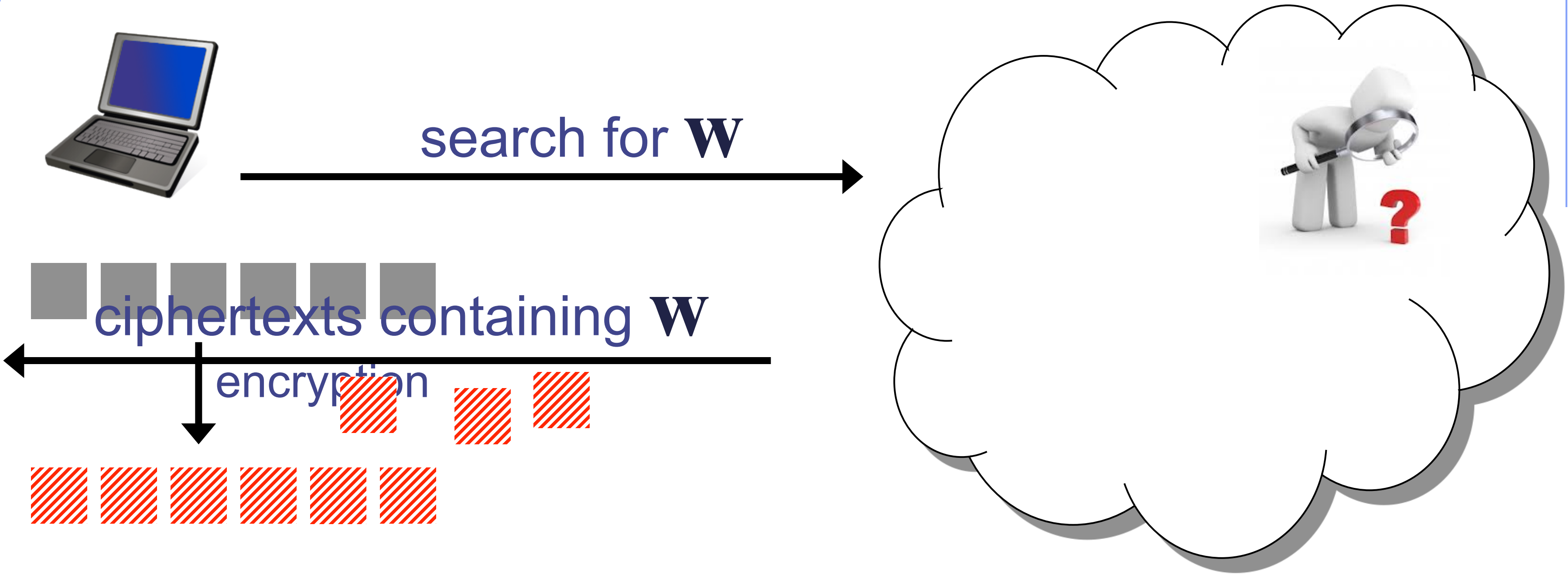
Practical Dynamic Searchable Encryption with Small Leakage

Charalampos (Babis) Papamanthou
University of Maryland
cpap@umd.edu

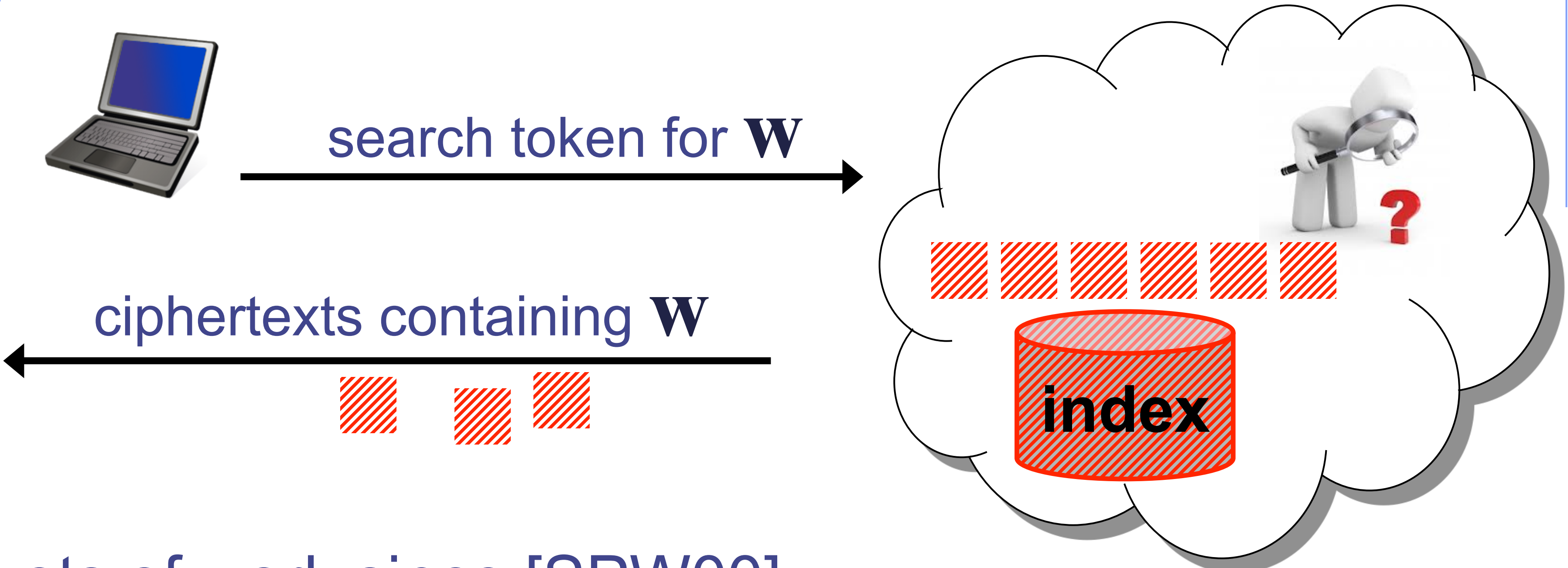
joint work with **Emil Stefanov** (UC Berkeley) and **Elaine Shi** (University of Maryland)

Storing private files in the cloud



- How can you search your encrypted files?
  - Not feasible with a widely-used encryption algorithm (e.g., AES)
  - Encrypt with fully-homomorphic encryption (FHE)?
    - Not very practical
  - Access with an ORAM scheme?
    - Not very practical

Searchable encryption (SE)



- Lots of work since [SPW00]
- Static schemes (`setup`, `search`)
  - e.g., [CGKO06], [KO12], [CJJKRS13]

this talk

- Dynamic schemes (`setup`, `search`, `add`, `delete`)
  - e.g., [SPW00], [G03], [vSDHJ10], [KPR12], [KP13], [CJJJKRS14], [NPG14]

Some leakage

- All existing (dynamic) SE schemes leak
  - **search pattern**
    - hashes of keywords I am searching for
  - **access pattern**
    - matching document identifiers
  - **size pattern**
    - the current size of the index

More leakage

- Some dynamic SE schemes also leak
  - ~~**forward pattern**~~
    - ...uments can be searched with old
  - ~~**update pattern**~~
    - hashes of keywords in the updated documents

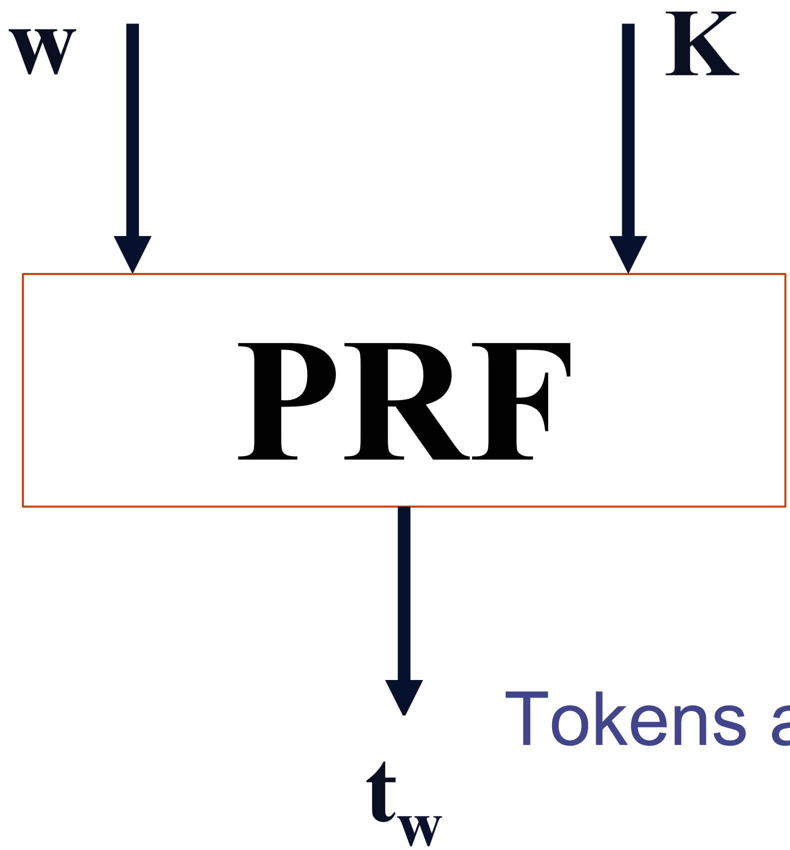
But, linear search or update time: $\mathbf{O}(N)$ ☹

Our contribution

- The first dynamic SE scheme
  - Supports **searches**, **insertions**, **deletions**
  - **No** forward pattern leakage
  - **No** update pattern leakage
  - Sublinear search time: $\mathbf{O}(\boldsymbol{m}\ \mathbf{log}^3 N)$
    - $\boldsymbol{m}$ is the number of documents matching the search
  - Sublinear update time: $\mathbf{O}(\boldsymbol{k}\ \mathbf{log}^2 N)$
    - $\boldsymbol{k}$ is the number of unique keywords contained in the document
  - Provably secure
  - System implementation
    - 100,000 queries per second for 100 search results

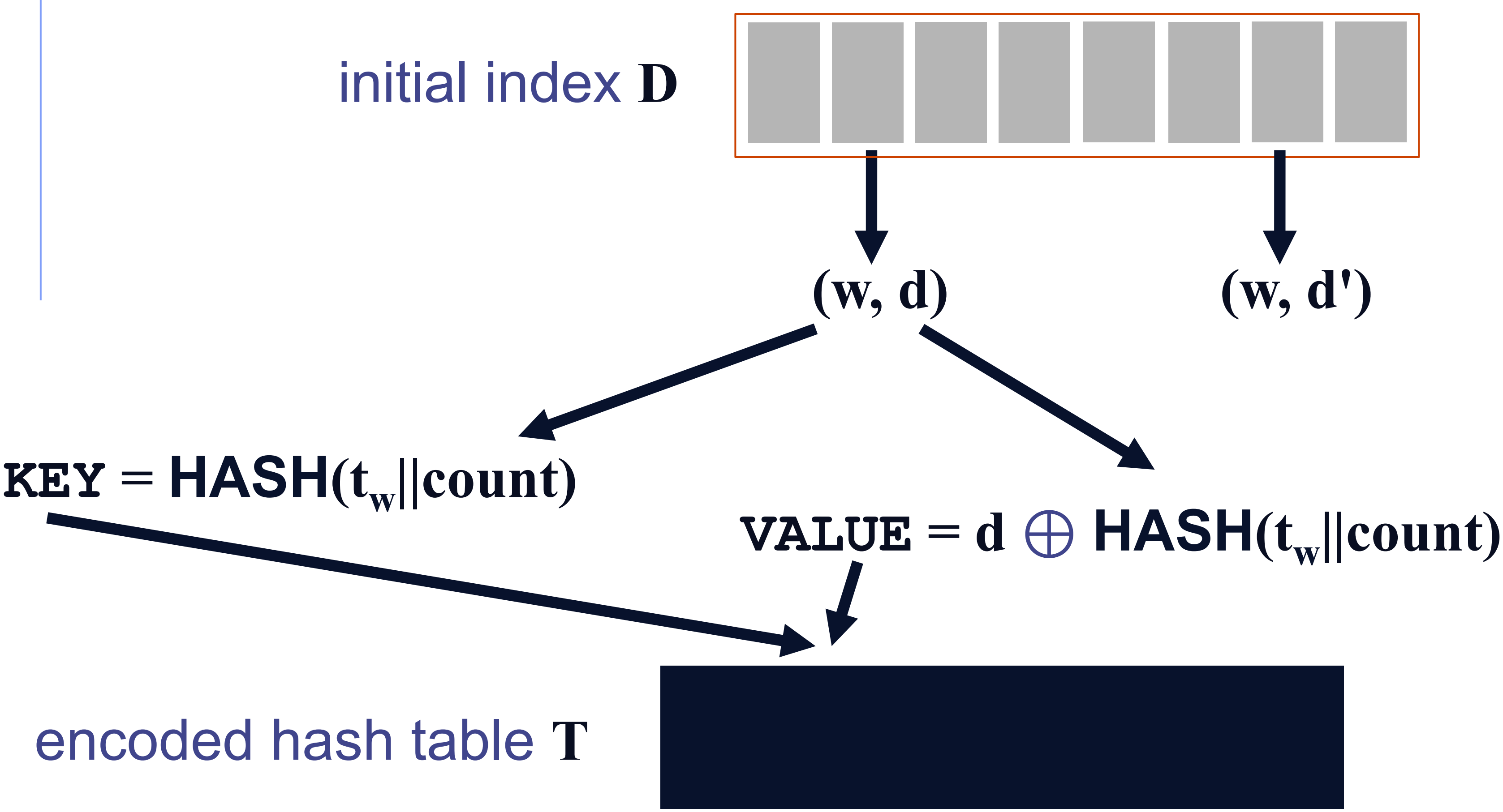
Simple SE scheme: Token

- Client has secret key **K**
- Definition of **token** for word **w**



Tokens are deterministic!

