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Full-text search with distributed search engines

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Agenda

- Overview
- Indexing: Analysis, Tokenization, Filtering, on disk data structures
- Searching: Scoring, Algorithms & Optimization
- Aggregations
- Distributed systems and search
- Q & A

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Overview

Full text search introduction

```
SELECT * FROM products
         WHERE name LIKE = '%topf%'
```

```
# grep "topf" my_dataset.txt
```

Problem

- Scales linearly with the data set size
- Relevancy
- Spell correction
- Synonyms
- Phrases

Inverted Index

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The quick brown fox jumped over the lazy dog

Tokenize

The	1
quick	1
brown	1
fox	1
jumped	1
over	1
the	1
lazy	1
dog	1

Sort

The	1
brown	1
dog	1
fox	1
jumped	1
lazy	1
over	1
quick	1
the	1

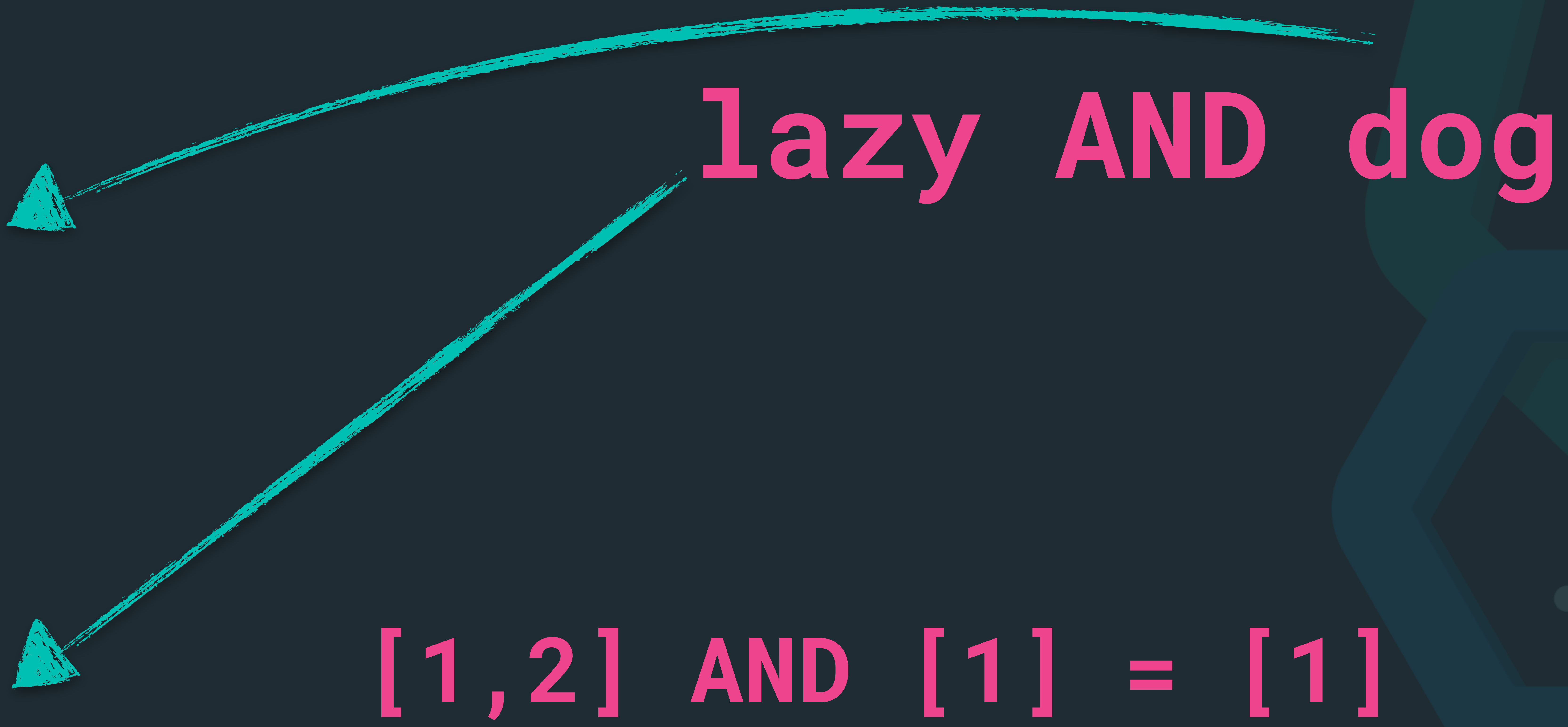
Quick brown foxes leap over lazy dogs in summer

Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1

Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1

lazy dog

Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1



lazy AND dog

[1,2] AND [1] = [1]

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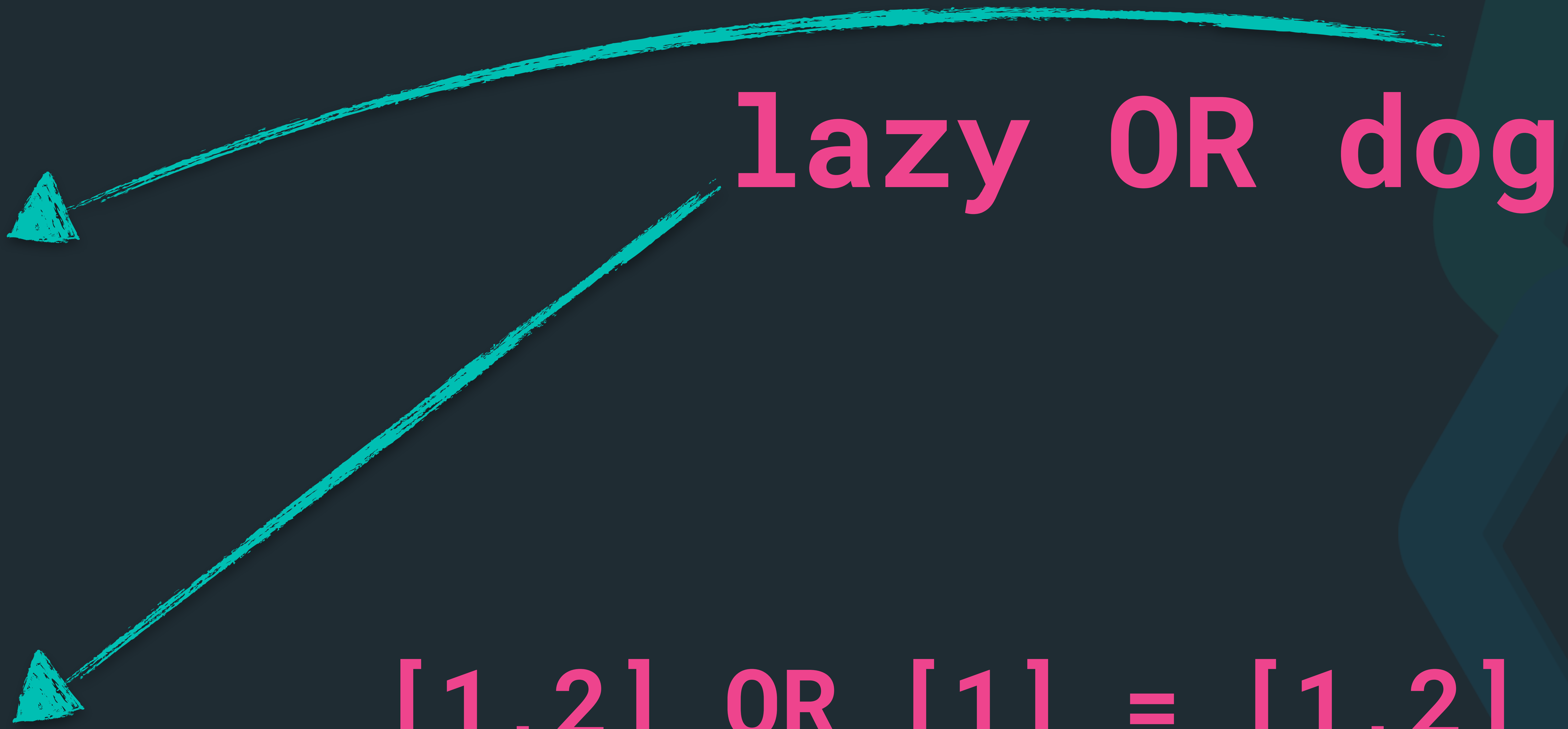
Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1



lazy OR dog

[1,2] OR [1] = [1,2]

Technologies used today

- Apache Lucene (search library)
- Elasticsearch (distributed search engine built on top of Apache Lucene)

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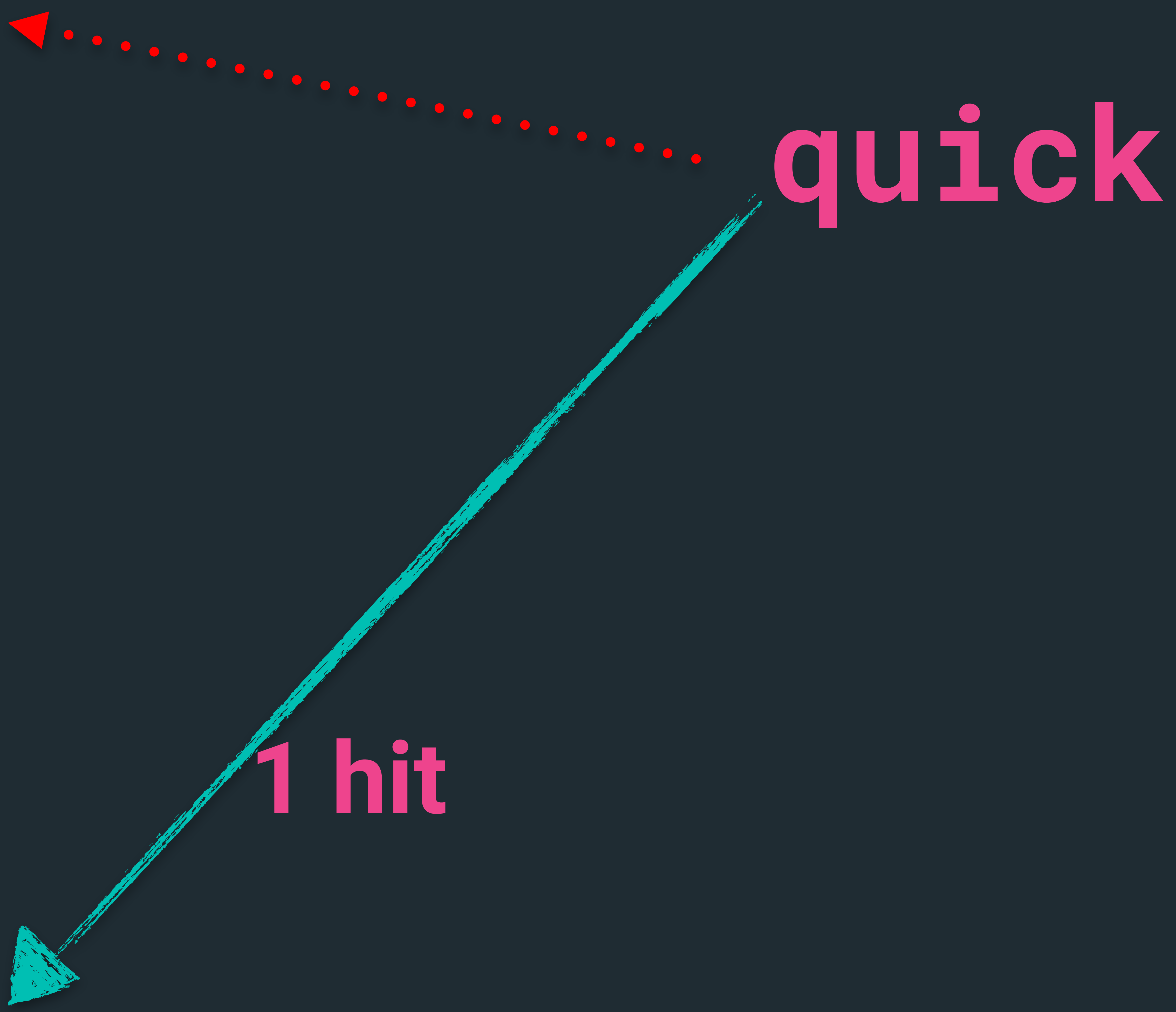
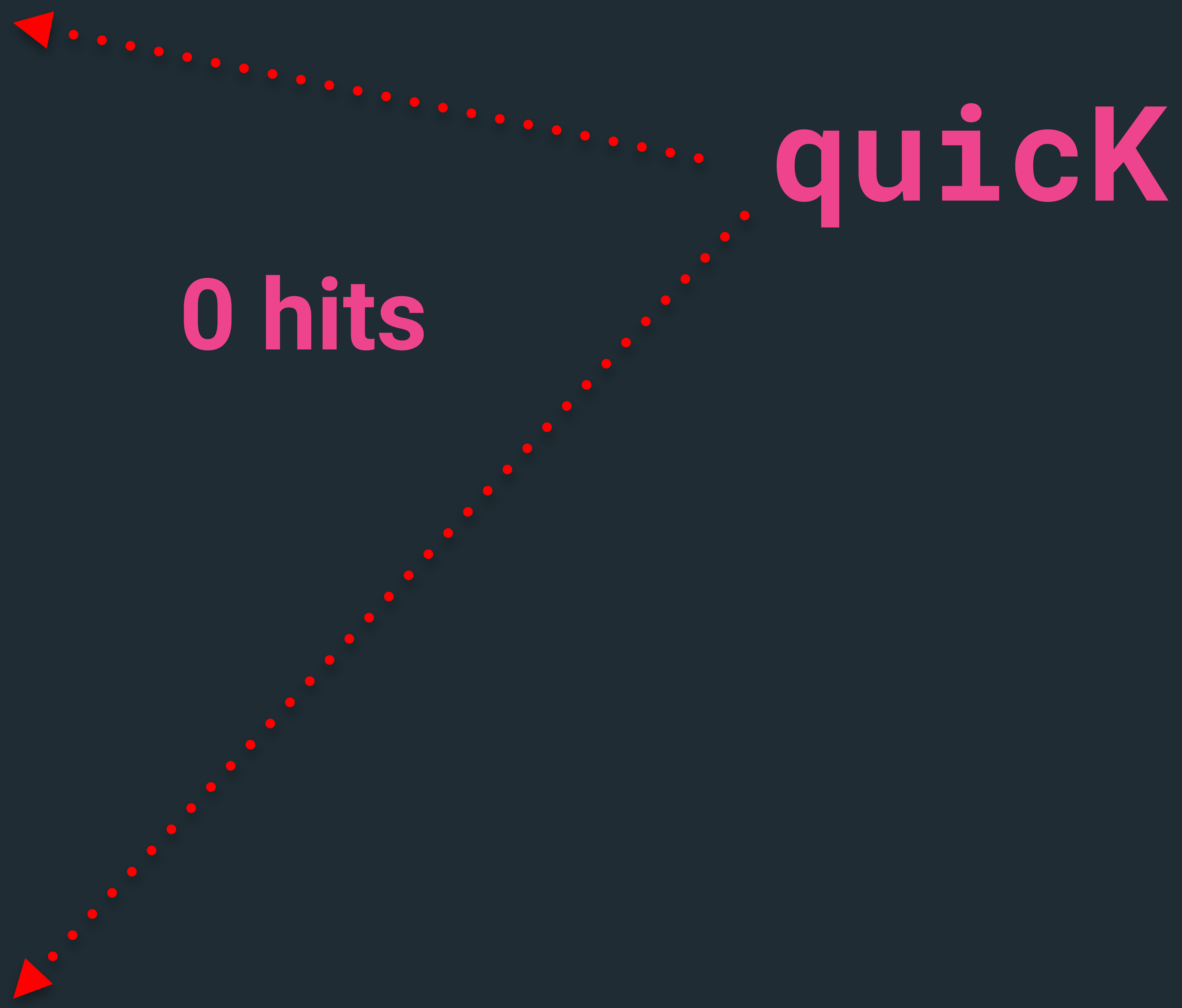
Indexing

Analysis, Tokenization, Filtering
Data structures

Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1



Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1



quicK

0 hits

Analysis: Tokenizer & Token Filters

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Tokenization

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Tokenization

```
quick brown fox
```

