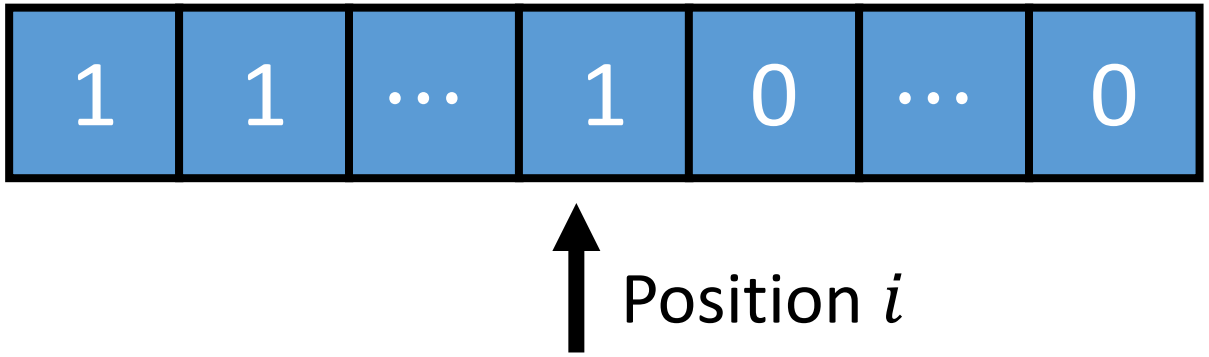
associate a key with each value



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

Small-Domain ORE with Best-Possible Security

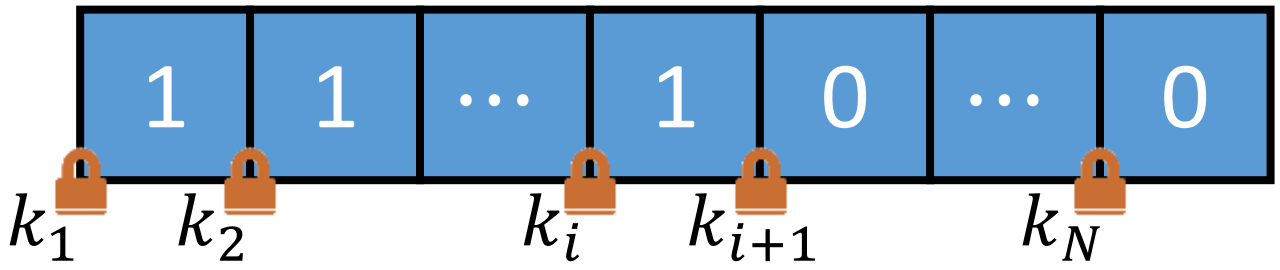
Encrypting a value i



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

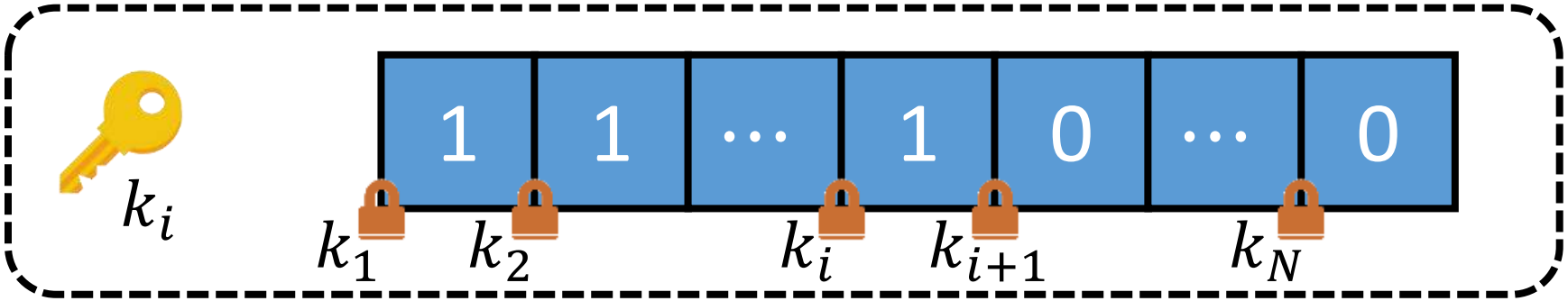
Small-Domain ORE with Best-Possible Security

Encrypting a value i



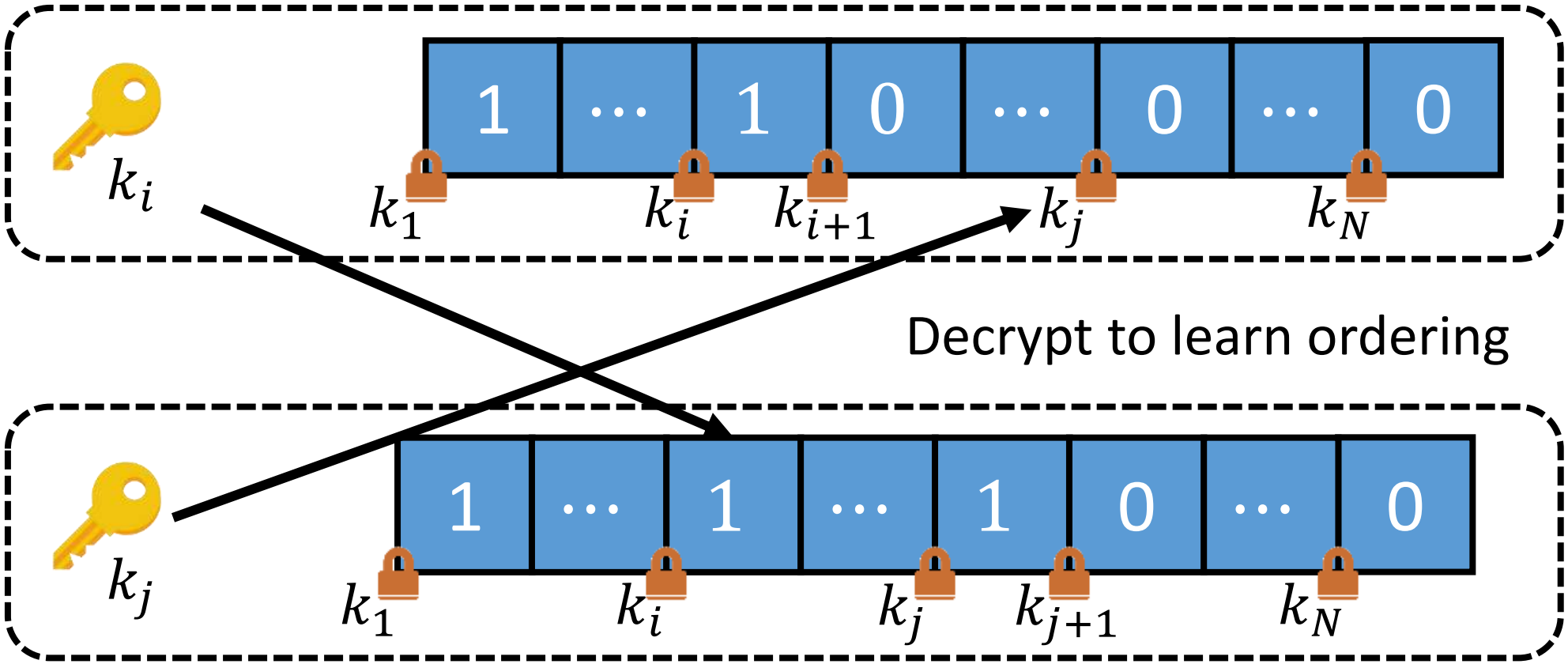
encrypt each slot with key for that slot