Simple SE scheme: Construction



Searching for keyword $\mathbf{w}$

- Client: Sends $\mathbf{t_w}$
- Server: Looks up the entries mapping to $\mathbf{t_w}$
  - Learns nothing about keyword $\mathbf{w}$

$\mathbf{t_w}$

Adding (w', d')

- Client: Sends new **(KEY,VALUE)** for **(w', d')**

(KEY,VALUE)

Adding (w', d')

- Client: Sends new **(KEY,VALUE)** for **(w', d')**
- Server: Updates the hash table
- But…
  - Tokens are deterministic
  - No forward privacy ☹

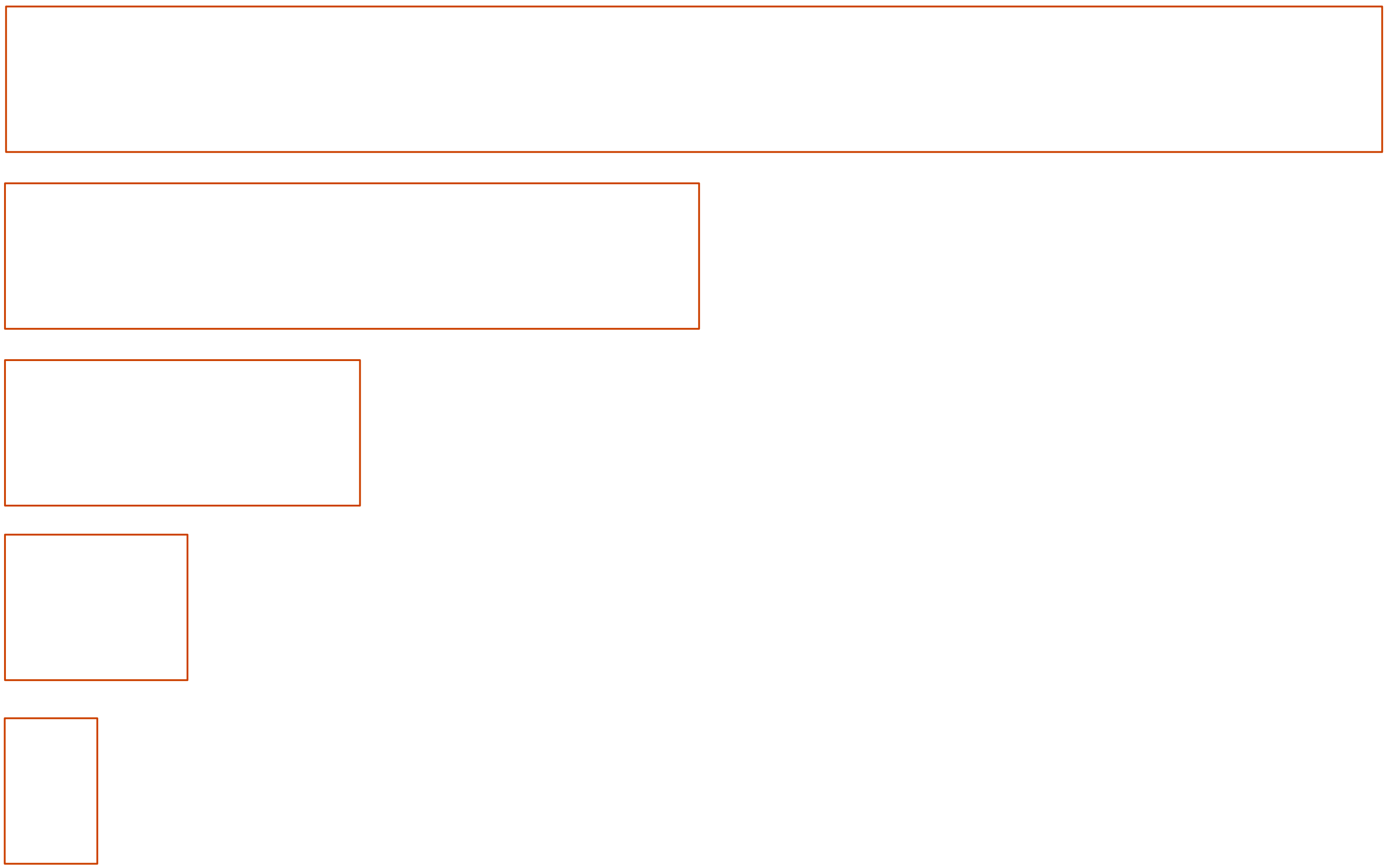
(KEY,VALUE)

How about re-encrypting with a different key?

Linear time: $\mathbf{O}(N)$ ☹

Levelled data structure

- $l = \log N + 1$ levels



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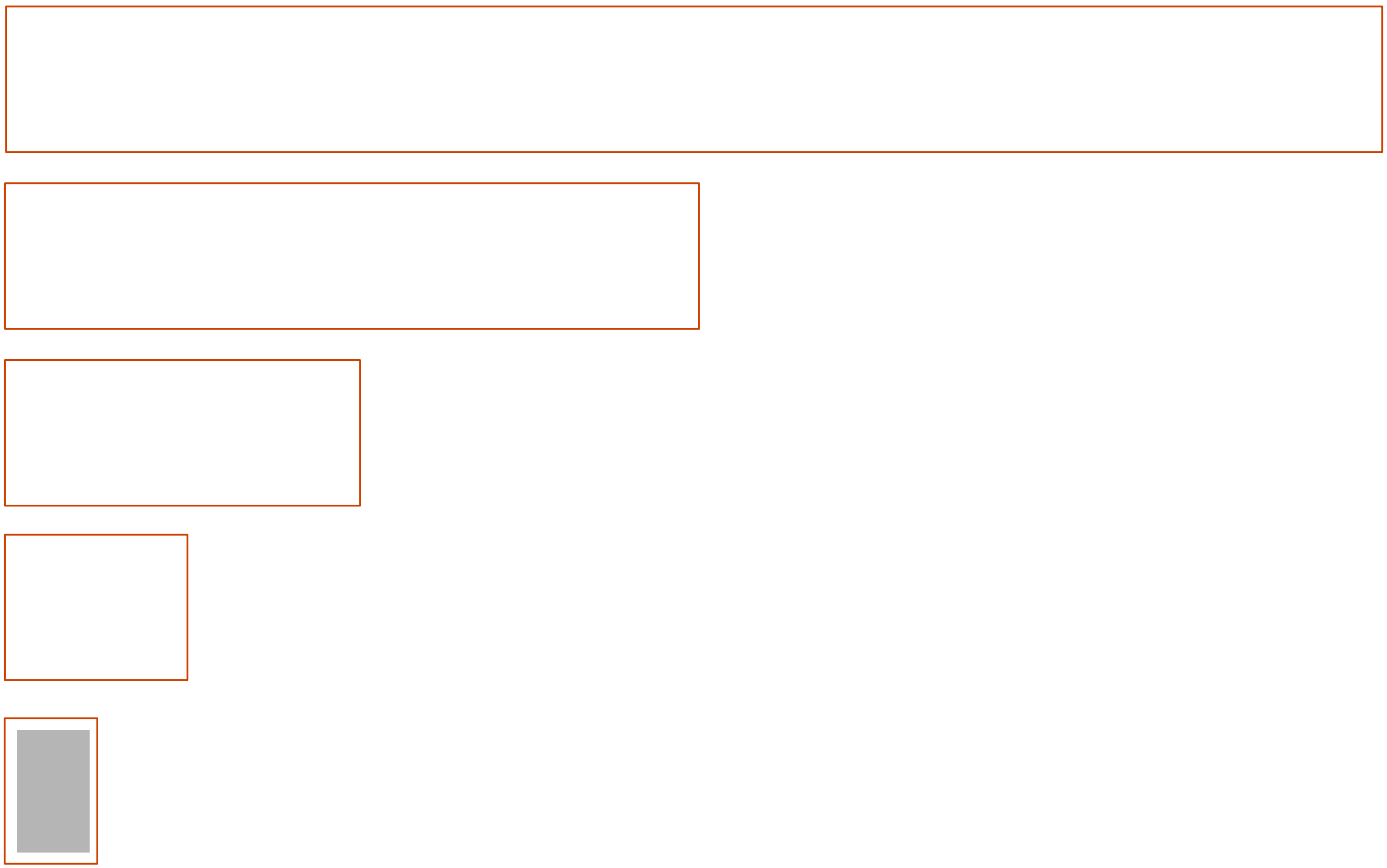

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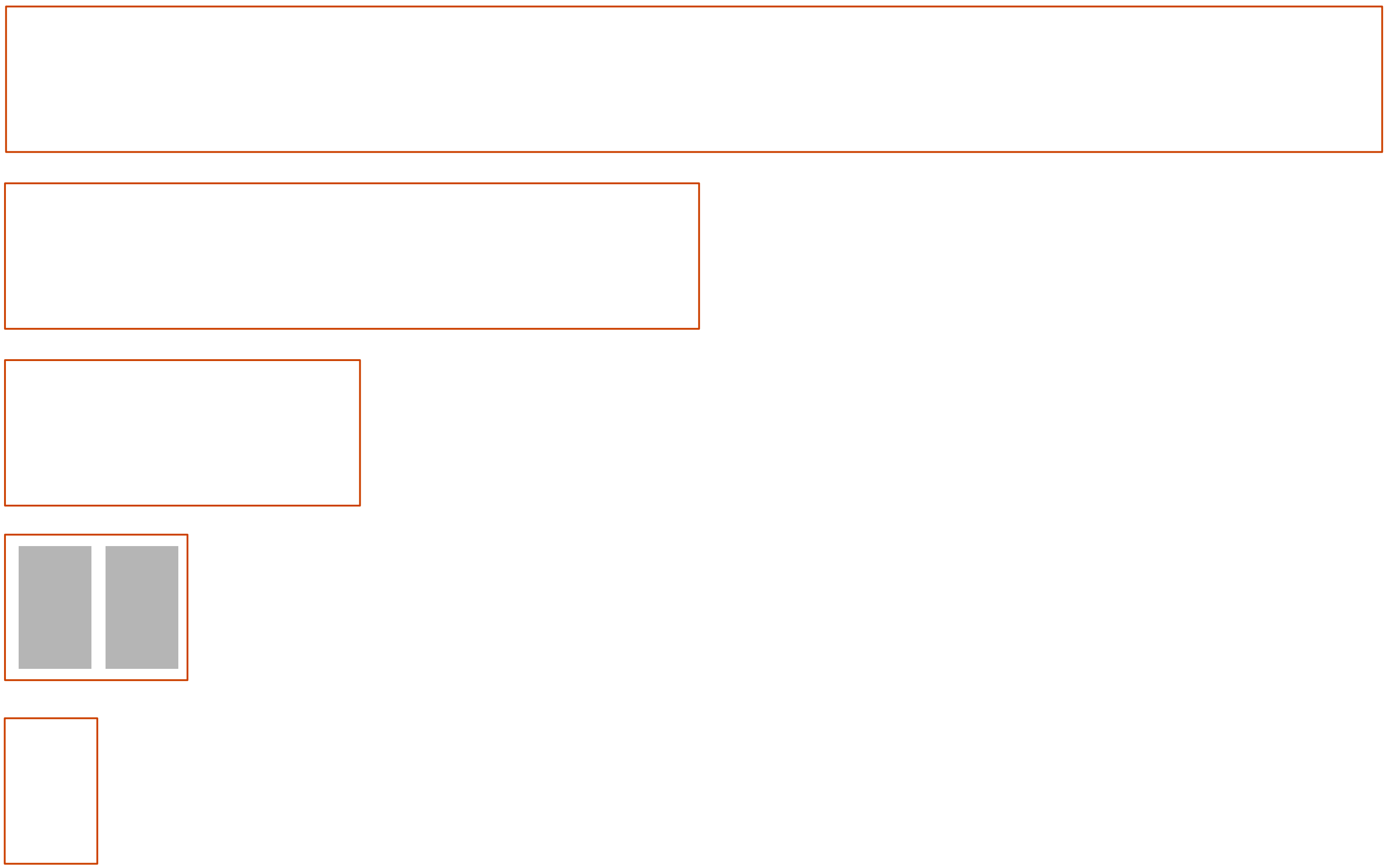

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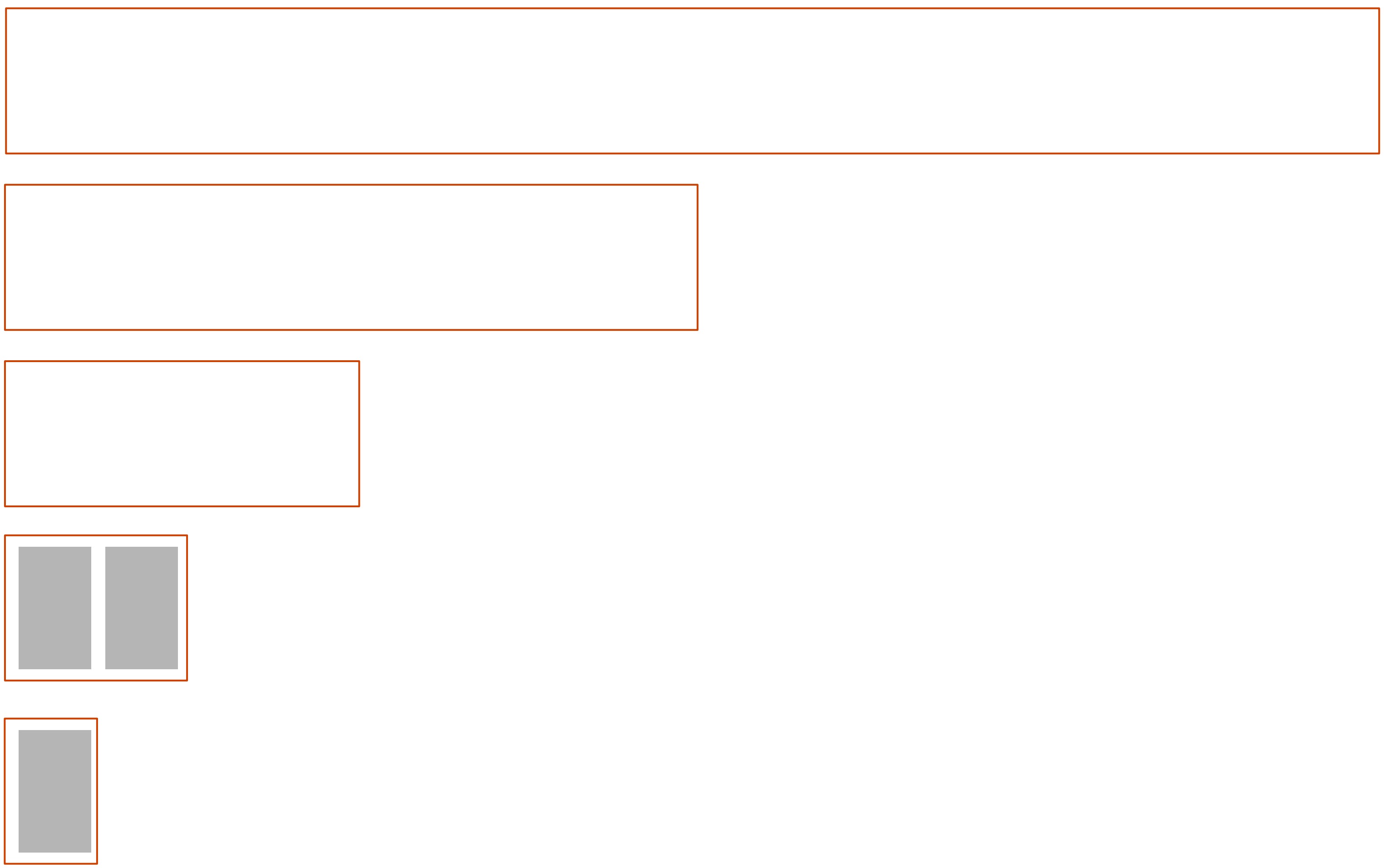