Tokenization

```
quick_brown_fox
```

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Tokenization

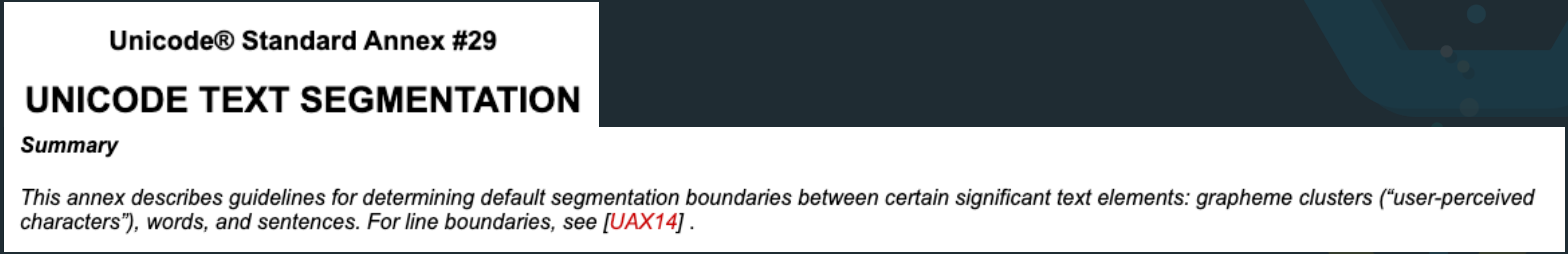
```
quick_brown_fox
the lazy, white dog.
```

Tokenization

```
quick_brown_fox
the_lazy_white_dog
```

Tokenization

```
quick_brown_fox
the_lazy_white_dog
```



Unicode® Standard Annex #29

UNICODE TEXT SEGMENTATION

Summary

This annex describes guidelines for determining default segmentation boundaries between certain significant text elements: grapheme clusters ("user-perceived characters"), words, and sentences. For line boundaries, see [UAX14] .

https://unicode.org/reports/tr29/

Tokenization

```
quick_brown_fox
the_lazy_white_dog
https://www.jade-hs.de
```

Tokenization

```
quick_brown_fox
the_lazy_white_dog
https_www.jade_hs.de
```

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Token Filter

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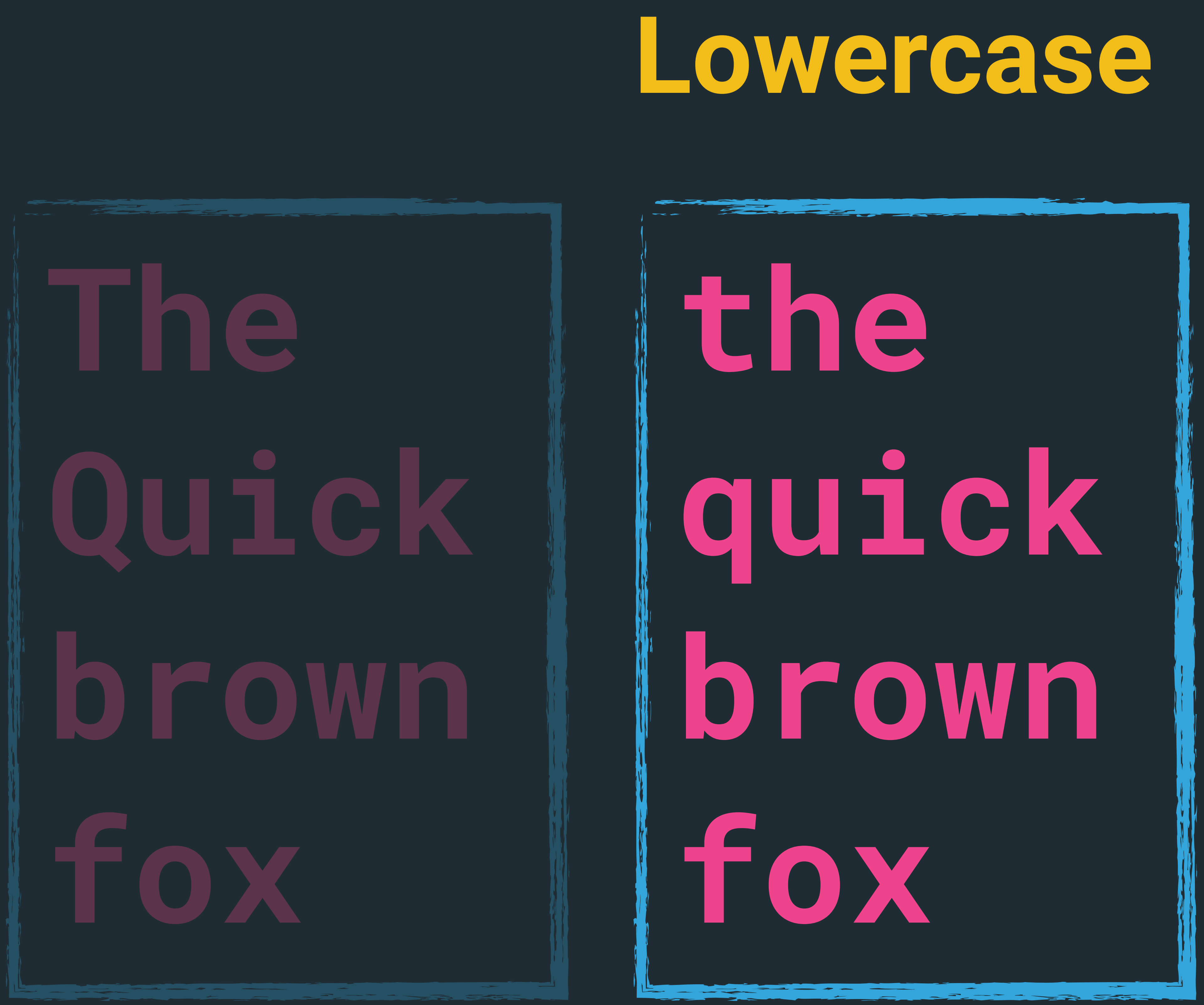
Quick	2
The	1
brown	1,2
dog	1
dogs	2
fox	1
foxes	2
in	2
jumped	1
lazy	1,2
leap	2
over	1,2
quick	1
summer	2
the	1

Token filter

The
Quick
brown
fox

Token filter

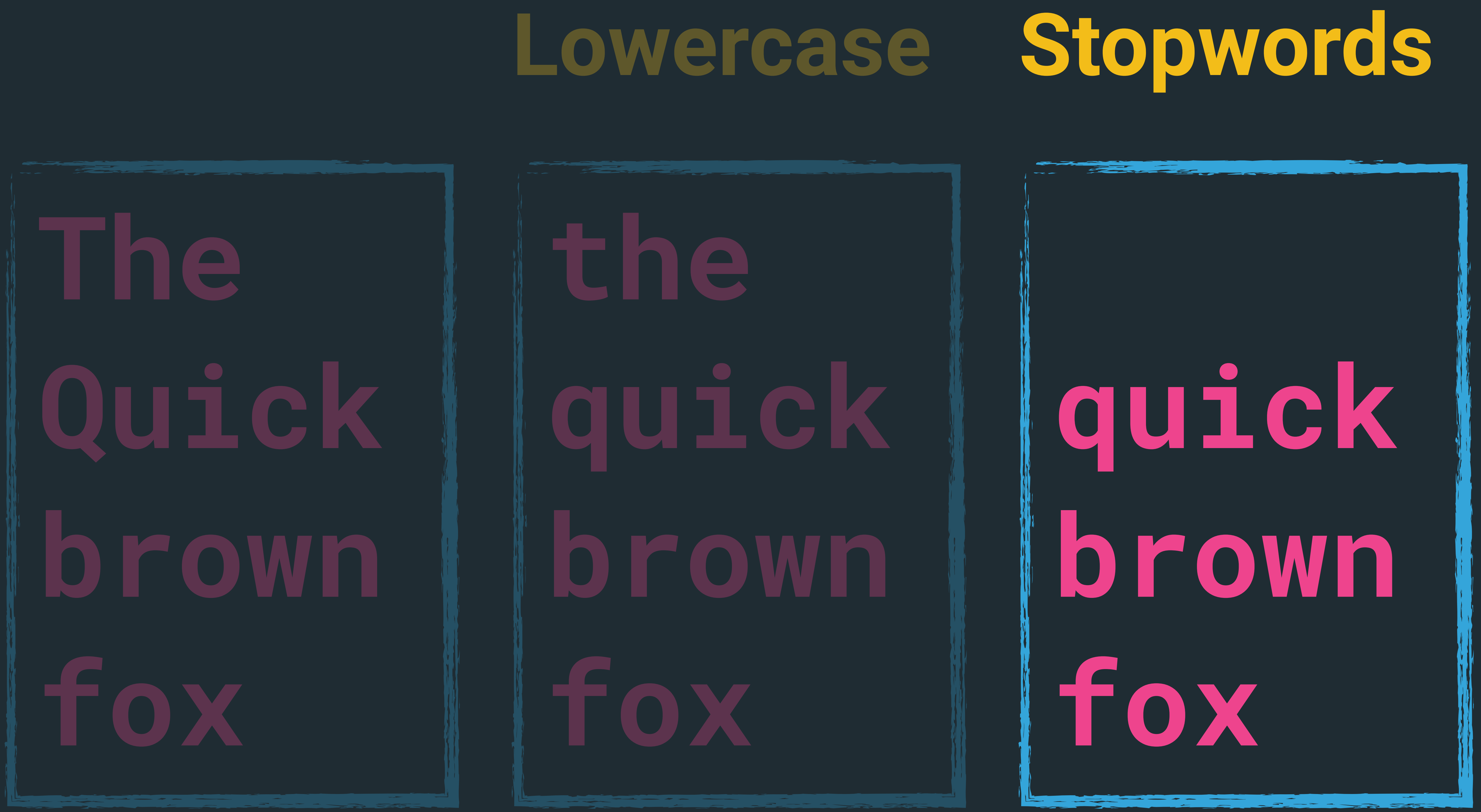


Lowercase

The
Quick
brown
fox

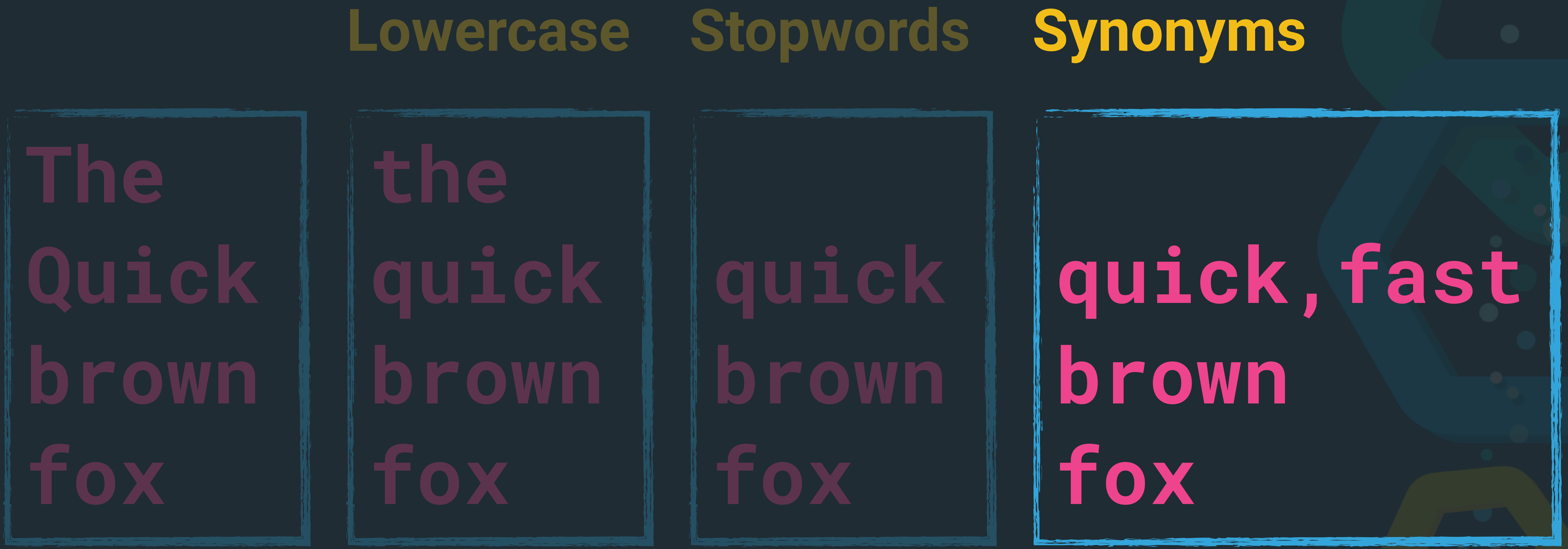
the
quick
brown
fox

Token filter



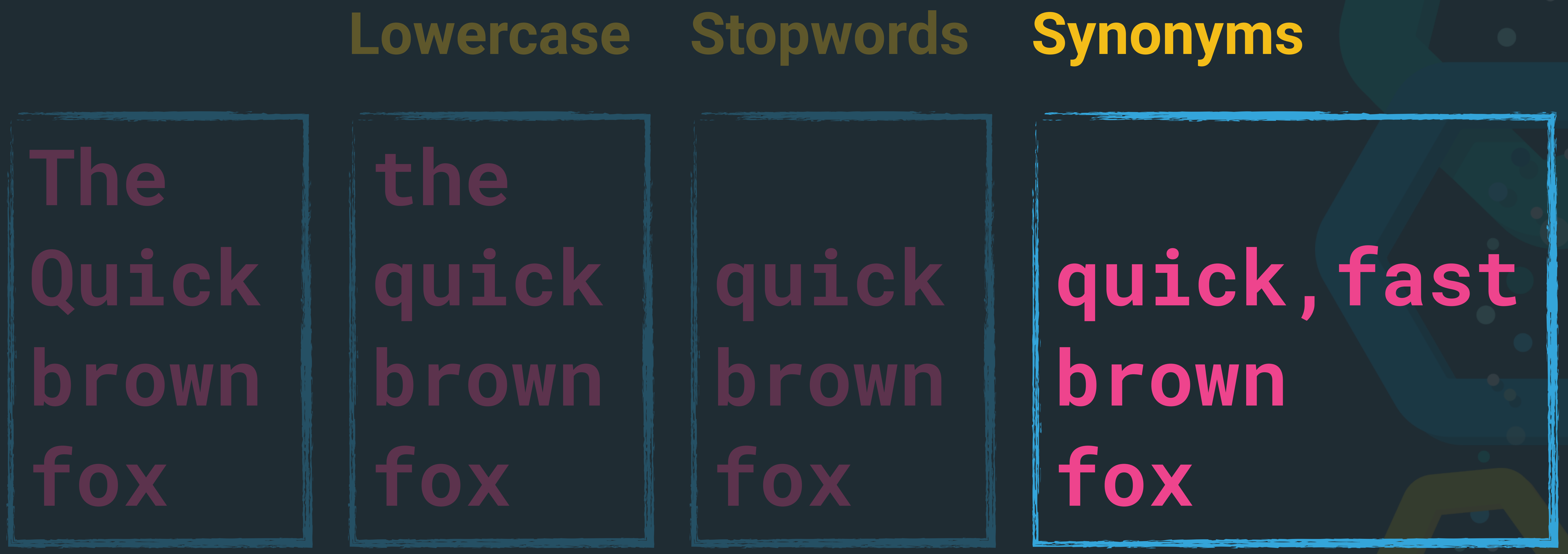
	Lowercase	Stopwords
The	the	
Quick	quick	quick
brown	brown	brown
fox	fox	fox

Token filter



	Lowercase	Stopwords	Synonyms
The	the		
Quick	quick	quick	quick,fast
brown	brown	brown	brown
fox	fox	fox	fox

Token filter



Lowercase

Stopwords

Synonyms

The
Quick
brown
fox

the
quick
brown
fox

quick
brown
fox

quick, fast
brown
fox

Tokens can be changed, added, removed

Token filter

	Lowercase	Stopwords	Synonyms
The	the		
Quick	quick	quick	quick, fast
brown	brown	brown	brown
fox	fox	fox	fox

Queries need to be processed as well!

More analysis strategies

- Phonetic analysis: `Meyer vs. Meier`
- Stemming: `foxes → fox`
- Compounding: `Blumentopf → blumen topf`
- Folding: `Spaß → Spass`

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(On-Disk) Data structures

What else is in an inverted index?