To allow comparisons, also give out key for slot i



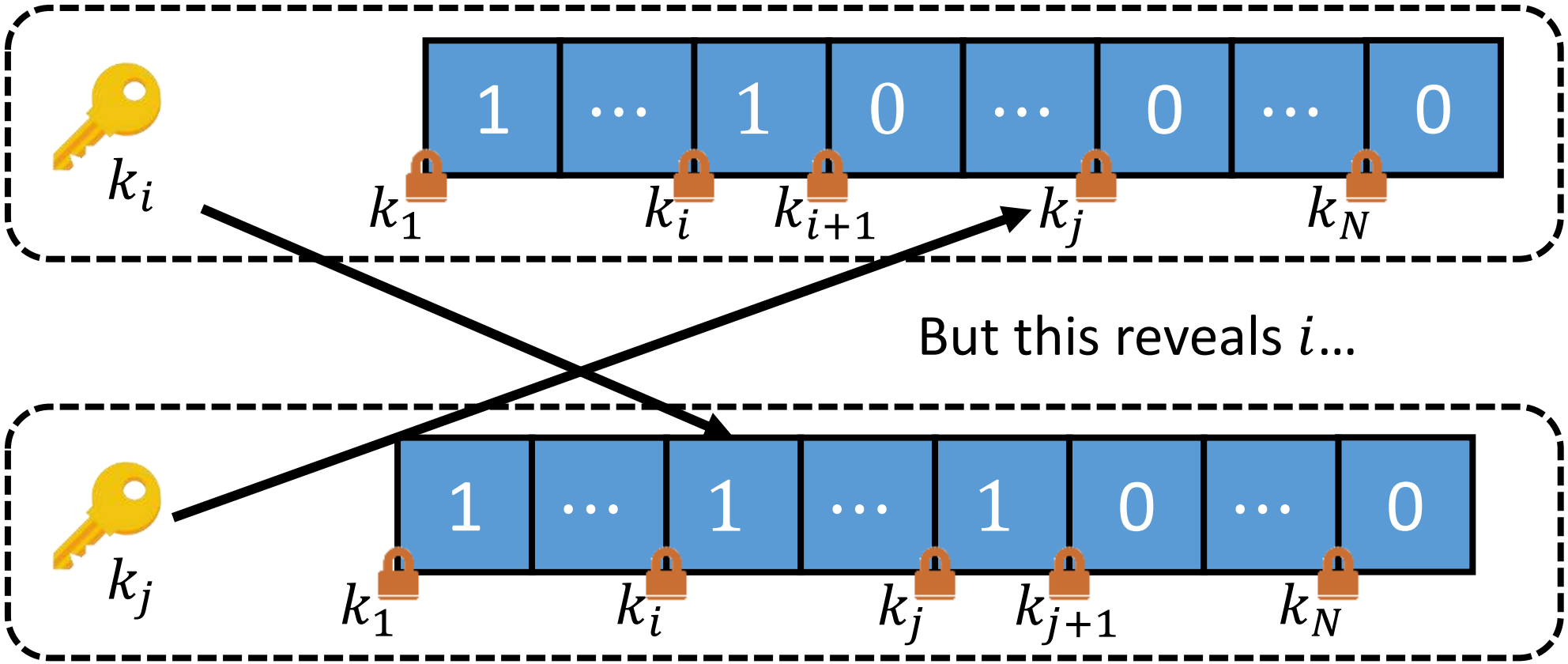
Small-Domain ORE with Best-Possible Security

Given two ciphertexts



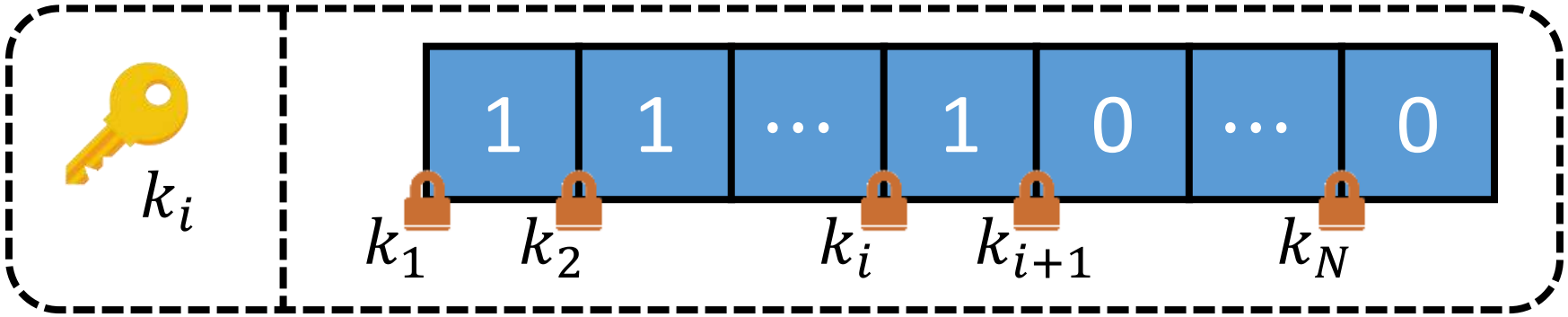
Small-Domain ORE with Best-Possible Security

Given two ciphertexts



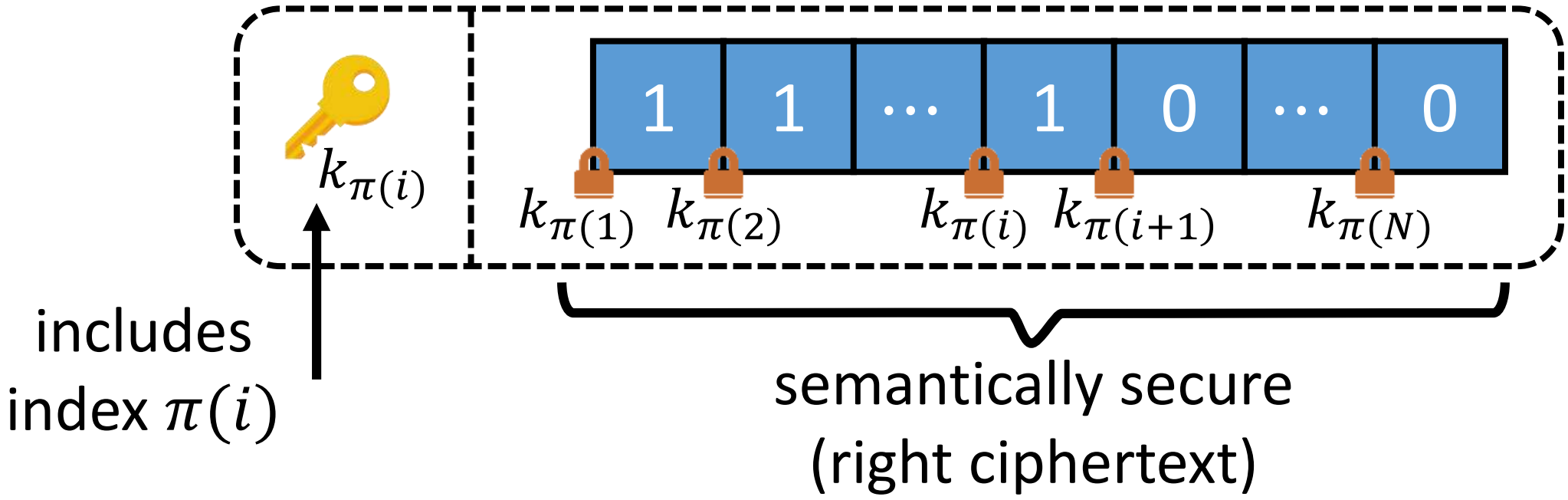
Small-Domain ORE with Best-Possible Security