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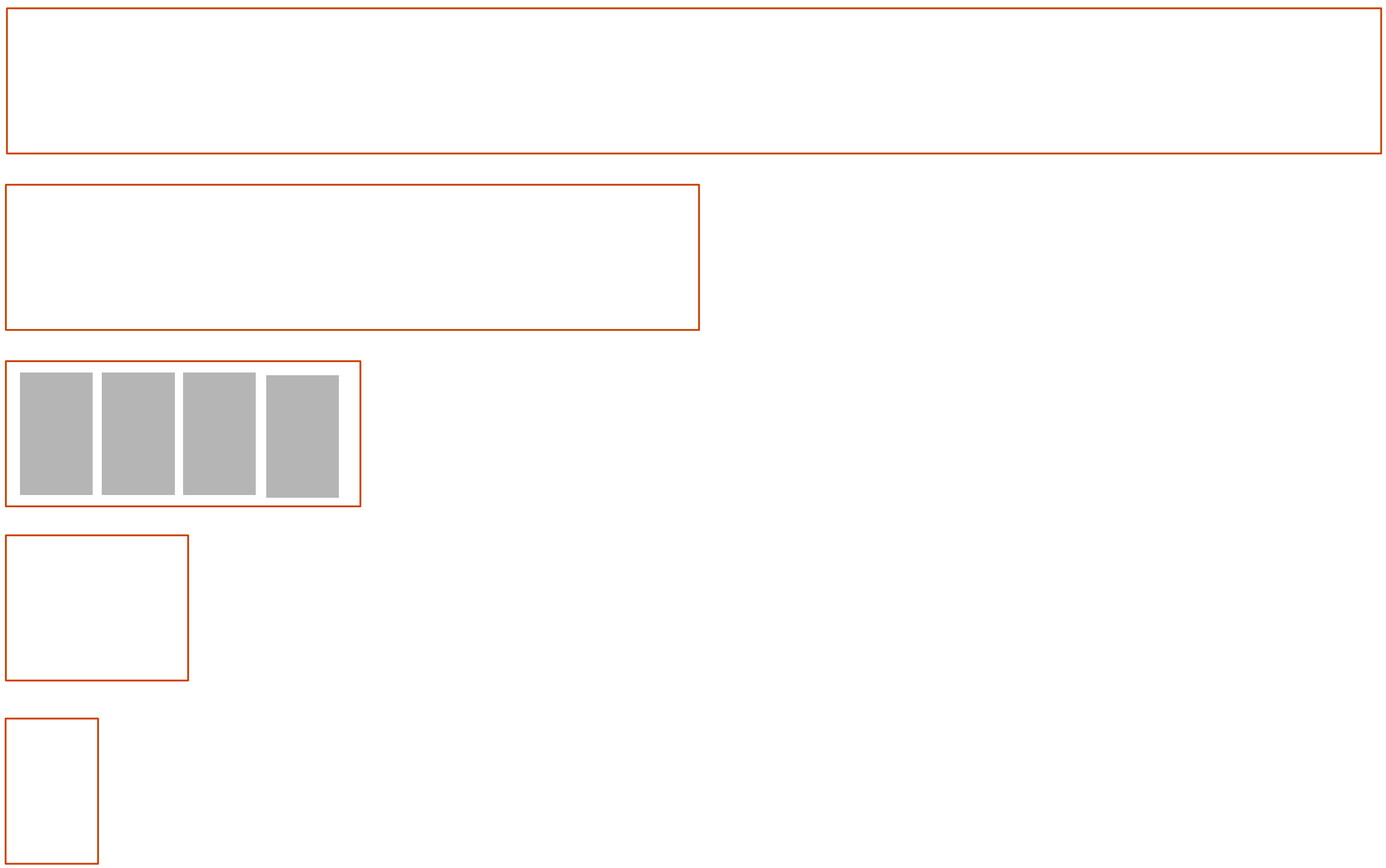

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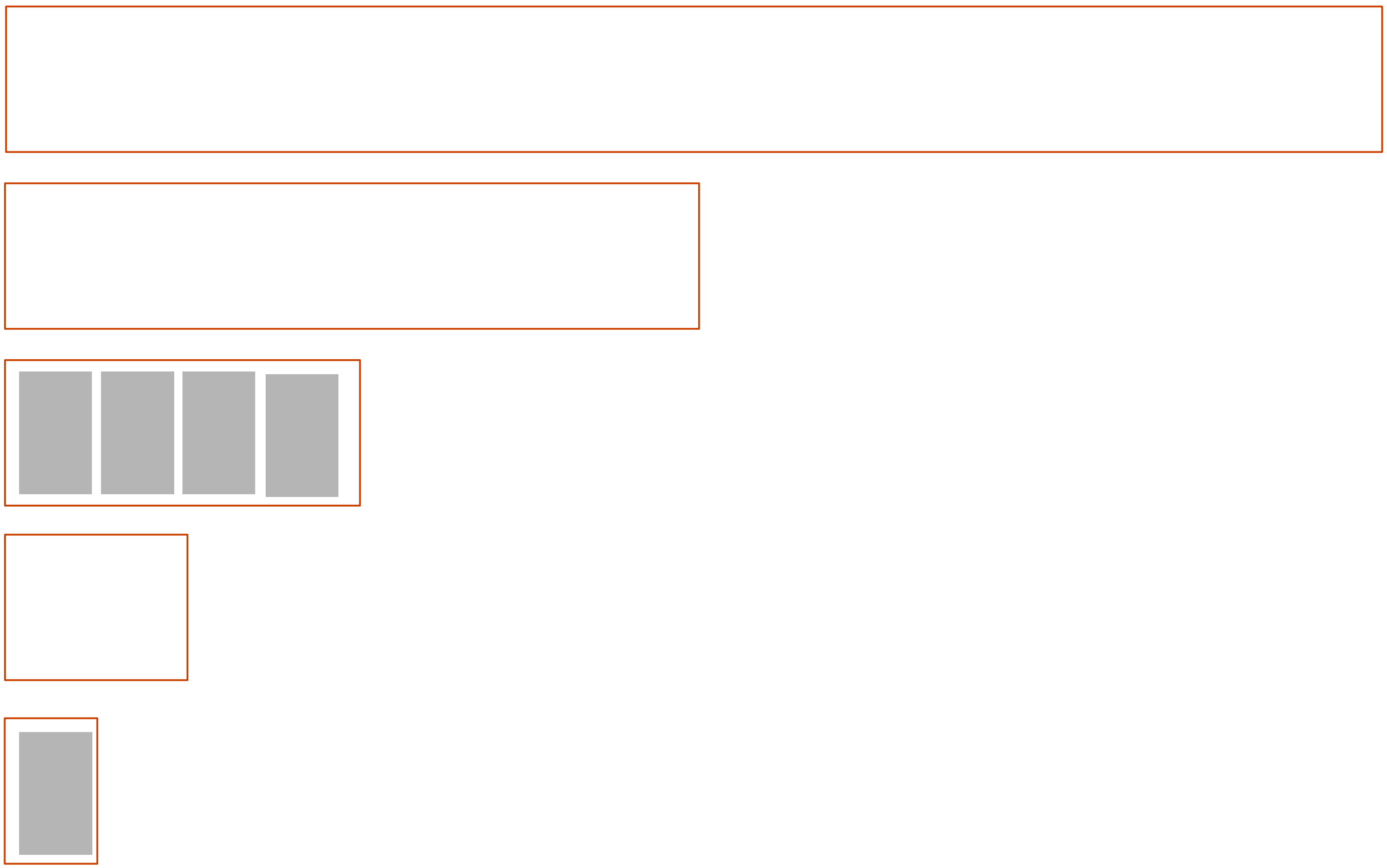

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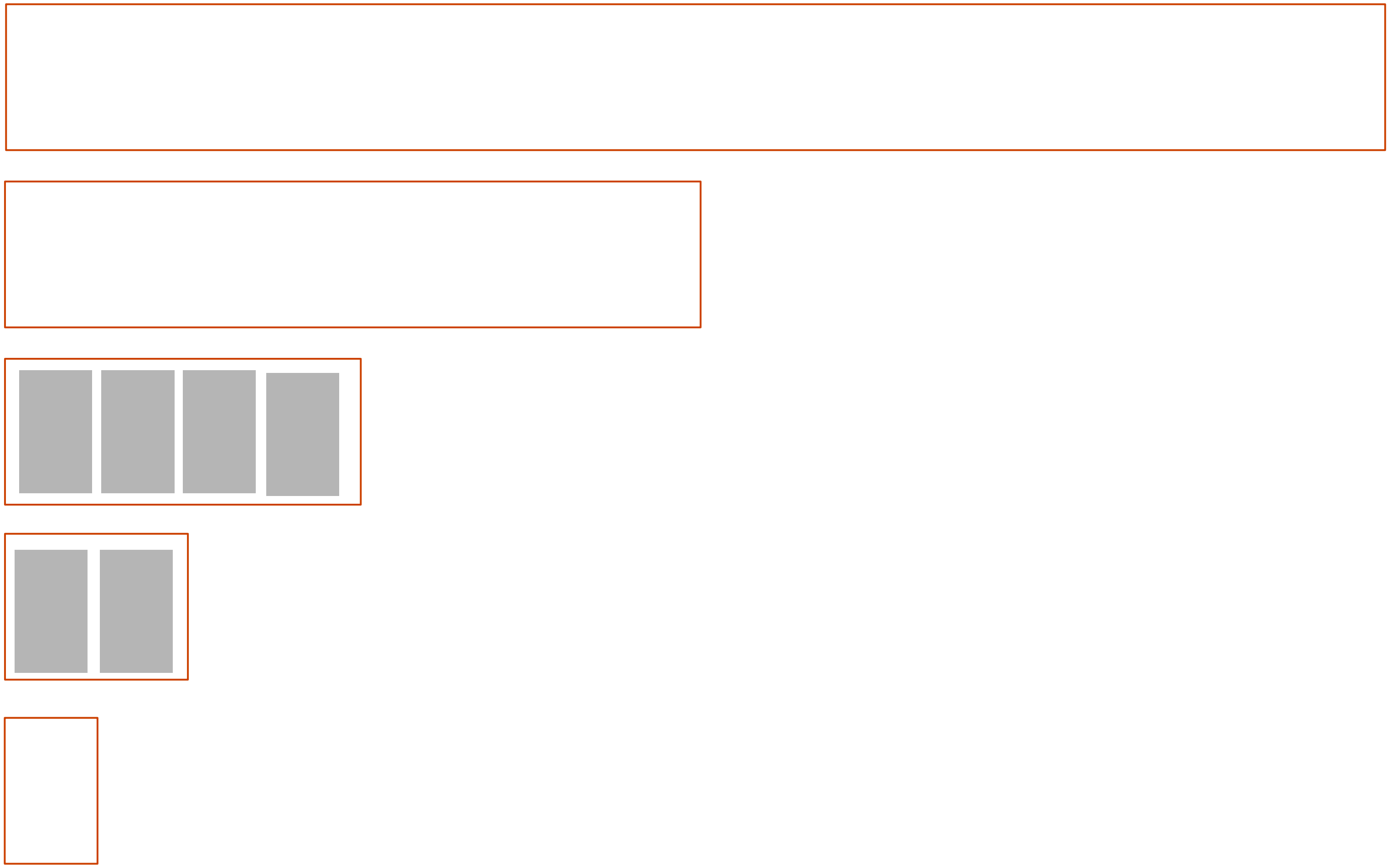

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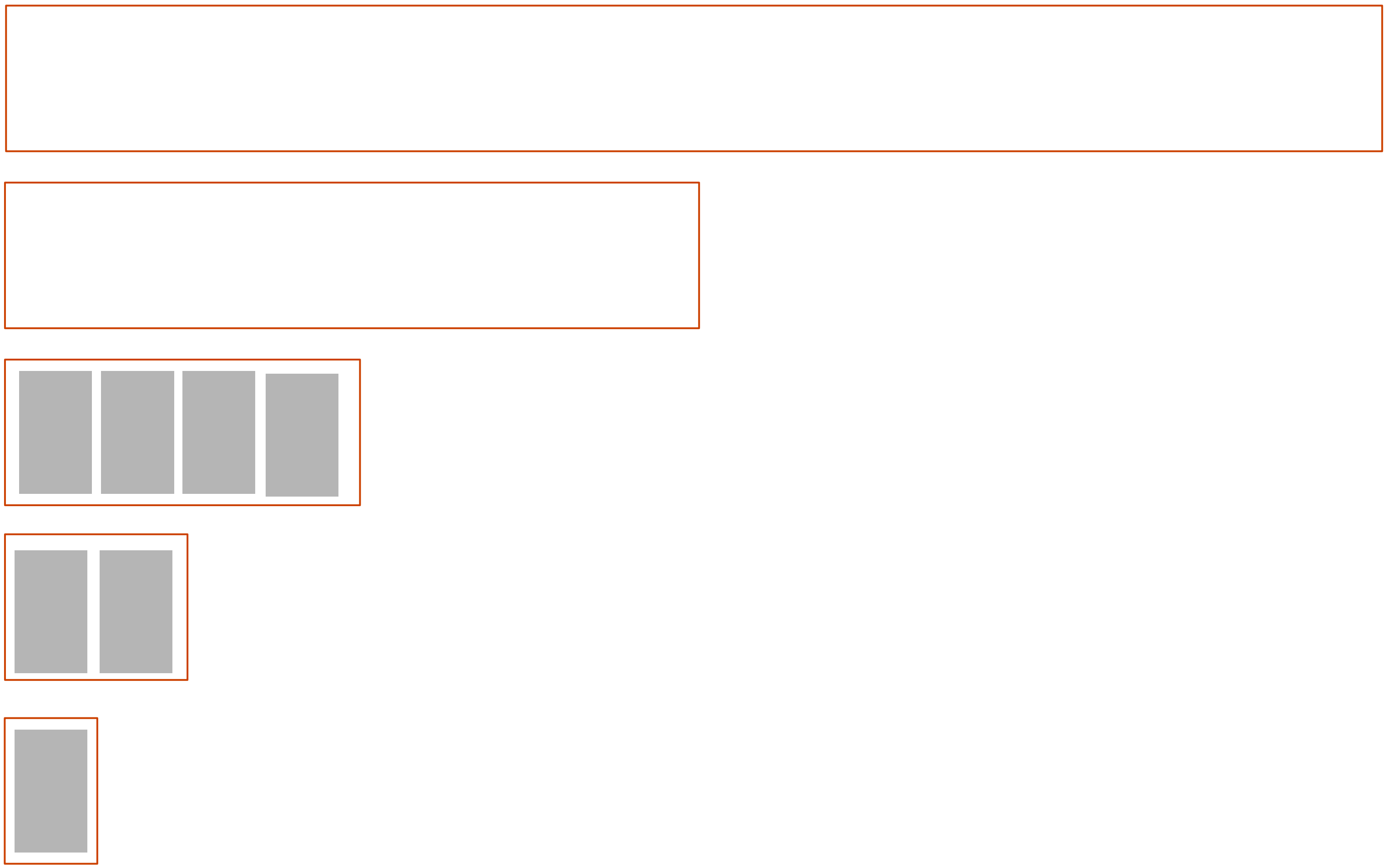