- Documents: Find documents
- Term frequencies: Relevancy
- Positions: Positional Queries
- Offsets: Highlighting
- Stored fields: The original data

Segment: Unit of work

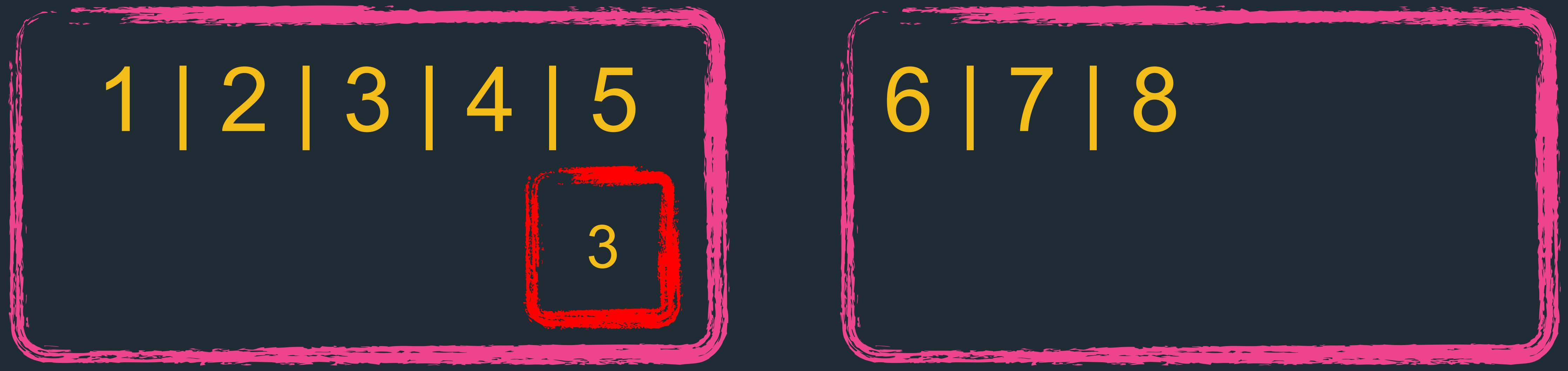
- A fully self sufficient inverted index
- An index consists of a number of segments
- New segments are created for newly added documents
- Segments are immutable!

Read-only data structures

- Pro: Write-once, sequentially
- Pro: Lock-free reading
- Pro: File system cache
- Contra: in-place updates & deletes
- Contra: Housekeeping
- Contra: Transactions

Segment: Deletes

- Mark a document as deleted in a special file
- Exclude it from searches
- No space is freed!



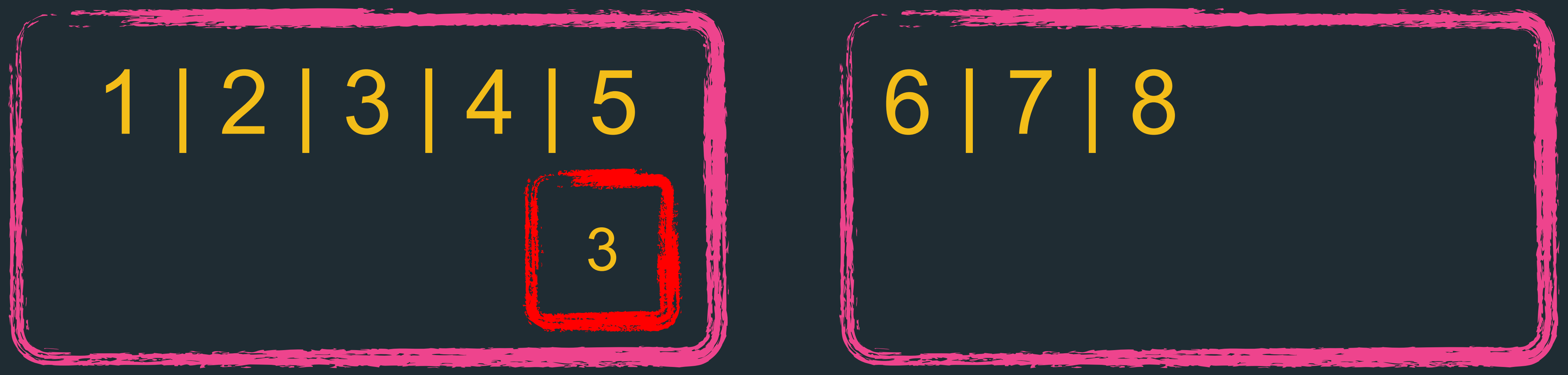
1 | 2 | 3 | 4 | 5

3

6 | 7 | 8

Segment: Merging

- Number of segments needs to be kept reasonable
- Merge multiple segments into one (smaller index)
- Delete expired documents



Segment: Merging

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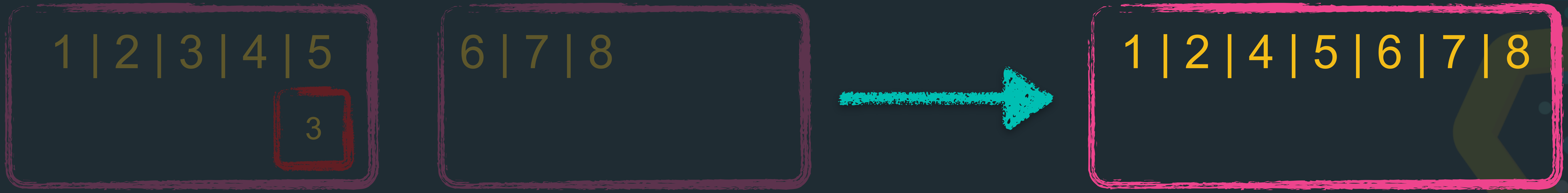

1 | 2 | 3 | 4 | 5

3

6 | 7 | 8

1 | 2 | 4 | 5 | 6 | 7 | 8

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Searching

Precision vs. recall
Scoring
Algorithms and optimizations

Relevancy

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Relevancy

- Textbook answer: How well matches a document a query?
- Business answer: Are the top search results those that make me the most money?
  - marketplace
  - hotel booking website
  - newspaper website

Scoring

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Scoring: `lazy dog`

- Naive: increase a counter if a term is matched
- "the lazy dog" => score 2
- "the lazy frog" => score 1
- "the lazy lazy lazy lazy cat" => score 4 or 1?

Scoring: More than term frequency

- How about incorporating information about the whole document corpus in scoring?
- Are lesser common terms more relevant?
- news paper: `"dieselgate news"`

Scoring: TF-IDF

- Term frequency: number of times a term occurs in a field
- Inverse document frequency: inverse function of the number of documents in which it occurs

Scoring: Vector space model

- Each term is a dimension
- The length is based on tf-idf calculation
- Similarity is the angle between vectors
- Cosine similarity: best match == angle 0°

Scoring: TF-IDF in Lucene

$$score(q,d) = \sum (tf(t \text{ in } d) \cdot idf(t)^2 \cdot t.getBoost() \cdot norm(t,d))$$

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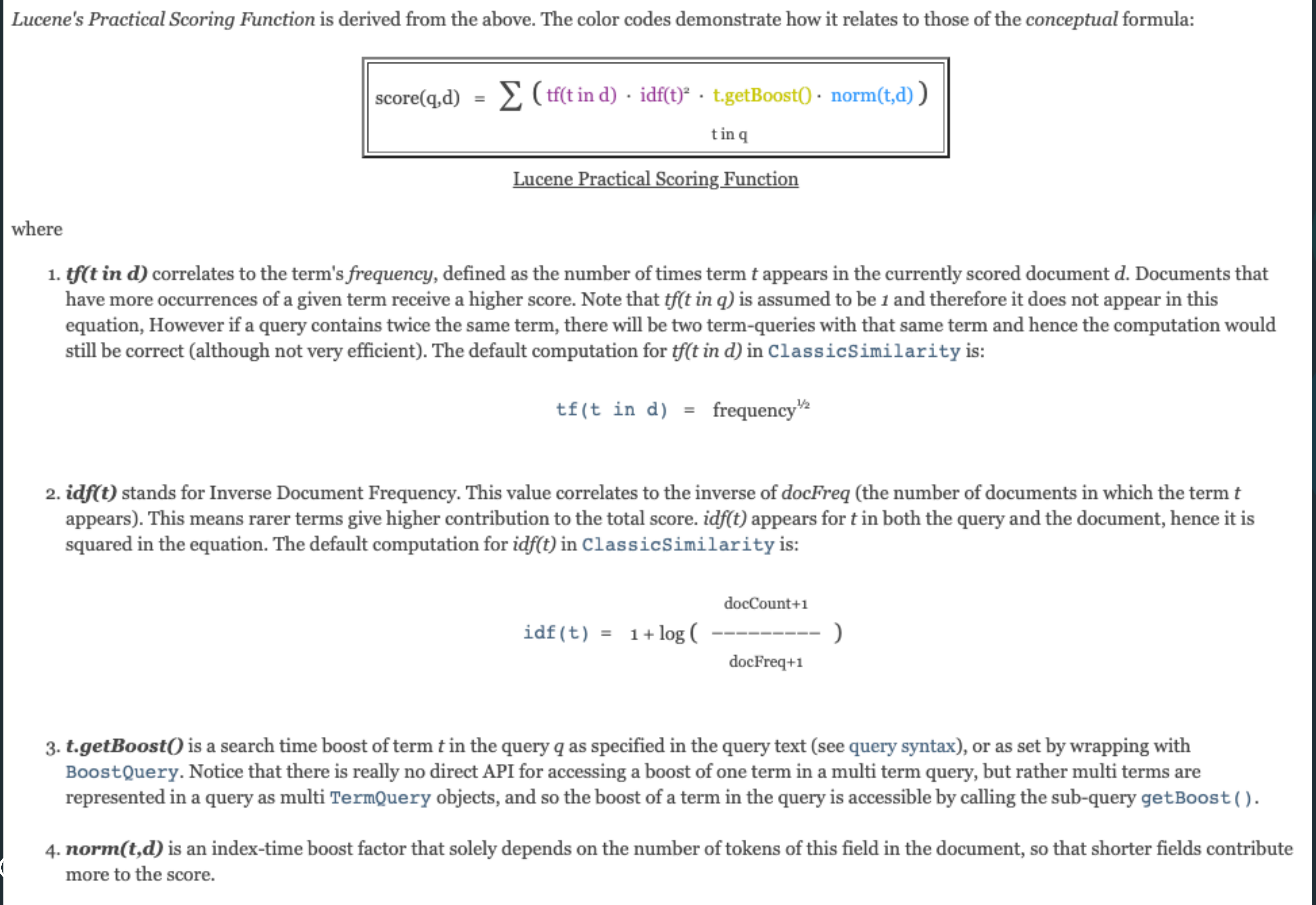


Lucene's Practical Scoring Function is derived from the above. The color codes demonstrate how it relates to those of the *conceptual* formula:

$$\boxed{\text{score}(q,d) \;=\; \sum_{t \text{ in } q} \left(\text{tf}(t \text{ in } d) \cdot \text{idf}(t)^2 \cdot \text{t.getBoost}() \cdot \text{norm}(t,d) \right)}$$

Lucene Practical Scoring Function

where

1. ***tf(t in d)*** correlates to the term's *frequency*, defined as the number of times term *t* appears in the currently scored document *d*. Documents that have more occurrences of a given term receive a higher score. Note that *tf(t in q)* is assumed to be *1* and therefore it does not appear in this equation, However if a query contains twice the same term, there will be two term-queries with that same term and hence the computation would still be correct (although not very efficient). The default computation for *tf(t in d)* in `ClassicSimilarity` is:

$$\texttt{tf(t in d)} \;=\; \text{frequency}^{1/2}$$

2. ***idf(t)*** stands for Inverse Document Frequency. This value correlates to the inverse of *docFreq* (the number of documents in which the term *t* appears). This means rarer terms give higher contribution to the total score. *idf(t)* appears for *t* in both the query and the document, hence it is squared in the equation. The default computation for *idf(t)* in `ClassicSimilarity` is:

$$\texttt{idf(t)} \;=\; 1 + \log\left(\frac{\text{docCount+1}}{\text{docFreq+1}} \right)$$

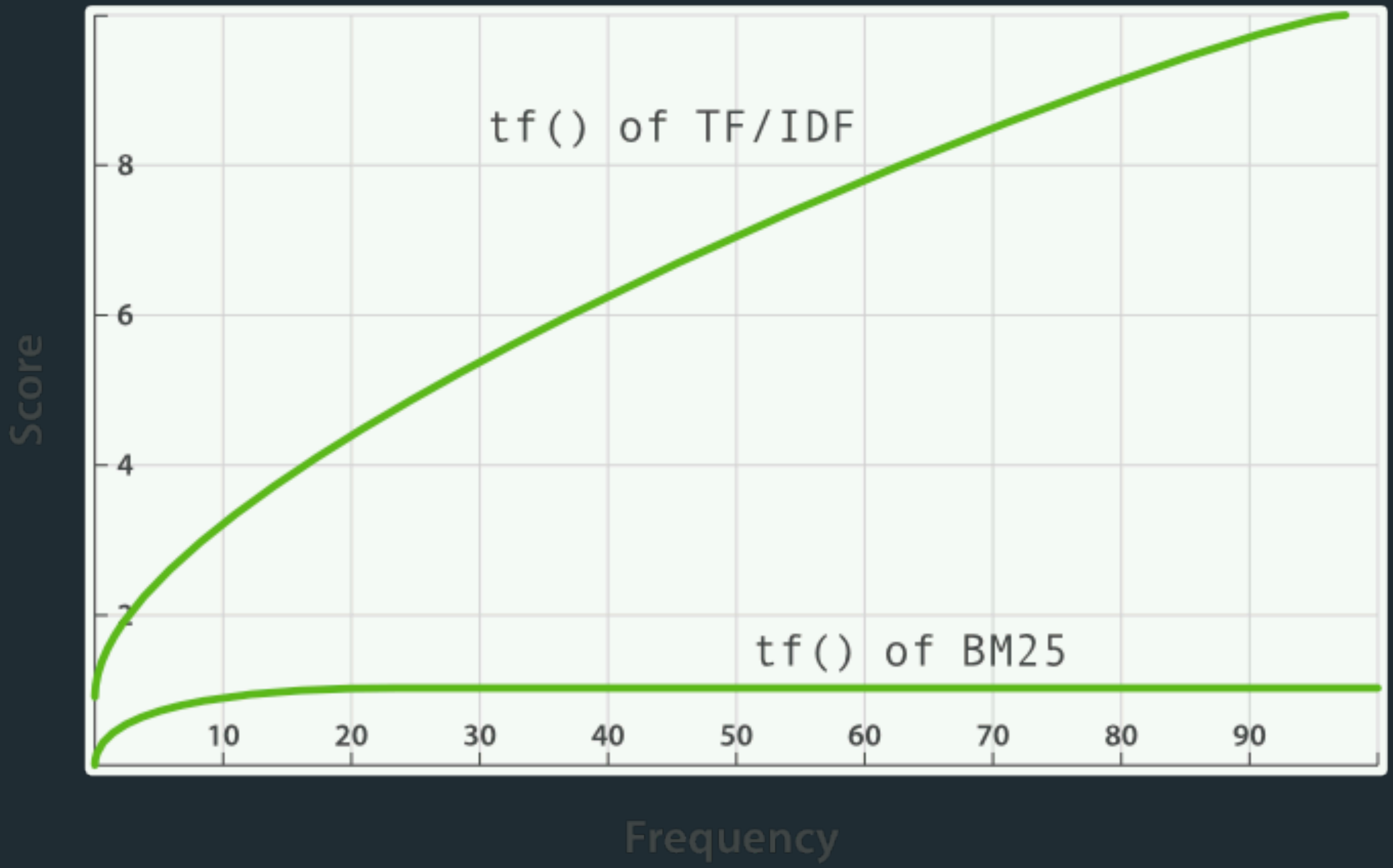
3. ***t.getBoost()*** is a search time boost of term *t* in the query *q* as specified in the query text (see query syntax), or as set by wrapping with `BoostQuery`. Notice that there is really no direct API for accessing a boost of one term in a multi term query, but rather multi terms are represented in a query as multi `TermQuery` objects, and so the boost of a term in the query is accessible by calling the sub-query `getBoost()`.

4. ***norm(t,d)*** is an index-time boost factor that solely depends on the number of tokens of this field in the document, so that shorter fields contribute more to the score.