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



Small-Domain ORE with Best-Possible Security

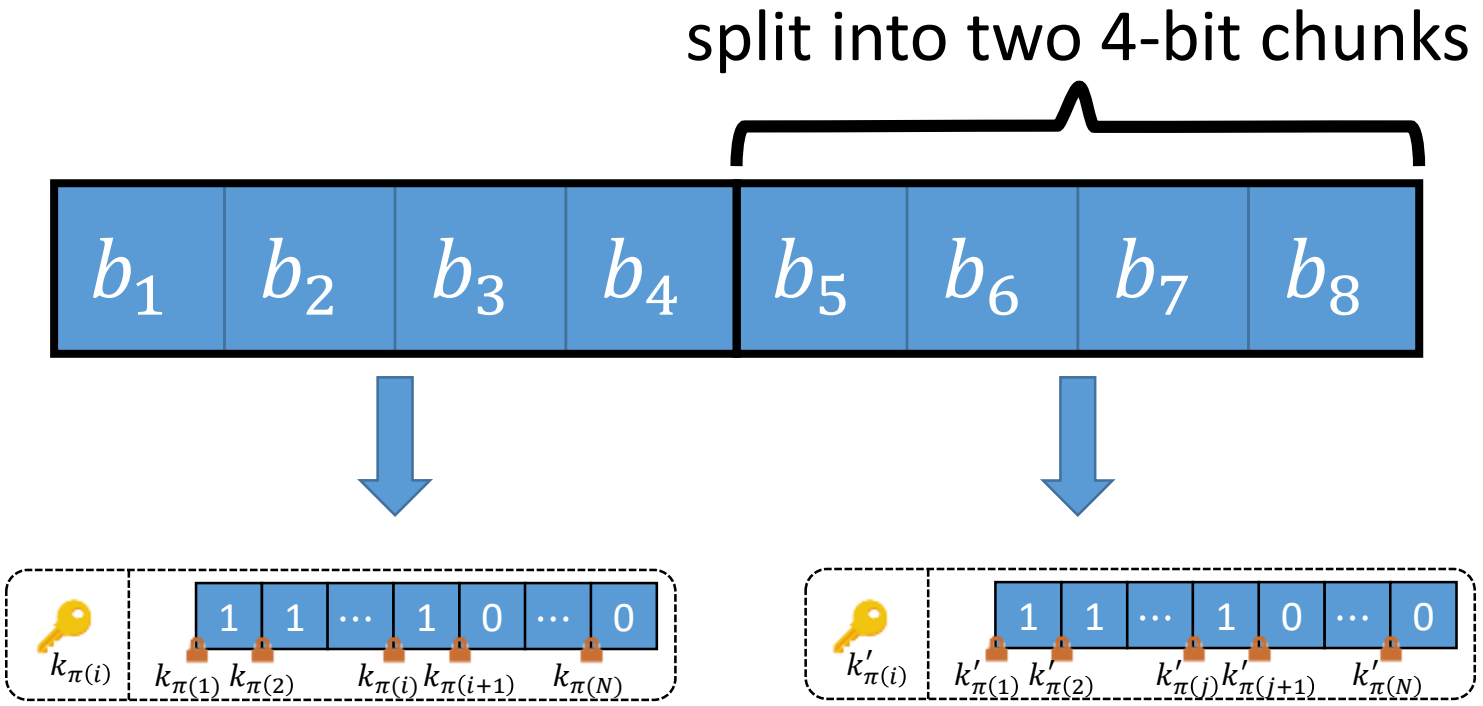
Solution: apply random permutation π (part of the secret key) to the slots



Achieves best-possible security, but ciphertexts are big

Domain Extension for ORE

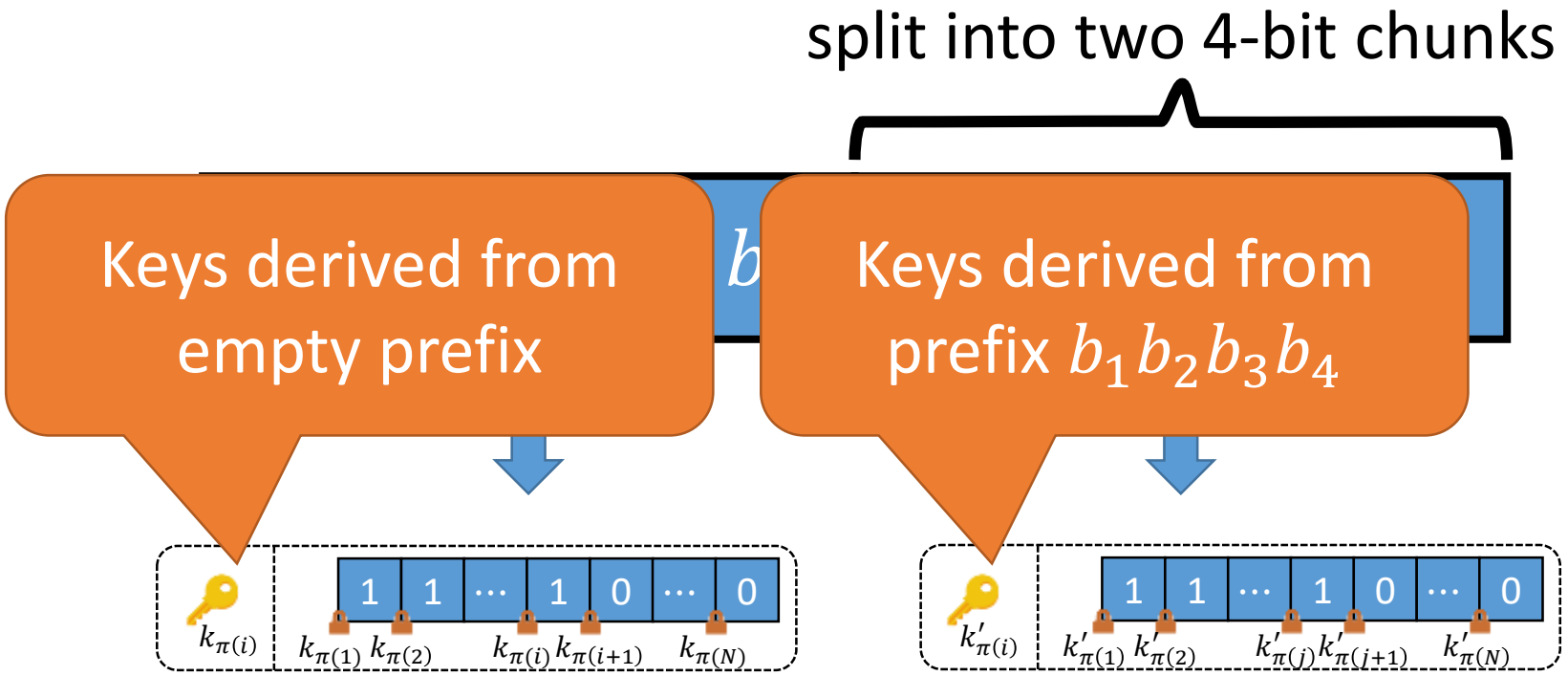
Key idea: decompose message into smaller blocks and apply small-domain ORE to each block



