The Locality of Searchable Symmetric Encryption

David Cash

Rutgers

Stefano Tessaro

UCSB

Connecting **security** and **i/o efficiency**

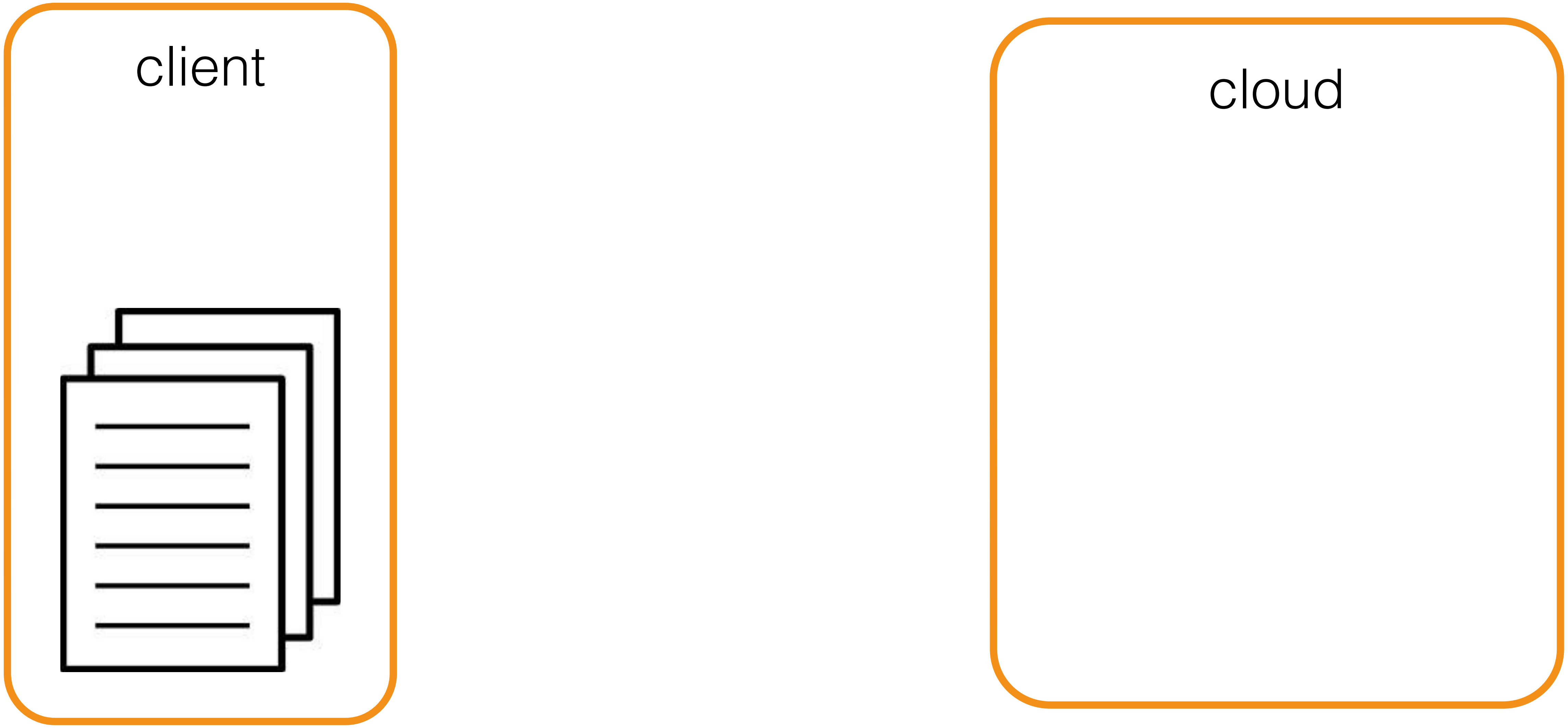
or

How a security notion can force inefficient disk utilization when encrypting large files

➡ new type of lower bound

➡ new constructions

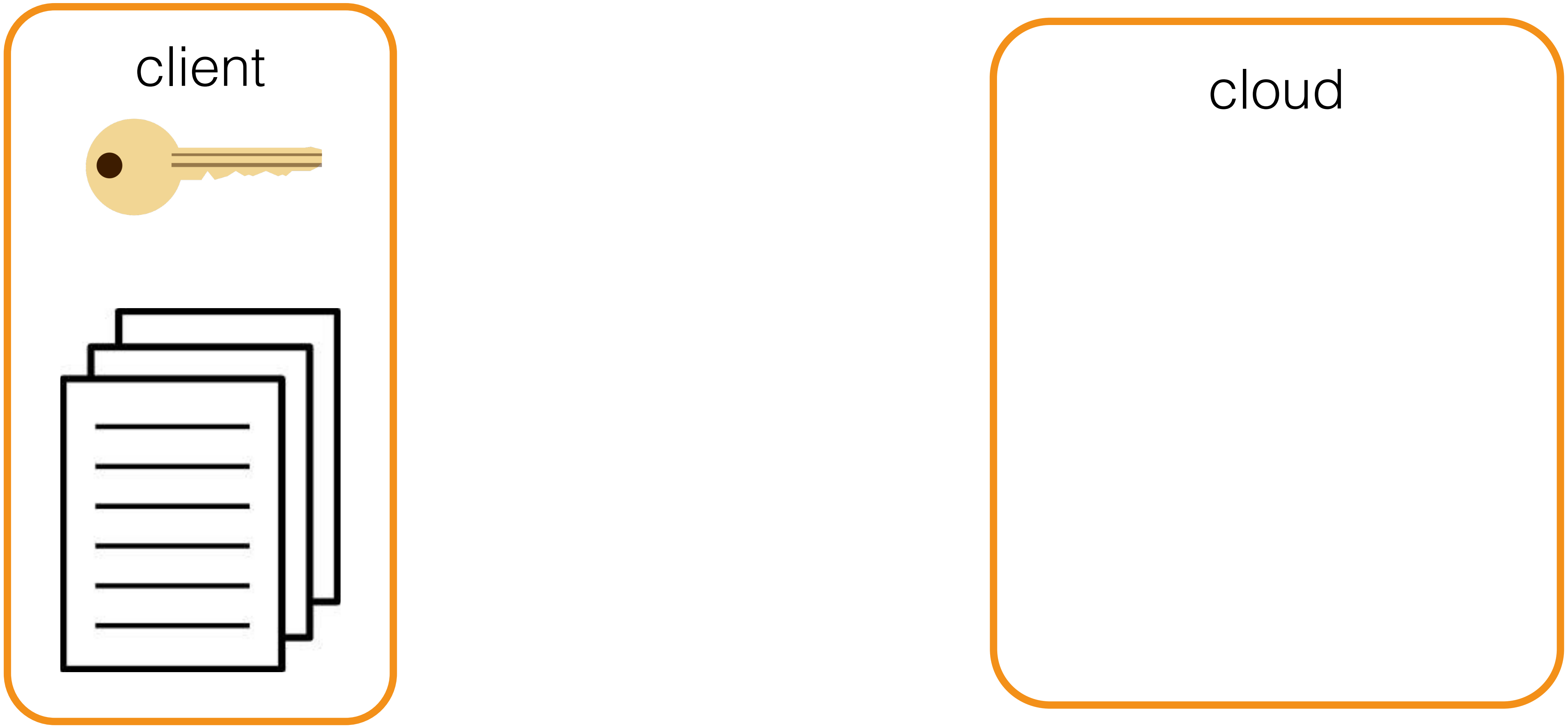
remotely storing encrypted documents



client

cloud

remotely storing encrypted documents



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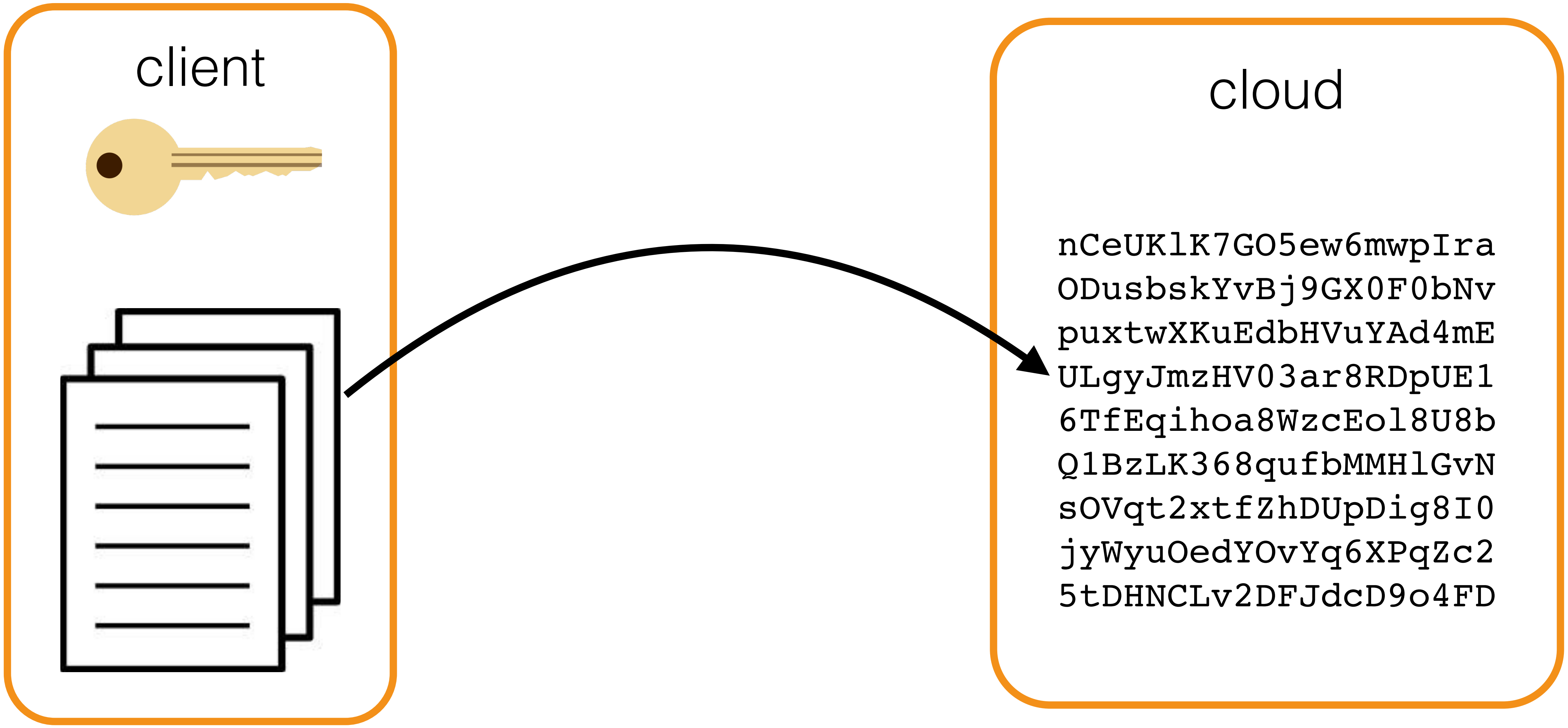

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```
nCeUKlK7GO5ew6mwpIra
ODusbskYvBj9GX0F0bNv
puxtwXKuEdbHVuYAd4mE
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6TfEqihoa8WzcEol8U8b
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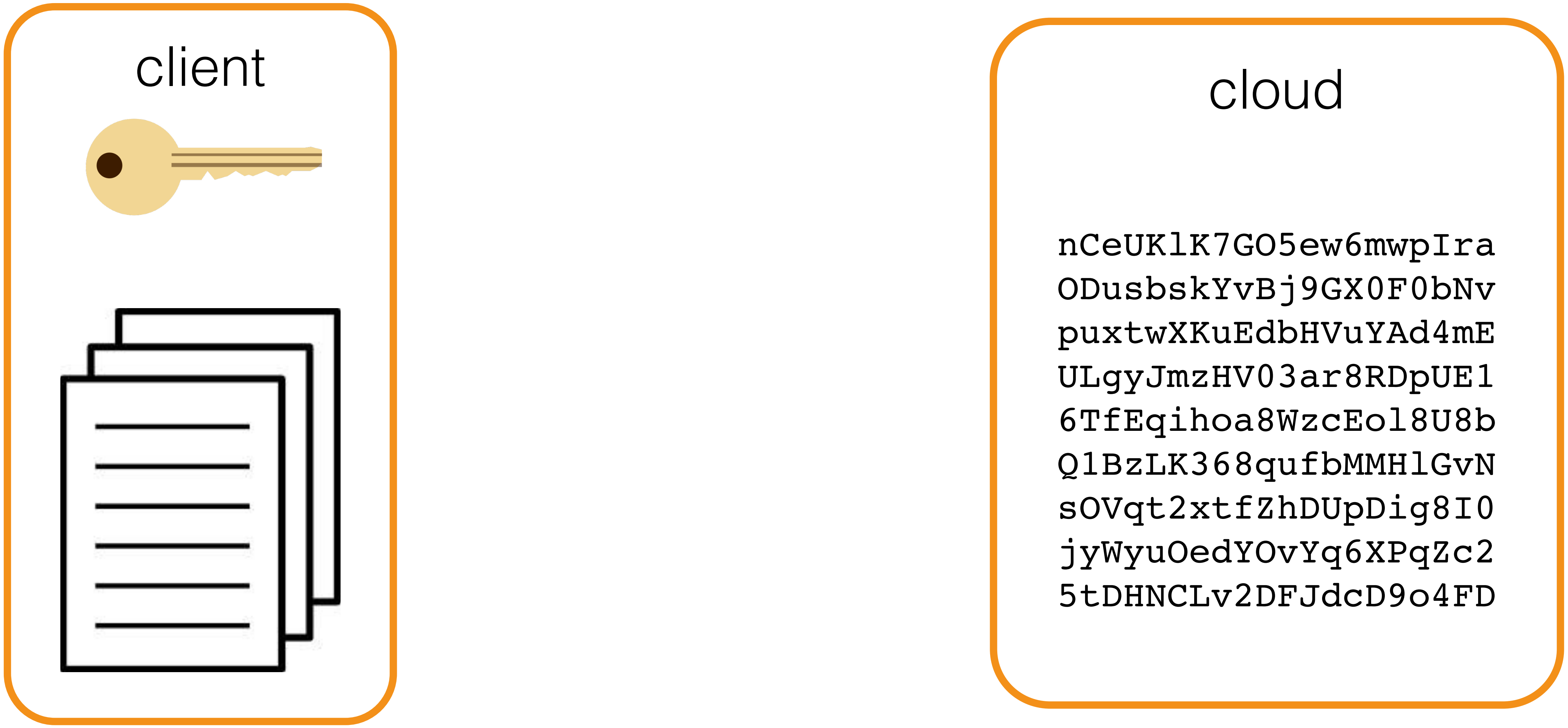

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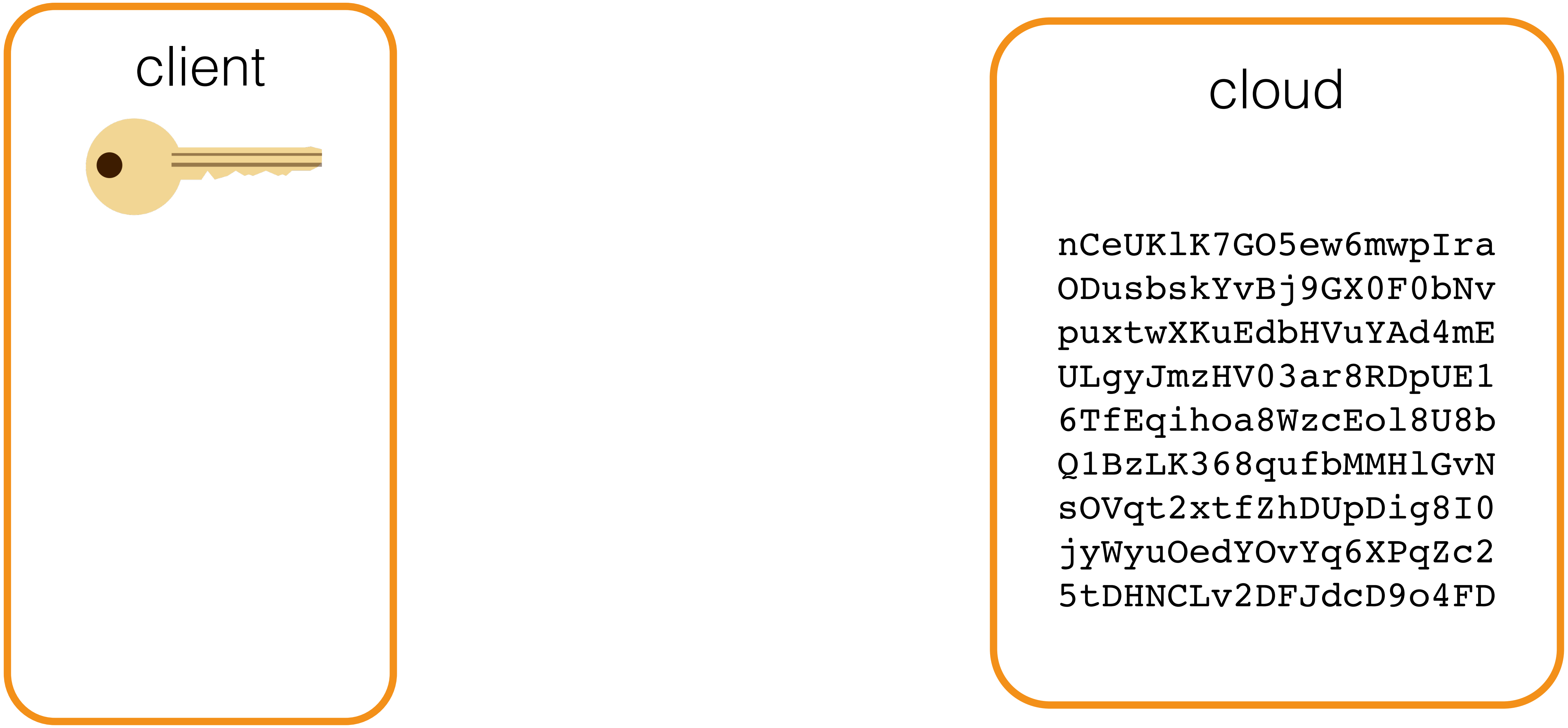