BM25

- Default in Apache Lucene/Elasticsearch
- Works better with stopwords (high TF)
- Term frequency saturation
- Improved field length normalization (per document)

BM25



https://www.elastic.co/guide/en/elasticsearch/guide/2.x/pluggable-similarites.html

Precision vs. recall

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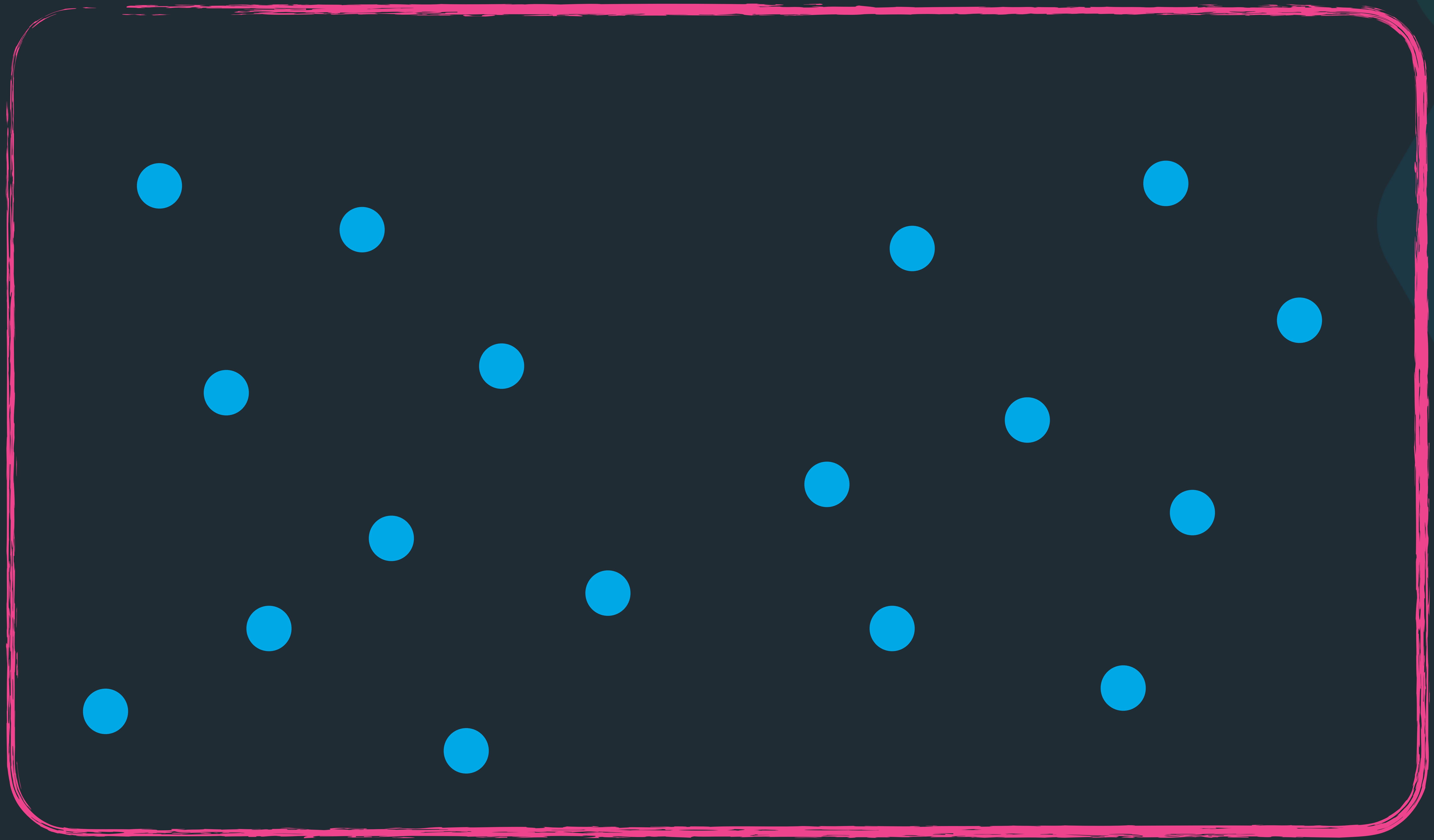
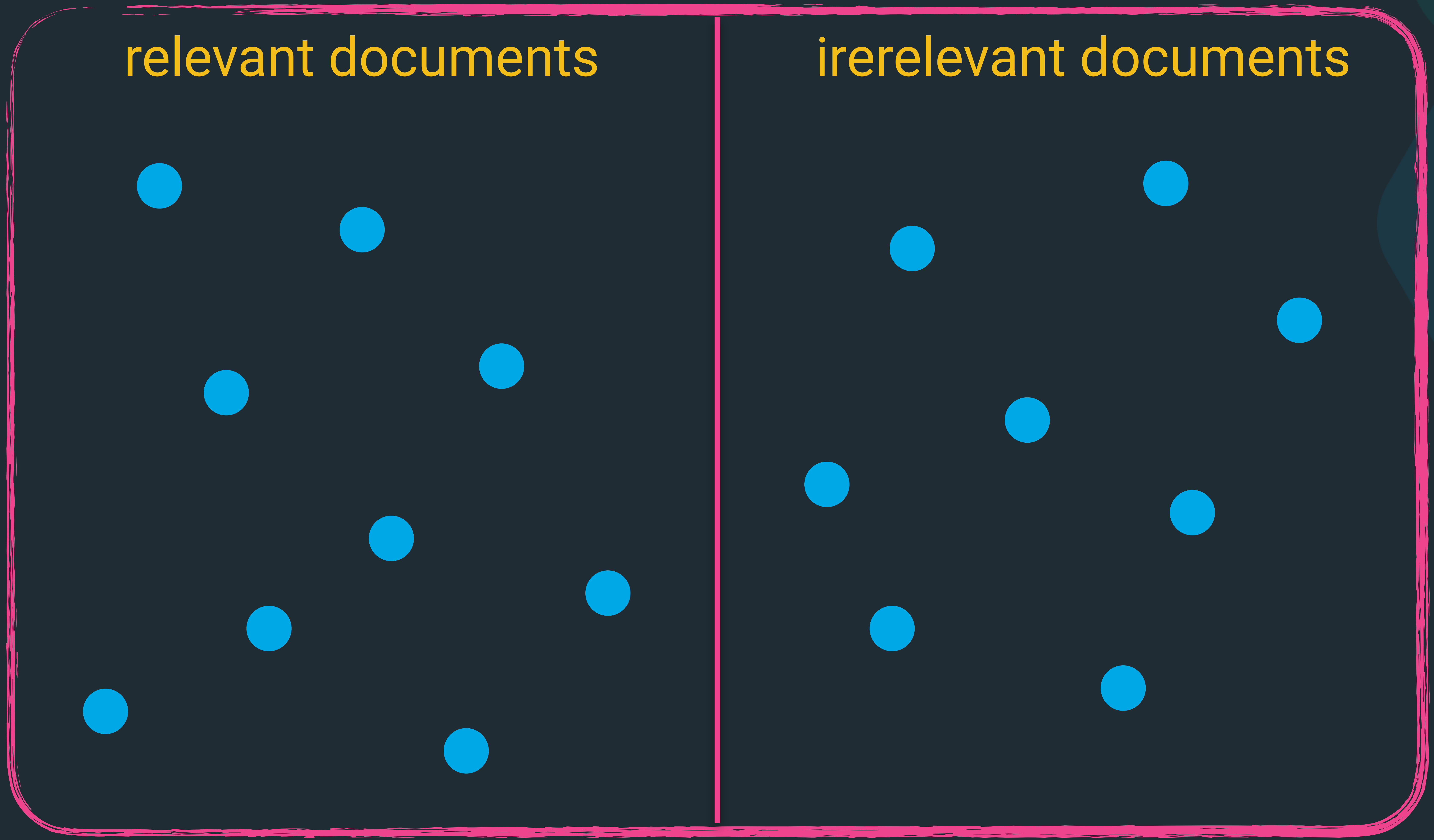
Precision and Recall



Precision and Recall



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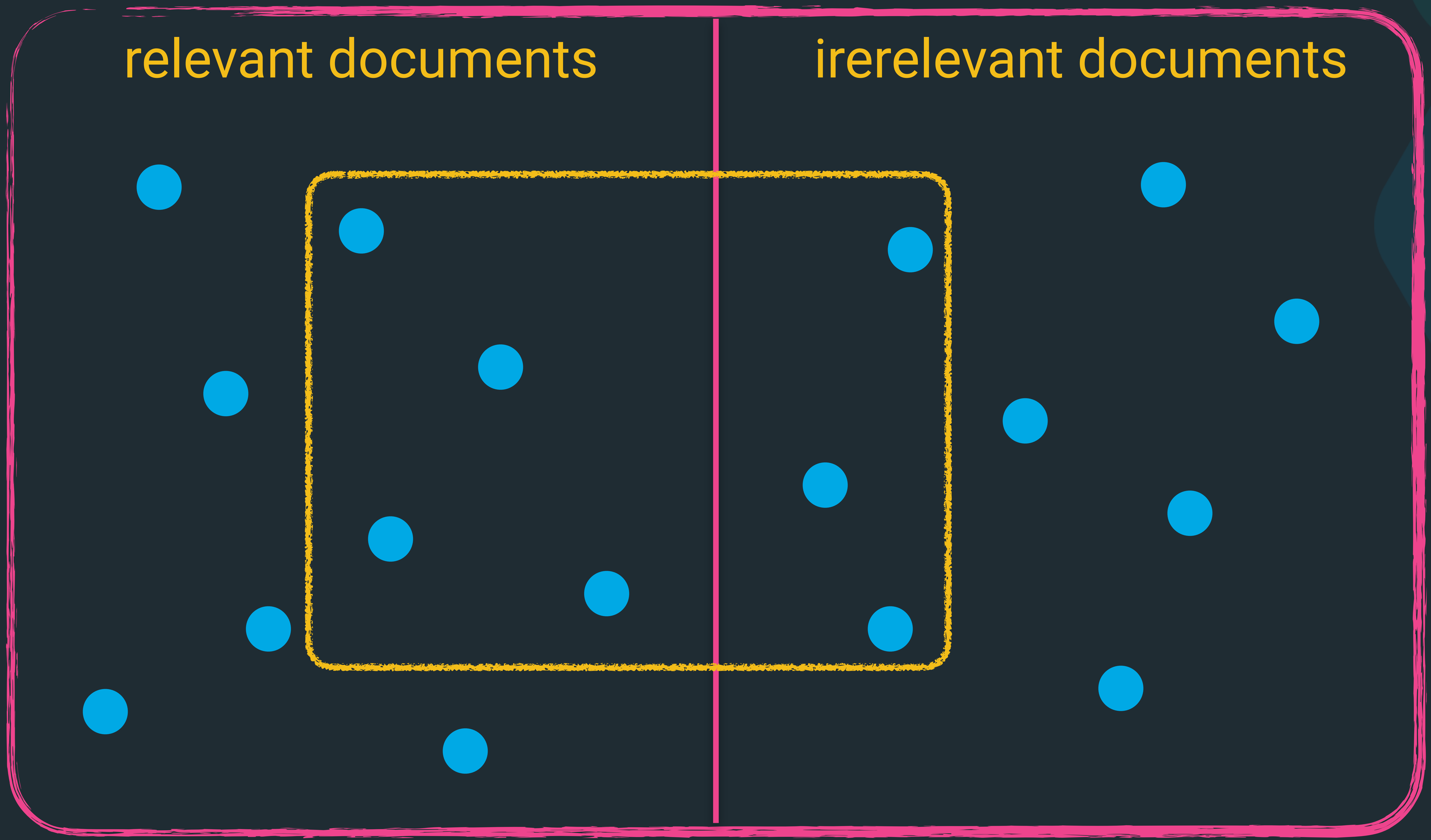
Precision and Recall



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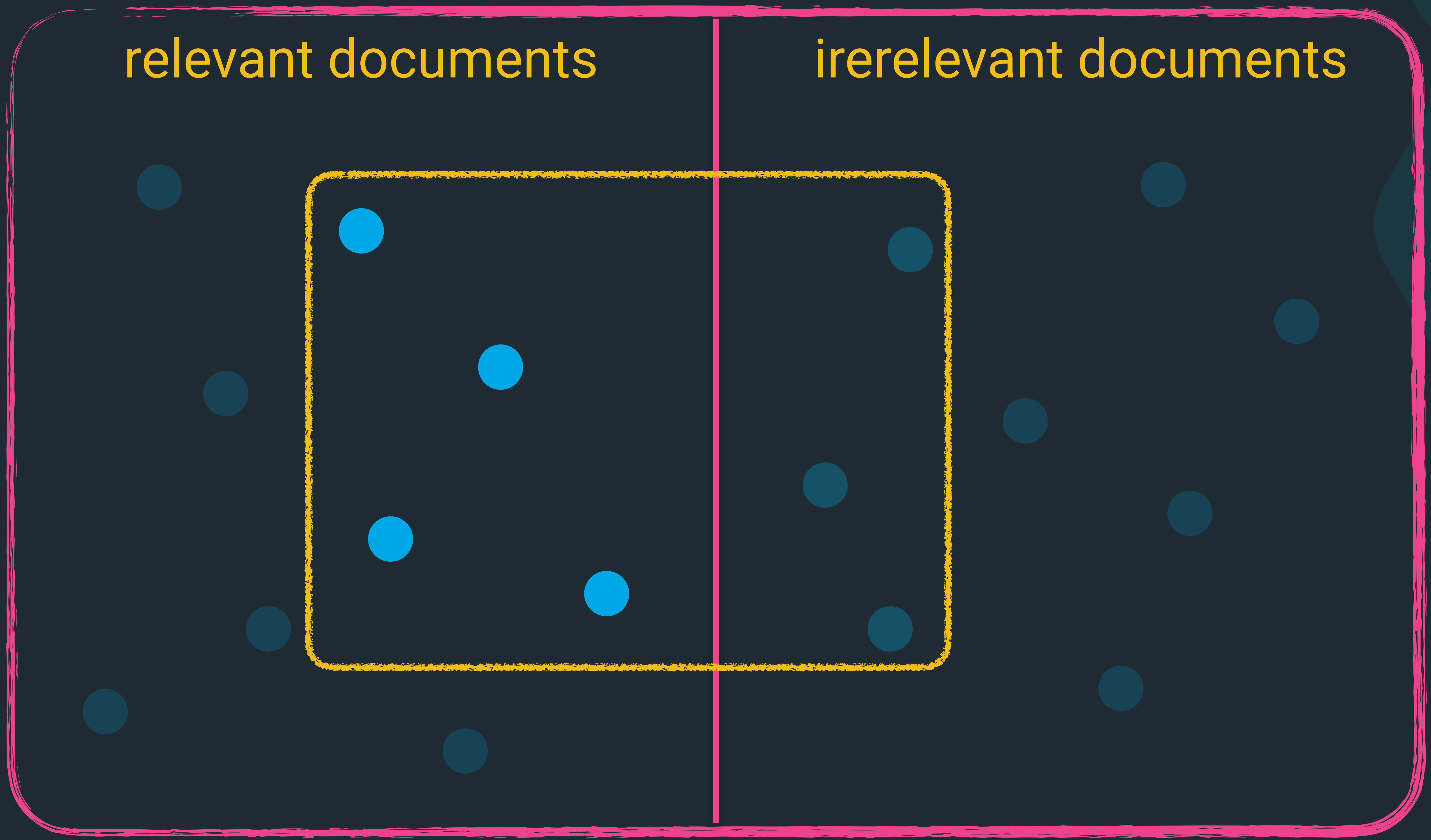
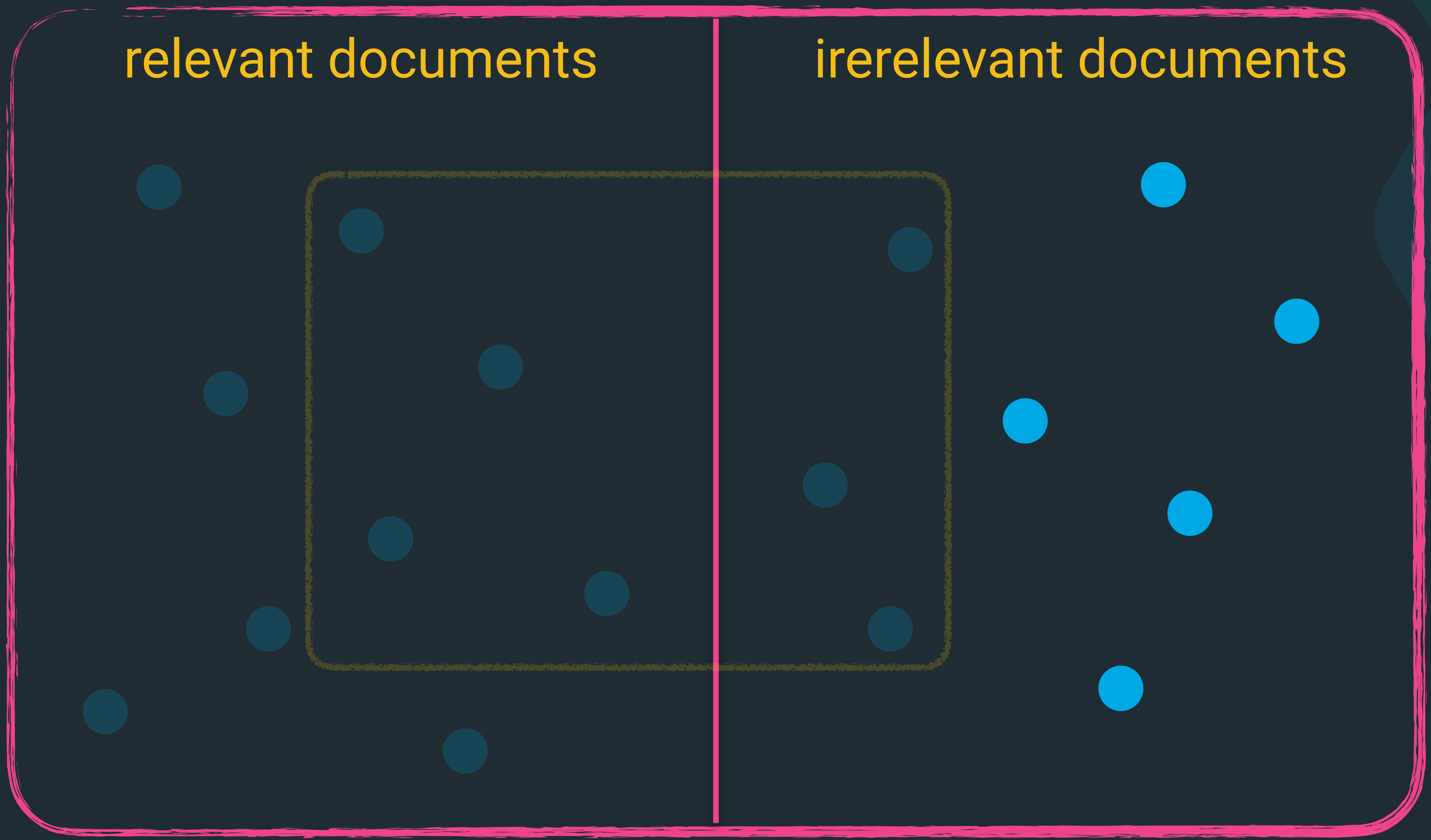
True positives