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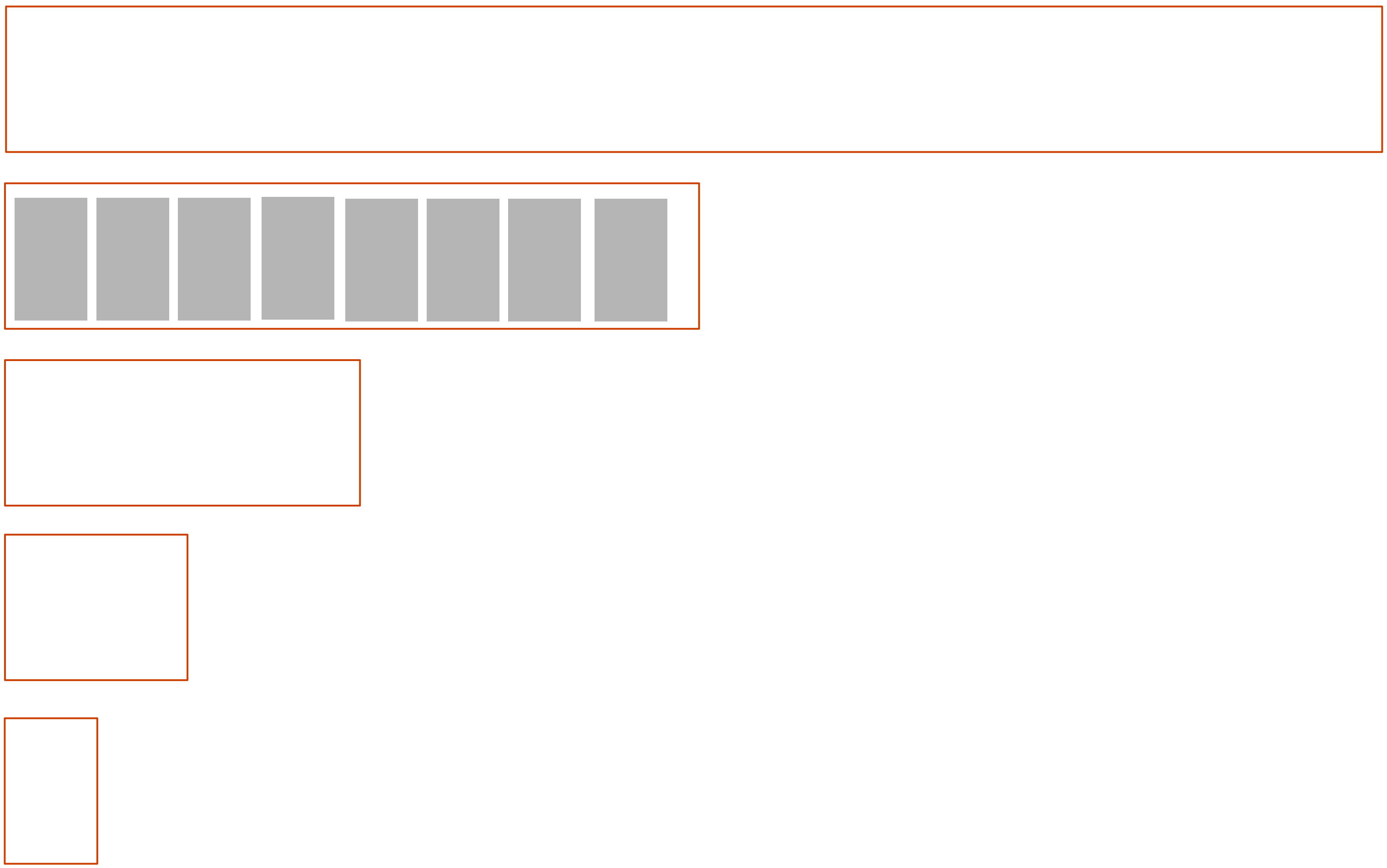

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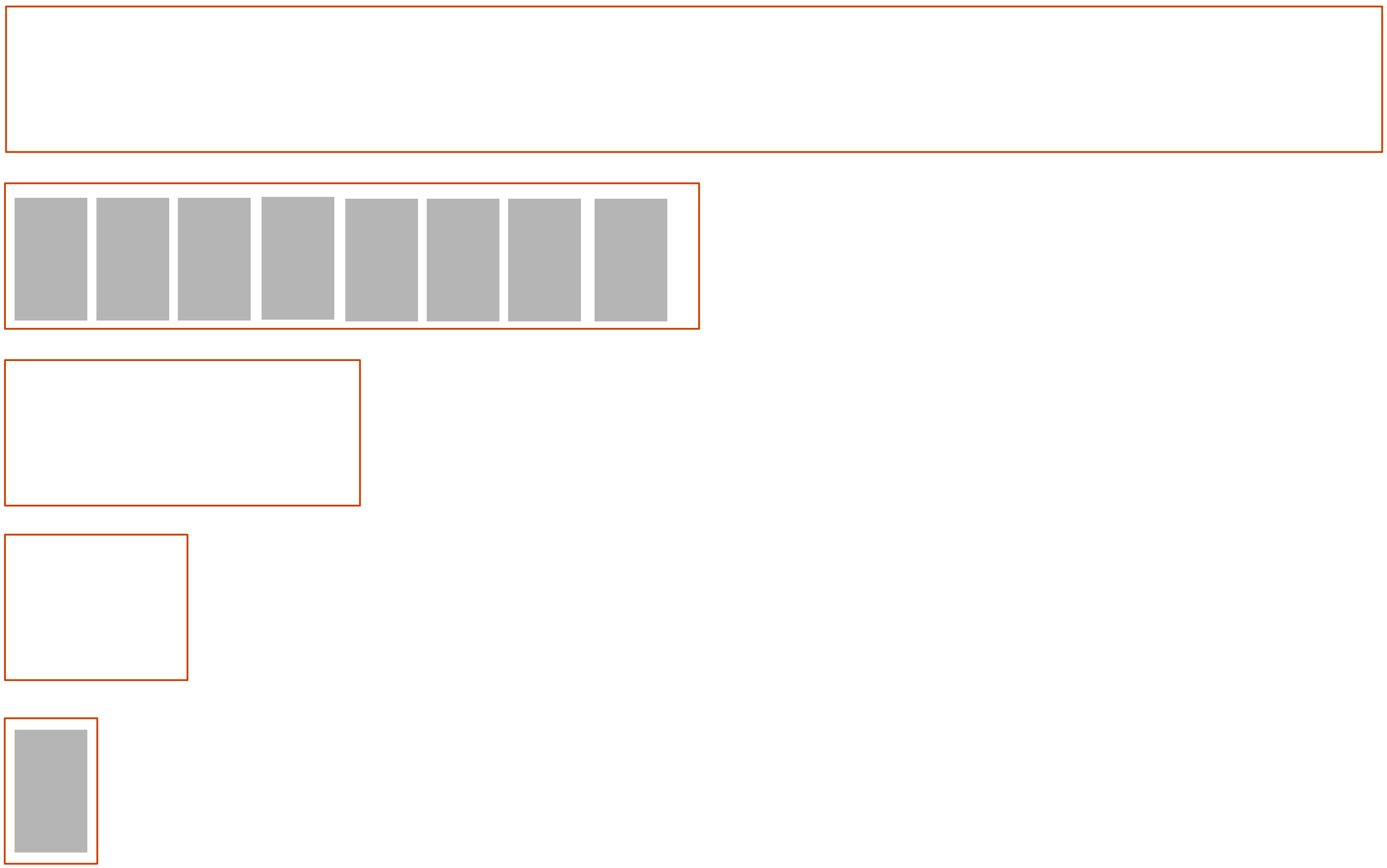

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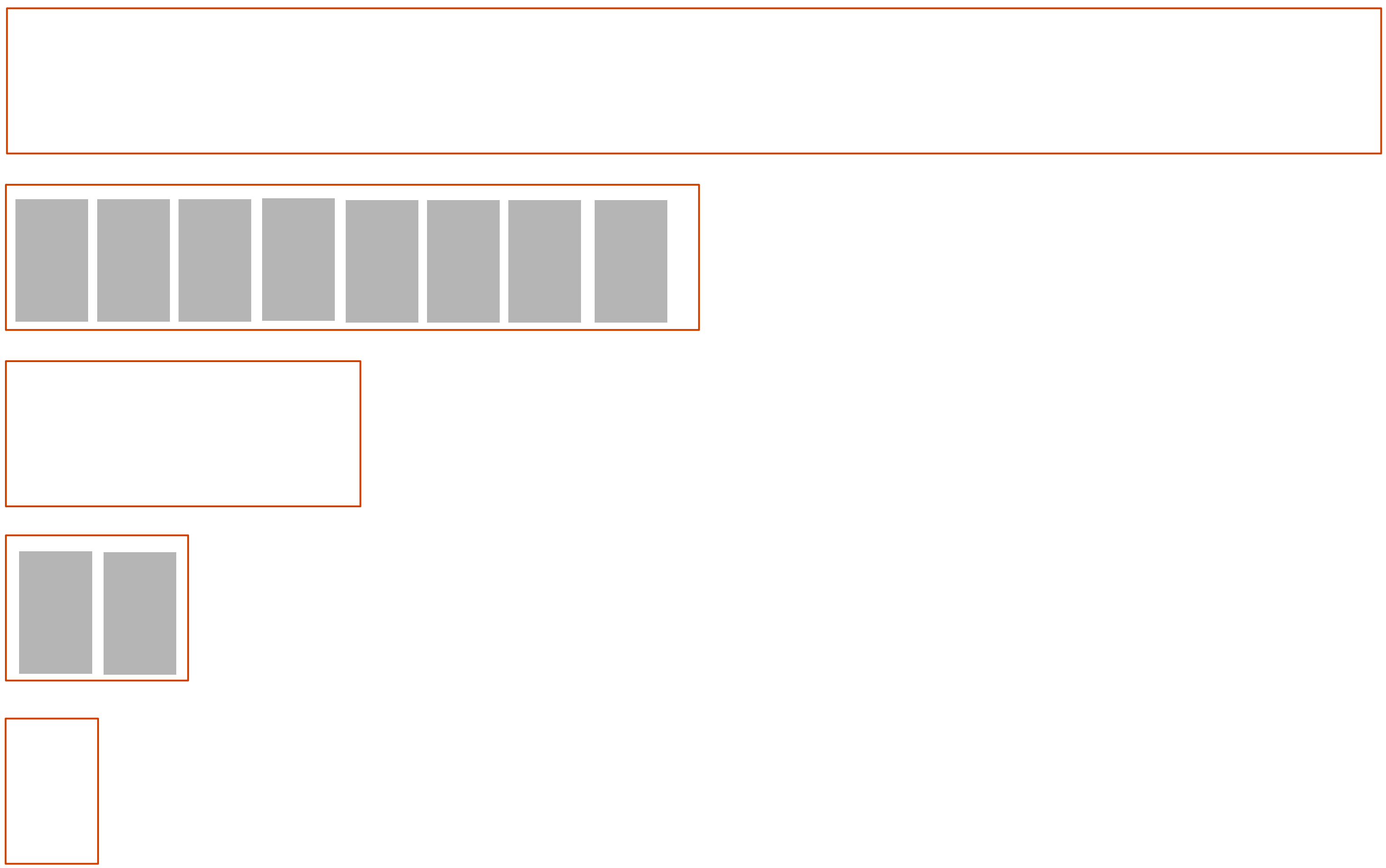

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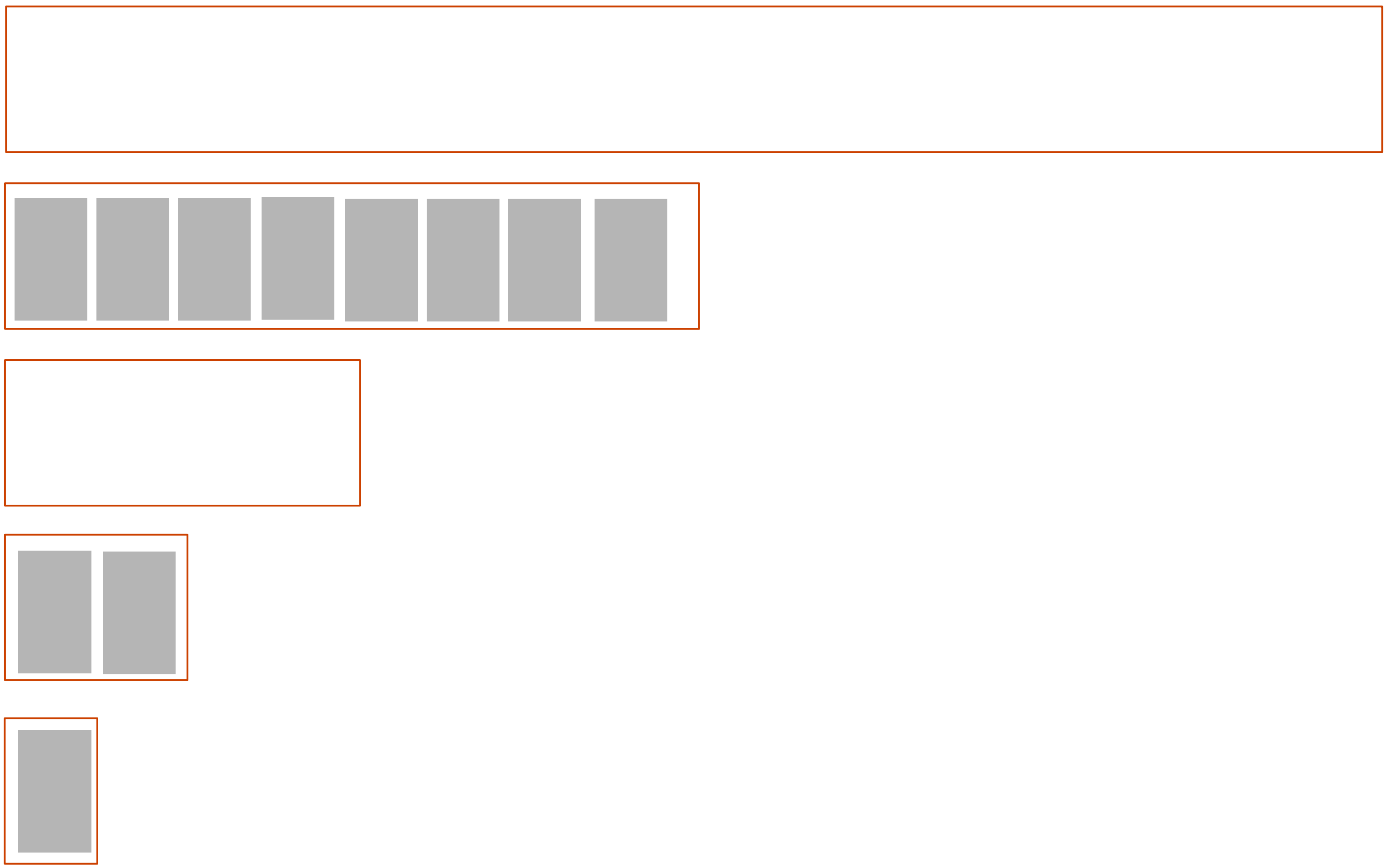