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

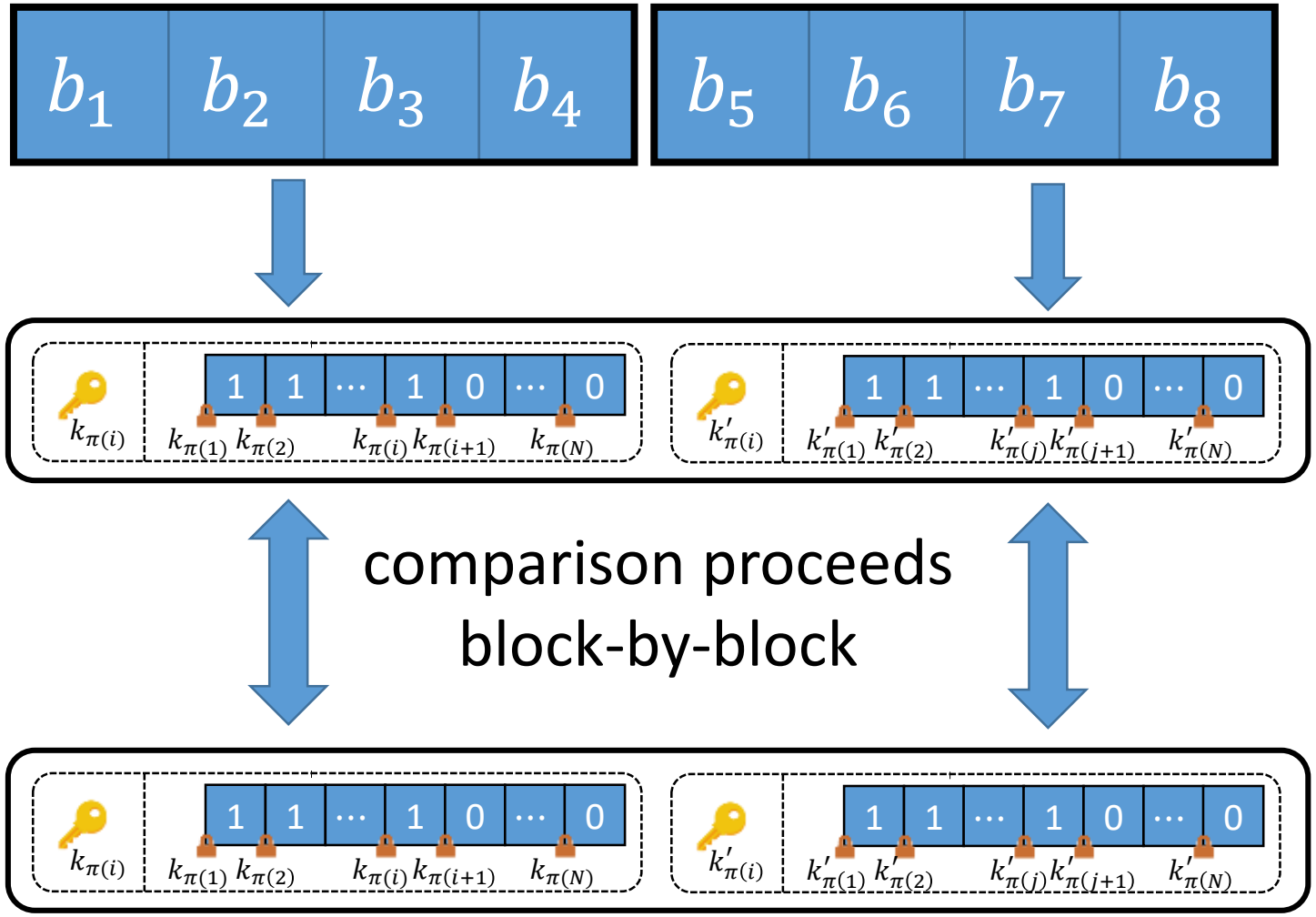
Domain Extension for ORE

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

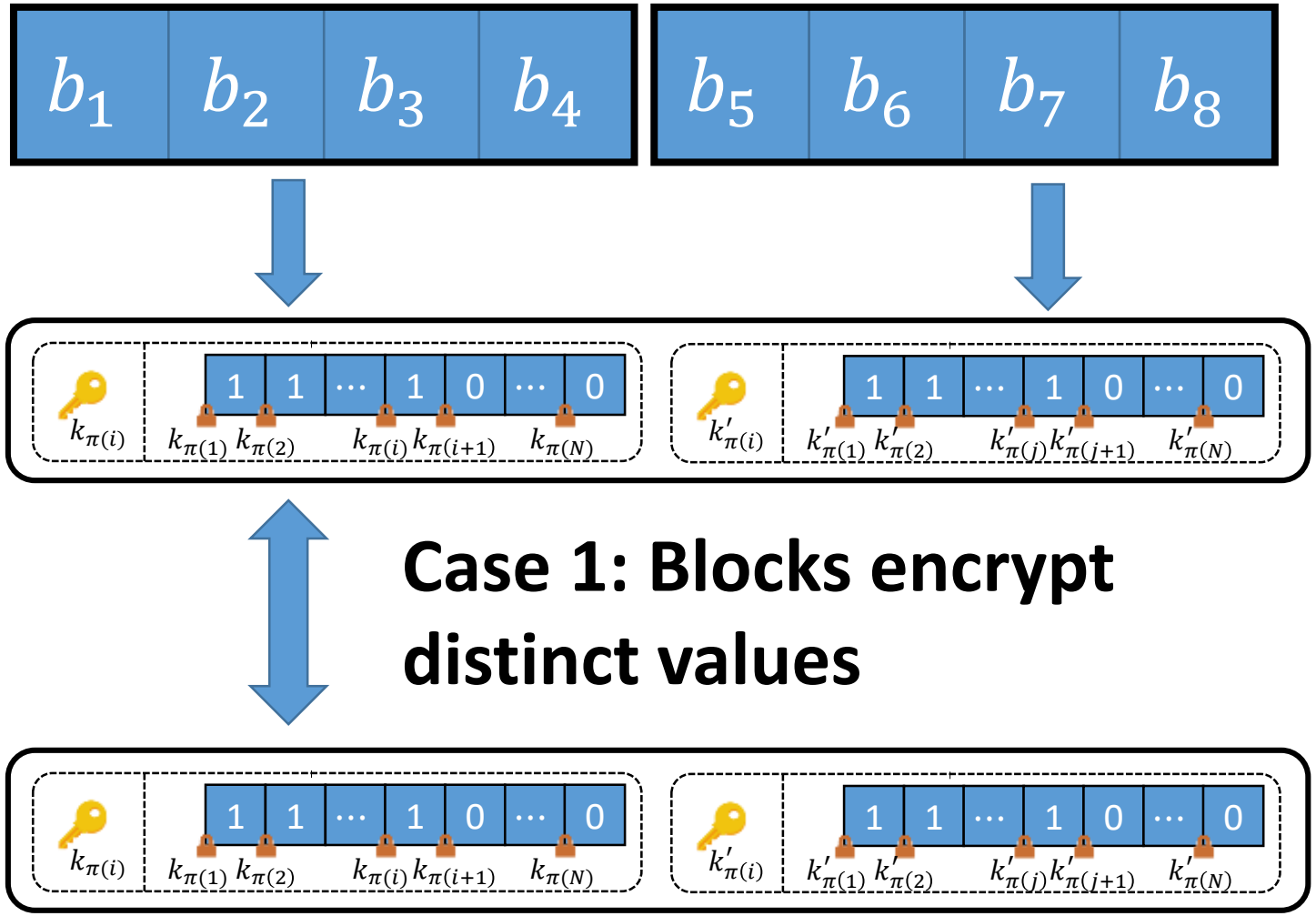


encrypt each chunk using an ORE instance with a secret key derived from the *prefix*