True negatives



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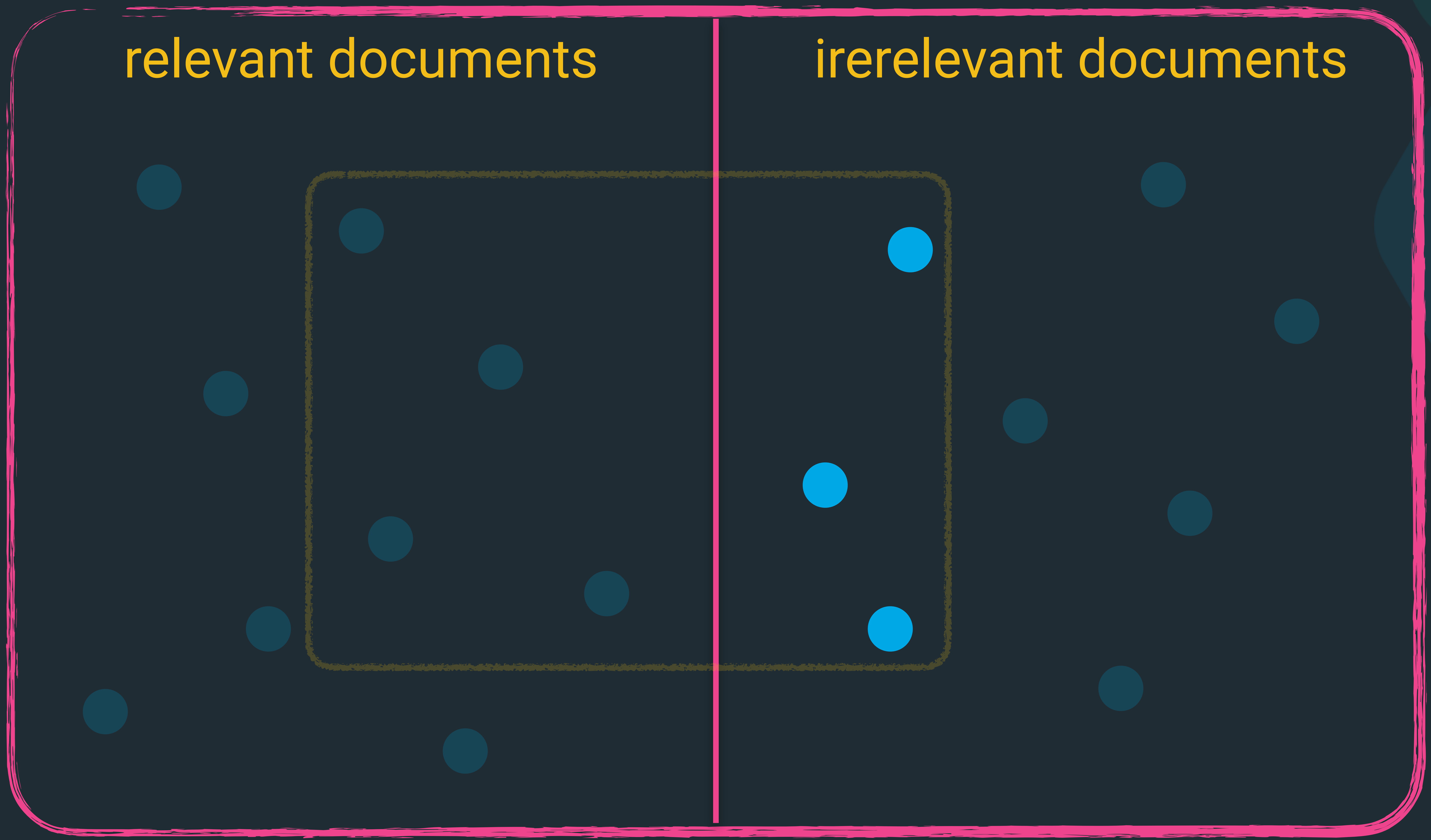
False positives



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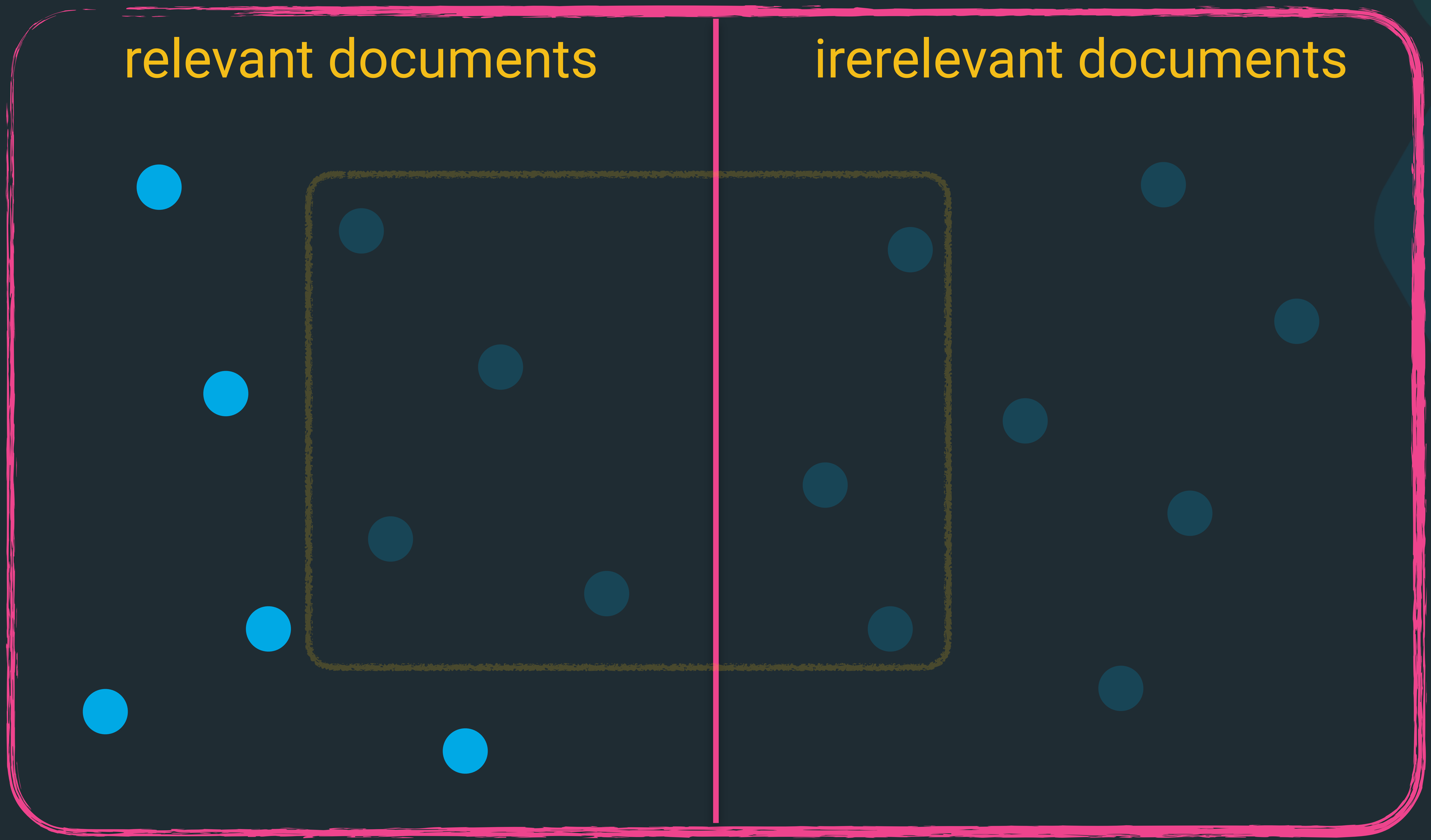
False negatives



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Precision and recall

- Precision: How many selected documents are relevant?
- Recall: How many relevant documents are selected

Under the hood

Optimizations everywhere

- leap frogging, skip lists
- top-k
- two phase iterations
- integer compression

Query two phase iteration

Two phase iteration: Phrase query

- Phrase query: `"quick fox"`
- Approximation phase: document contains terms `quick` and `fox`
- Verification phase: read positions of terms

Two phase iteration: Geo distance query

- Geo distance query: Distance from reference point
- Approximation phase: bbox around point
- Verification phase: exact distance calculation

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Two phase iteration: Geo distance query

```
GET /my_locations/_search
{
  "query": {
    "bool" : {
      "filter" : {
        "geo_distance" : {
          "distance" : "200km",
          "pin.location" : {
            "lat" : 40,
            "lon" : -70
          }
        }
      }
    }
  }
}
```

Two phase iteration: several queries

- Powerful when several queries are used
- `"quick fox" AND brown`
- Approximation: `quick AND fox AND brown`
- Verification: `"quick fox"` position check for hits

Skip lists & leap frogging

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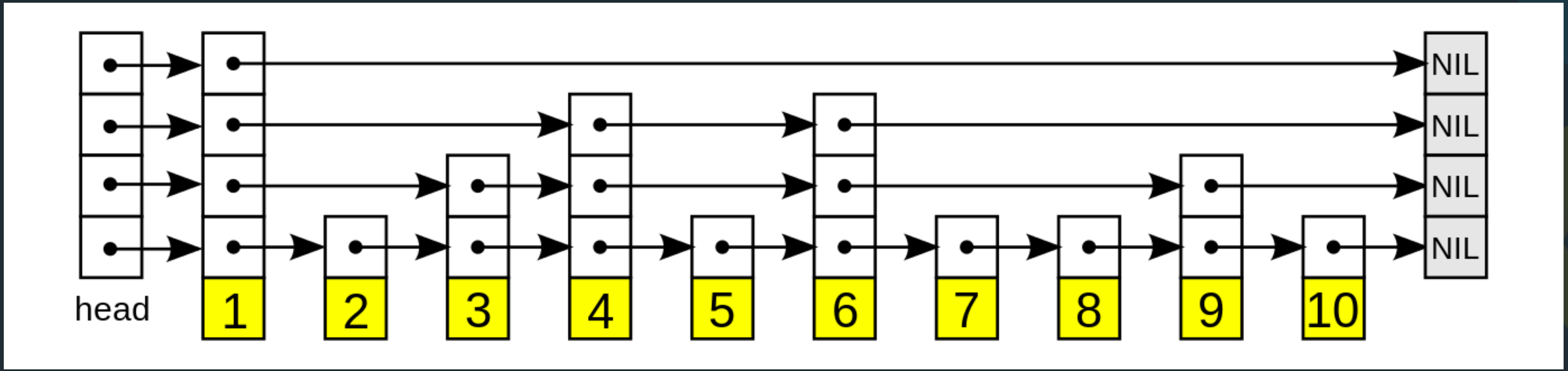
Skip lists

- Term dictionary is a sorted skip list
- Skip list is a linked list with 'express lanes' to leap forward



https://en.wikipedia.org/wiki/Skip_list

Leap frogging

```
elasticsearch AND kibana AND logstash
```

Leap frogging

```
elasticsearch AND kibana AND logstash
```

266	568	266
102	302	199
98	102	150
60	59	102
18	5	5
5	3	
1		

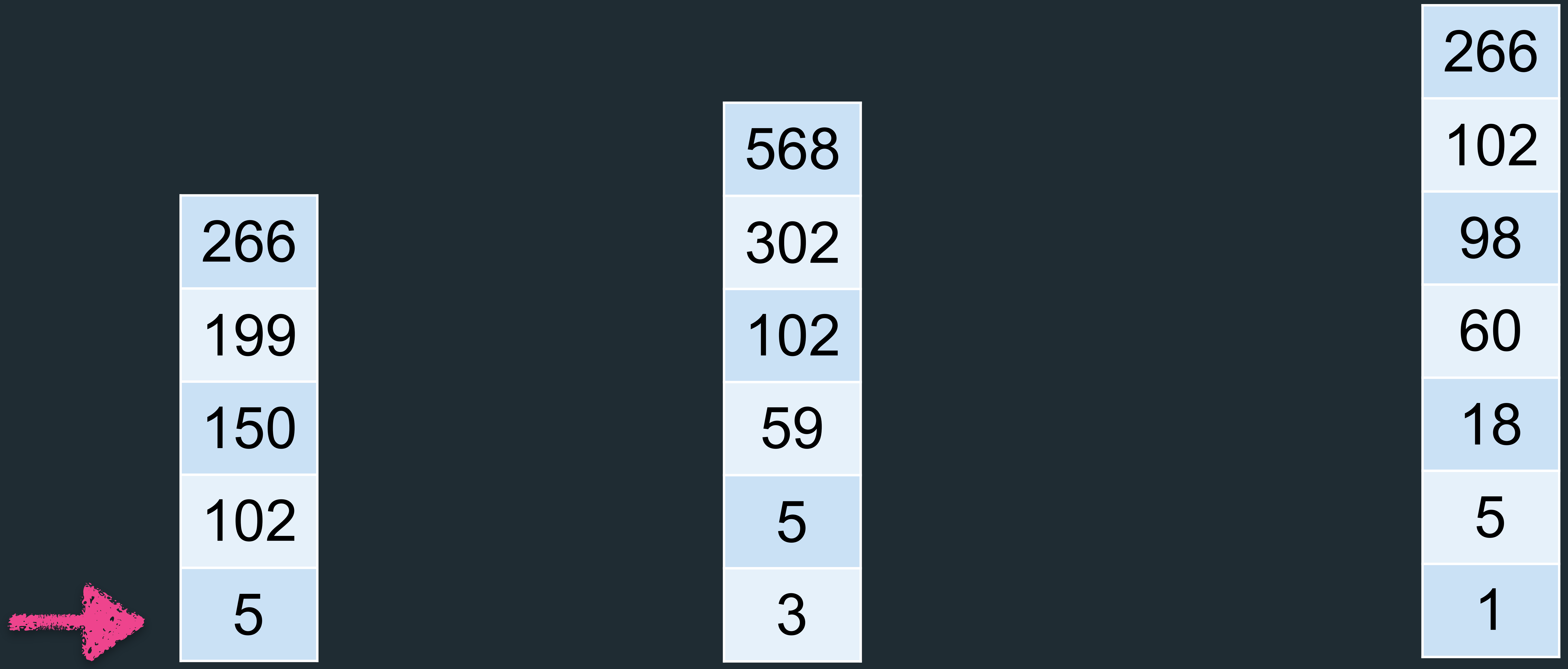
Leap frogging

```
logstash AND kibana AND elasticsearch
```