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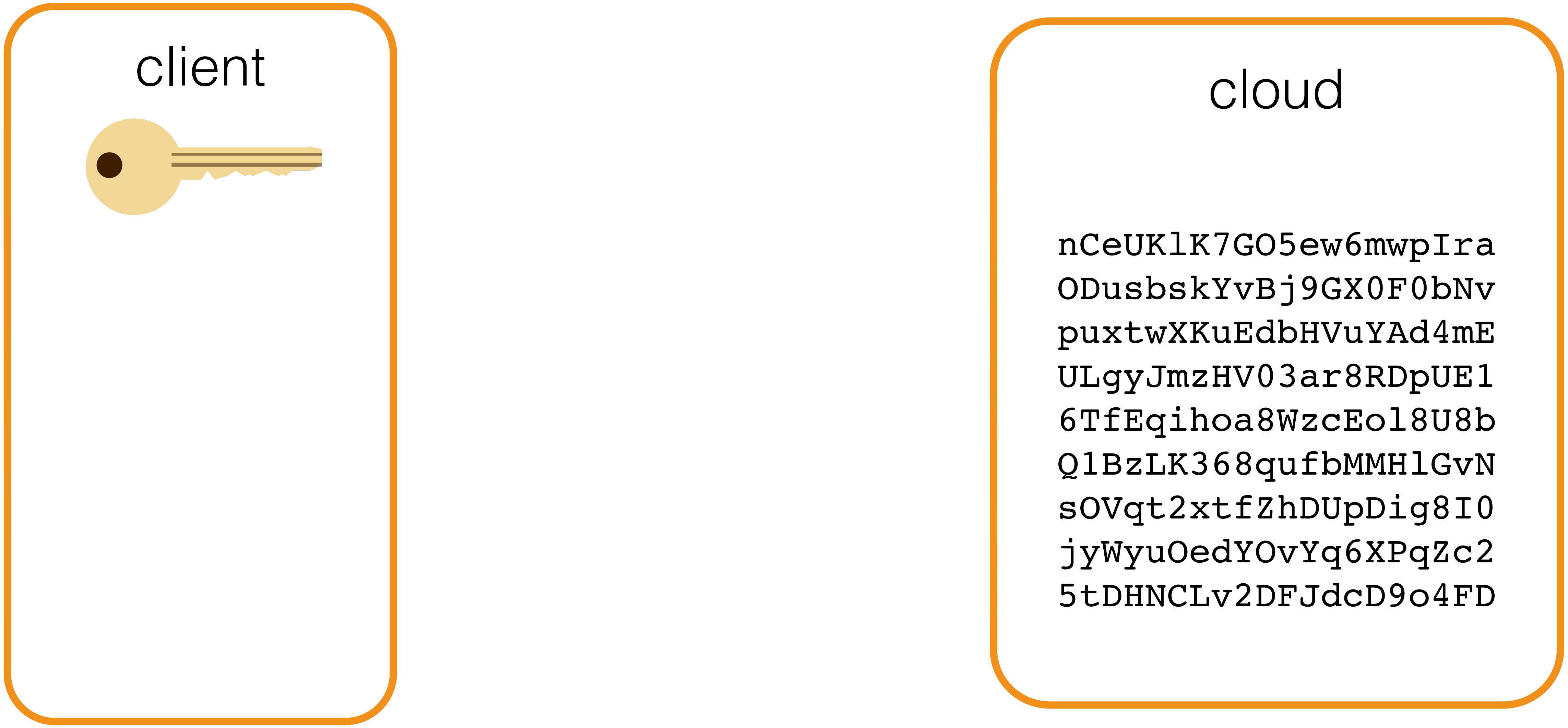

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➡ client encryption prevents server from helping by indexing, searching, organizing, …

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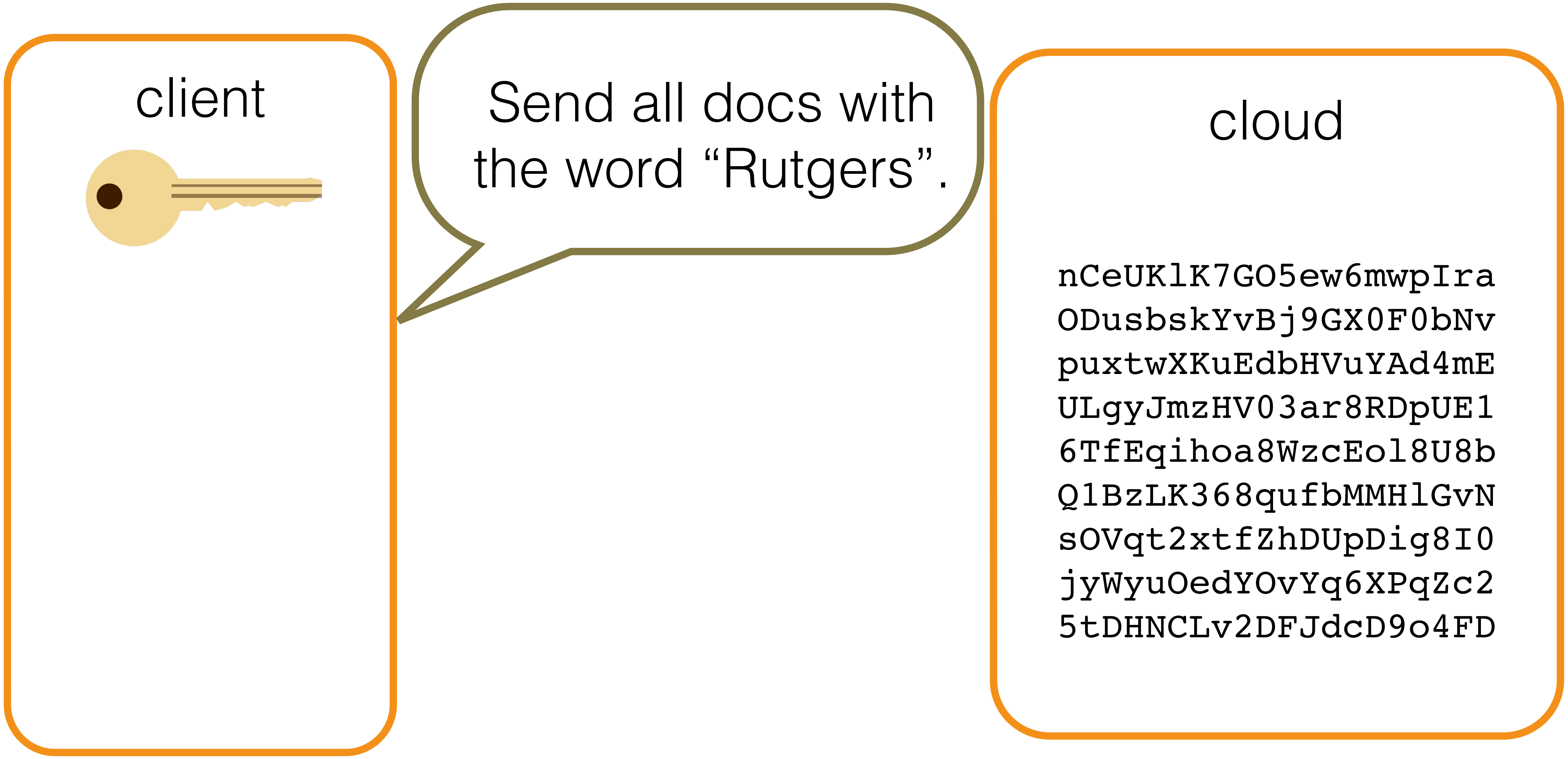

client

Send all docs with the word “Rutgers”.

cloud

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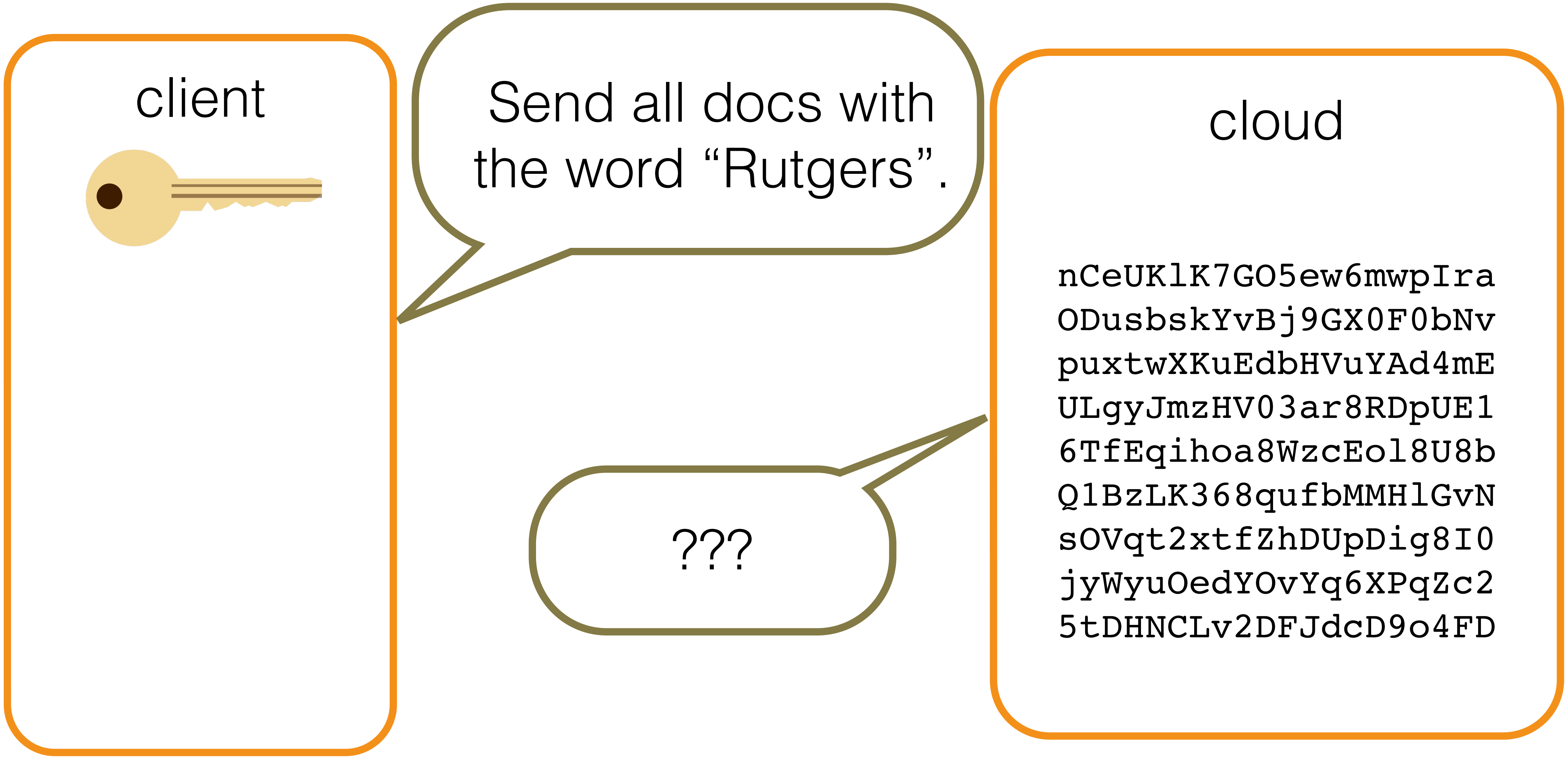

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- homomorphic encryption
- private information retrieval
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- hide doc plaintexts, query values, even which docs are downloaded

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➡ minimal "leakage" to server

- hide doc plaintexts, query values, even which docs are downloaded

➡ none currently in use for encrypted search

[Song, Wagner, Perrig] & [Curtmola, Garay, Kamara, Ostrovsky]:

Different approach to encrypted search:

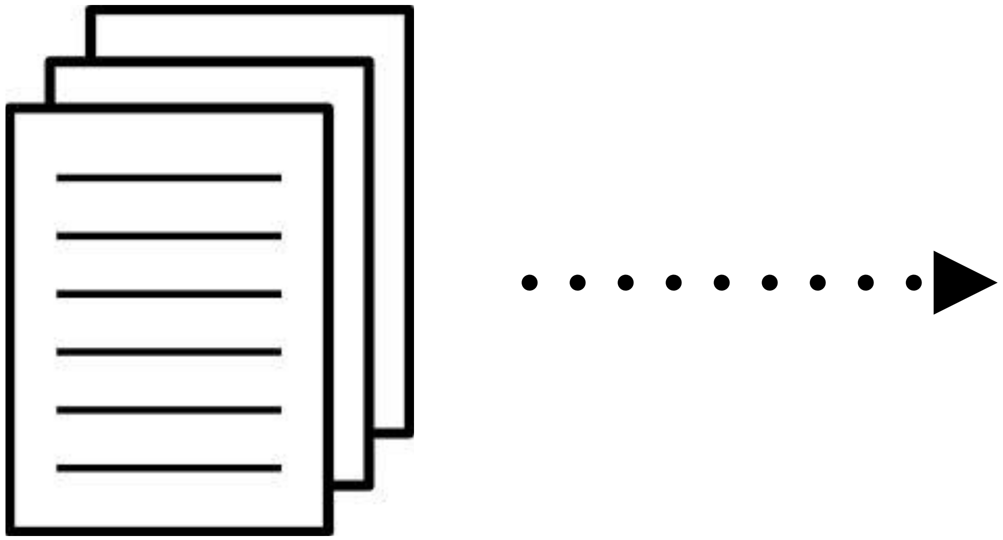
- Almost as efficient as unencrypted search
- Target weaker security - “leak the results”

- implementable - use only AES/HMAC/etc + data structures

[SWP] with [CGKO] refinement:

➡ Encrypt actual files using regular encryption

➡ Build and encrypt “(inverted) index” then delegate decryption of it later



Keyword	Doc IDs
“Rutgers”	4,9,37
“Admissions”	9,37,93,94,95,96
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“Accept”	2,37,62,75

information retrieval terminology

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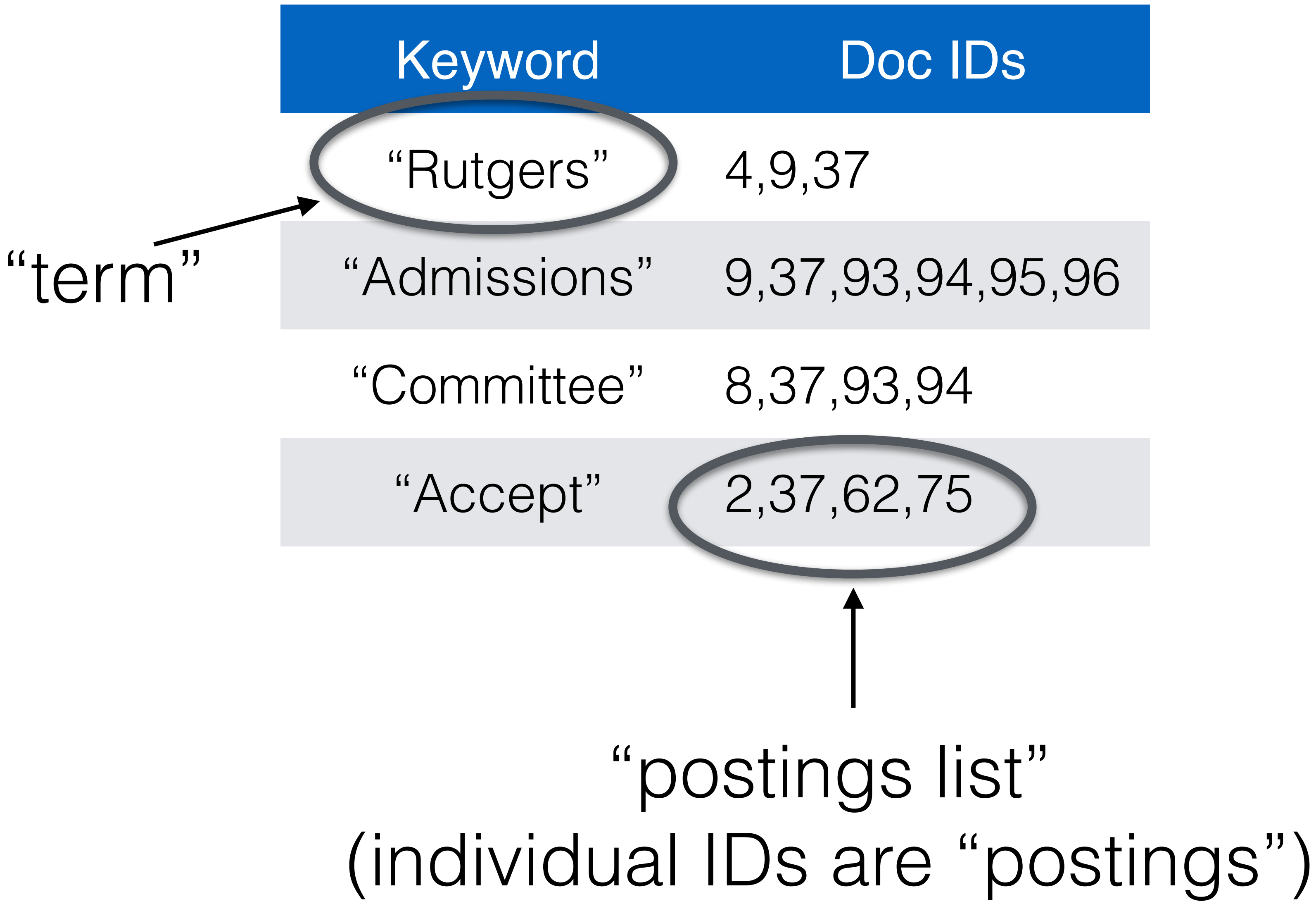