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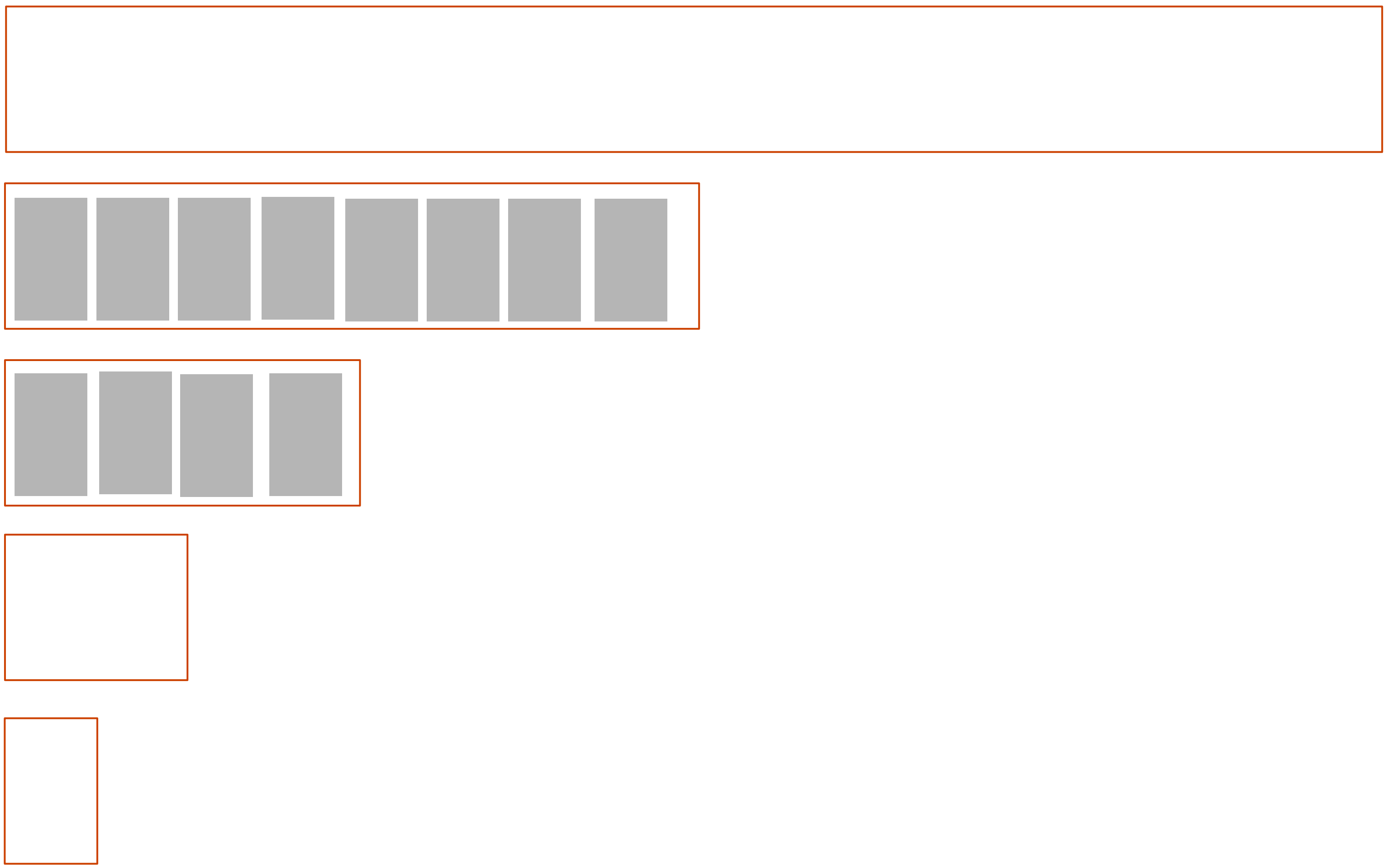

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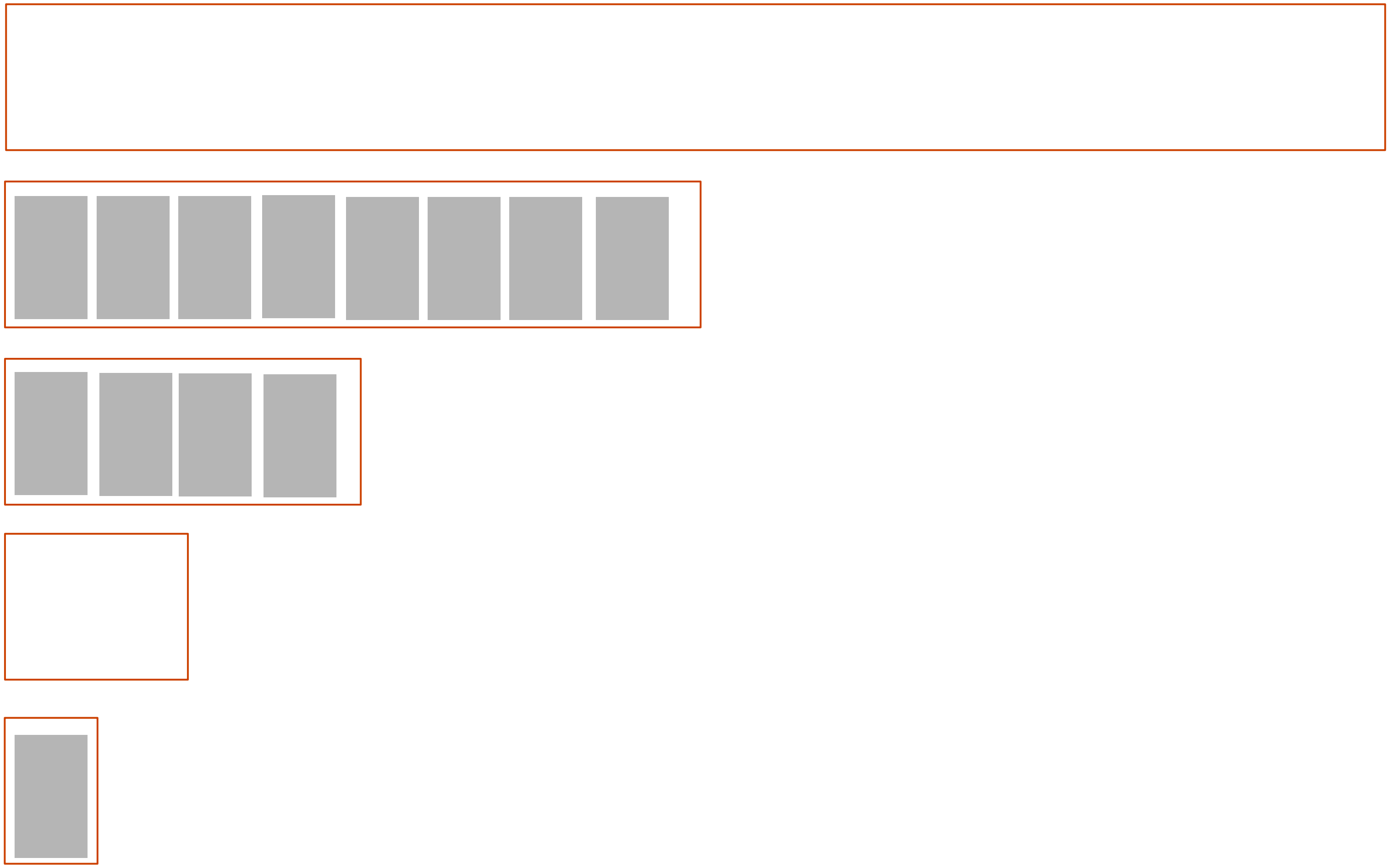

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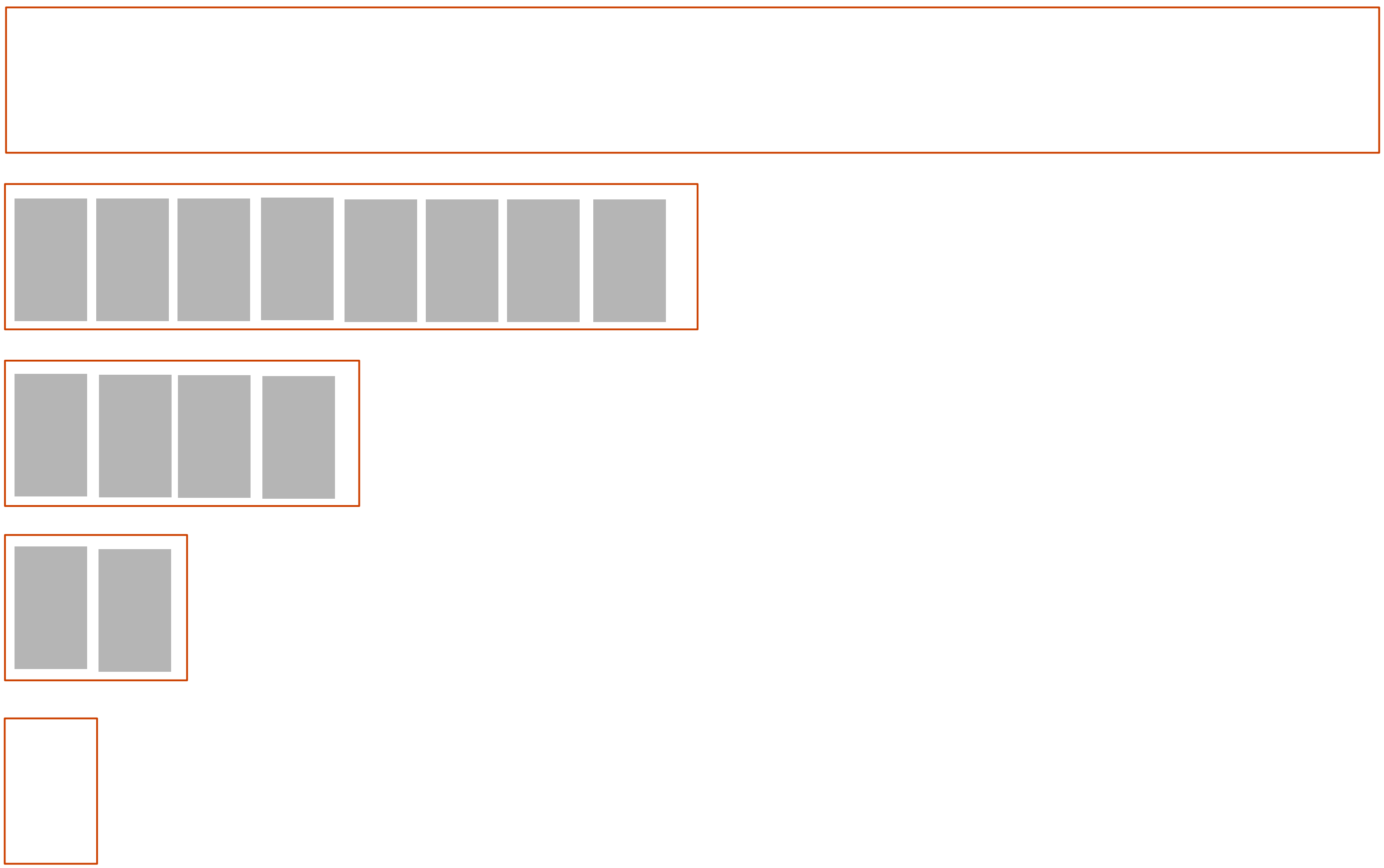

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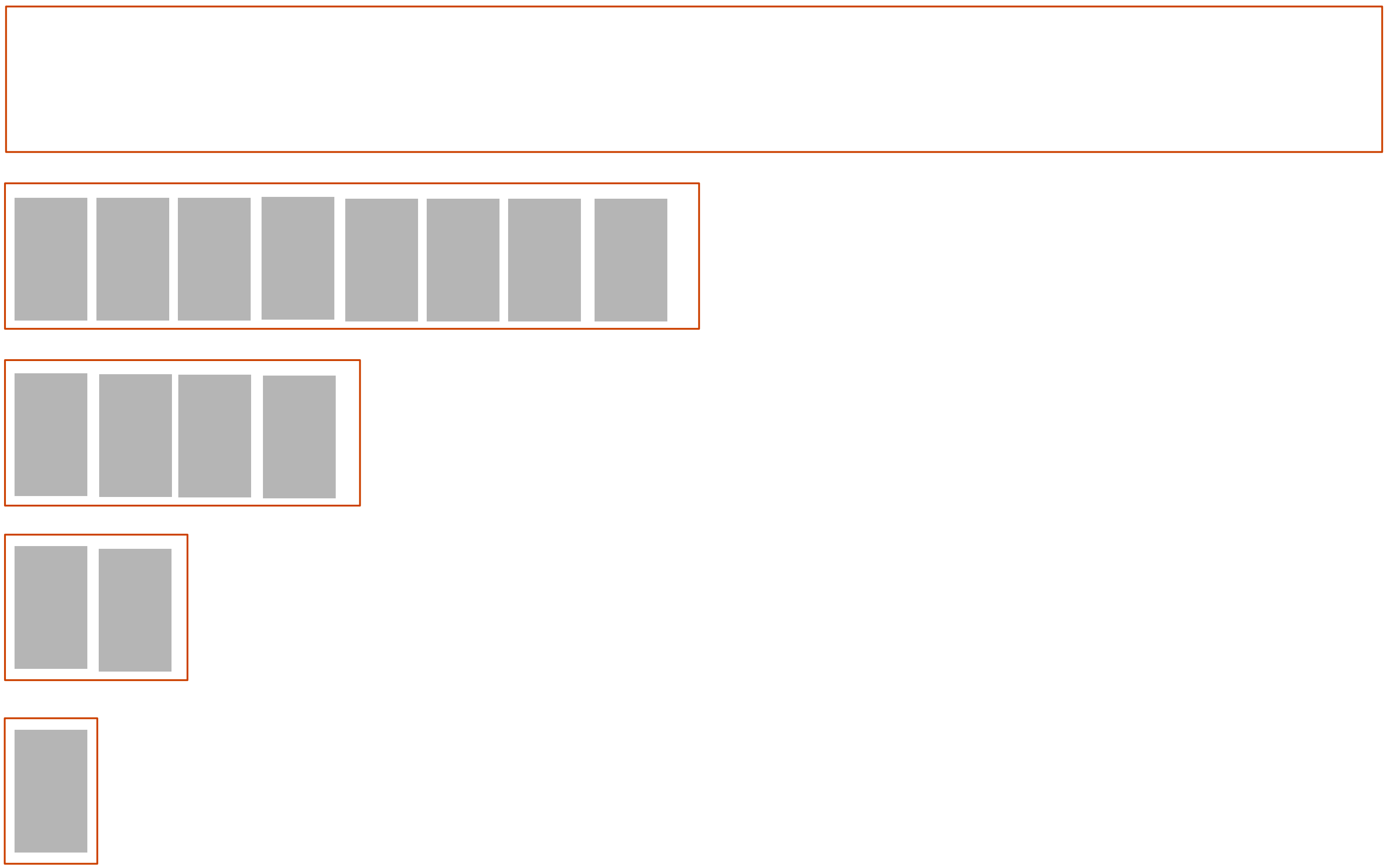