		266
	568	102
266	302	98
199	102	60
150	59	18
102	5	5
5	3	1

Leap frogging

`logstash AND kibana AND elasticsearch`



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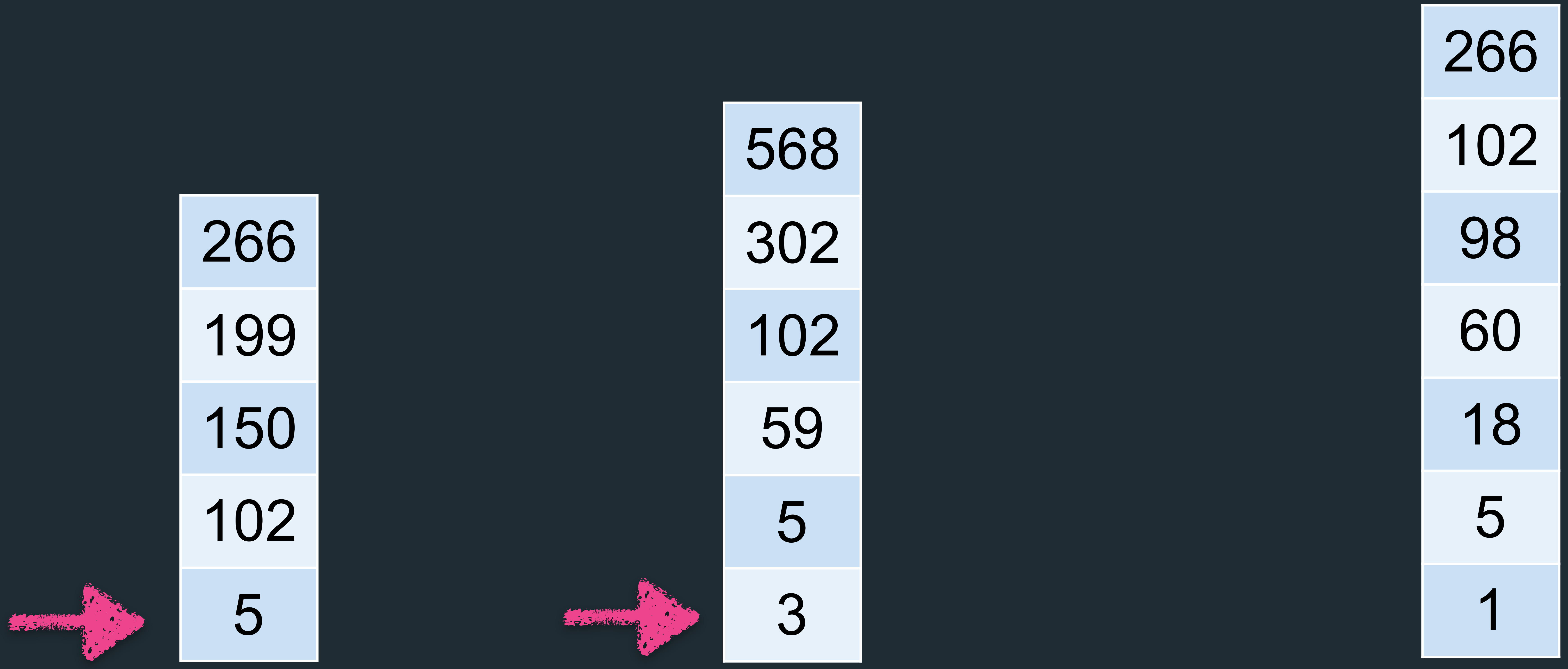
elastic

Leap frogging

`logstash AND kibana AND elasticsearch`



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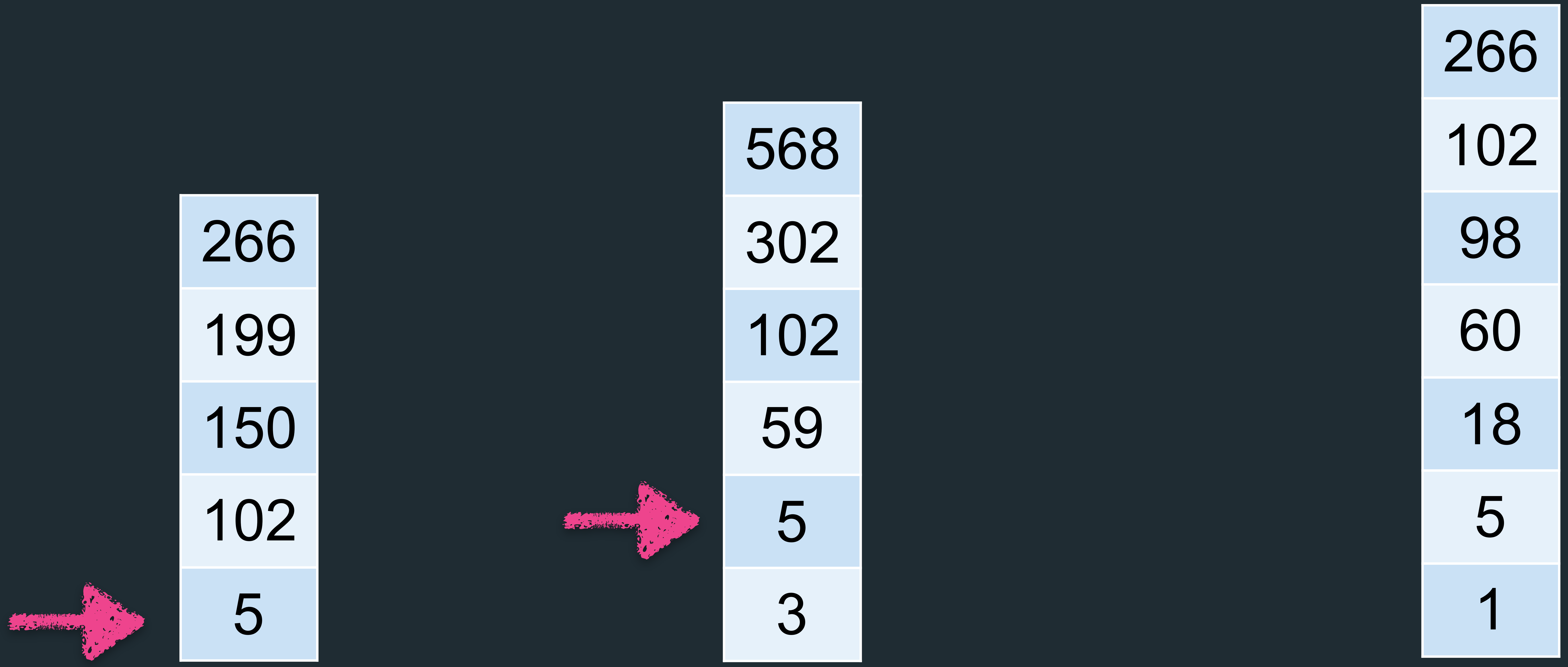

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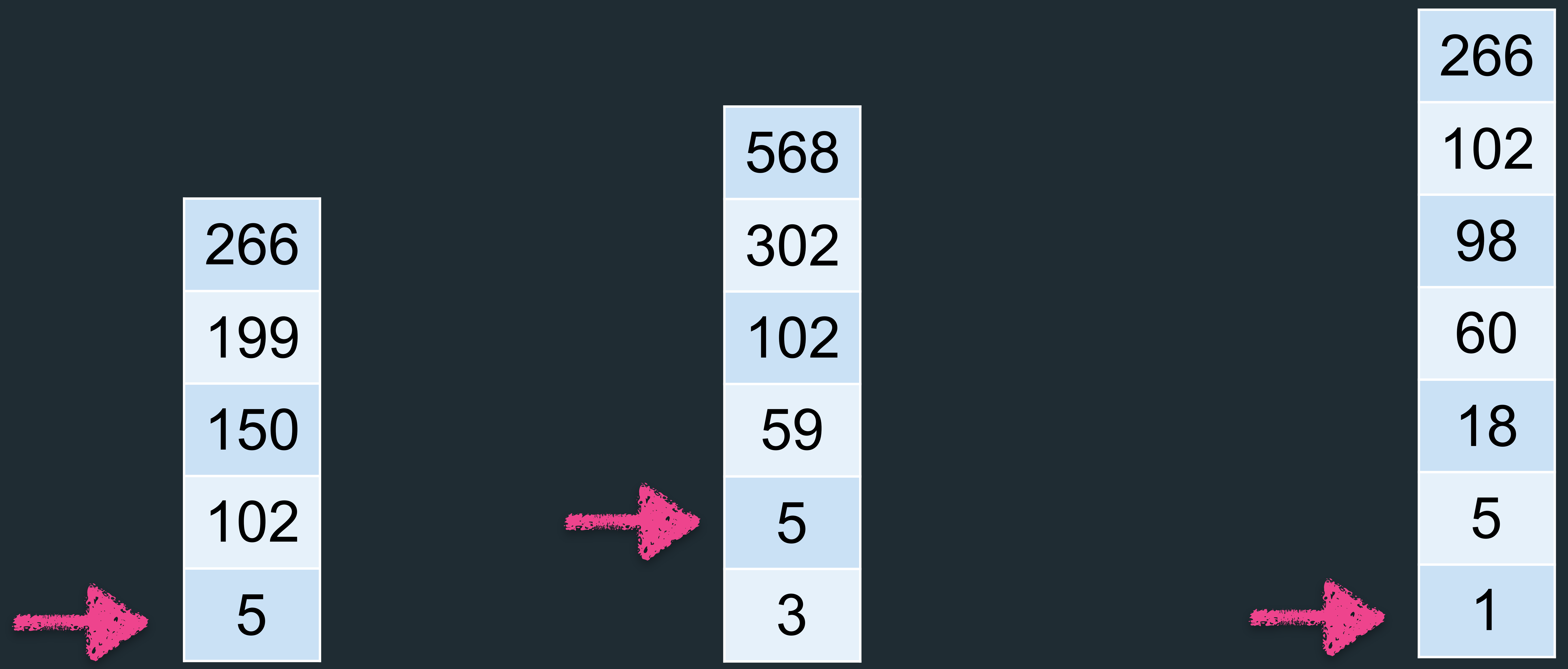

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Leap frogging

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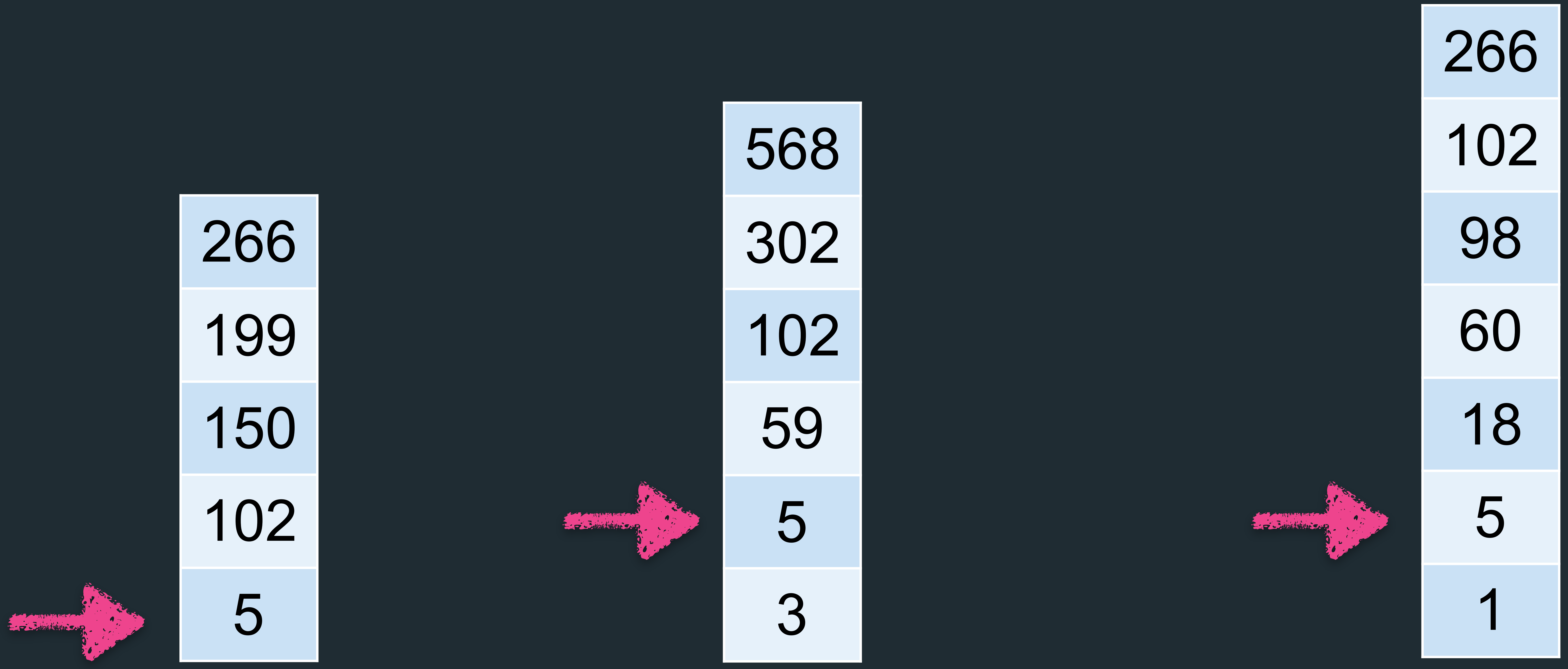

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Leap frogging

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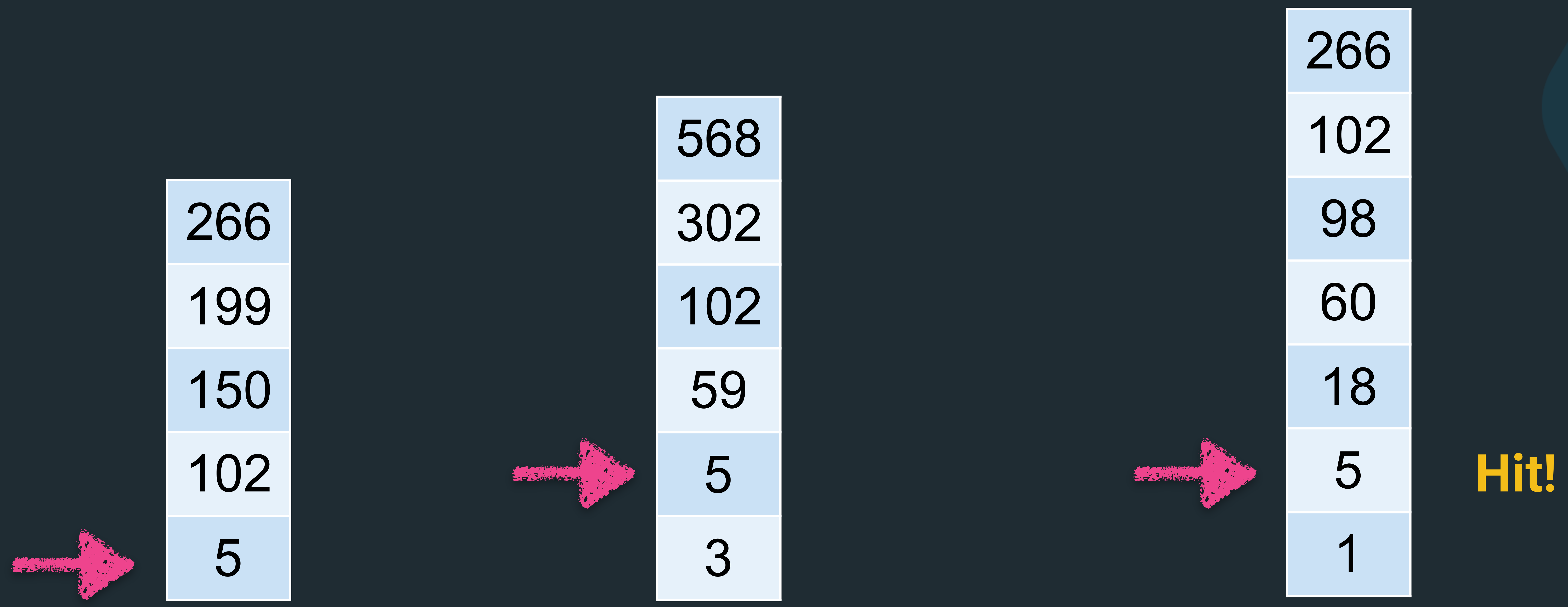

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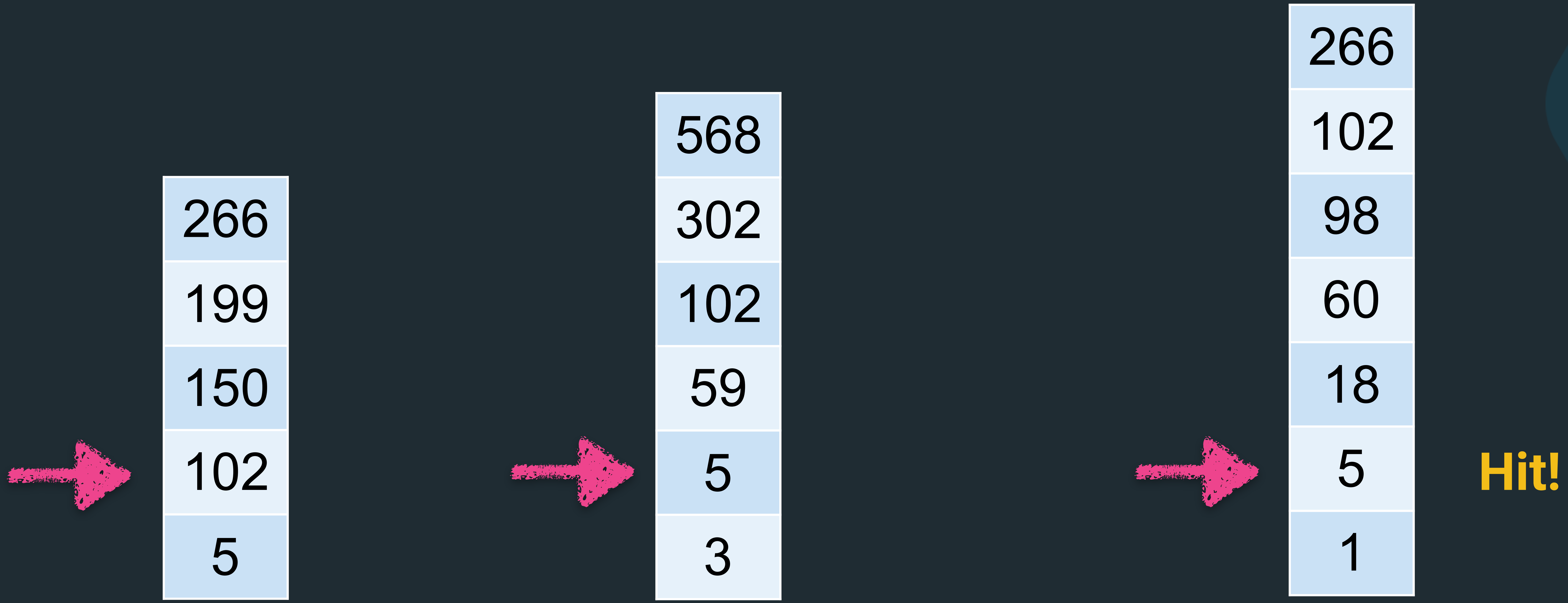
Hit!