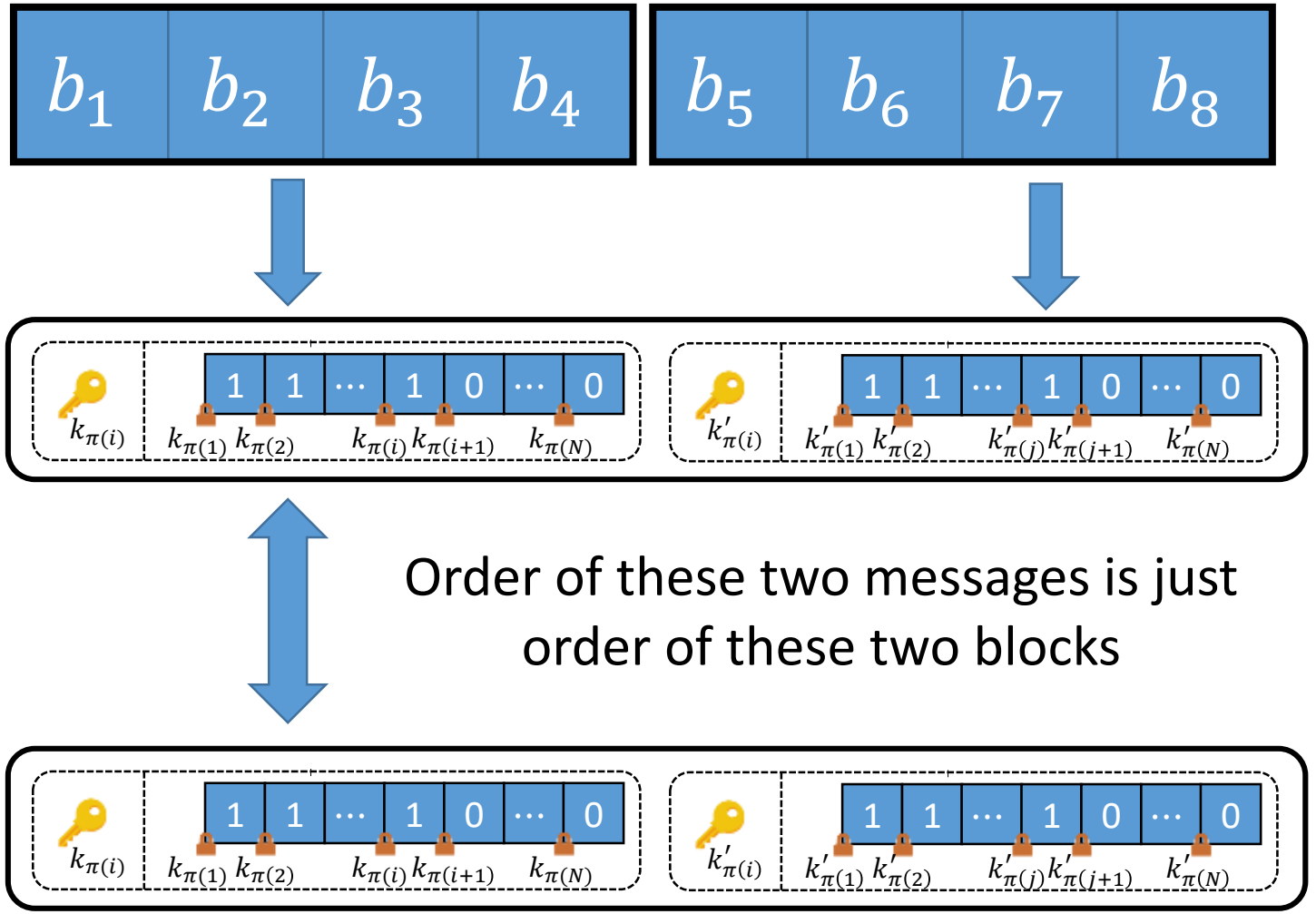
Domain Extension for ORE



Domain Extension for ORE

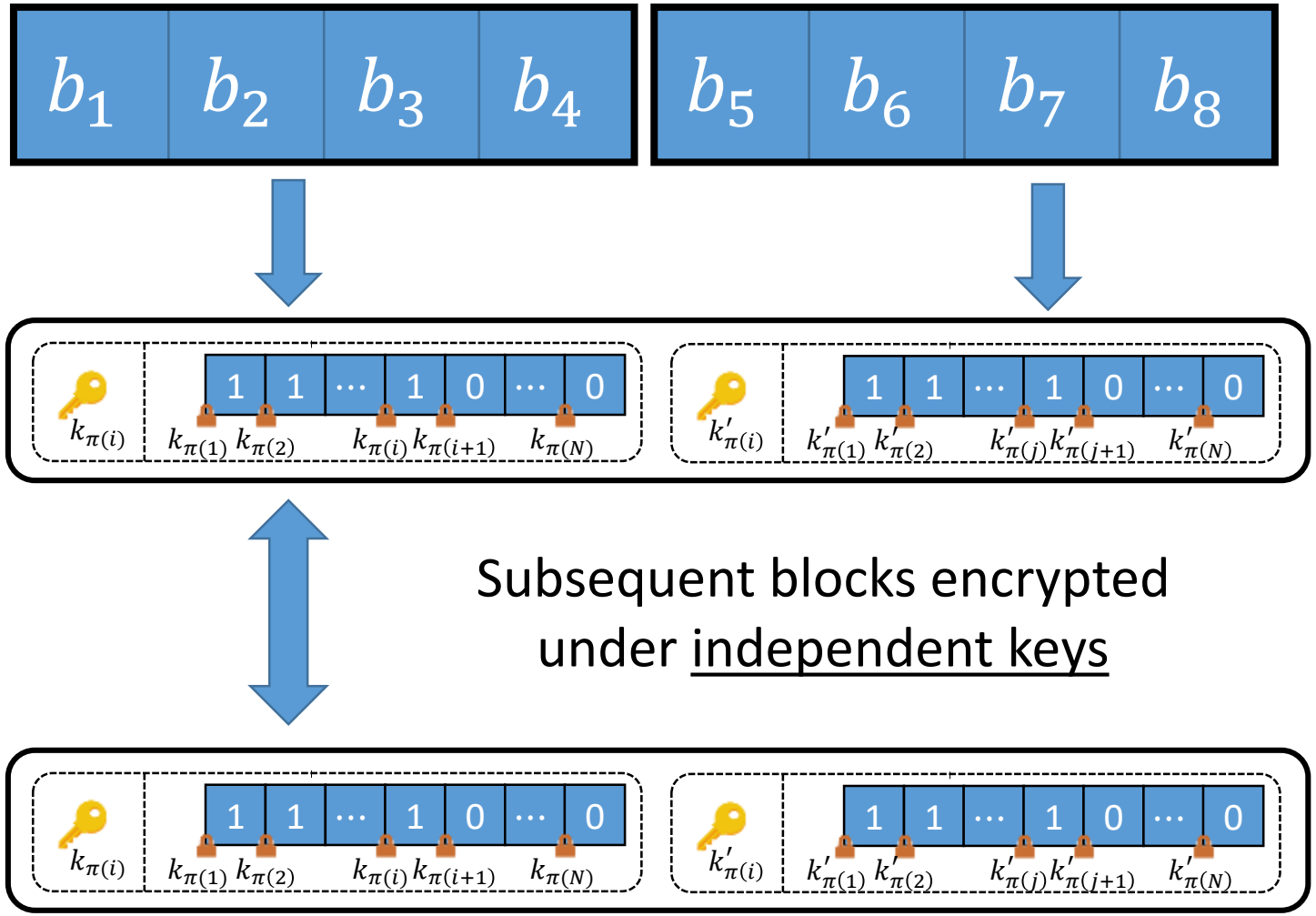


Domain Extension for ORE



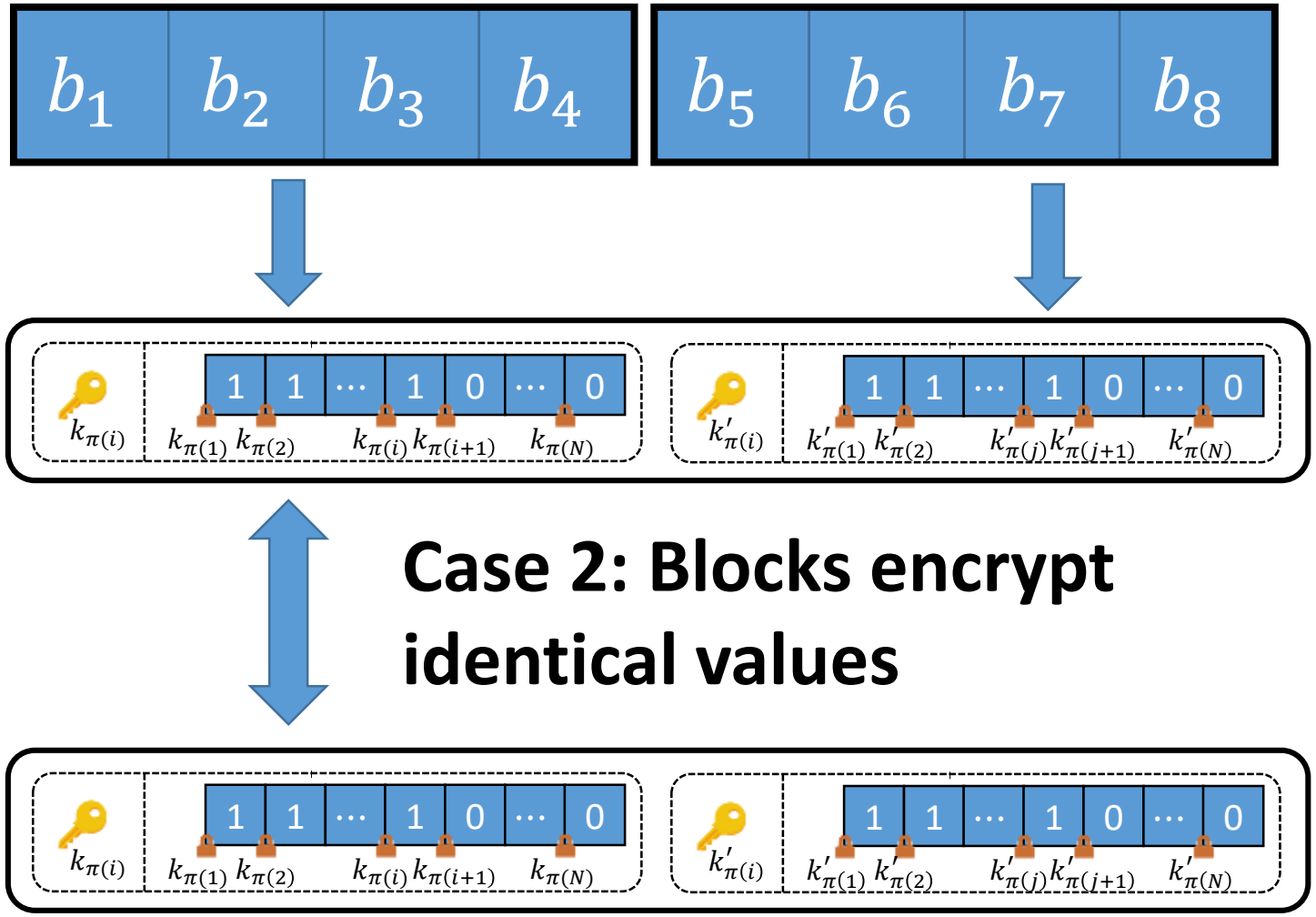
Case 1: Blocks encrypt distinct values

Domain Extension for ORE

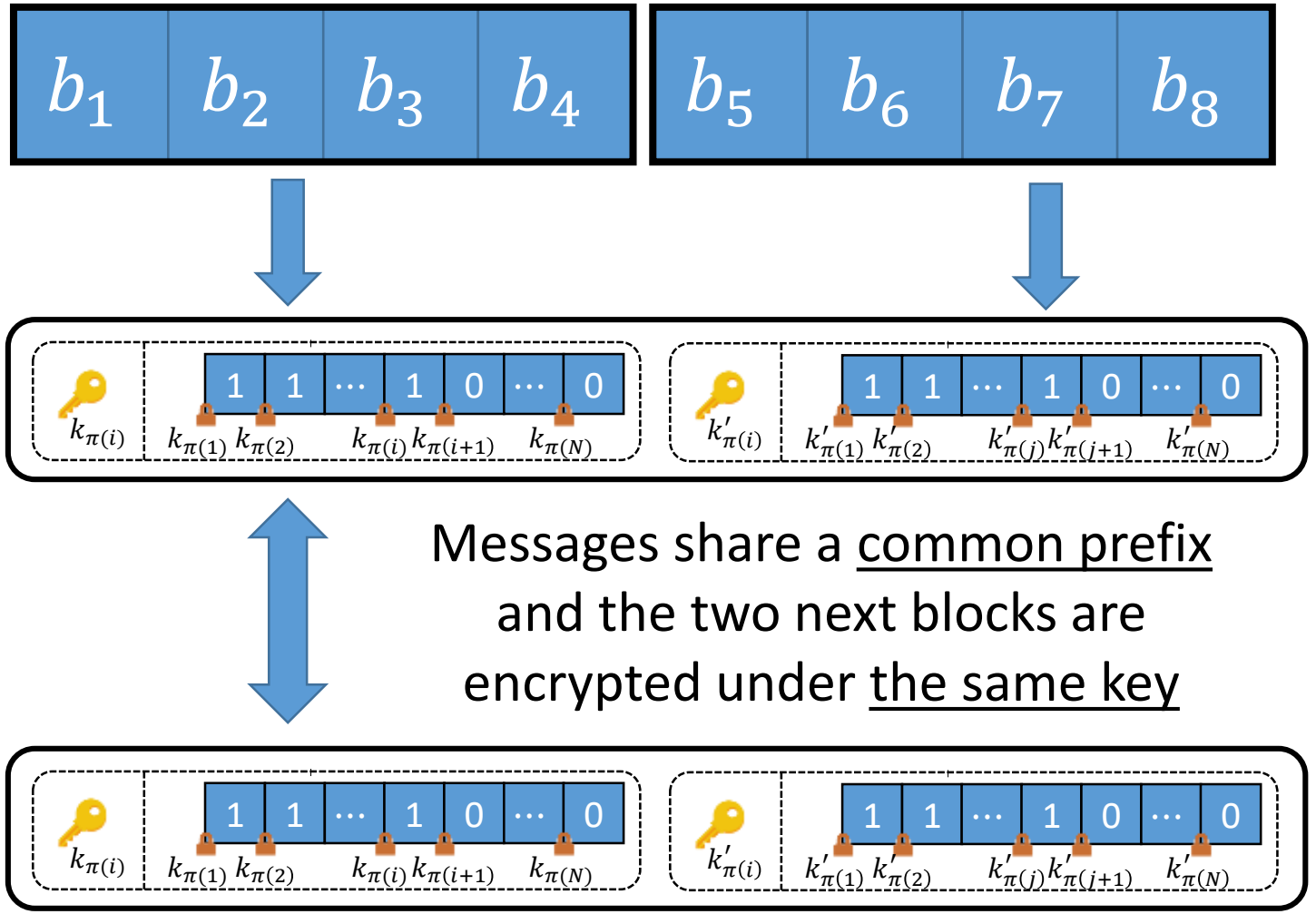