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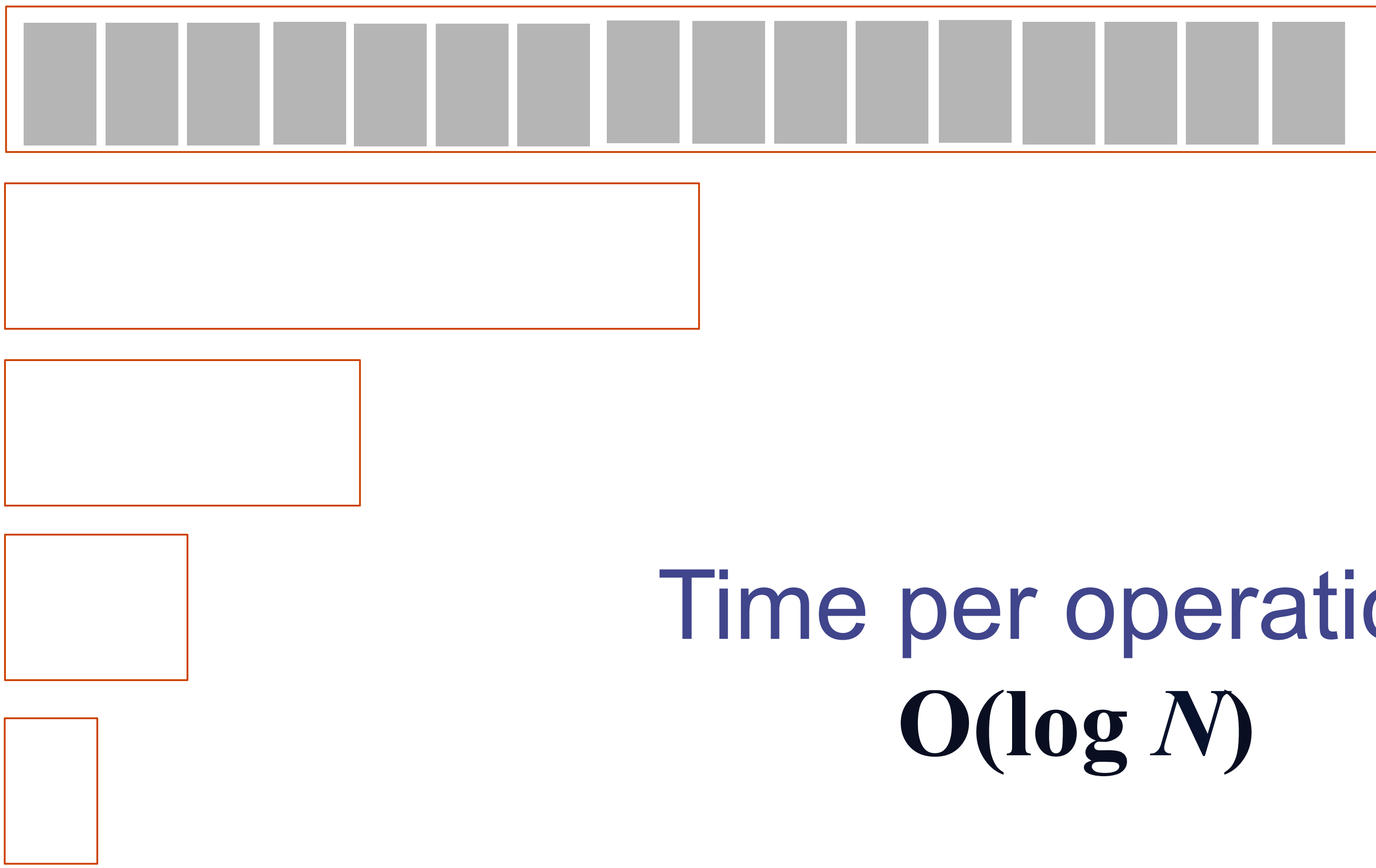
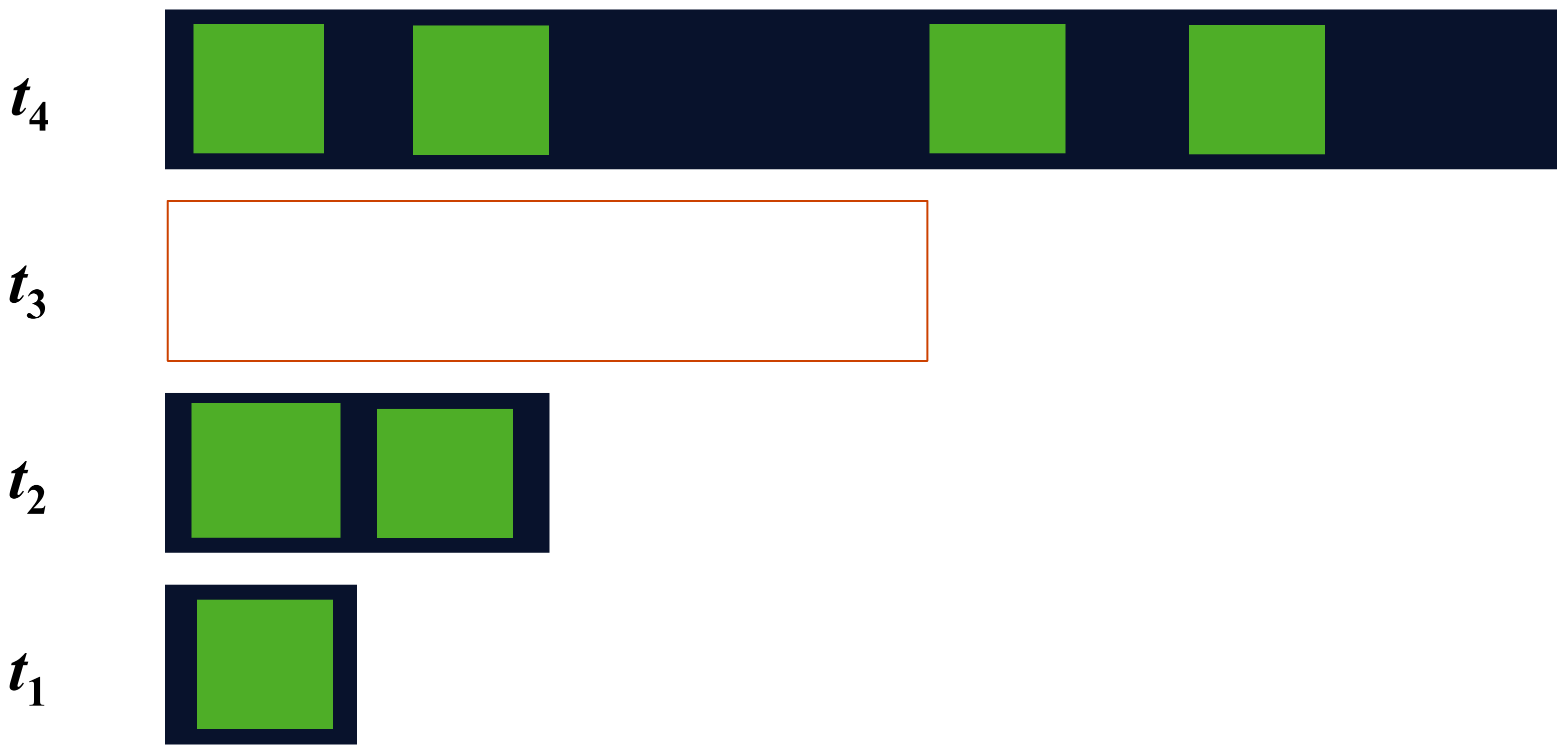


Time per operation:

$\mathbf{O(\log} \ N\mathbf{)}$

Our scheme: Search

- Maintain on key per level
- Client: Sends tokens $t_1\ t_2,\ldots,t_l$ for $\mathbf{w}$
- Server: For each level i, unmasks entries for $\mathbf{w}$



Our scheme: Add

- Try level 1: It does not fit

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- Client downloads consecutive-filled levels (levels 1 and 2)

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- Try level 1. It does not fit.
- Client downloads consecutive-filled levels (levels 1 and 2)
- Client **reencrypts with new secret keys** and uploads to level 3
- Only $\mathbf{O}(\mathbf{log}^2 N)$ per operation

Forward privacy:

Old tokens are no good

How about deletes?

- Treat them as special “add” entries
- Can create problems
  - 5 addition entries for word **w** at level 4
  - 4 deletion entries for word **w** at level 3

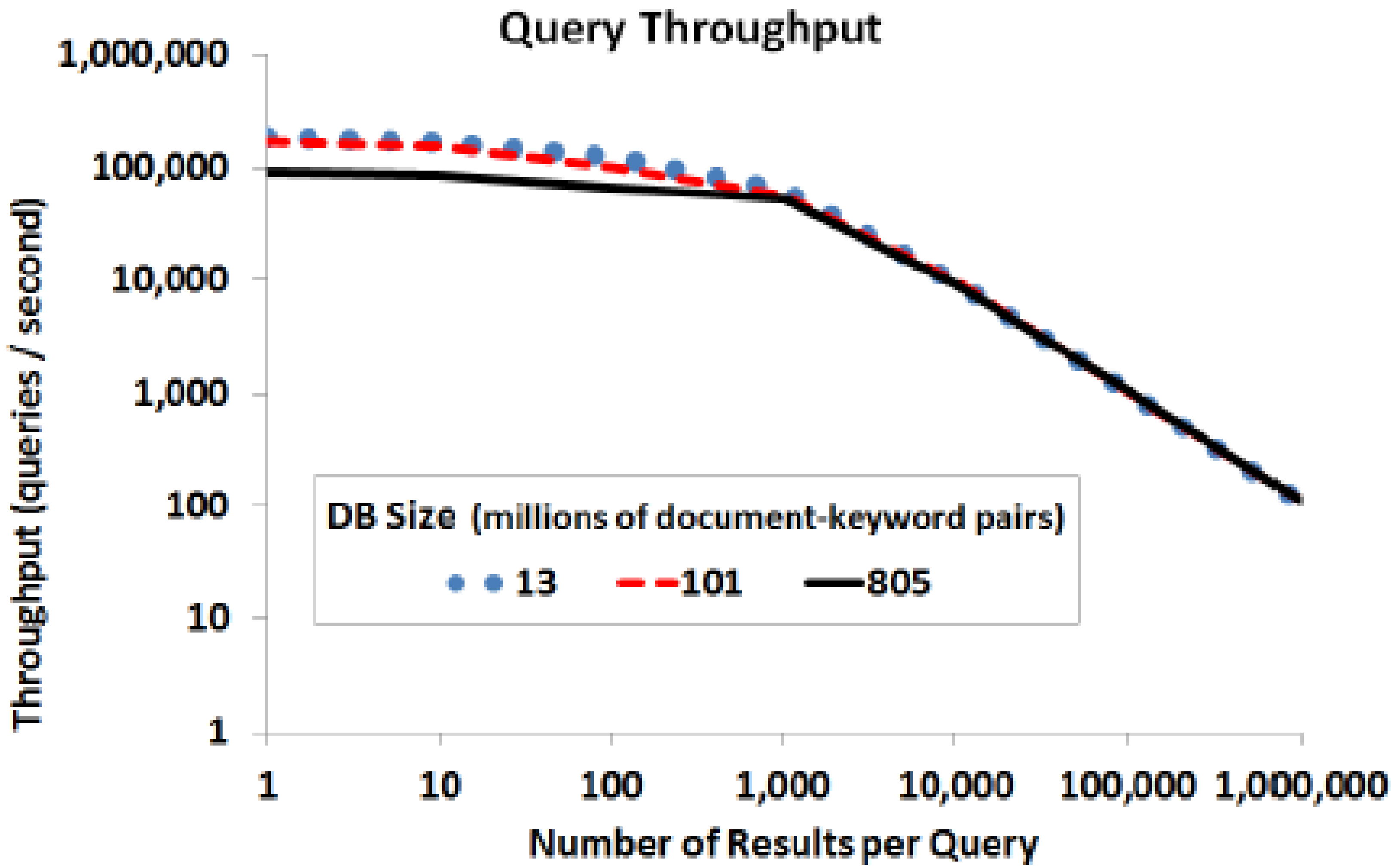
O(N) time for retrieving one document ☹

We show in the paper how to do that in O($\log^3 N$)