Leap frogging

`logstash AND kibana AND elasticsearch`



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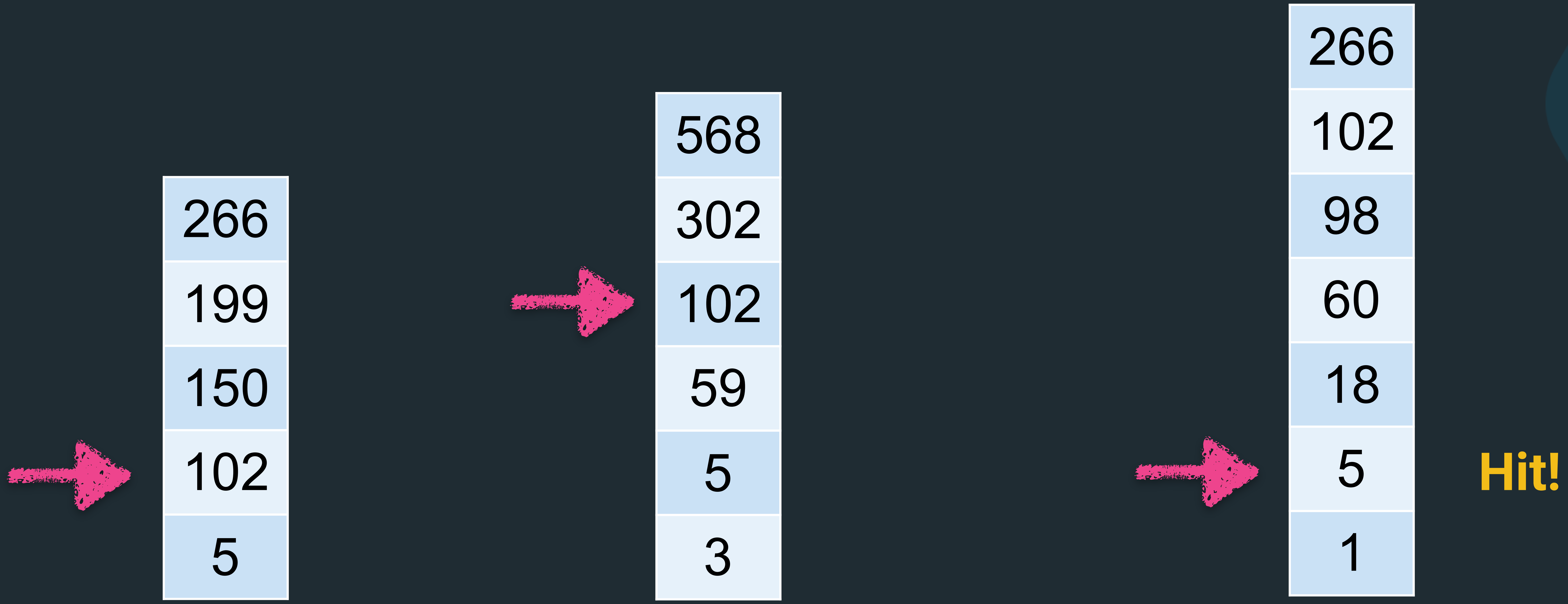

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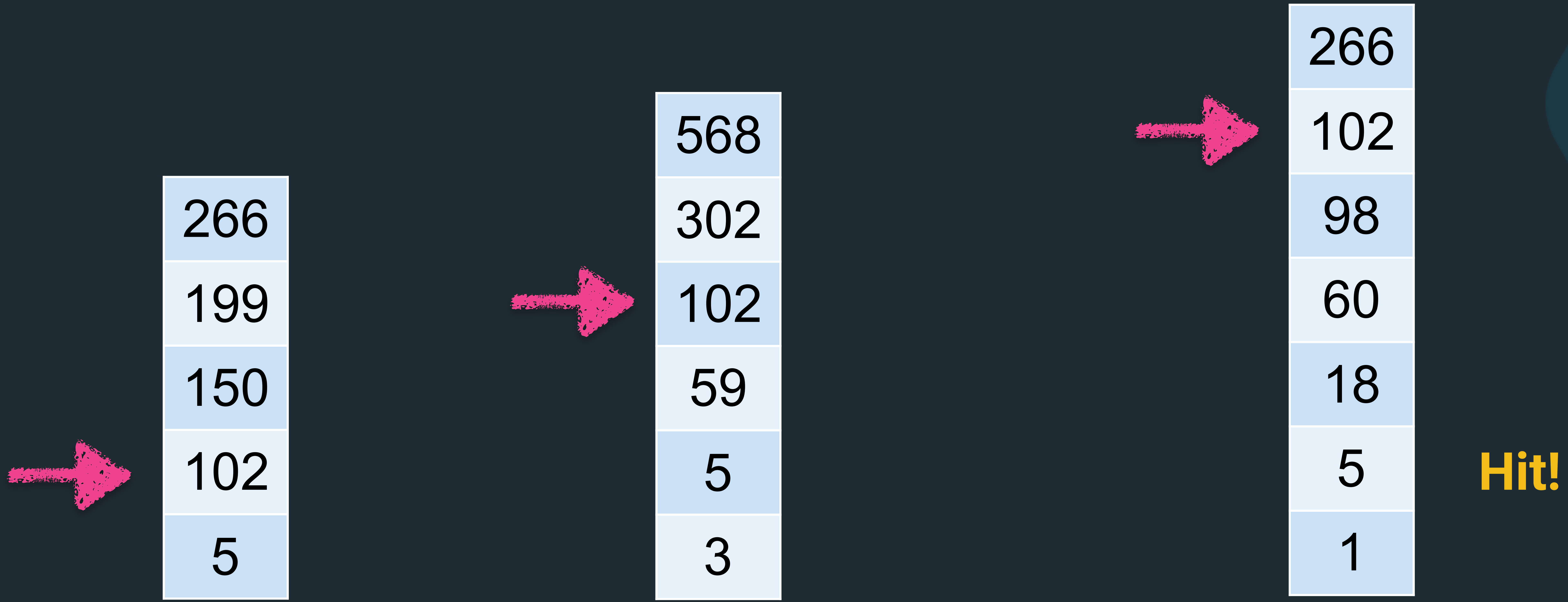

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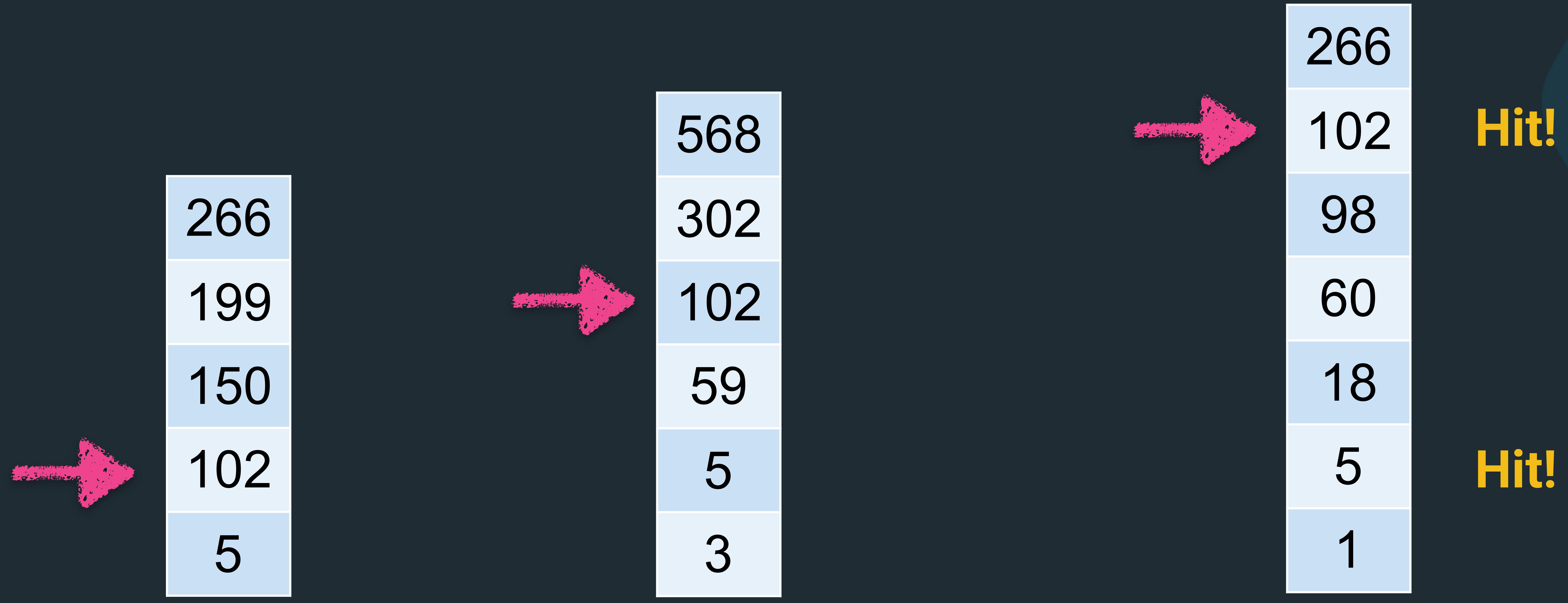

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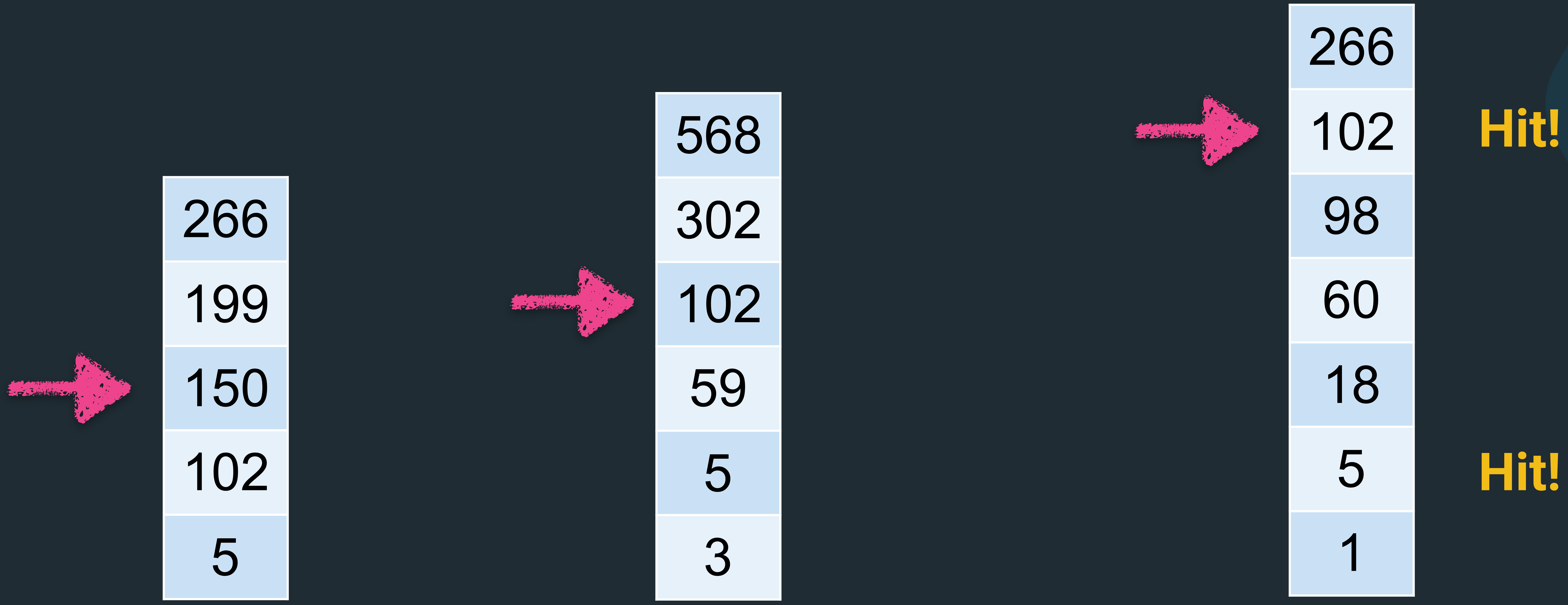

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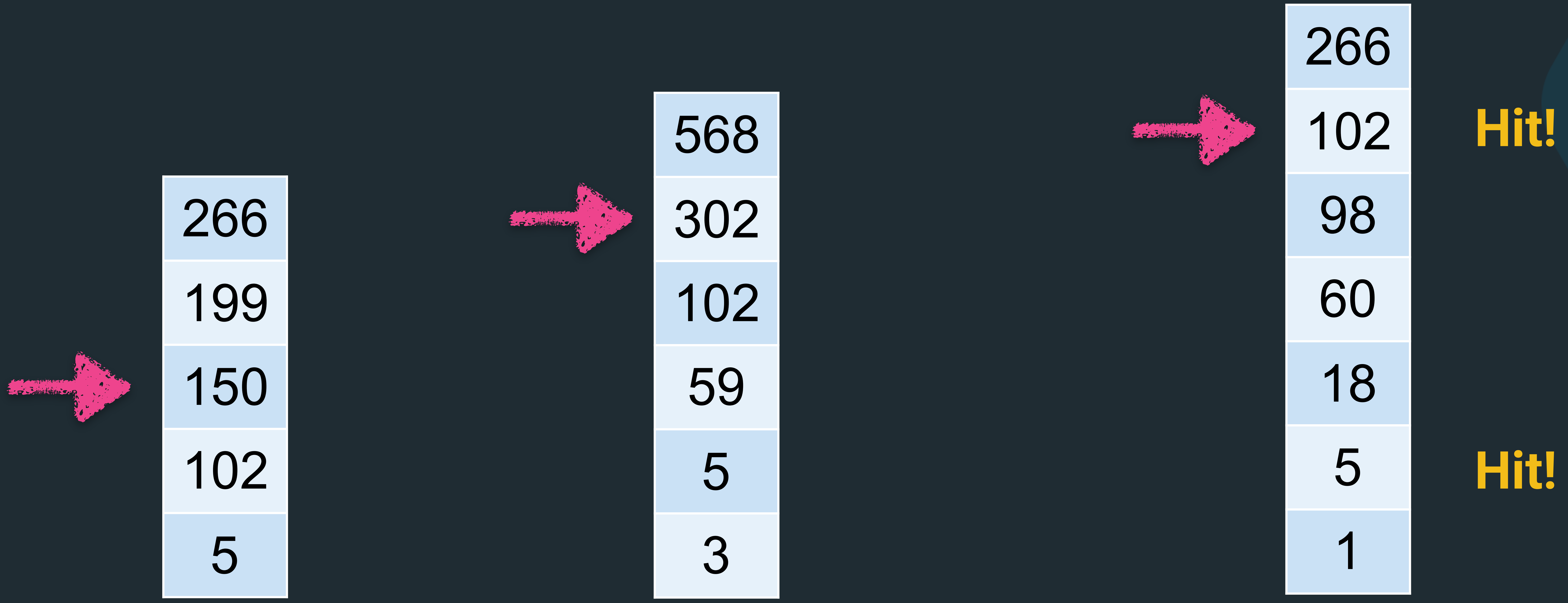