Case 1: Blocks encrypt distinct values

Domain Extension for ORE

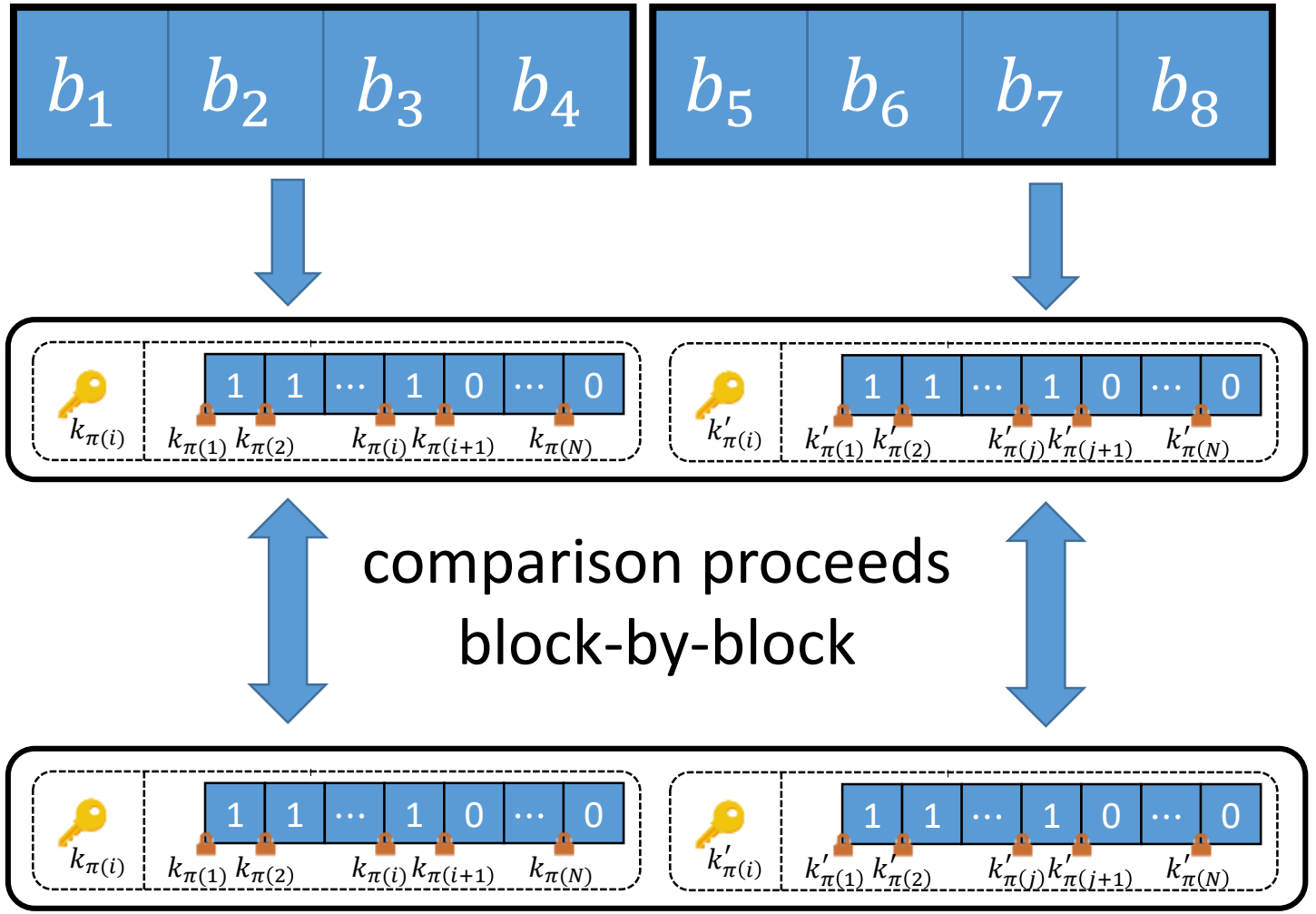


Domain Extension for ORE



Case 2: Blocks encrypt identical values

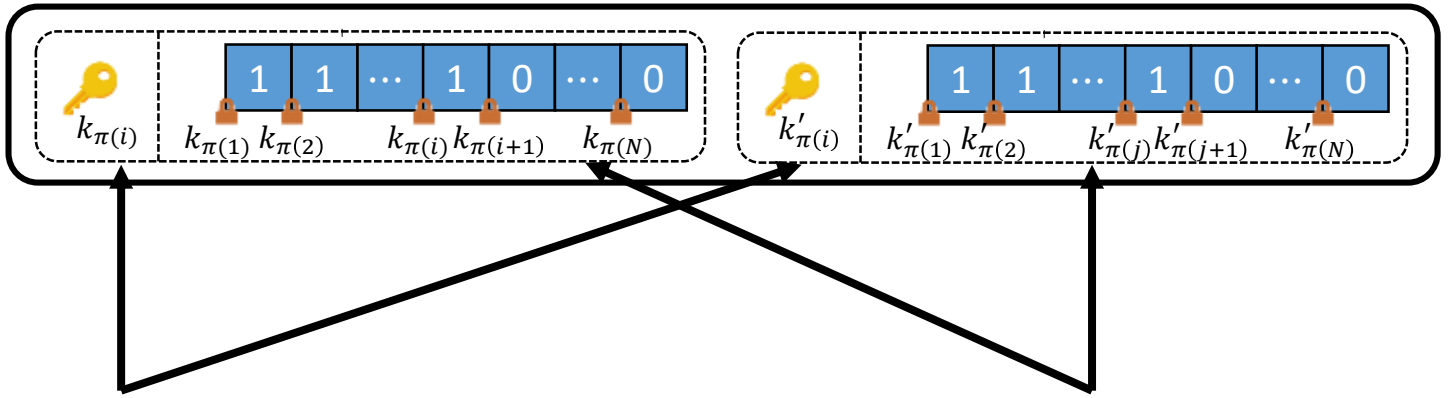
Domain Extension for ORE



Overall leakage: first **block** that differs

Domain Extension for ORE