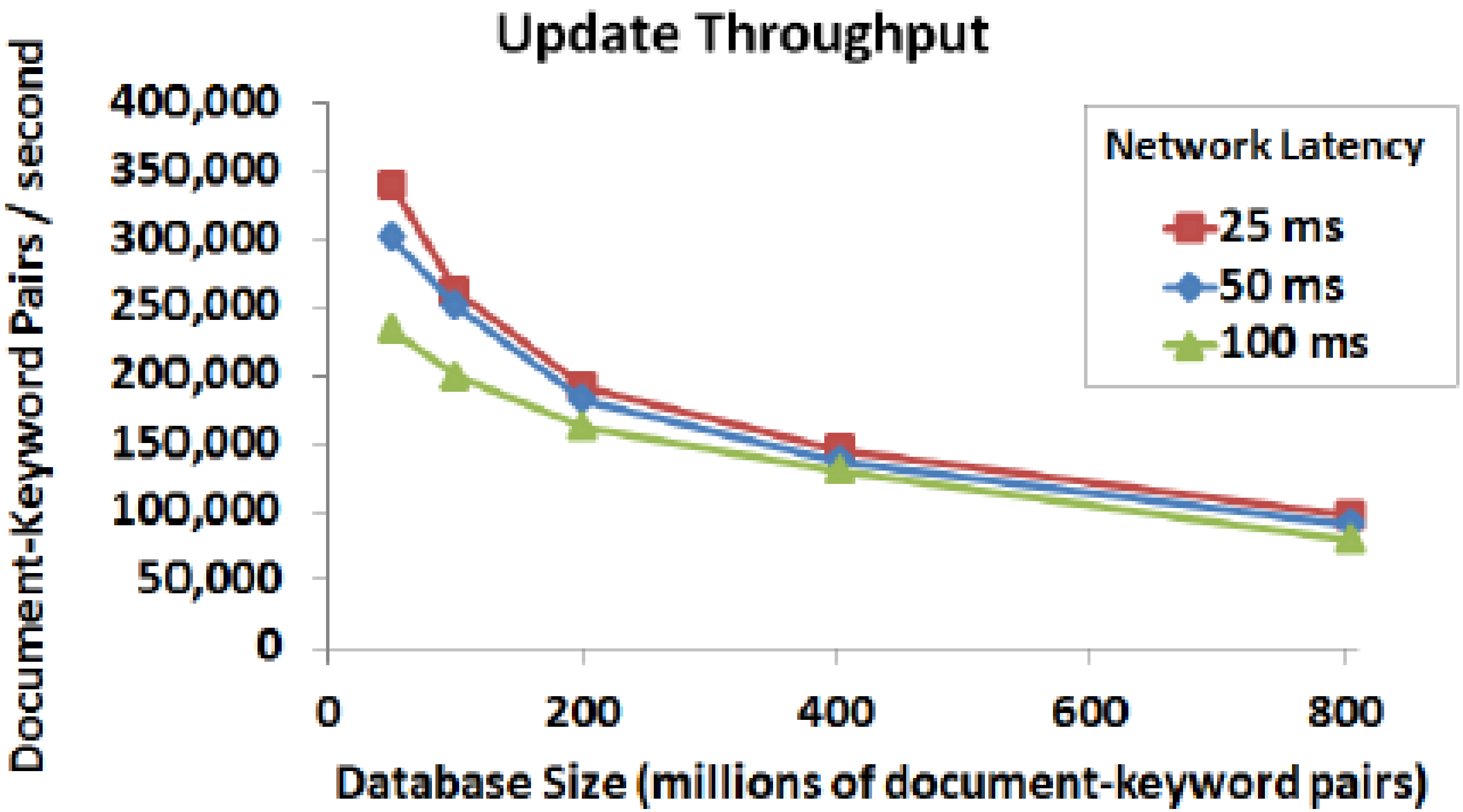
Implementation

- Implementation in C#
- Experiments were run on Amazon EC2
- 244 GB of memory

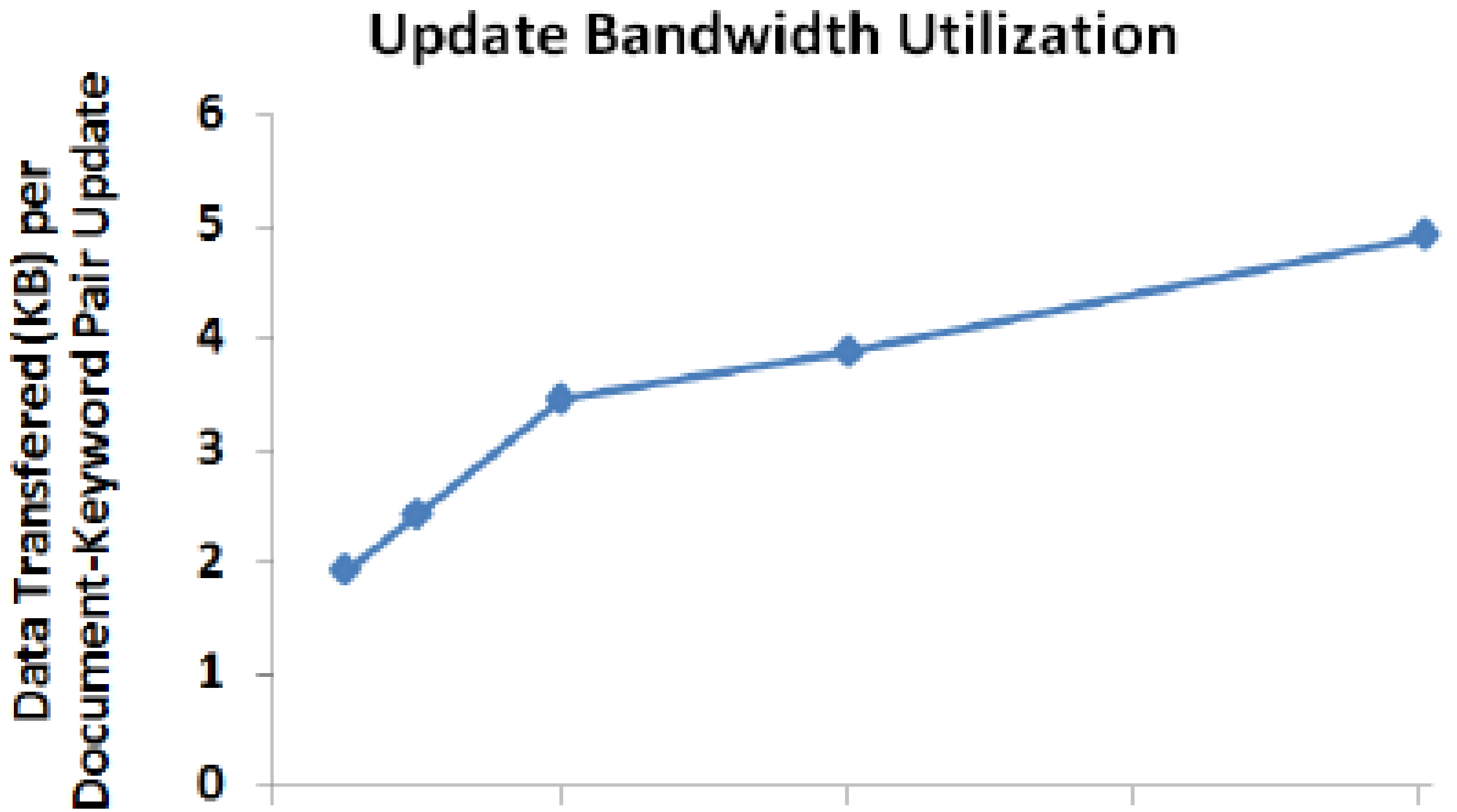
Query throughput



Update throughput

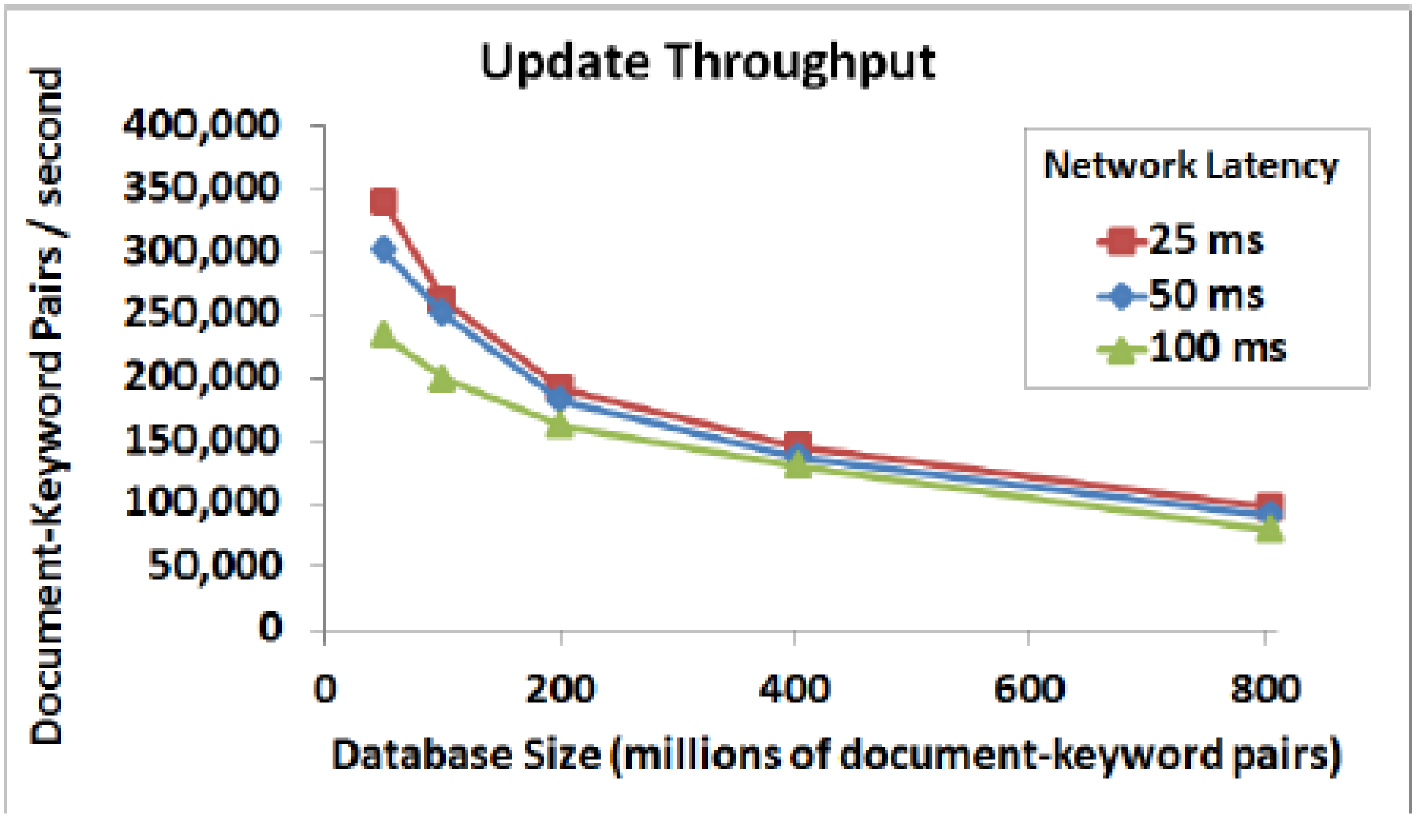


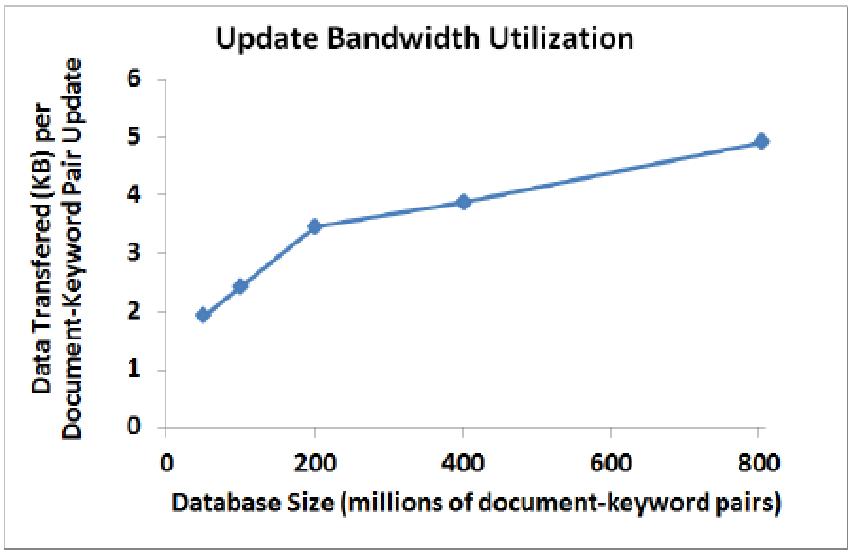
Bandwidth utilization



Thanks!

Updates: Data structure



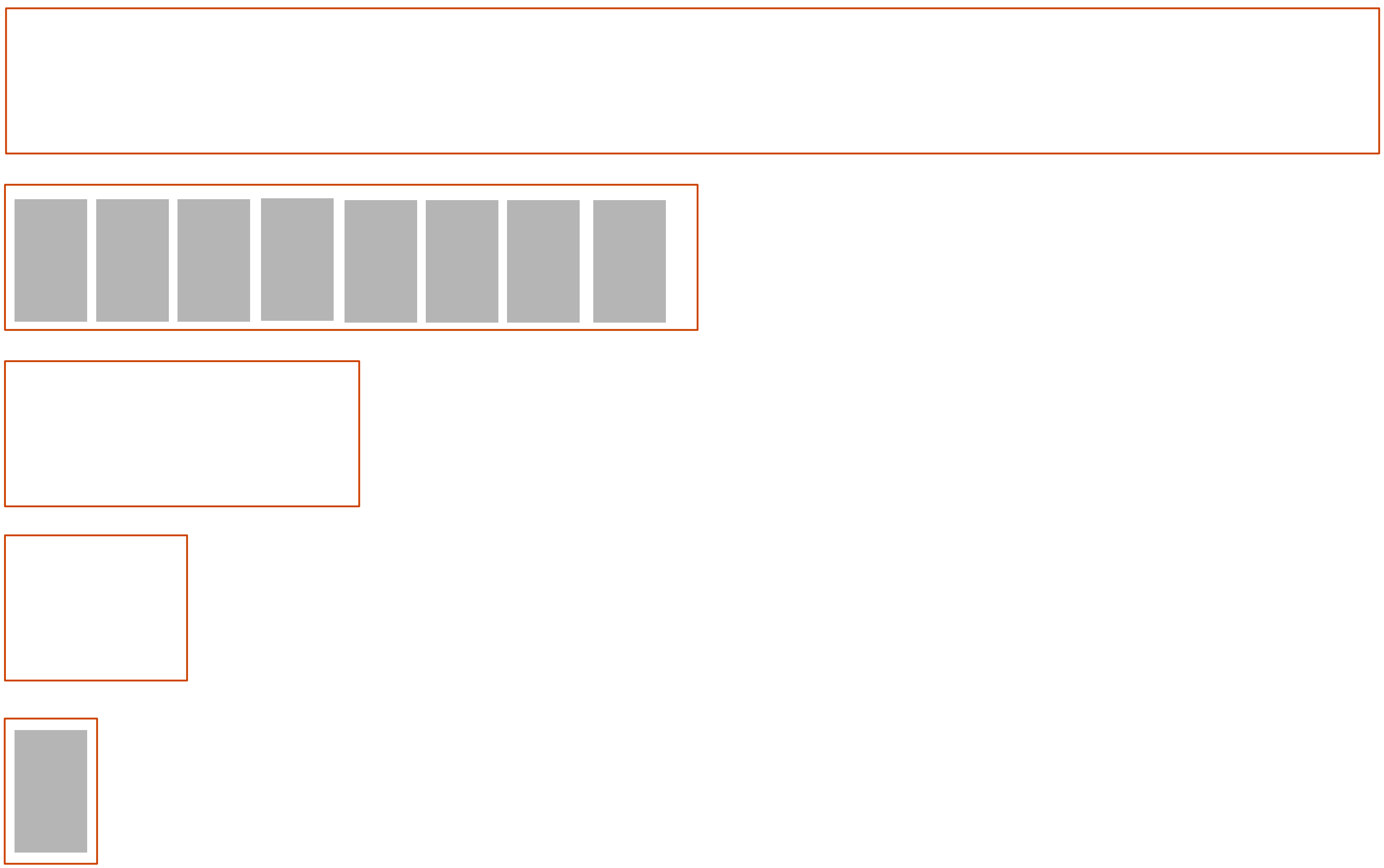

Update Bandwidth Utilization
Data Transfered (KB) per Document-Keyword Pair Update
0
1
2
3
4
5
6
0
200
400
600
800
Database Size (millions of document-keyword pairs)

Updates: Encrypted data structure

- ι hash tables

Updates: Data structure

- $l = \log N + 1$ levels



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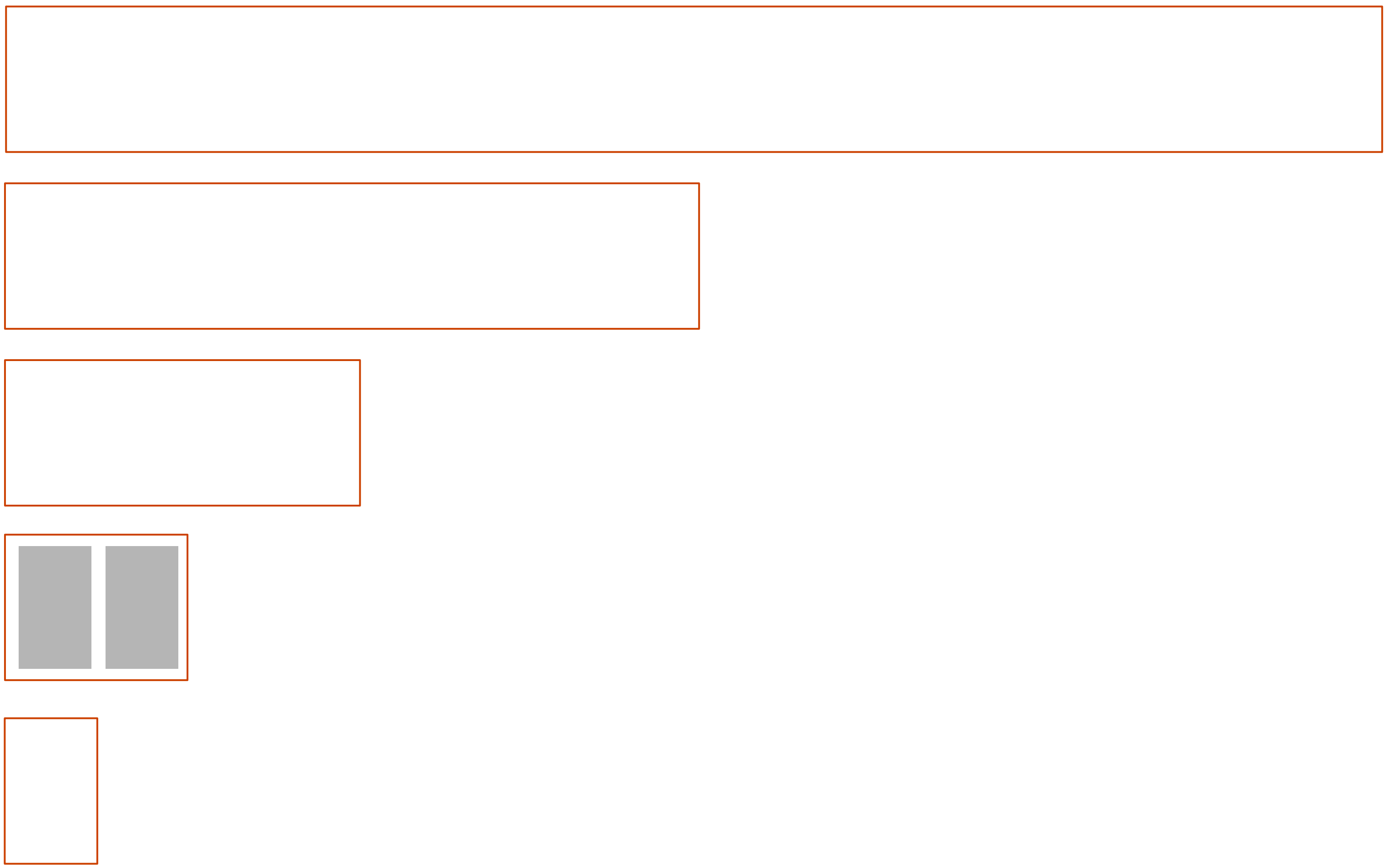