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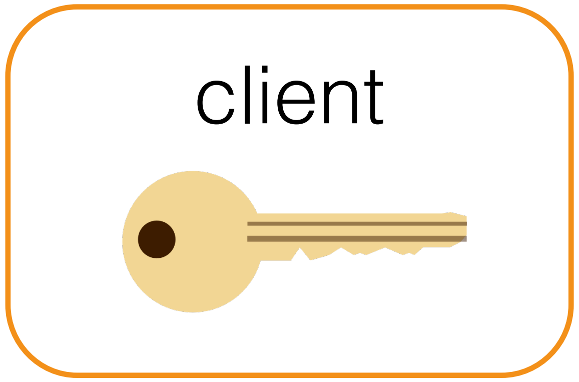
“term”

“postings list”
(individual IDs are “postings”)

searchable encryption: three algorithms

[Curtmola-Garay-Kamara-Ostrovsky]



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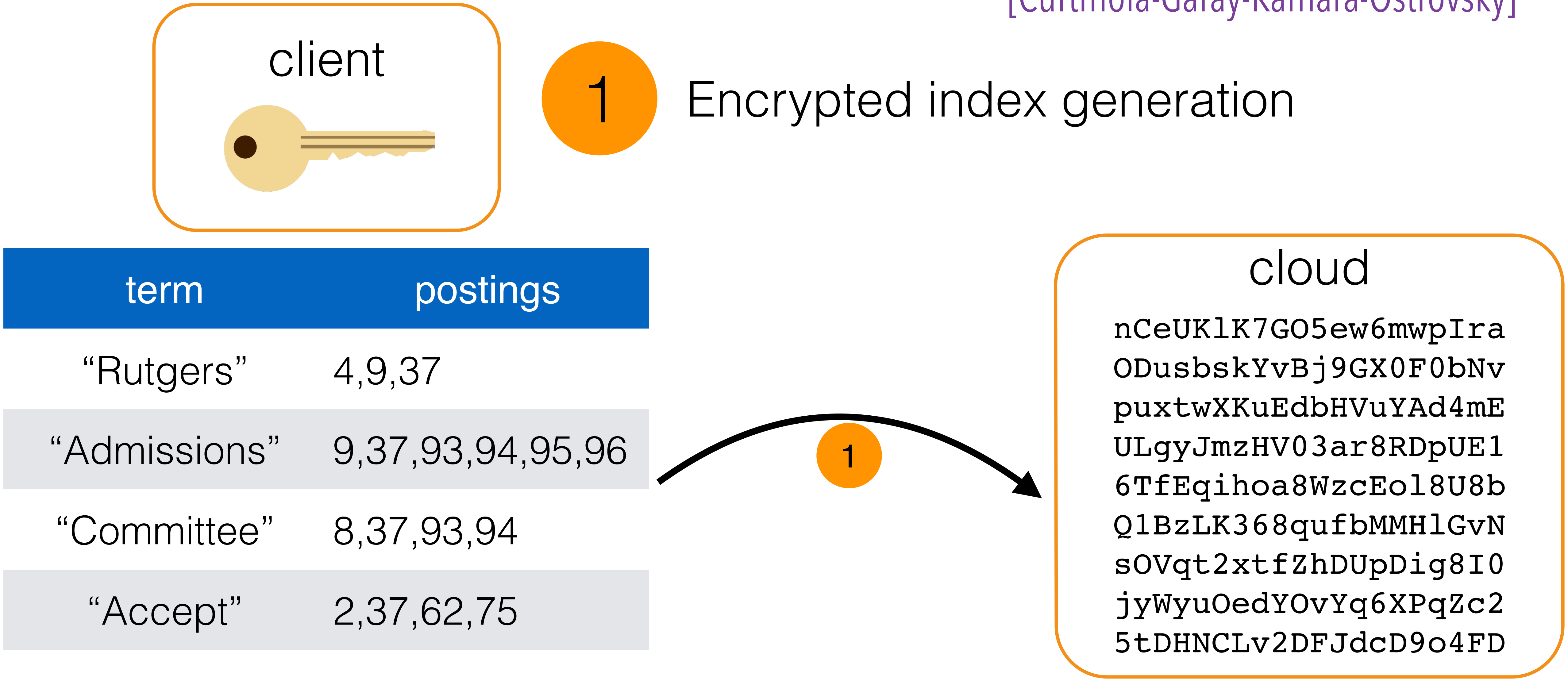

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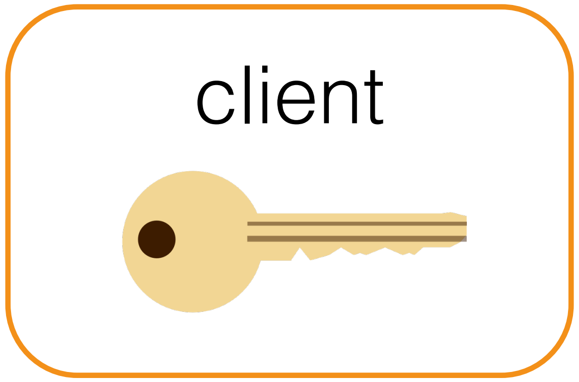

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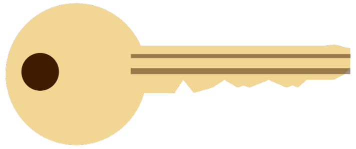
2 Token generation

searchable encryption: three algorithms

[Curtmola-Garay-Kamara-Ostrovsky]

client



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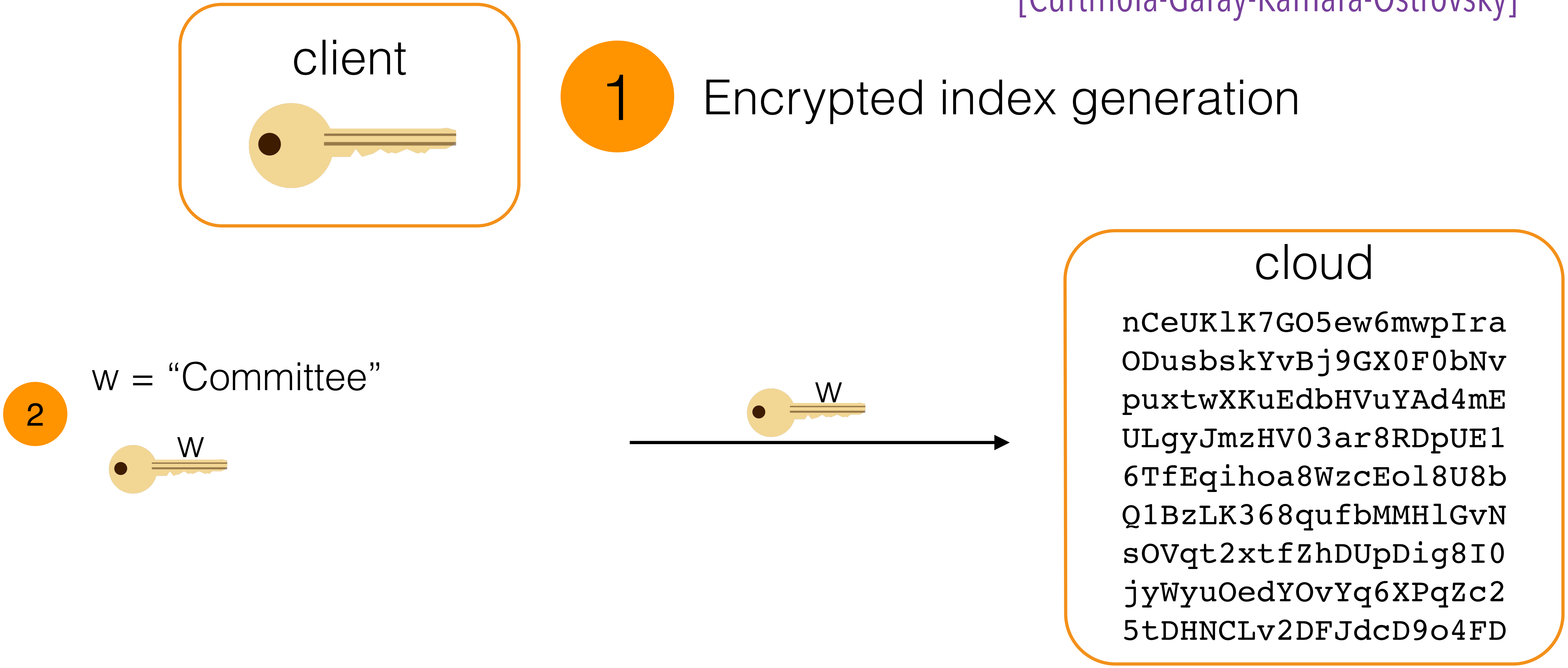

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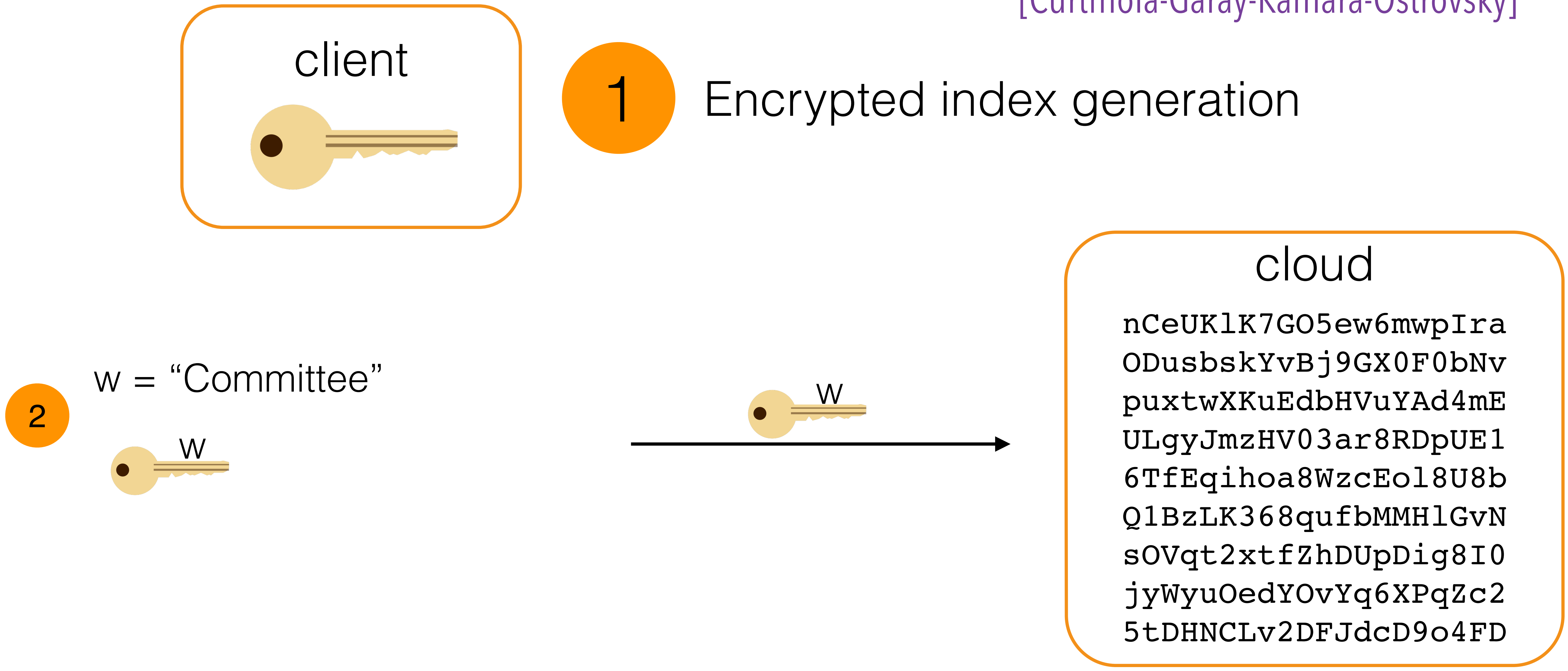

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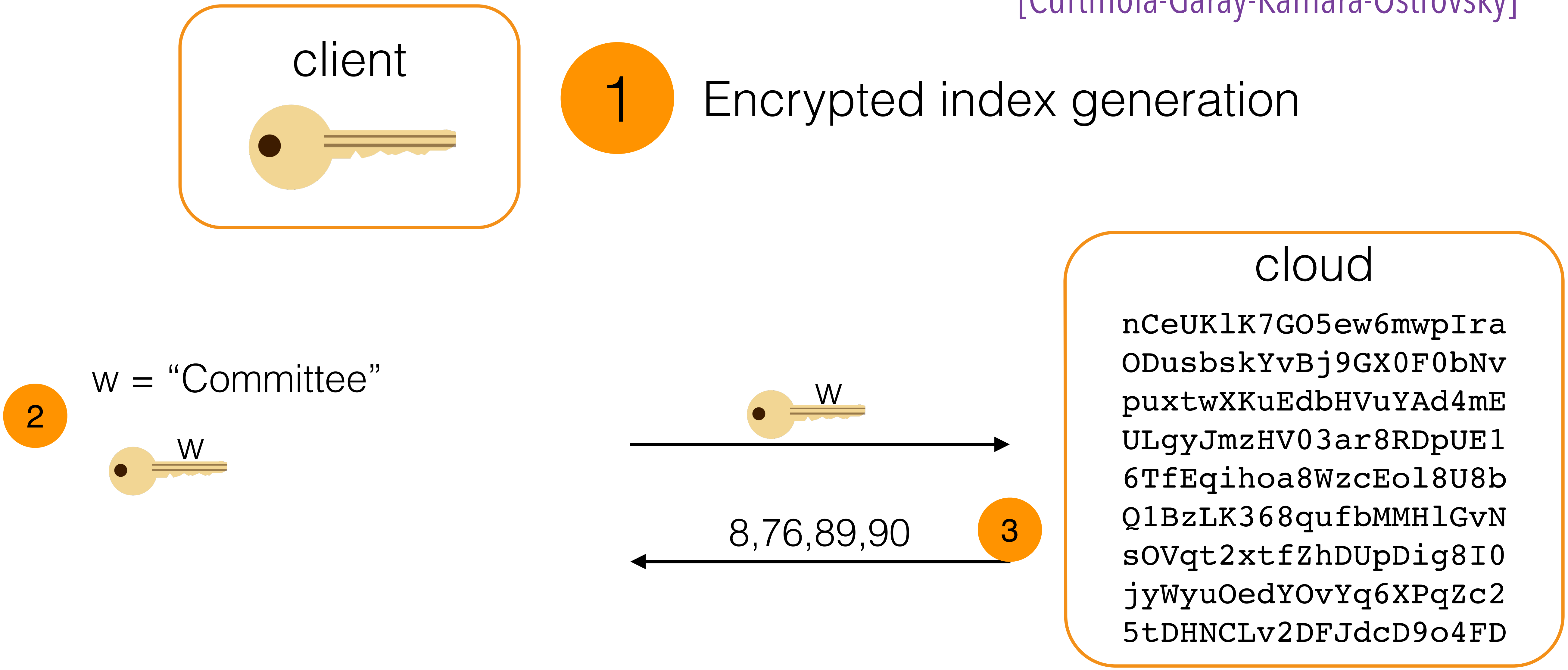