Same decomposition into left and right ciphertexts:

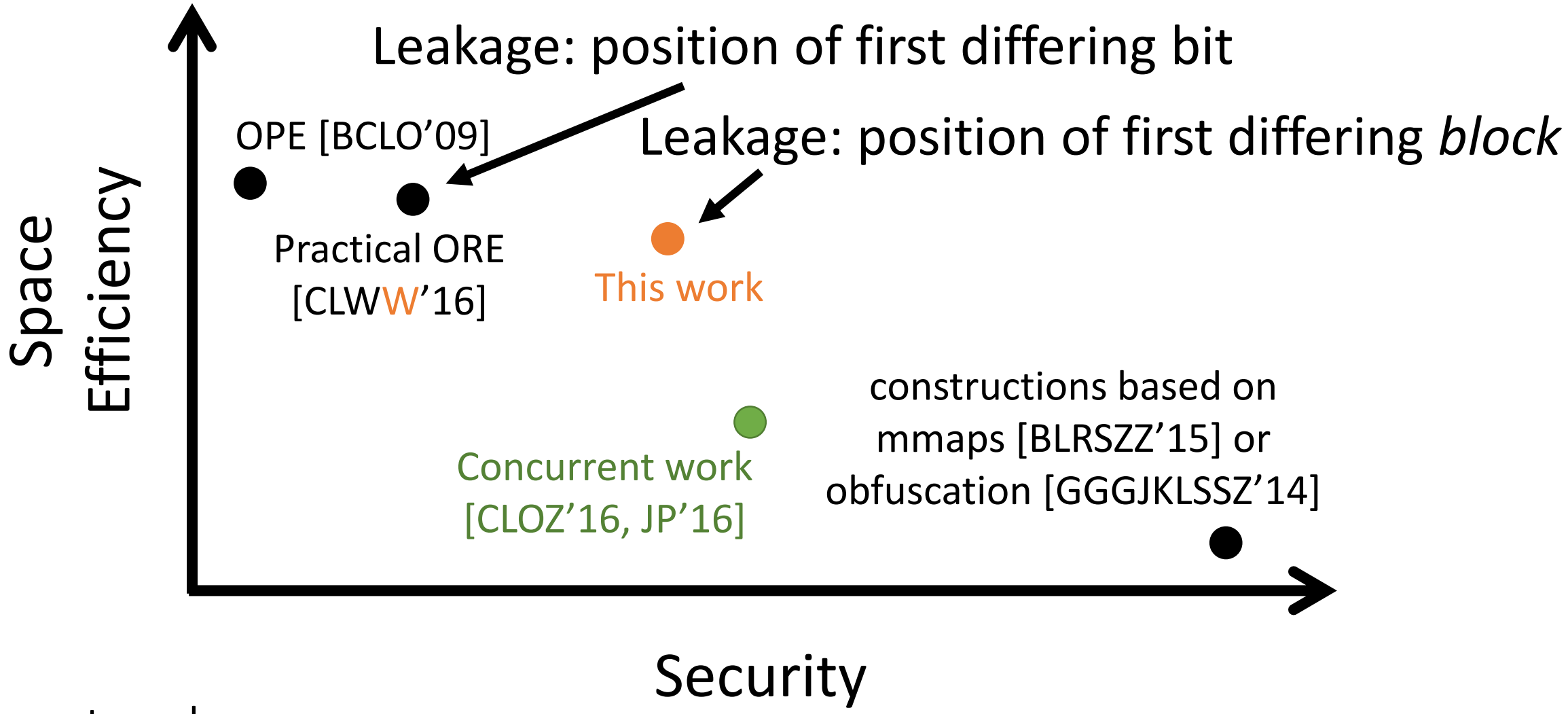


left ciphertext right ciphertext

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



not drawn to scale

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

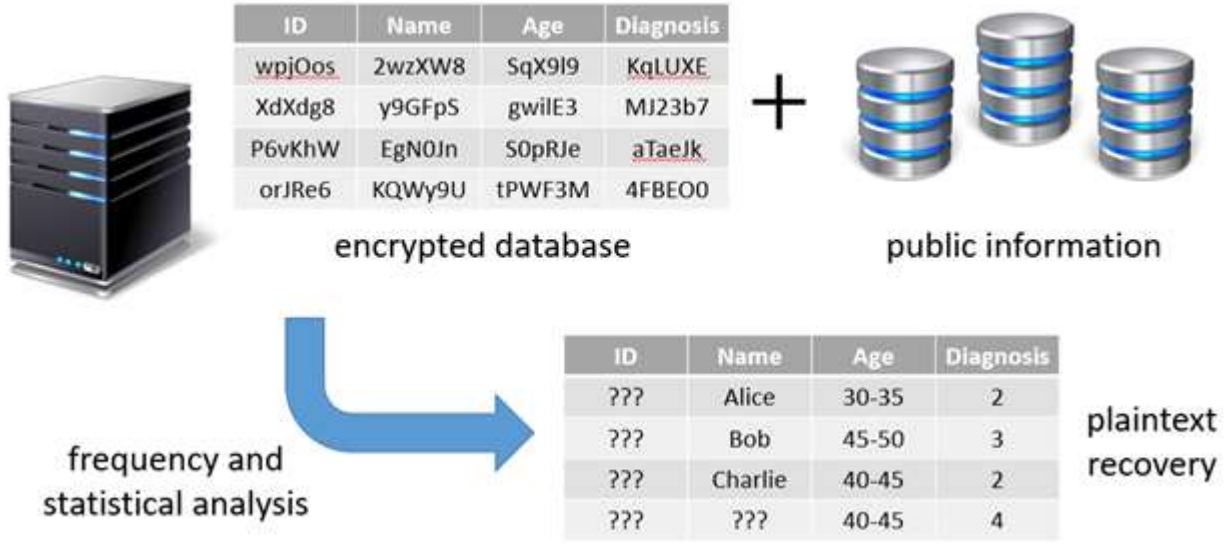
Benchmarks taken for C implementation of different schemes (with AES-NI). Measurements for encrypting 32-bit integers.

Performance Evaluation

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

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 simple assumptions?
- 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