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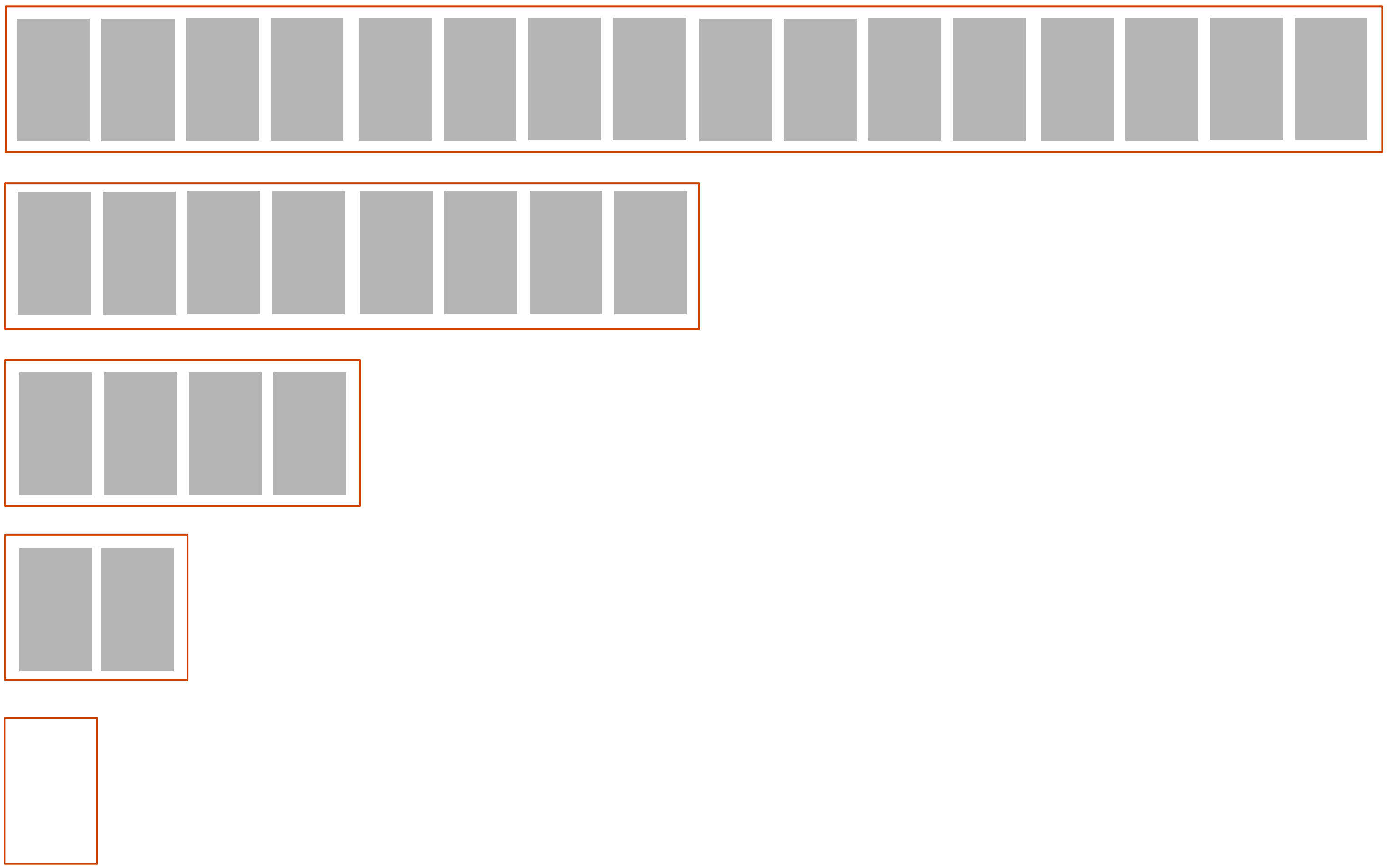

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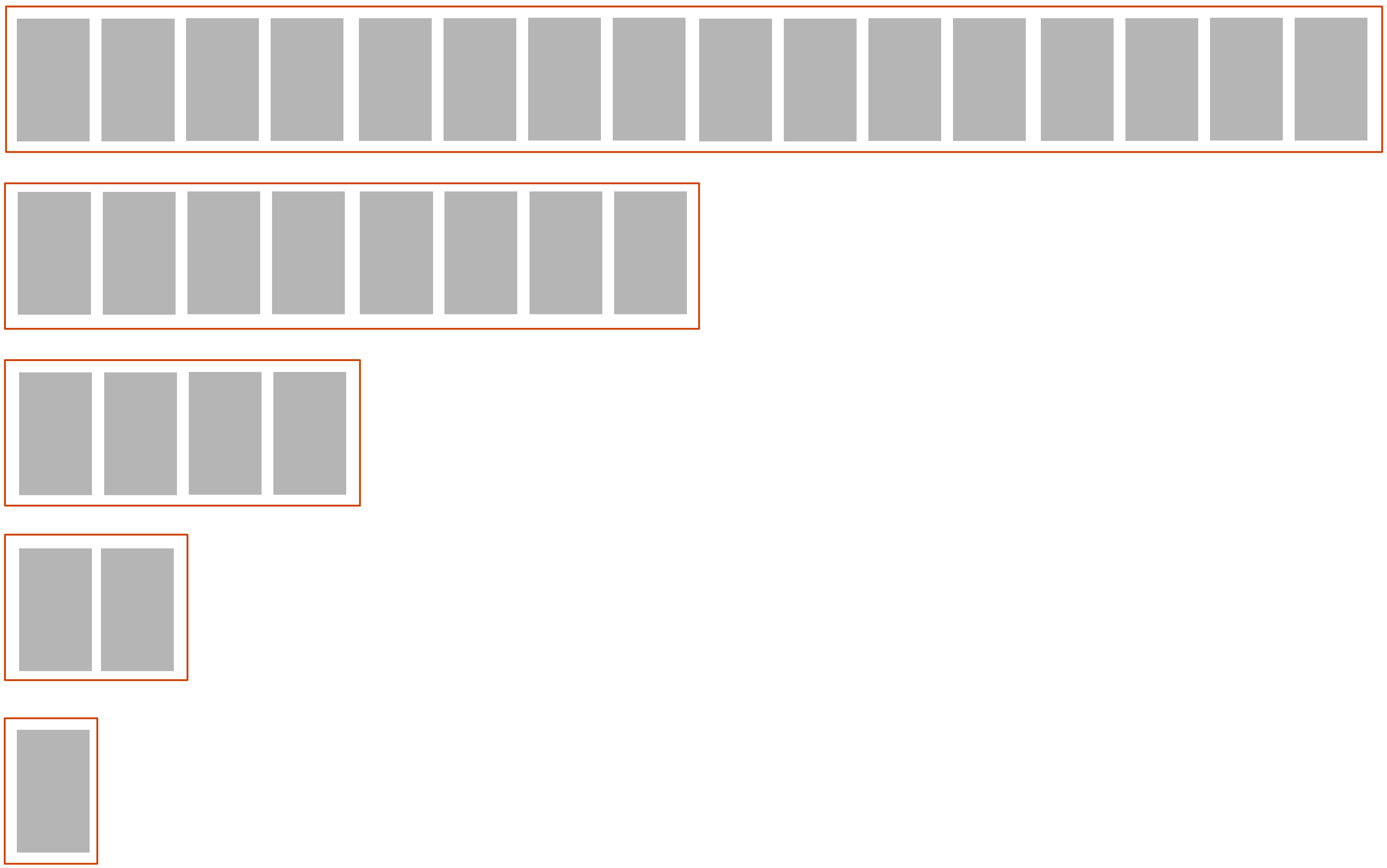
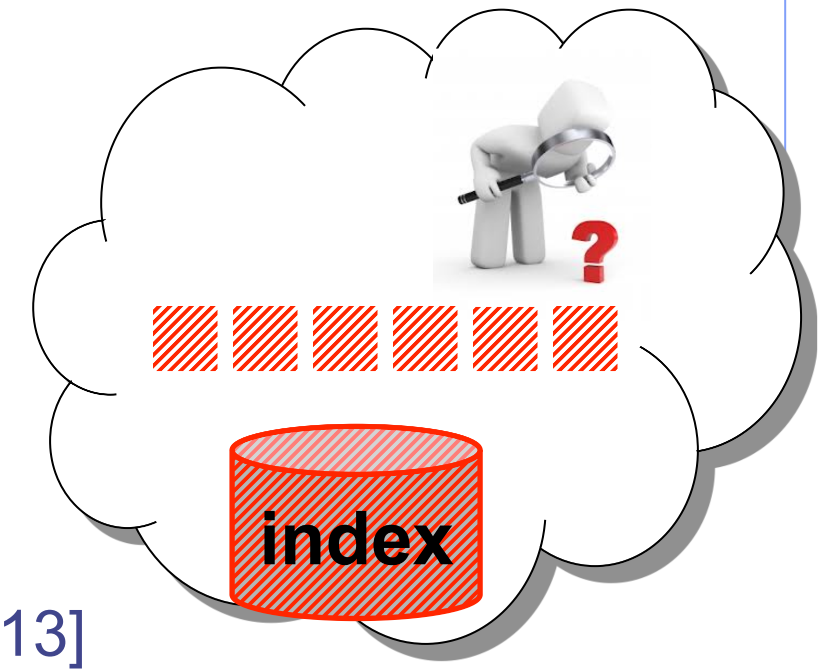


Searchable encryption



- Lots of work since 2000
- Static constructions
  - [][CGKO06], [KO12], [CJJKRS13]
- Dynammic constructions

- **My work:** First dynamic efficient scheme, [CCS12]
  - Privately indexes keywords, not only files
  - Efficient system implementation

Verifiable Computing

input u →

output **F**(u) ←

proof π

F:

circuit

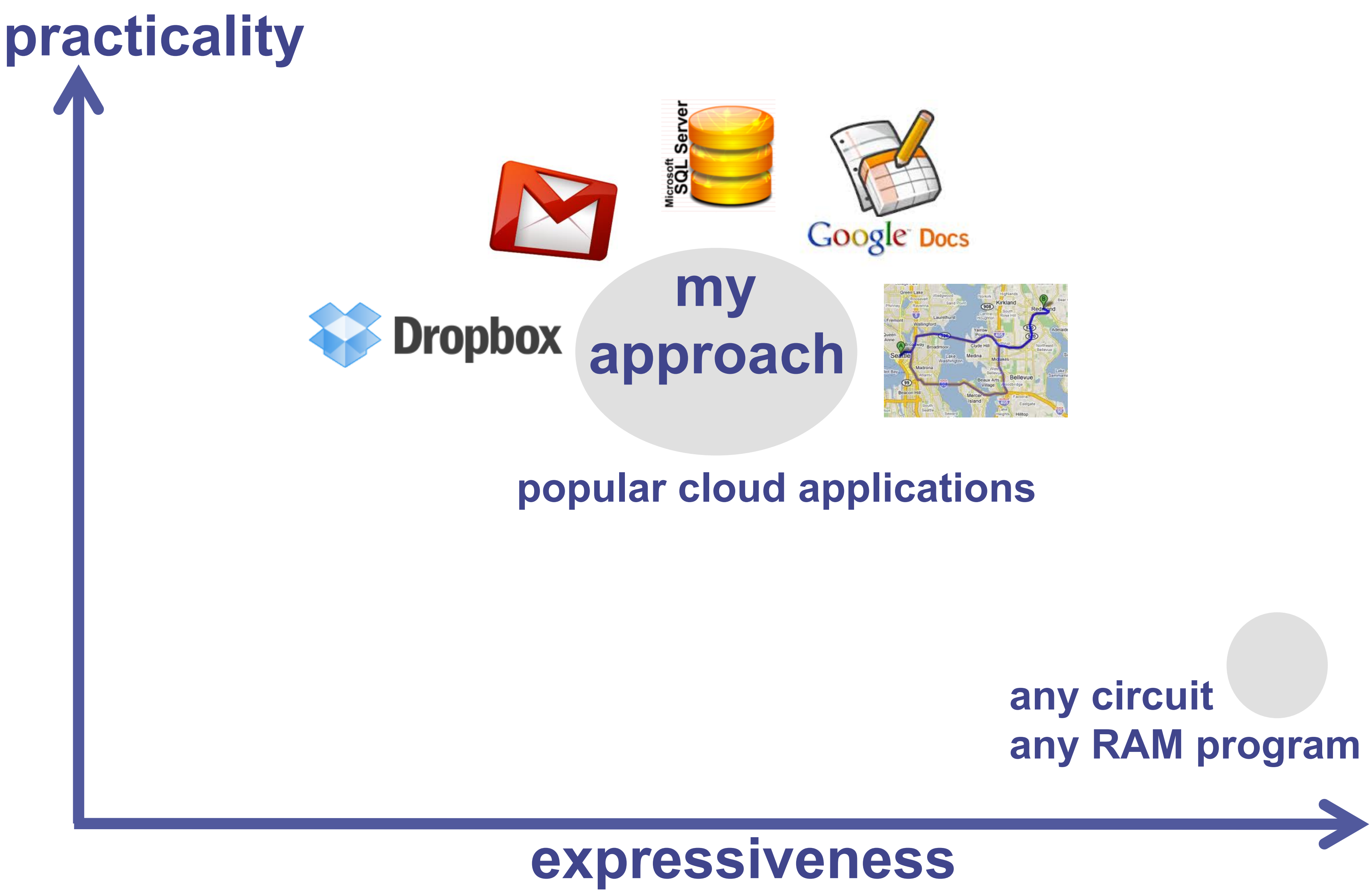
RAM program

- π should be O(|**F**(u)|)
- Cloud should not be able to cheat
- Many works in the literature

Recent breakthroughs

- In theory
  - Give me any circuit C, I can create a VC protocol for you
    - E.g., Quadratic Span Programs (EUROCTYPT 13)
- In practice
  - Many systems have been developed to implement VC
    - E.g., Pinocchio (SSP 13), Pantry (SOSP 13)
  - Immense improvement in the practical landscape of VC since 2010…
    - …when the only way to do general VC was FHE and PCPs
  - Still not practical for real-life applications
    - E.g, a SELECT query over a database of one billion records?

My approach: Focus on popular applications



Some numbers

- **Intersection** of two sets of 10,000 entries each where the output is 200 elements:
  - ~2 seconds (proof computation)
- **Shortest path** over a planar graph of 10,000 nodes
  - ~3 seconds (proof computation)
- **Pattern matching** of a 10-character pattern (match/mismatch) over a text of 100,000 characters
  - ~25 μs (proof computation)
- Verification is always fast

Grand challenges ahead

- Still we are not practical enough
- Normal conjunctive keyword search takes order of microseconds
  - The added verifiability guarantee takes order of seconds
  - Same with shortest paths
- Plenty of room for improvement
  - Expertise from crypto and systems and algorithms required
- Grand challenge: Build a verifiable DBMS with reduced overhead