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8,76,89,90 3

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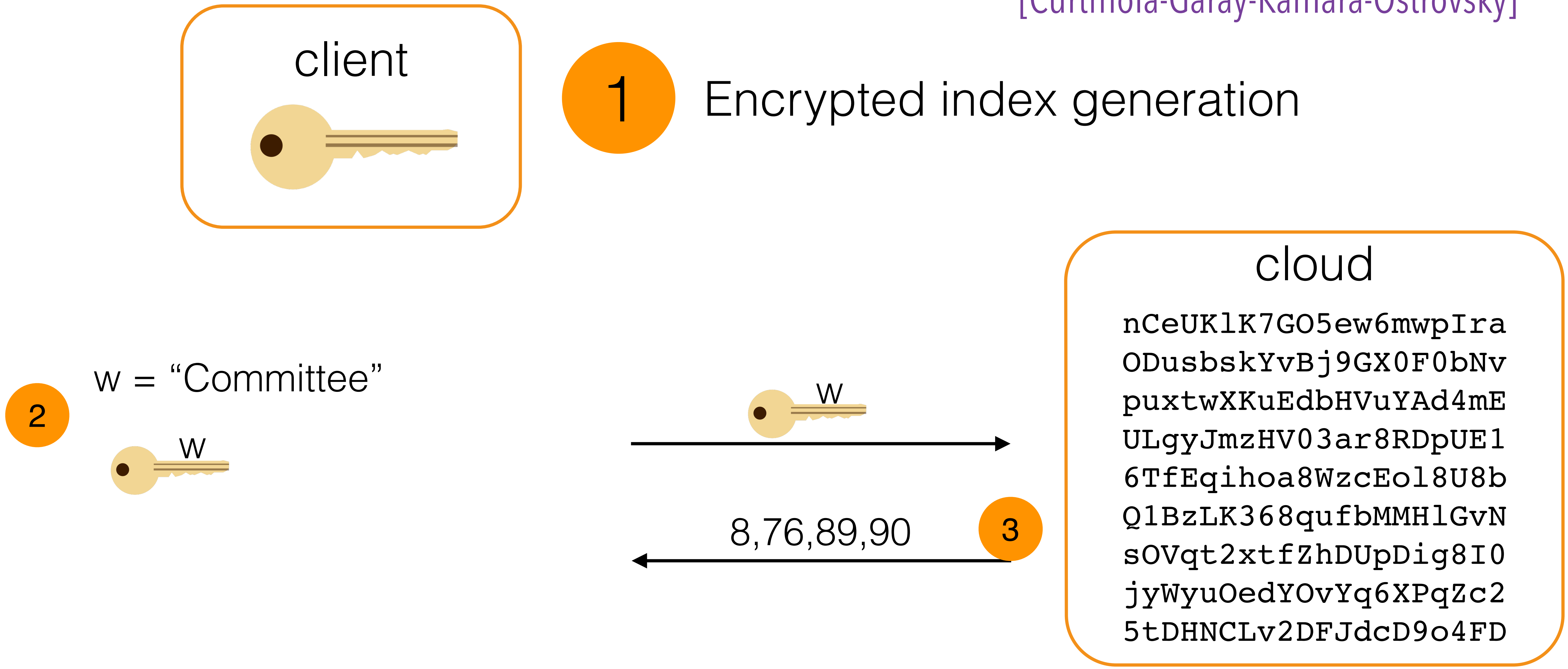

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correctness ⇒ server learns postings for w

searchable encryption security definition [CGKO]

$\mathcal{A}$

challenger

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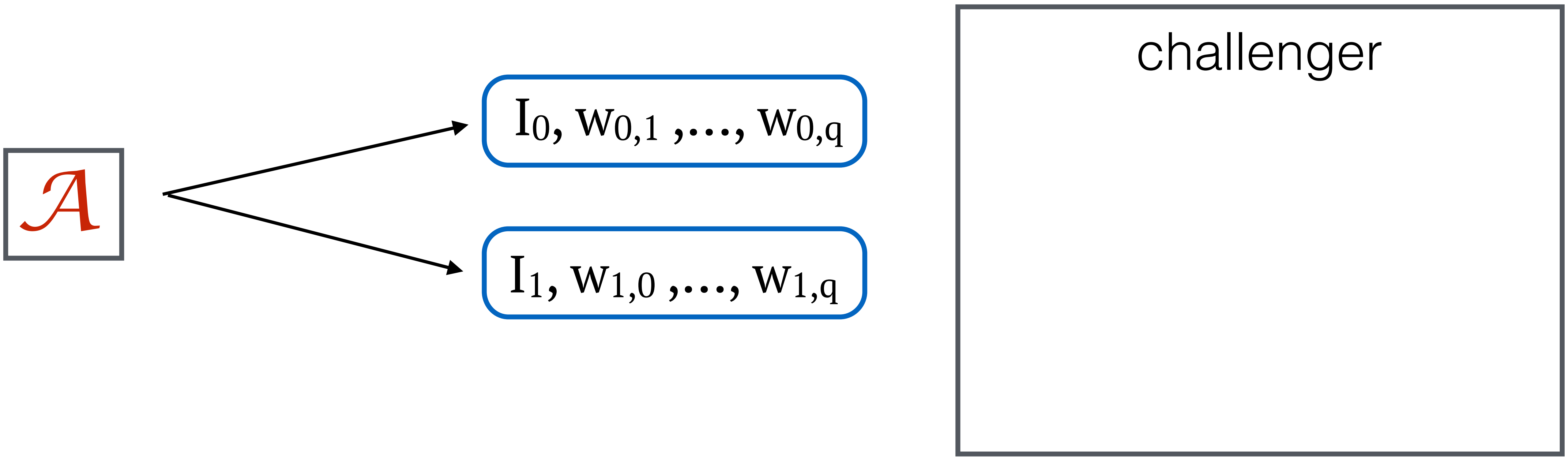

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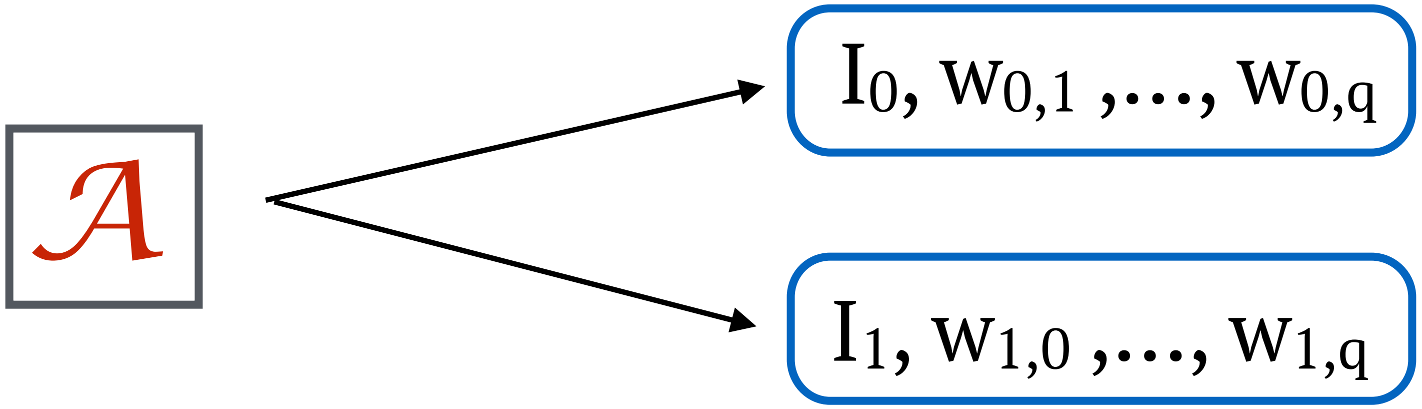

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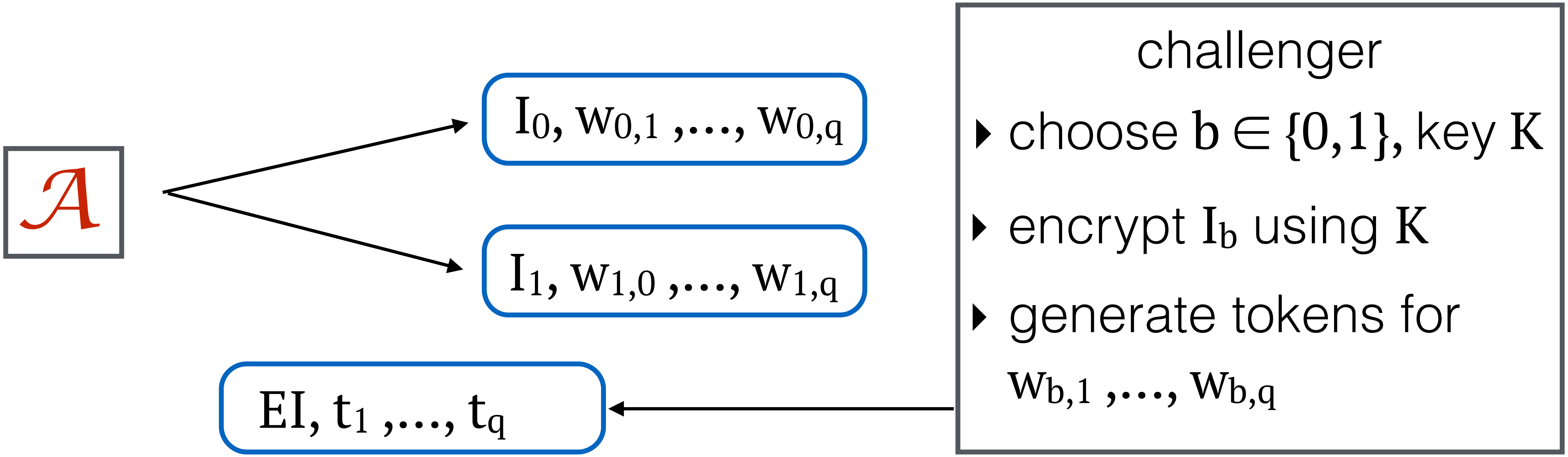

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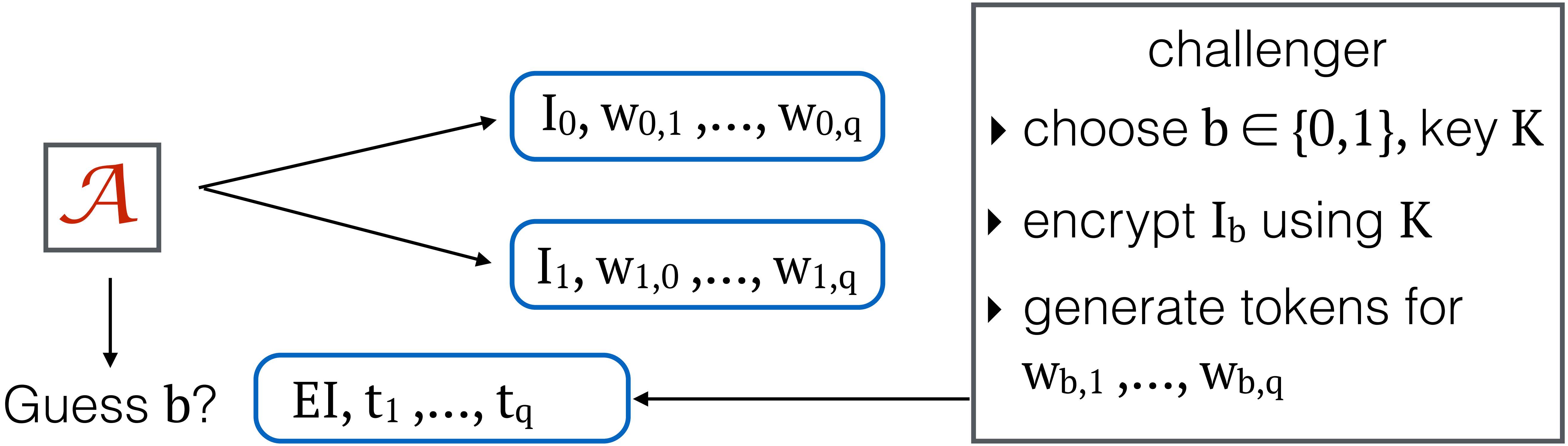

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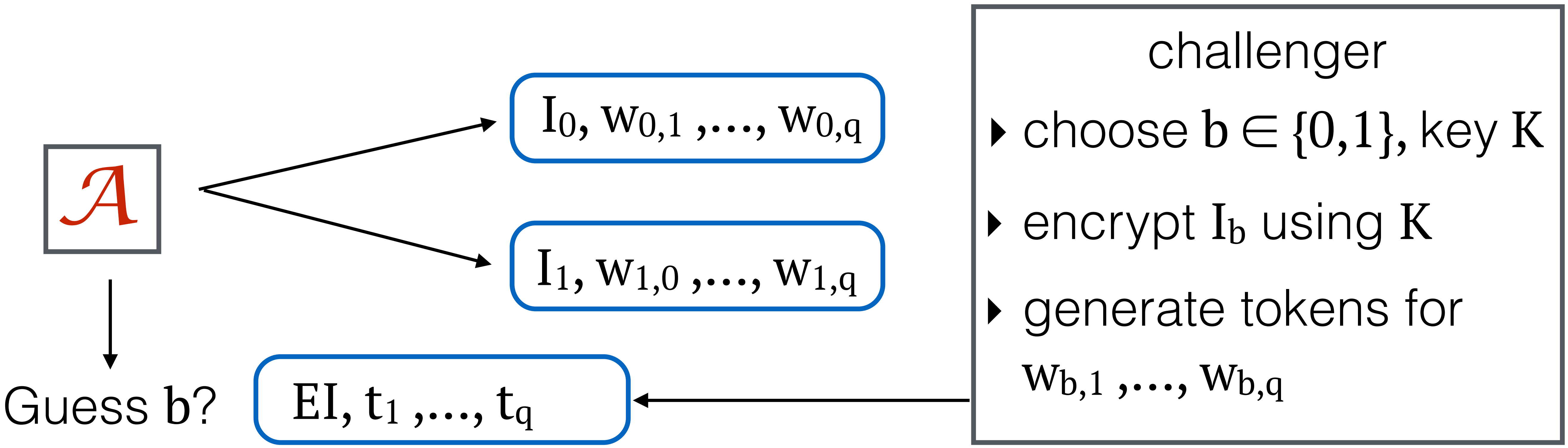

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Guess b?

- Restrictions to prevent trivial attacks:
  - I_0, I_1 have same no. postings
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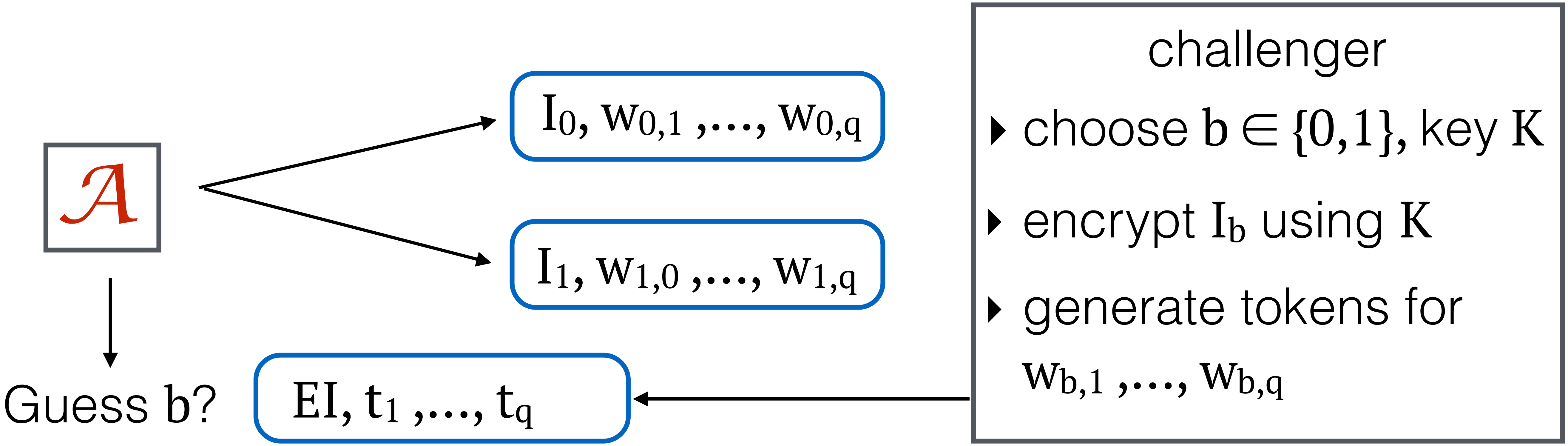

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__Def__: Scheme is __**secure**__ if all poly-time $\mathcal{A}$ guess b with probability $\approx 1/2$

what does searchable encryption leak?

will not hide:

- postings lists as searches are issued
- when searches repeat
- total # postings in index

hides everything for part of index not searched, including:

- sizes of postings lists
- postings in lists
- # of postings lists in index

research on searchable encryption

- secure updates after initial upload [KPR, KP, CJJJKRS, NPG]
- other security properties (auth, UC, etc) [KO, LSDHJ, CK]
- boolean search queries [CJJKRS]
- keyword search with “web structure” [CK]
- used in DB encryption in CryptDB & Monomi [PRZB, TKMZ]
- Challenges with flexibility, usability

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systems collaborators at IBM complained:

> “ Fine, the asymptotics are optimal, but this stuff is unusably slow for large indexes.

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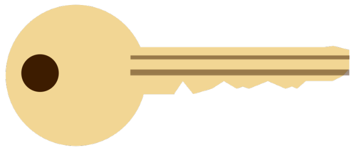
➡ Runtime bottleneck: disk latency, not crypto processing.

memory access during encrypted search

client



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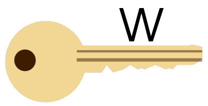

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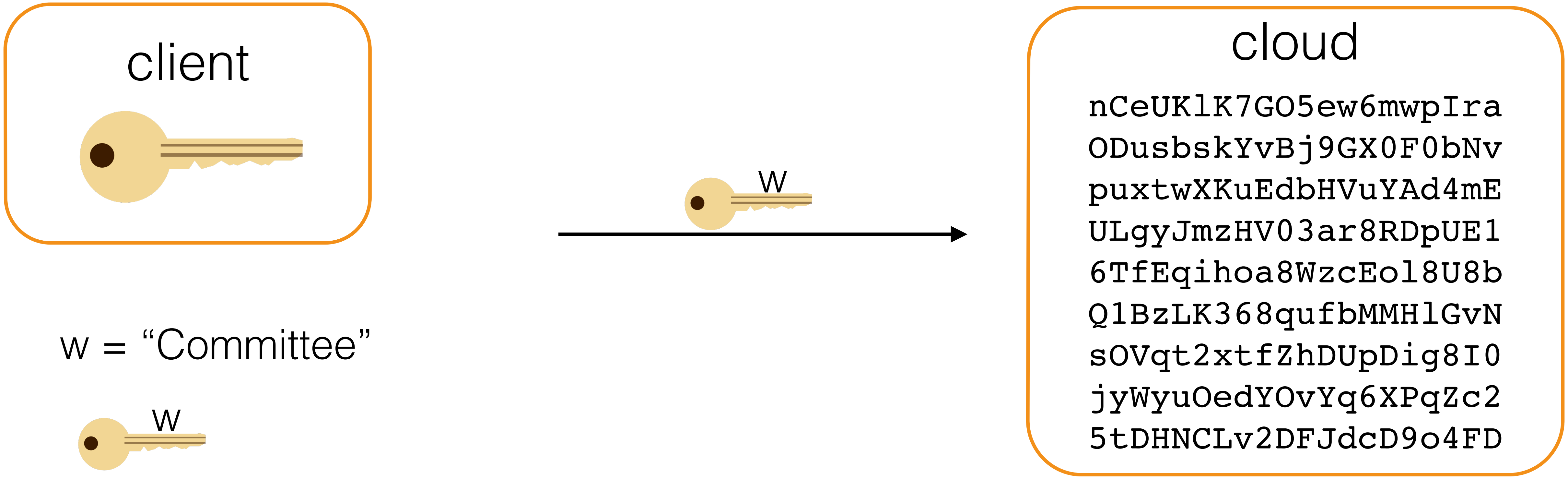
ULgyJmzHV03ar8RDpUE1
6TfEqihoa8WzcEol8U8b
Q1BzLK368qufbMMHlGvN
sOVqt2xtfZhDUpDig8I0
jyWyuOedYOvYq6XPqZc2
5tDHNCLv2DFJdcD9o4FD

memory access during encrypted search



w = “Committee”

```
nCeUKlK7GO5ew6mwpIra
ODusbskYvBj9GX0F0bNv
puxtwXKuEdbHVuYAd4mE
ULgyJmzHV03ar8RDpUE1
6TfEqihoa8WzcEol8U8b
Q1BzLK368qufbMMHlGvN
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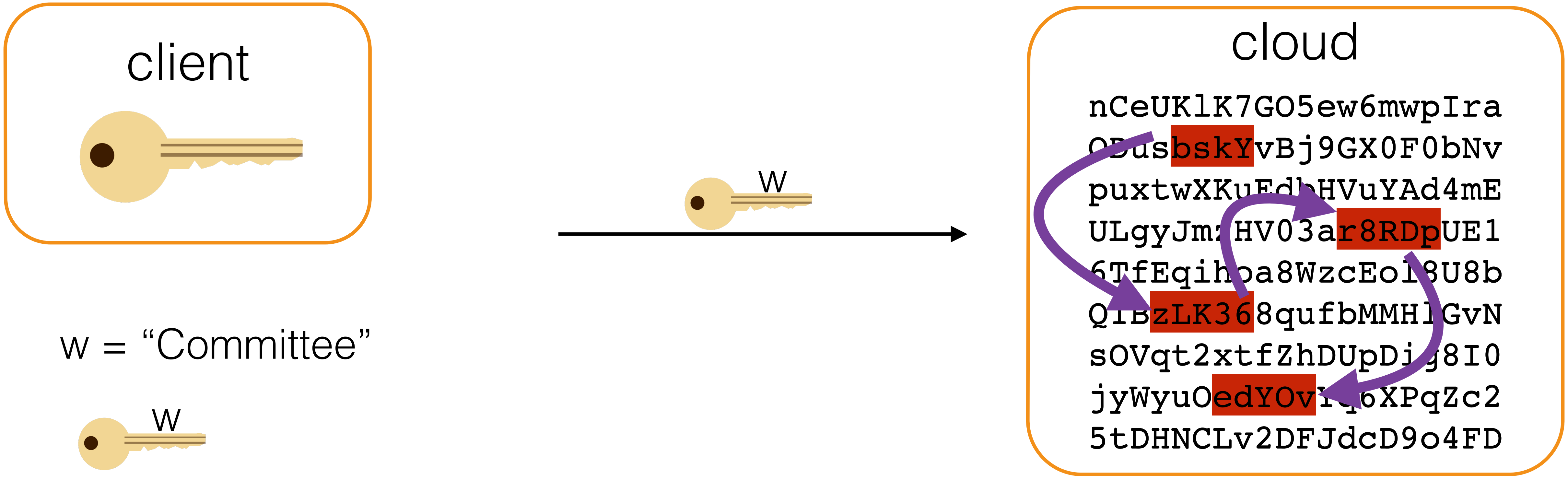

client

w

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w

cloud

nCeUKlK7GO5ew6mwpIra
QDusbskYvBj9GX0F0bNv
puxtwXKuFdbHVuYAd4mE
ULgyJmzHV03ar8RDpUE1
6TfEqihpa8WzcEoI8U8b
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➡ constructions access one random part of memory per posting

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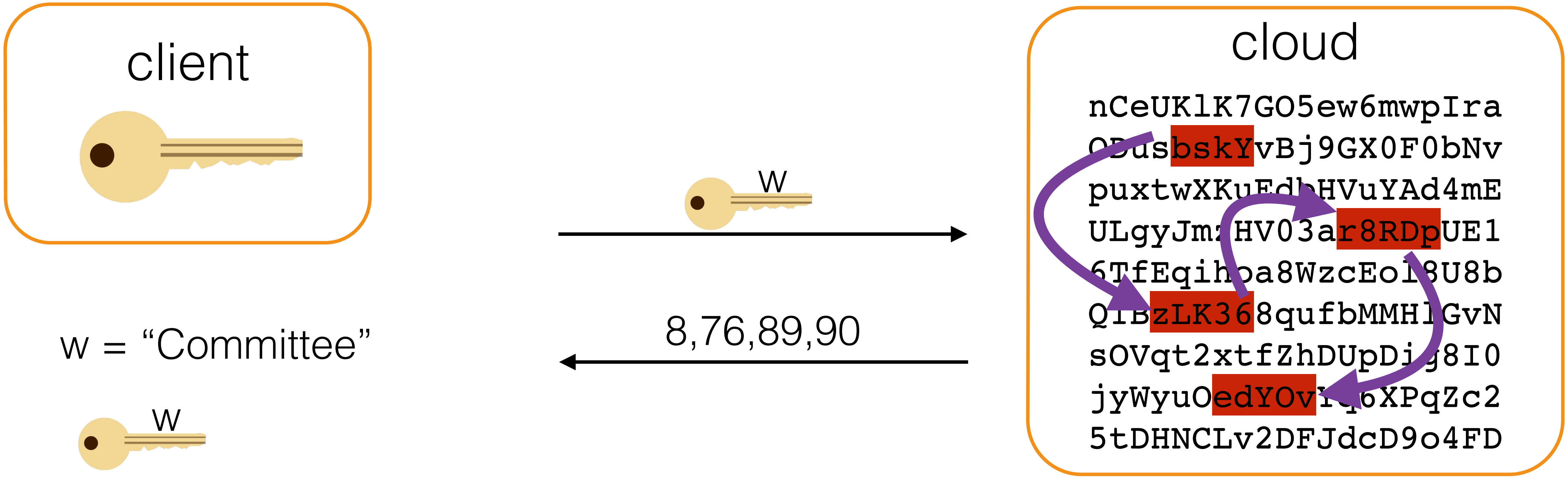

client

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8,76,89,90

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w

cloud

nCeUKlK7GO5ew6mwpIra
ODusbskYvBj9GX0F0bNv
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ULgyJmzHV03ar8RDpUE1
6TfEqihpa8WzcEol8U8b
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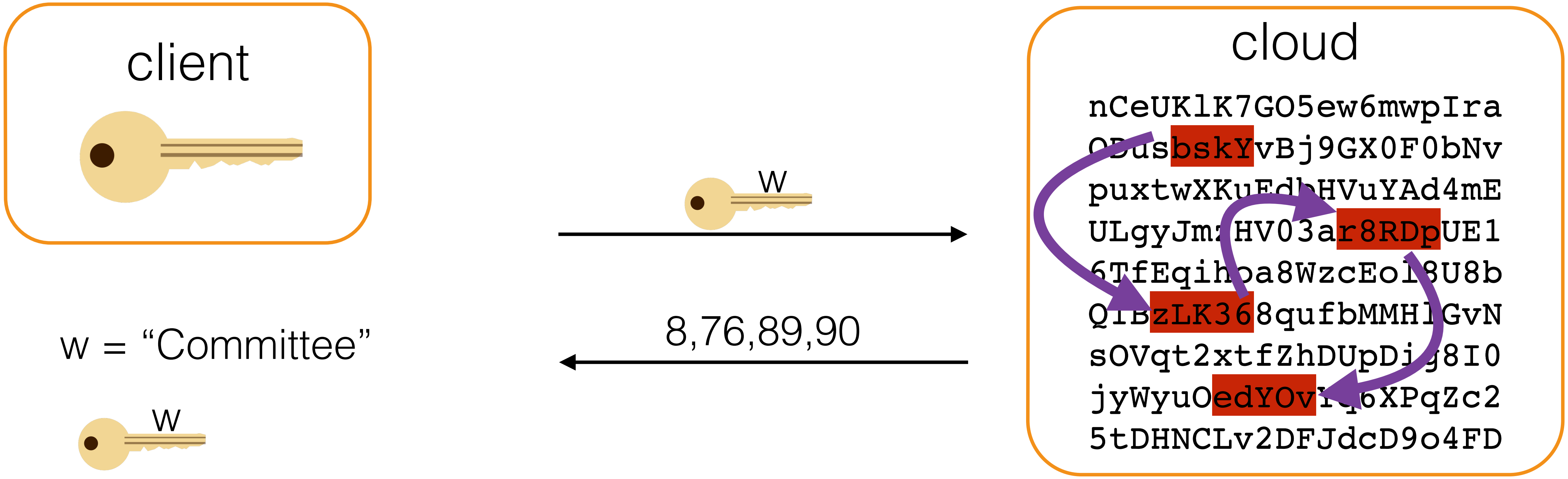

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nCeUKlK7GO5ew6mwpIra
QDusbskYvBj9GX0F0bNv
puxtwXKuEdbHVuYAd4mE
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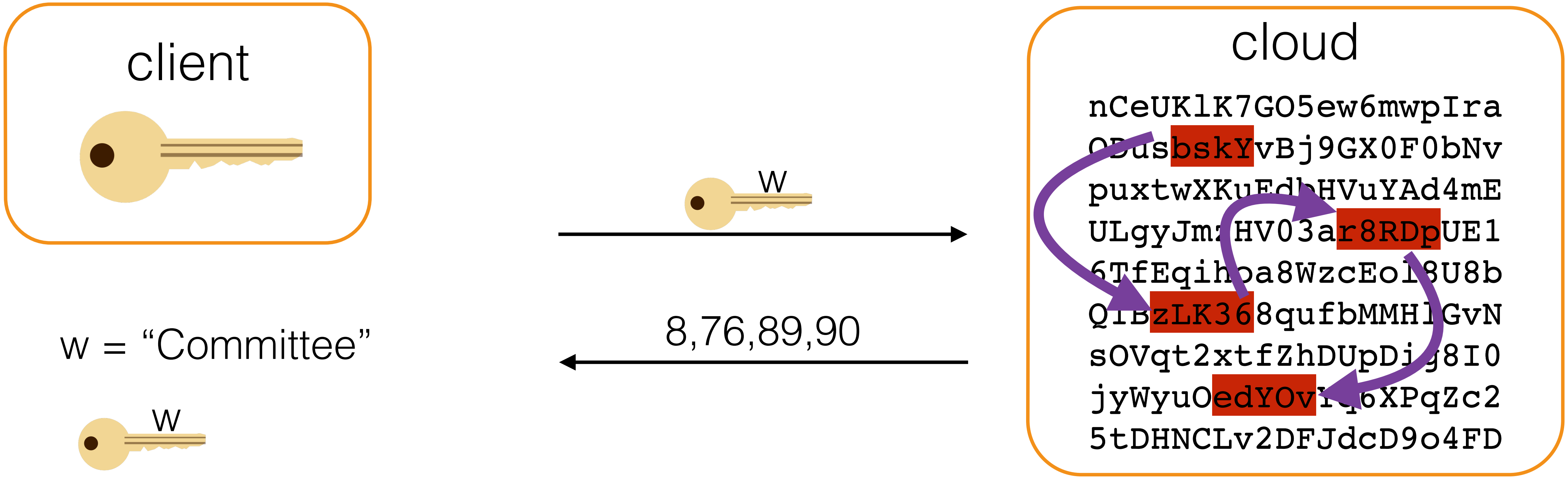

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- one disk seek per posting (≈ only few bytes, wasteful)

➡ plaintext search can use one contiguous access for entire postings list

i/o efficiency theory

- count *only* # of blocks moved to/from disk [Aggarwal-Vitter]
  - to read a block in new location, incur seek time
  - seek time overwhelms time for computation
- numerous versions of theory i/o models (see [Vitter] text)
  - optimal results (matching upper/lower bounds) for many problems like sorting, dictionary look-up, …

our results: i/o efficiency and searchable encryption

- ➡initiate study of i/o efficiency and security
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  - ‣ new proof technique
- ➡construction improving i/o efficiency of prior work

our results: i/o efficiency lower bound

“Theorem”: Secure searchable encryption must either:

(1) Have a very large encrypted index,

or

(2) Read memory in a highly “non-local” fashion,

or

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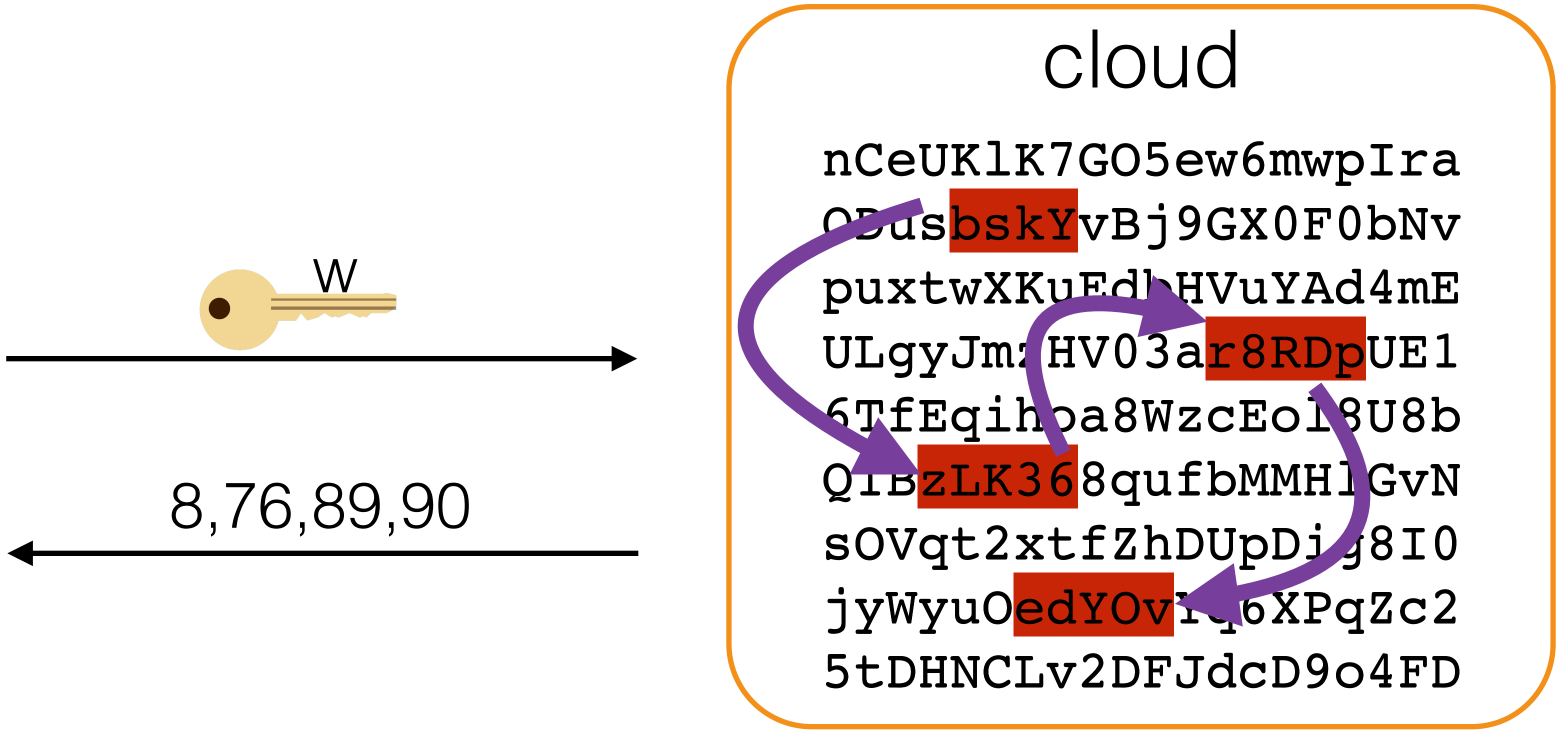
- ➡ unconditional (no complexity assumptions)
- ➡ applies to any scheme (no assumption about how it works)
- ➡ different type of i/o lower bound: security vs. correctness

memory utilization in searching

any construction can be seen as “touching” contiguous regions of memory during search processing:



```
nCeUKlK7GO5ew6mwpIra
QDusbskYvBj9GX0F0bNv
puxtwXKuEdbHVuYAd4mE
ULgyJmzHV03ar8RDpUE1
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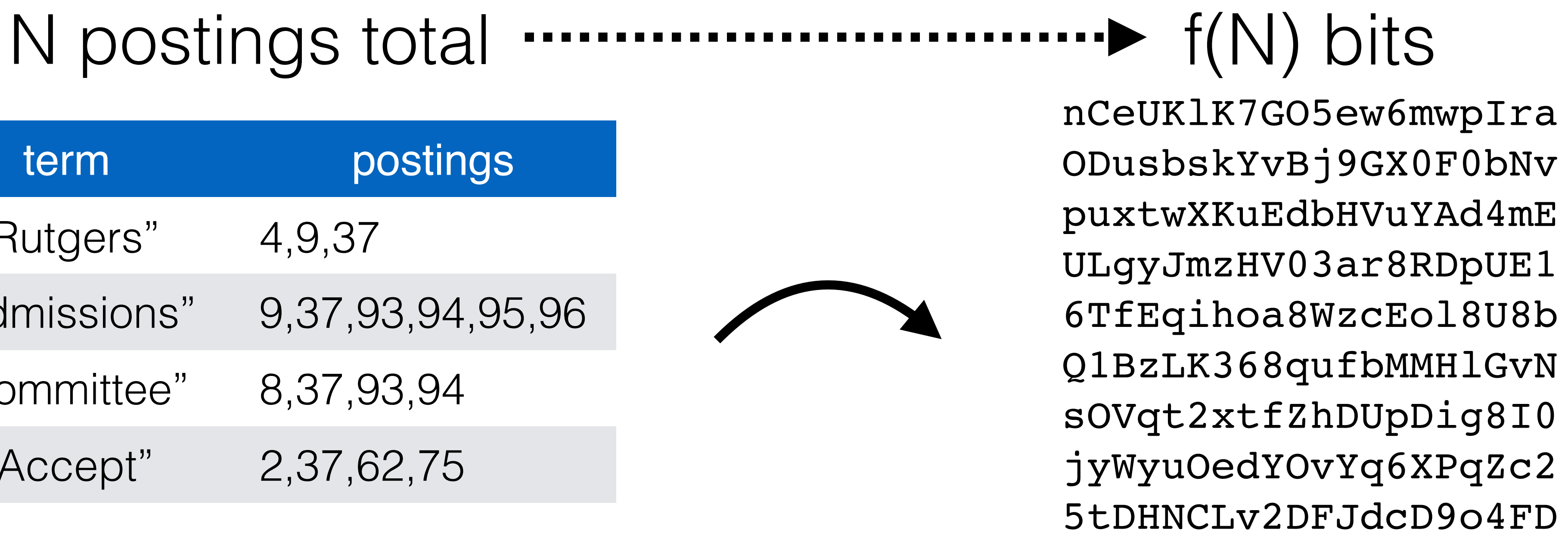

N postings total

f(N) bits

term	postings
“Rutgers”	4,9,37
“Admissions”	9,37,93,94,95,96
“Committee”	8,37,93,94
“Accept”	2,37,62,75

```
nCeUKlK7GO5ew6mwpIra
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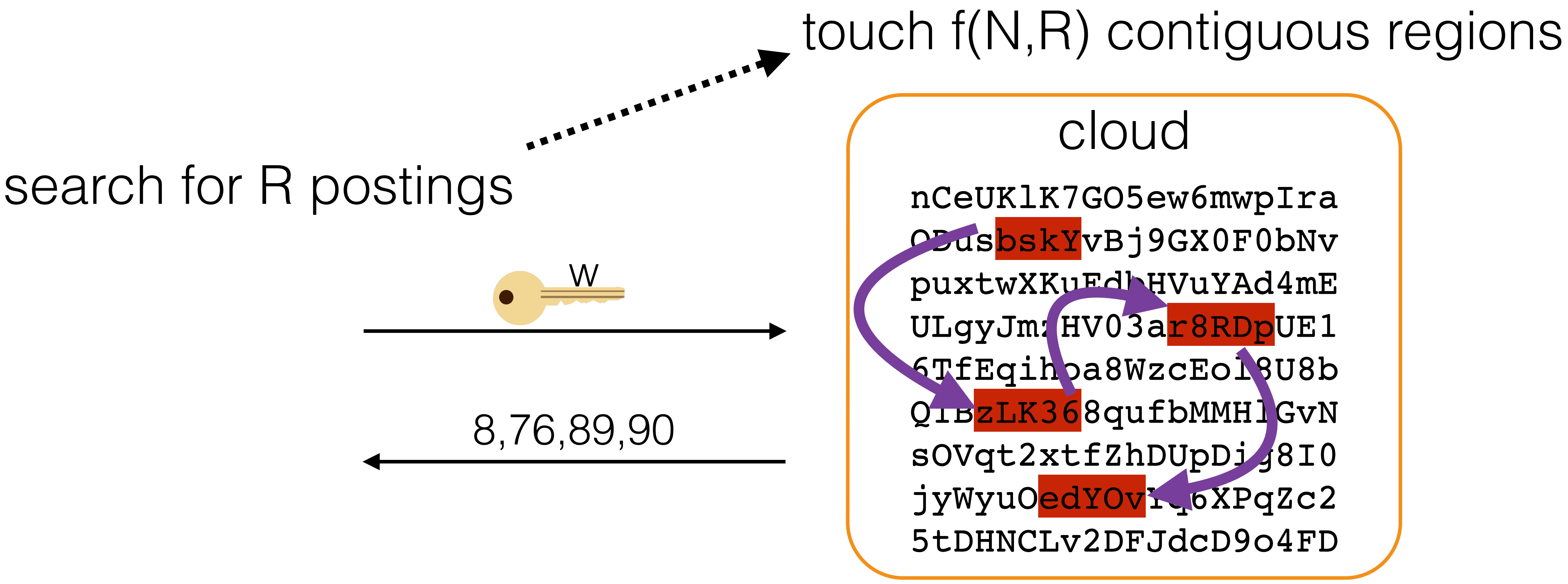


memory utilization in searching

we use three (very primitive) measures:

1. encrypted index size: measured relative to #-postings
2. locality: number of contiguous regions touched
3. read overlaps: amount of touched memory common between searches

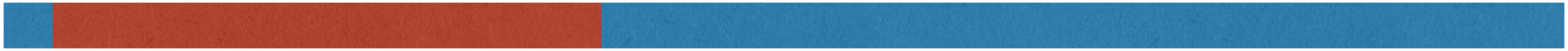
read overlaps

Encrypted index in memory:

read overlaps

Encrypted index in memory:

search for w_1



read overlaps

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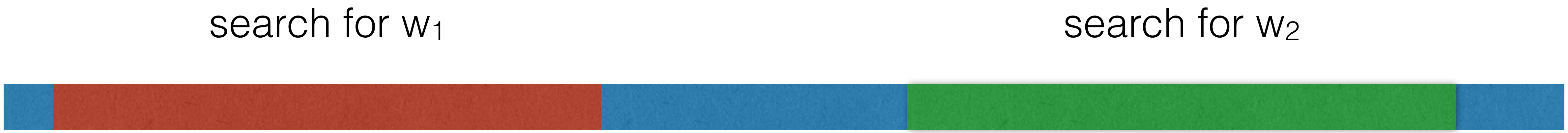

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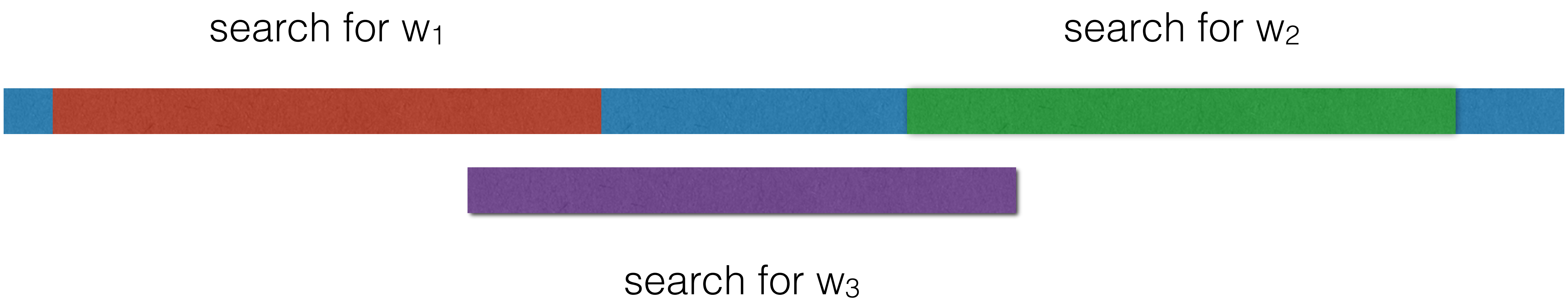

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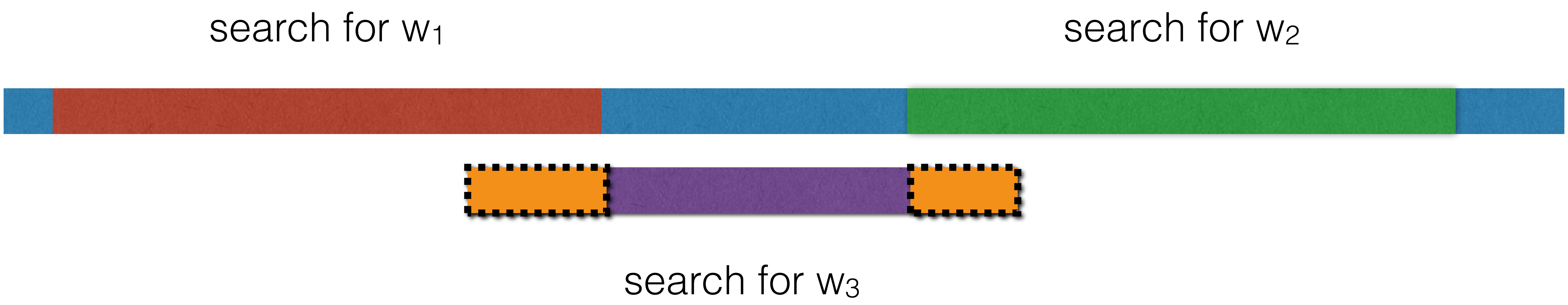

Overlap of search for w_3 = size of orange regions

read overlaps

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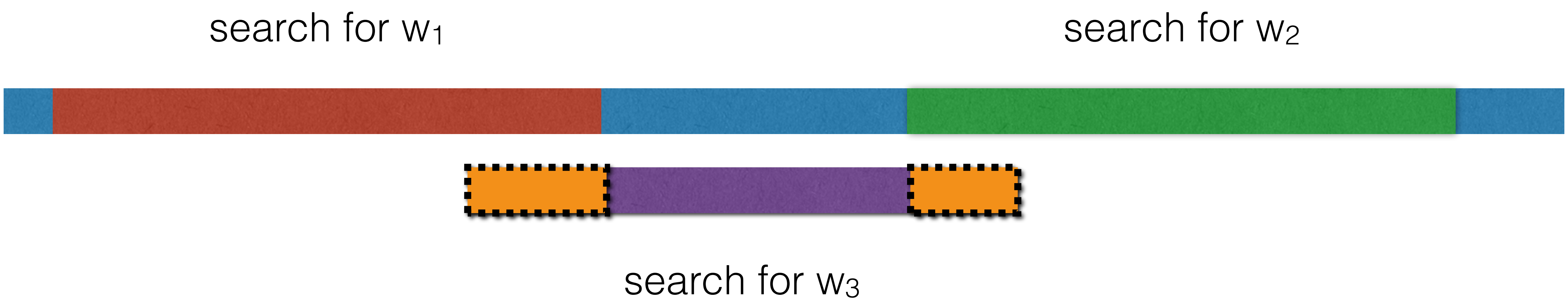

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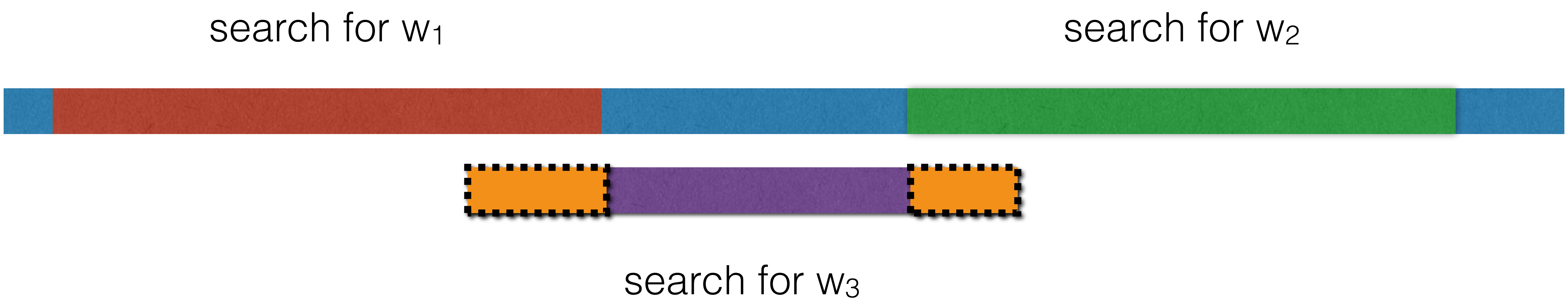

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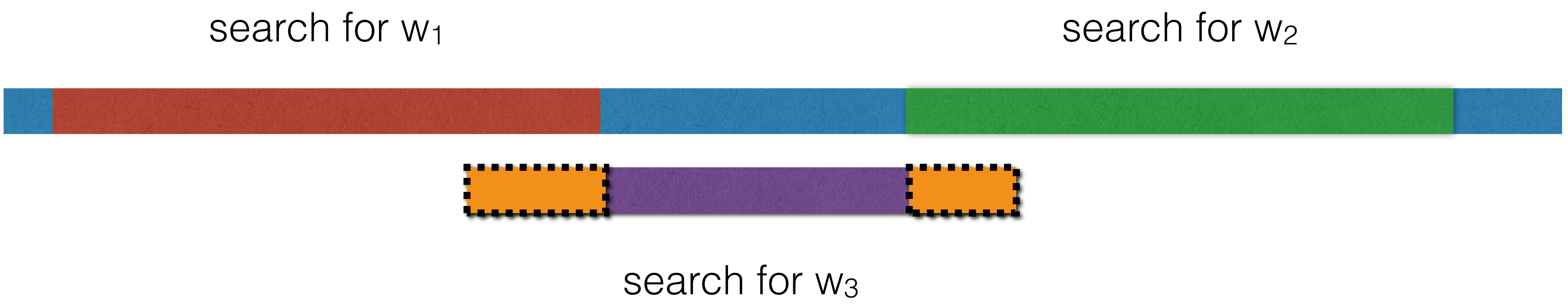

Overlap of search for w_3 = size of orange regions

- ➡ f-overlap $\Longrightarrow$ any search touches f common bits
- ➡ **intuition**: large overlaps ≈ reading more bits than necessary
- ➡ small overlap in known constructions (e.g. hash table access)

our results: lower bound (formal)

Let N = no. postings in input index

Theorem: No secure searchable encryption can have all 3:

1. $O(N)$-size encrypted index
2. $O(1)$-locality
3. $O(1)$-overlap on searches

- ➡ super-linear blow-up in storage/locality or highly overlapping reads
- ➡ in paper: smooth trade-off
- ✳ can be circumvented by changing security def [CJJJKRS]

memory utilization of constructions

N = no. postings in input index, R = no. postings in search

	Enc Ind Size	Overlap	Locality
lower bound: 1 of	$\omega(N)$	$\omega(1)$	$\omega(1)$
[CGKO,KPR,…]	N	1	R
[CK]	N^2	1	1

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➡ open problem: get closer to lower bound

Rest of talk

- a prior construction and why it cannot be “localized”

- lower bound approach

[CGKO] construction

Encrypted Index Generation Step 1:

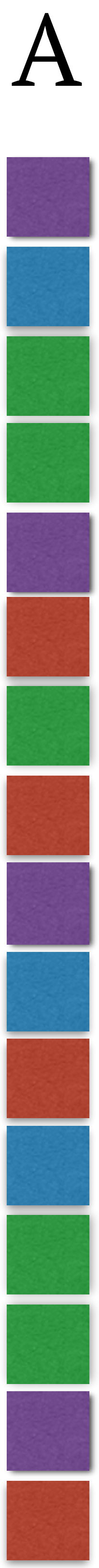
- derive per-term encryption keys: $K_i = \mathrm{PRF}(w_i)$

- encrypt individual postings under respective keys

term	postings
Rutgers	4, 9,37
Admissions	9,37,93,94,95
Committee	8,37,89,90
Accept	4,37,62,75

term	postings
K	🟦, 🟦, 🟦
K	🟩, 🟩, 🟩, 🟩, 🟩
K	🟥, 🟥, 🟥, 🟥
K	🟪, 🟪, 🟪, 🟪

[CGKO] construction



Encrypted Index Generation Step 2:

1. put ciphertexts in random order in array A
2. link together postings lists with encrypted pointers (encrypted under K_i)
3. encrypted index = A

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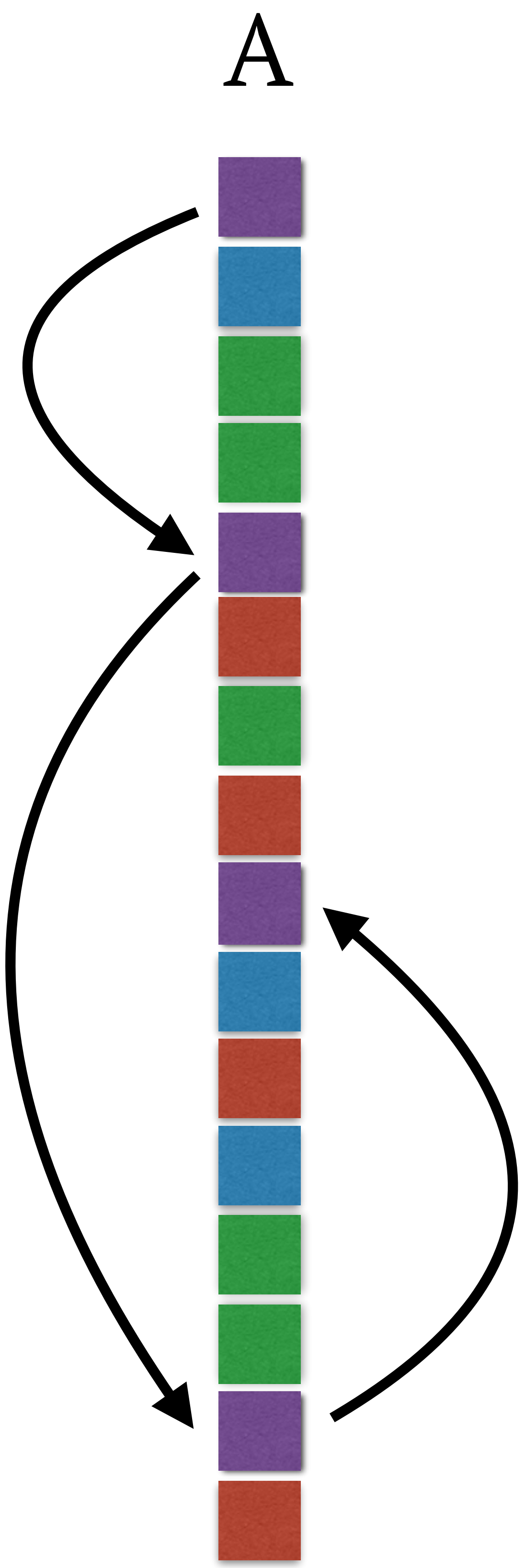


(example with pointers for word “Accept”)

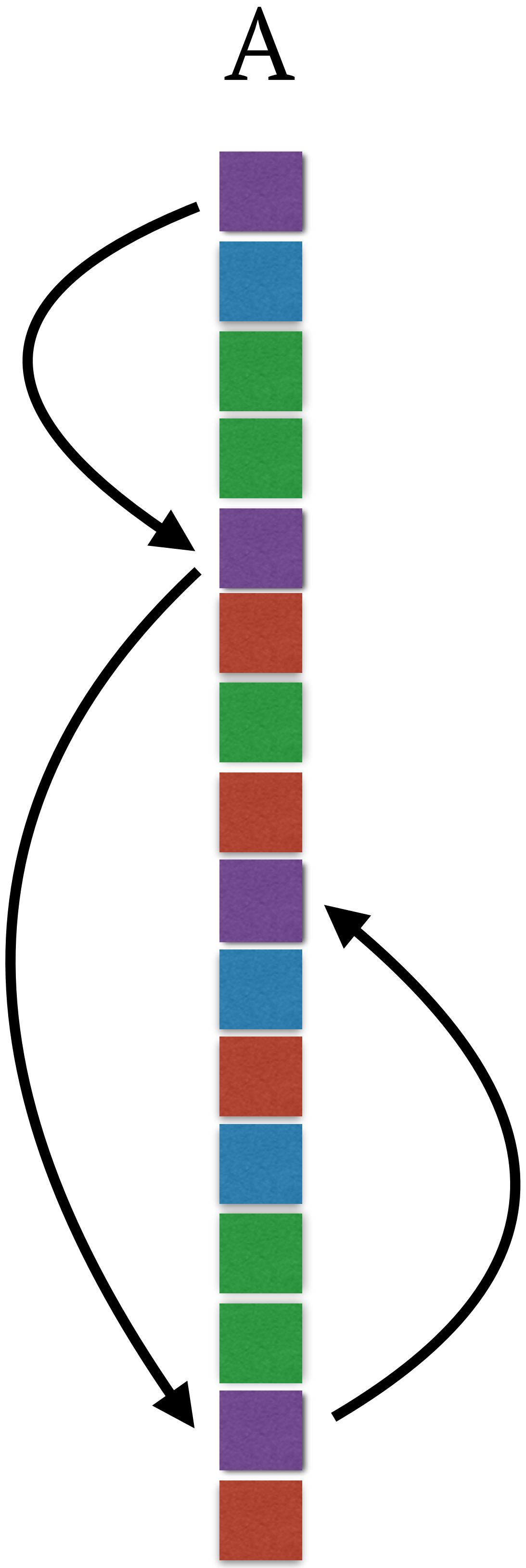
[CGKO] construction: searching

token generation for w:

- re-derive key K = PRF(w)
- token = K

server search using token:

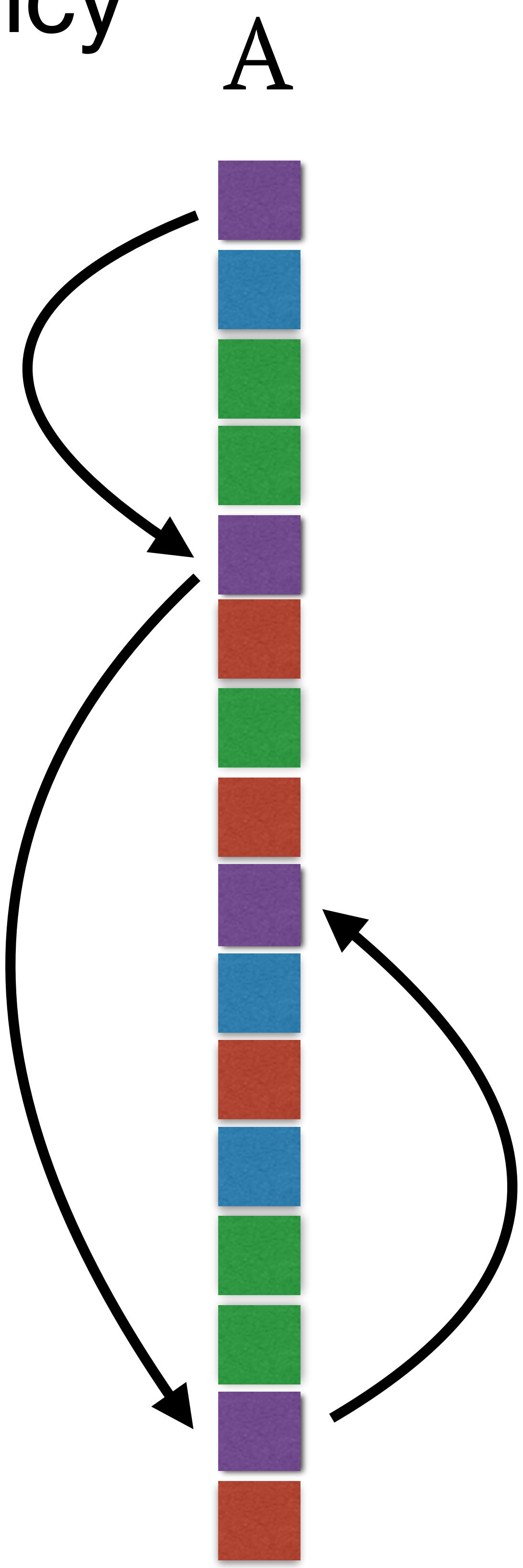
- step through list, decrypt postings/ pointers with K



[CGKO] construction: memory efficiency

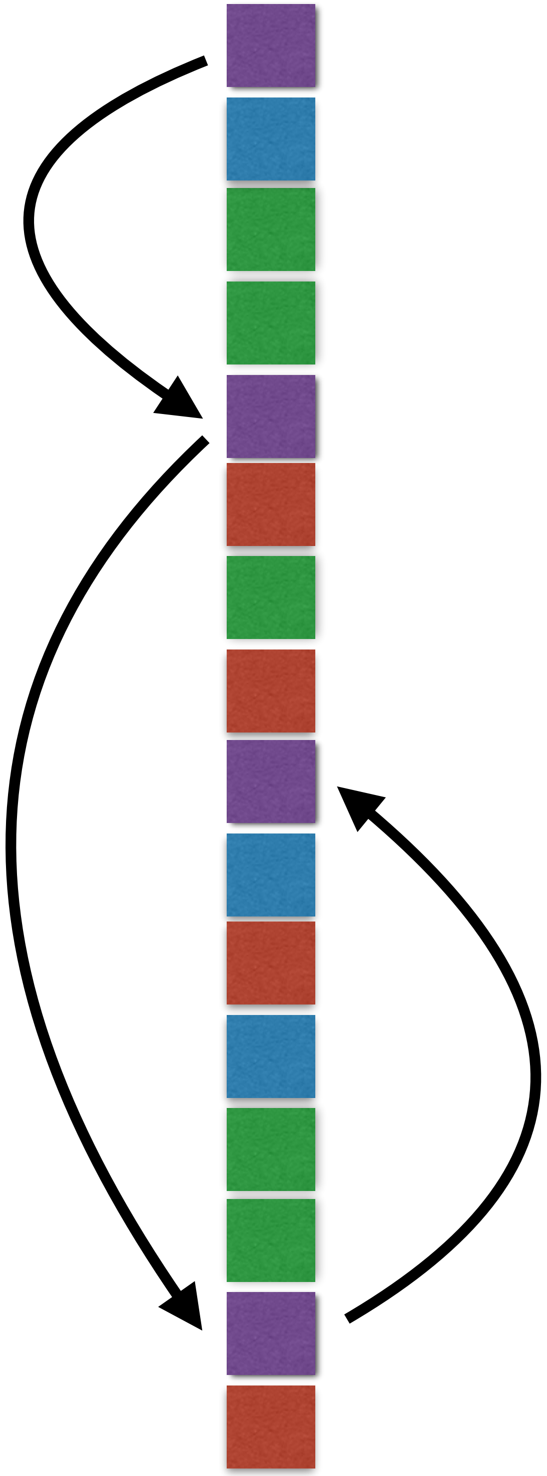
Memory utilization:

- O(N) size index
- O(R) locality for search w/ R postings
- O(1) read overlaps



suppose we try to make construction "local"

- ➡ store encrypted postings lists together.



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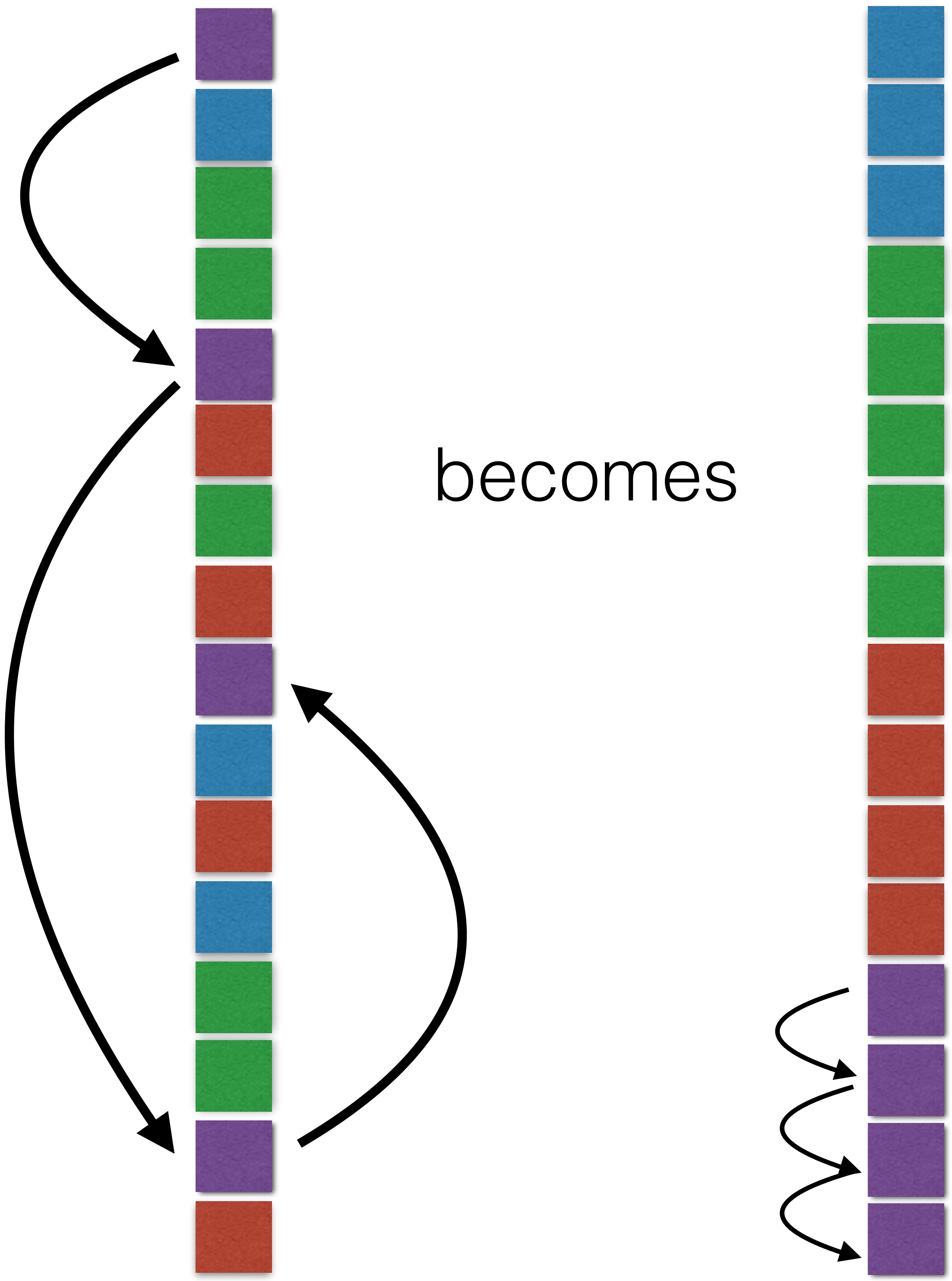

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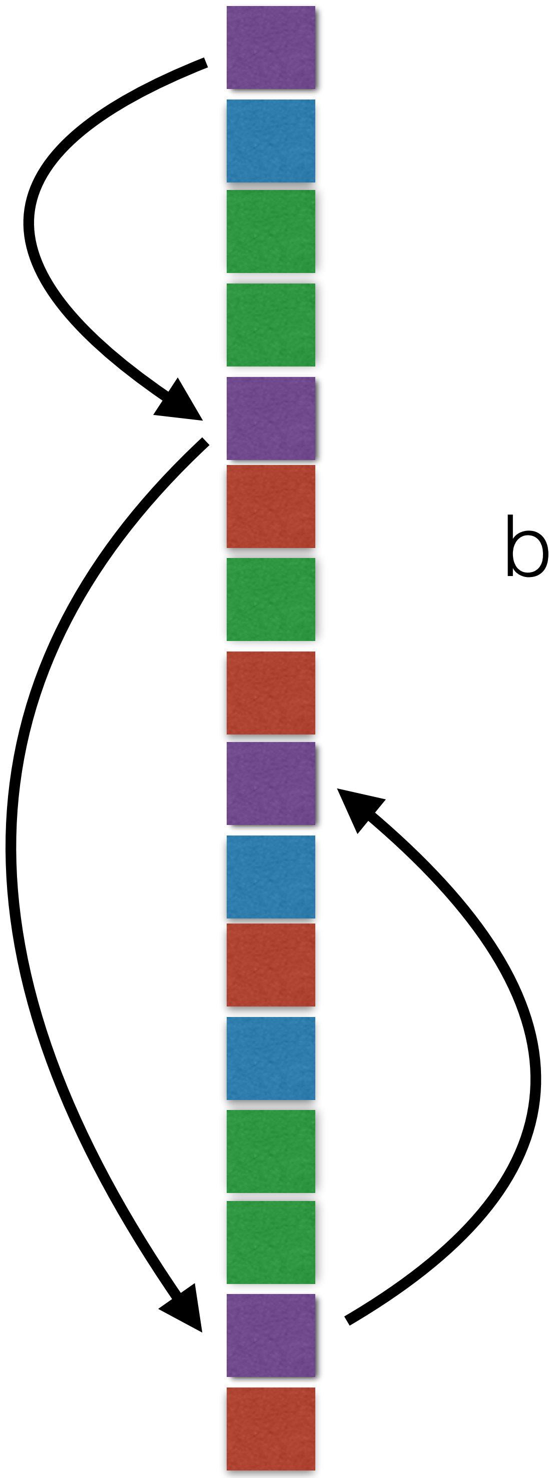
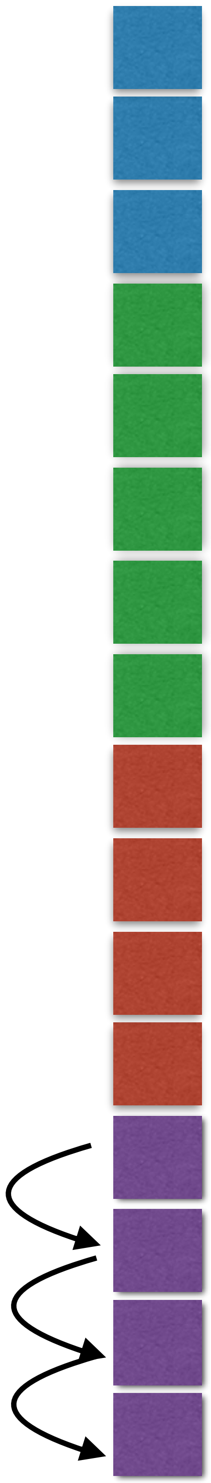
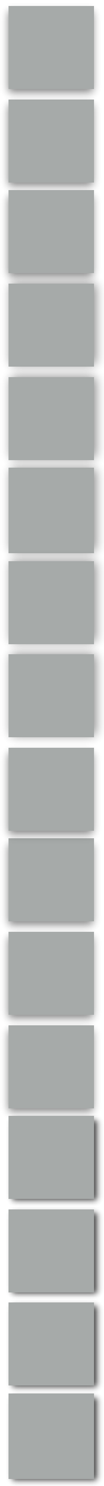


becomes



which looks like



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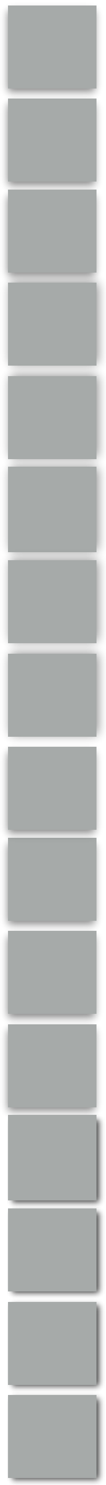

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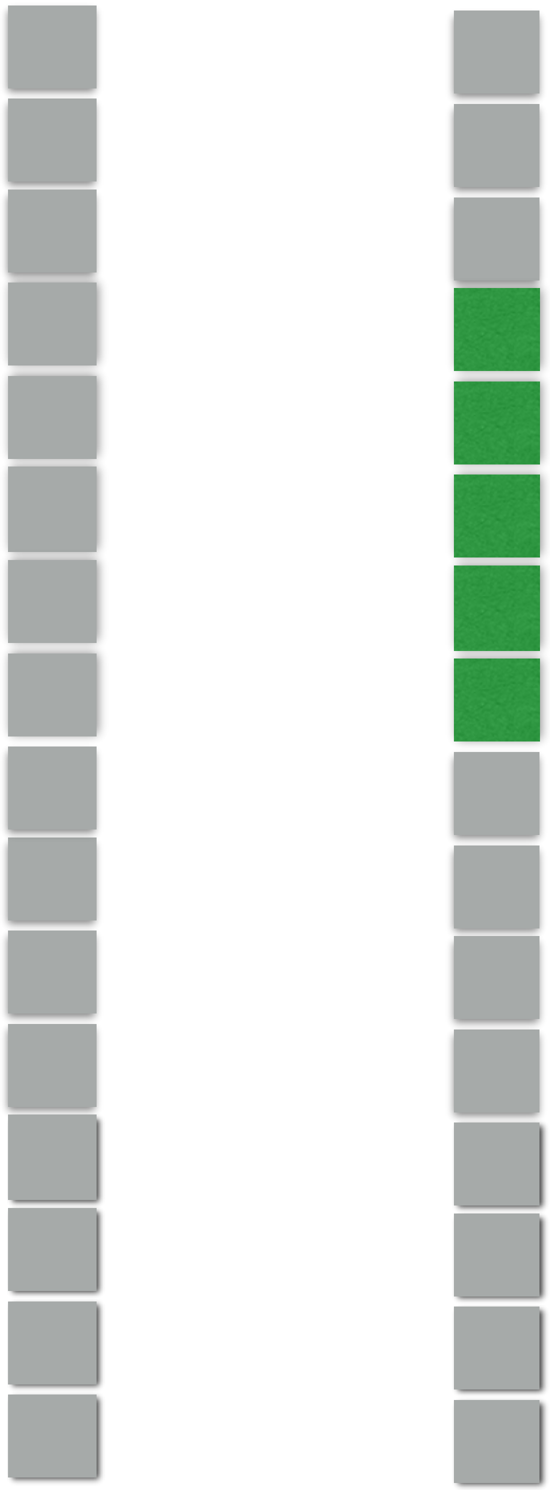

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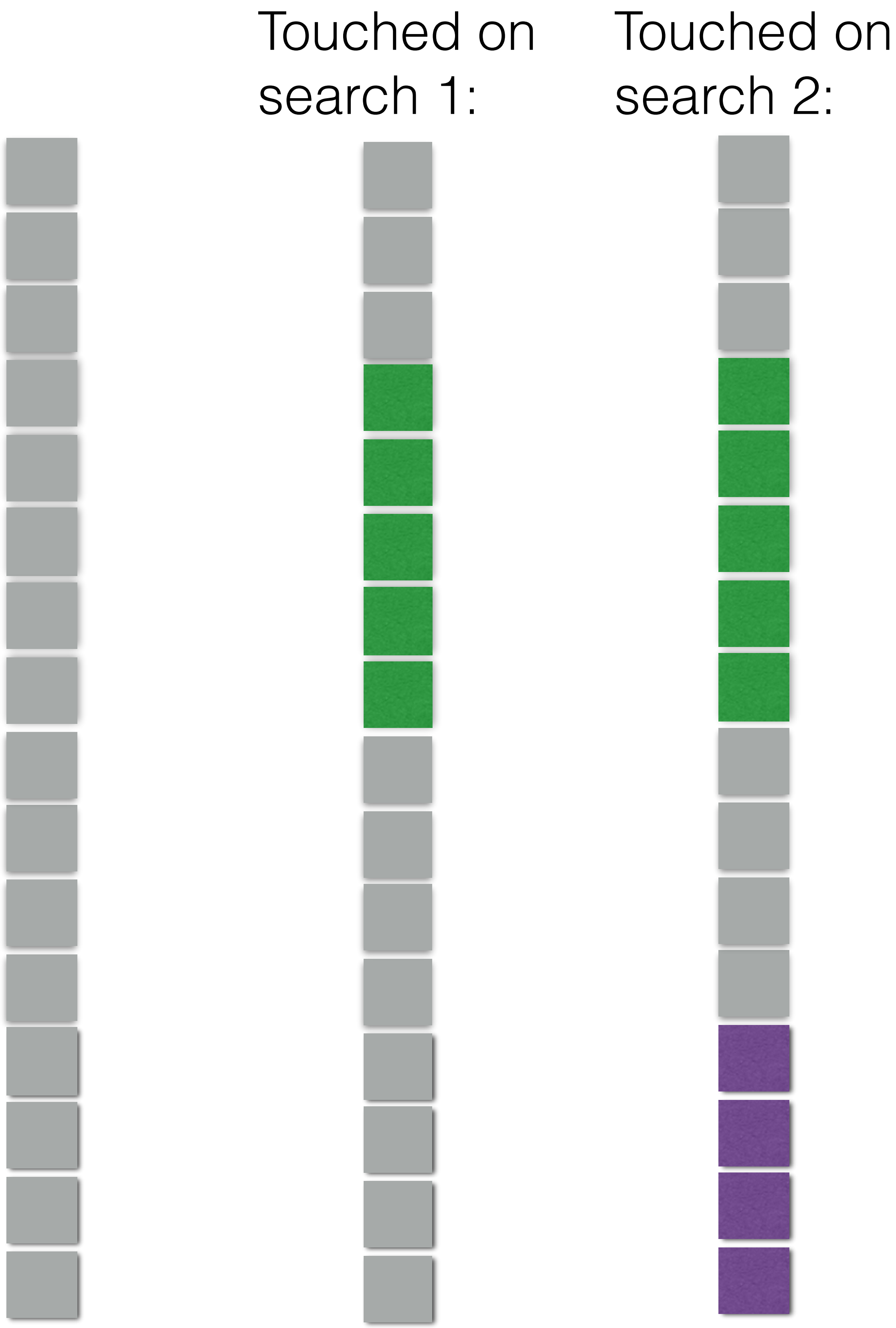
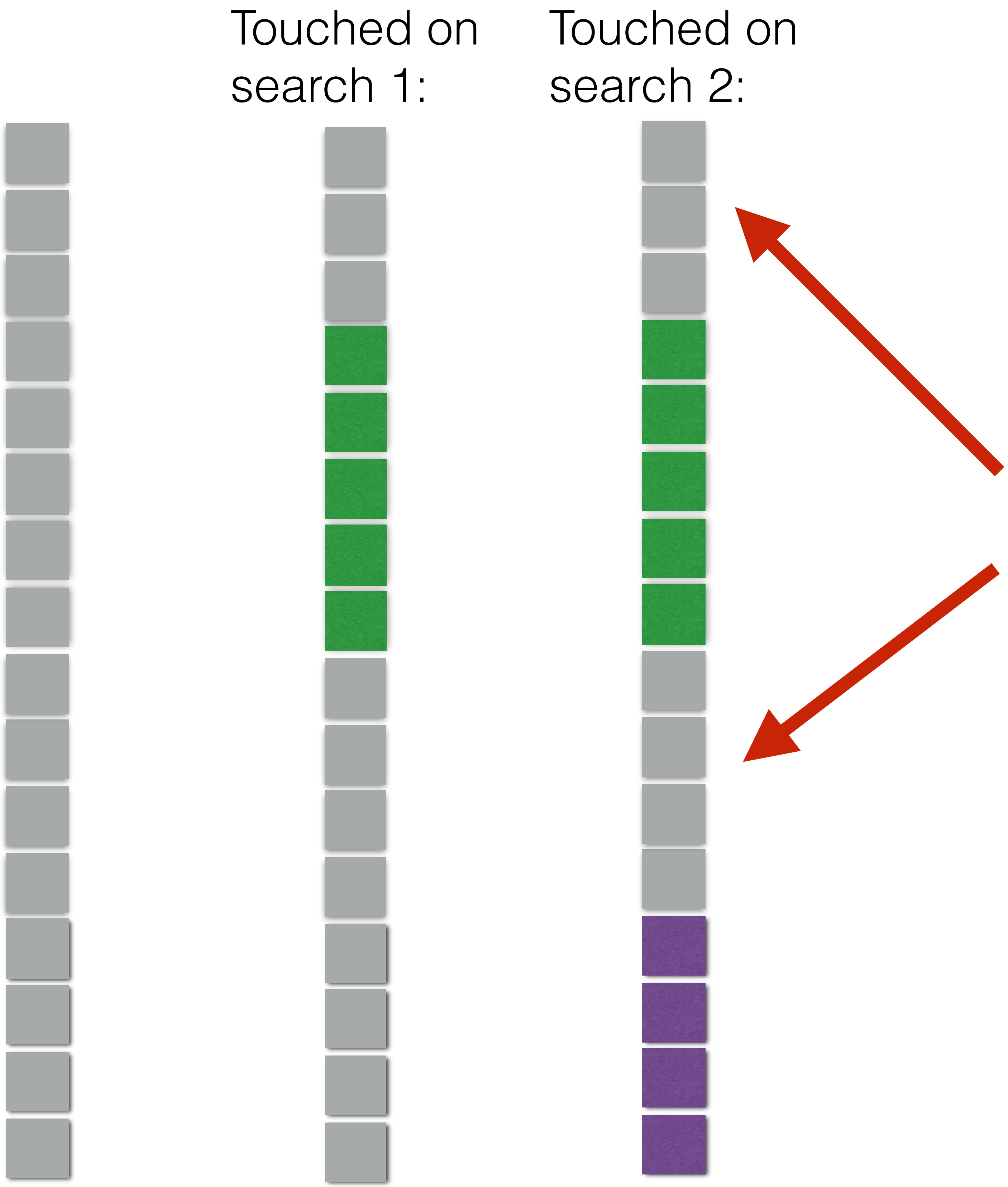


Touched on search 1:

Touched on search 2:

server can observe memory touched during searches:



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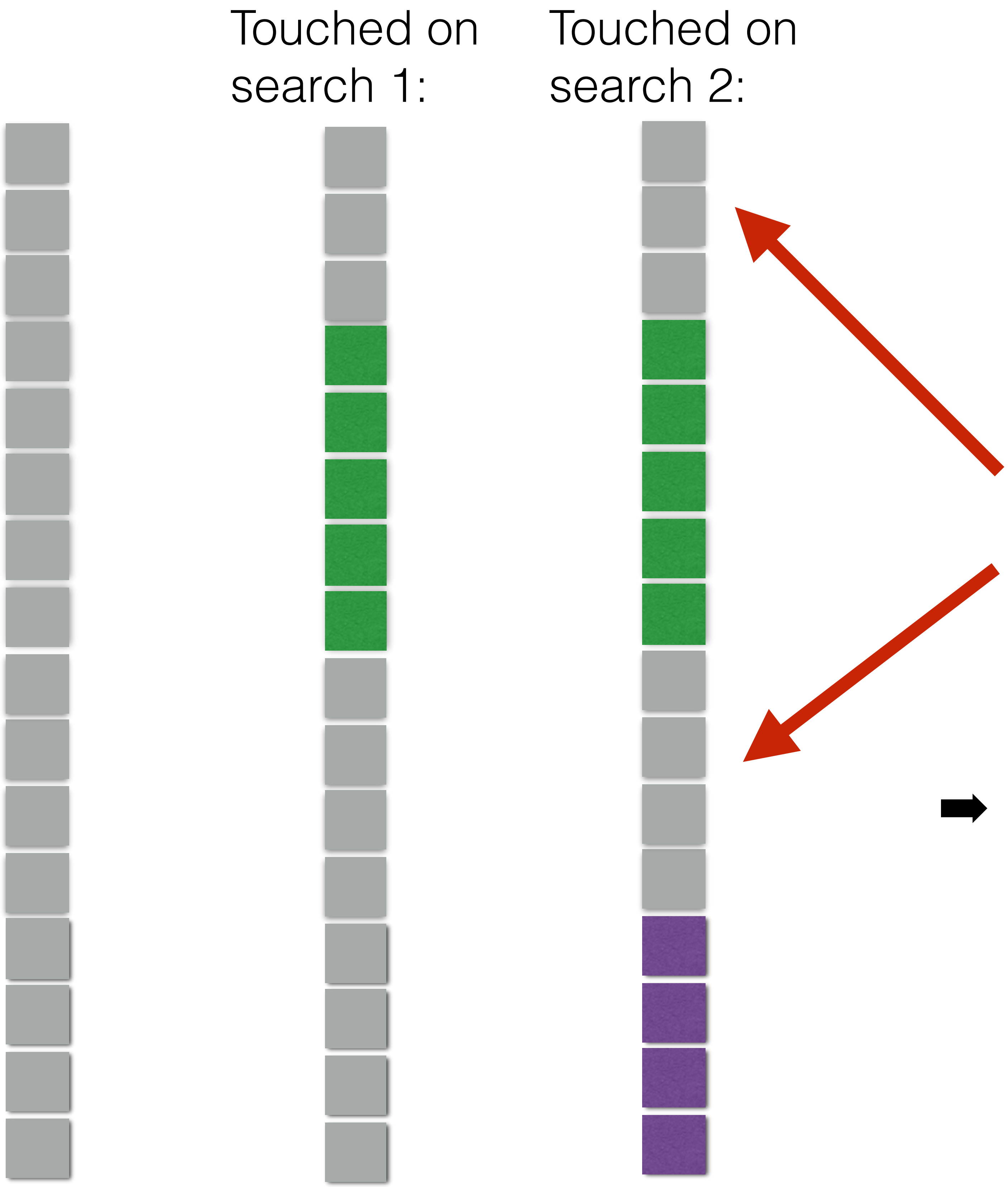

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➡ e.g. 7 remaining spots do not correspond to a single postings list

proof intuition

- adapt this attack to work against any scheme

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  - distinguish two crafted indexes by observing reads and testing for biases in their distribution

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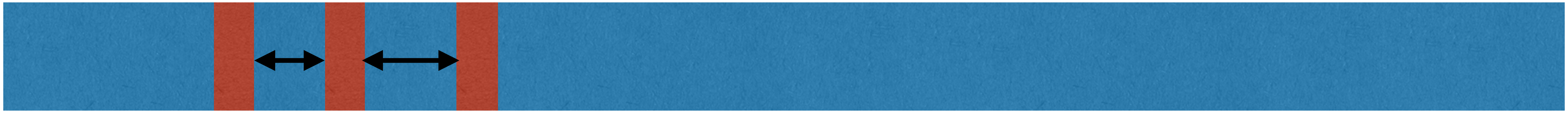

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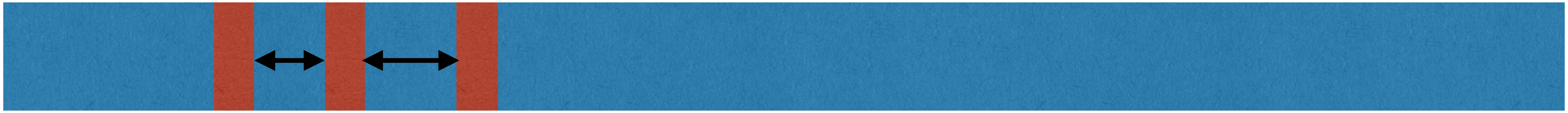

- small gaps can't hold contiguous intervals for other searches, so gap space is "dead" for searches with larger postings lists
- delicate argument to formalize, requires further techniques for full theorem

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Q1: Tighten gap between upper/lower bound?

Q2: Fine-grained lower bounds?

Q3: Other primitives where i/o efficiency dominates?

Thanks!