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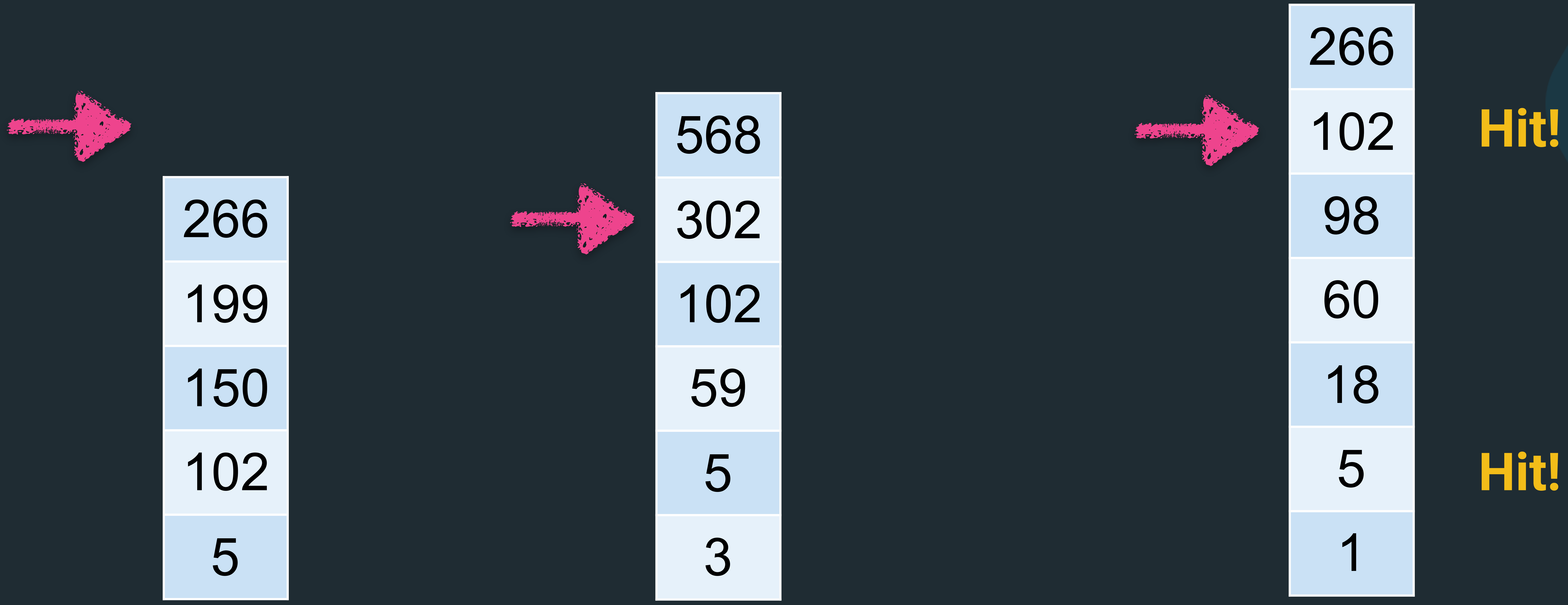

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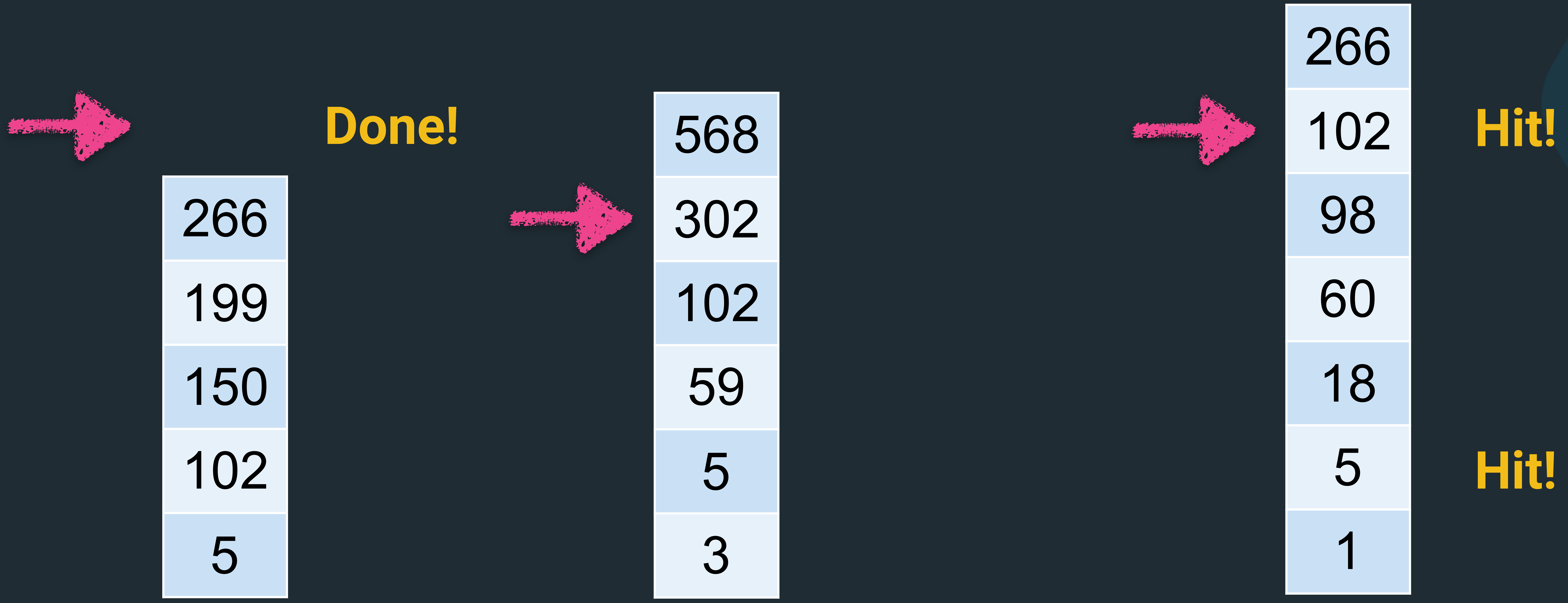
3

266
102 Hit!
98
60
18
5 Hit!
1

Leap frogging

```
logstash AND kibana AND elasticsearch
```



Done!

266
199
150
102
5

568
302
102
59
5
3

266
102
98
60
18
5
1

Hit!

Hit!

Top-k retrieval

elastic

Top-k retrieval

- `elasticsearch OR kibana`
- top 10 results wanted
- maximum score for `kibana` is 3.0
- maximum score for `elasticsearch` is 5.0
- collecting documents: when 10th hit has score > 3, then only documents with `elasticsearch` need to be collected
- total hit count is not accurate

Top-k retrieval

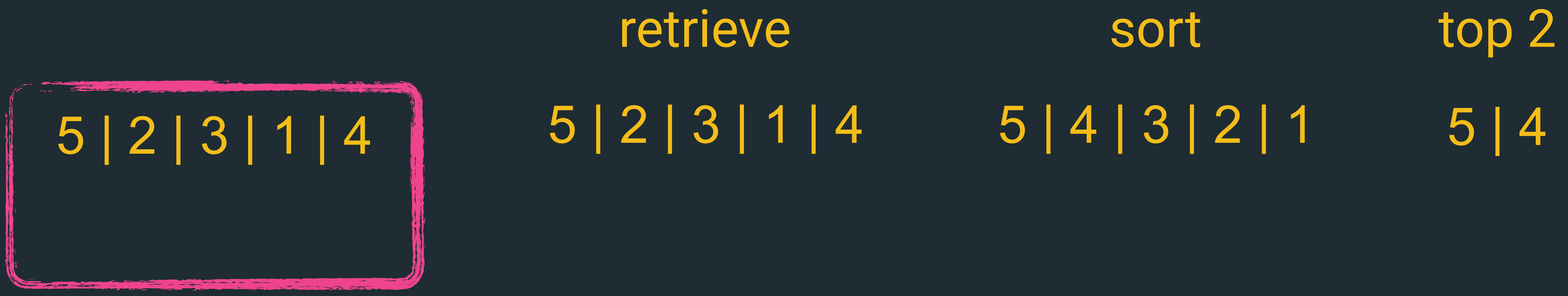
TermQuery
Queries/sec
1.3K
1.2K
1.1K
1K
900
800
700
600
500
400
300
200
100
0
Oct 2017
Jan 2018
Apr 2018
Jul 2018
Oct 2018
Date
CC
CD
CE
C
CG
CH
CJ
CK
CL
C
CN
CO
CP
CQ
BooleanQuery (OR, high freq, medium freq term)
2017/12/18 09:41:42:
QPS: 5.31
Queries/sec
28
26
24
22
20
18
16
14
12
10
8
6
4
Oct 2017
Jan 2018
Apr 2018
Jul 2018
Oct 2018
Jan 2019
Apr 2019
Jul 2019
Date
CC
CD
CE
C
CG
CH
CJ
CK
CL
CM
CN
CO
CP
CQ

Index sorting

elastic

Order index by field values

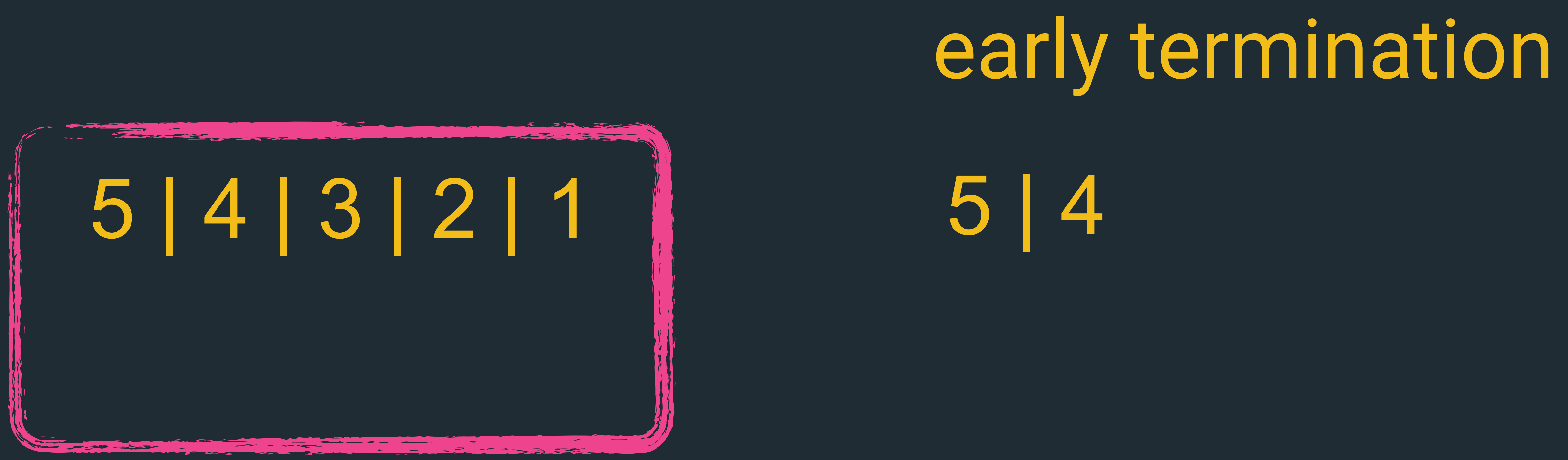
- each segment is sorted before write
- criteria can be chosen by the user



	retrieve	sort	top 2
5 | 2 | 3 | 1 | 4	5 | 2 | 3 | 1 | 4	5 | 4 | 3 | 2 | 1	5 | 4

Order index by field values

- each segment is sorted before write
- criteria can be chosen by the user



early termination

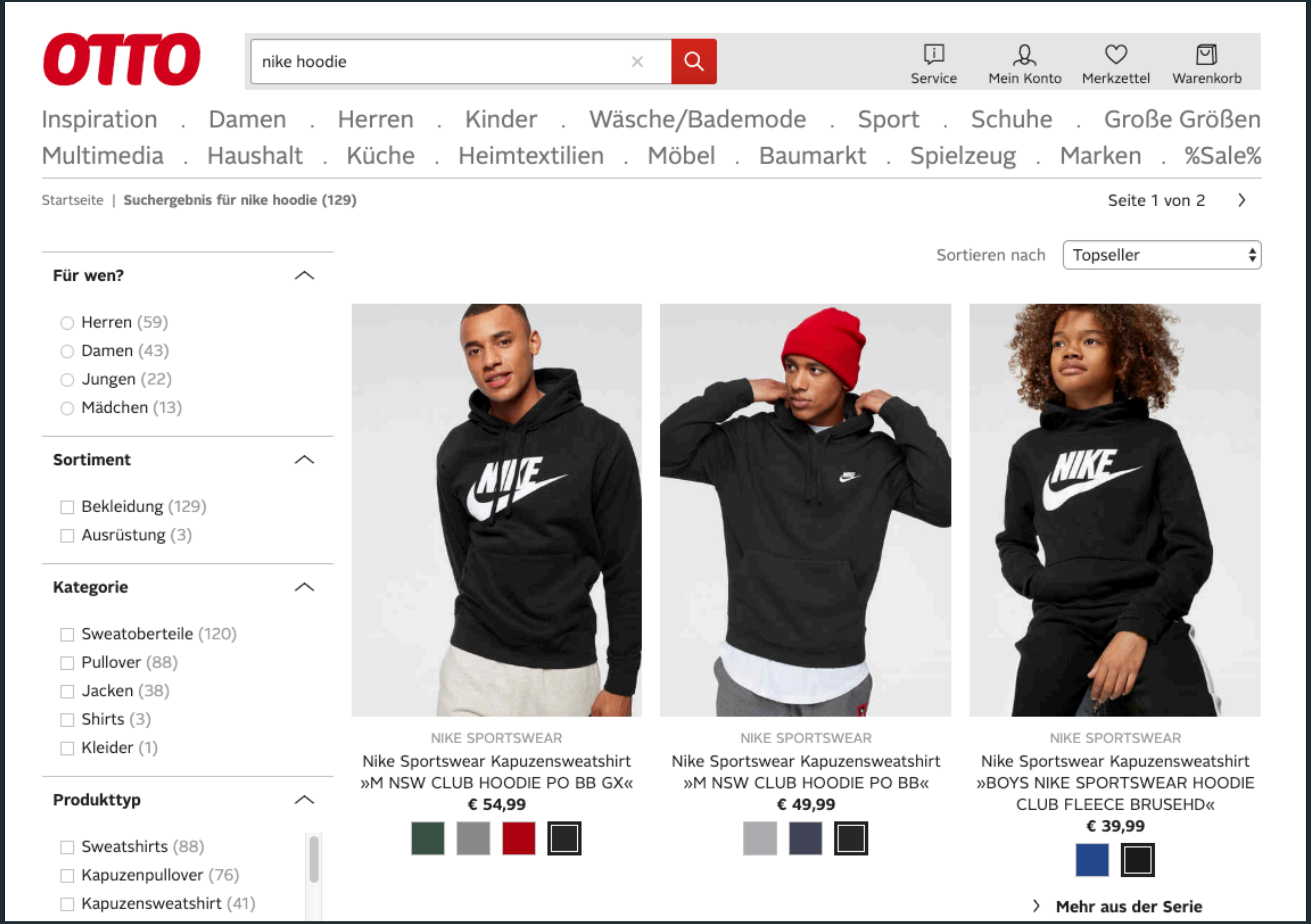
5 | 4 | 3 | 2 | 1

5 | 4

Aggregations

Reducing data

Aggregations



OTTO

nike hoodie

Service · Mein Konto · Merkzettel · Warenkorb

Inspiration . Damen . Herren . Kinder . Wäsche/Bademode . Sport . Schuhe . Große Größen
Multimedia . Haushalt . Küche . Heimtextilien . Möbel . Baumarkt . Spielzeug . Marken . %Sale%

Startseite | **Suchergebnis für nike hoodie (129)**

Seite 1 von 2

Sortieren nach: Topseller

Für wen?

- ○ Herren (59)
- ○ Damen (43)
- ○ Jungen (22)
- ○ Mädchen (13)

Sortiment

- □ Bekleidung (129)
- □ Ausrüstung (3)

Kategorie

- □ Sweatoberteile (120)
- □ Pullover (88)
- □ Jacken (38)
- □ Shirts (3)
- □ Kleider (1)

Produkttyp

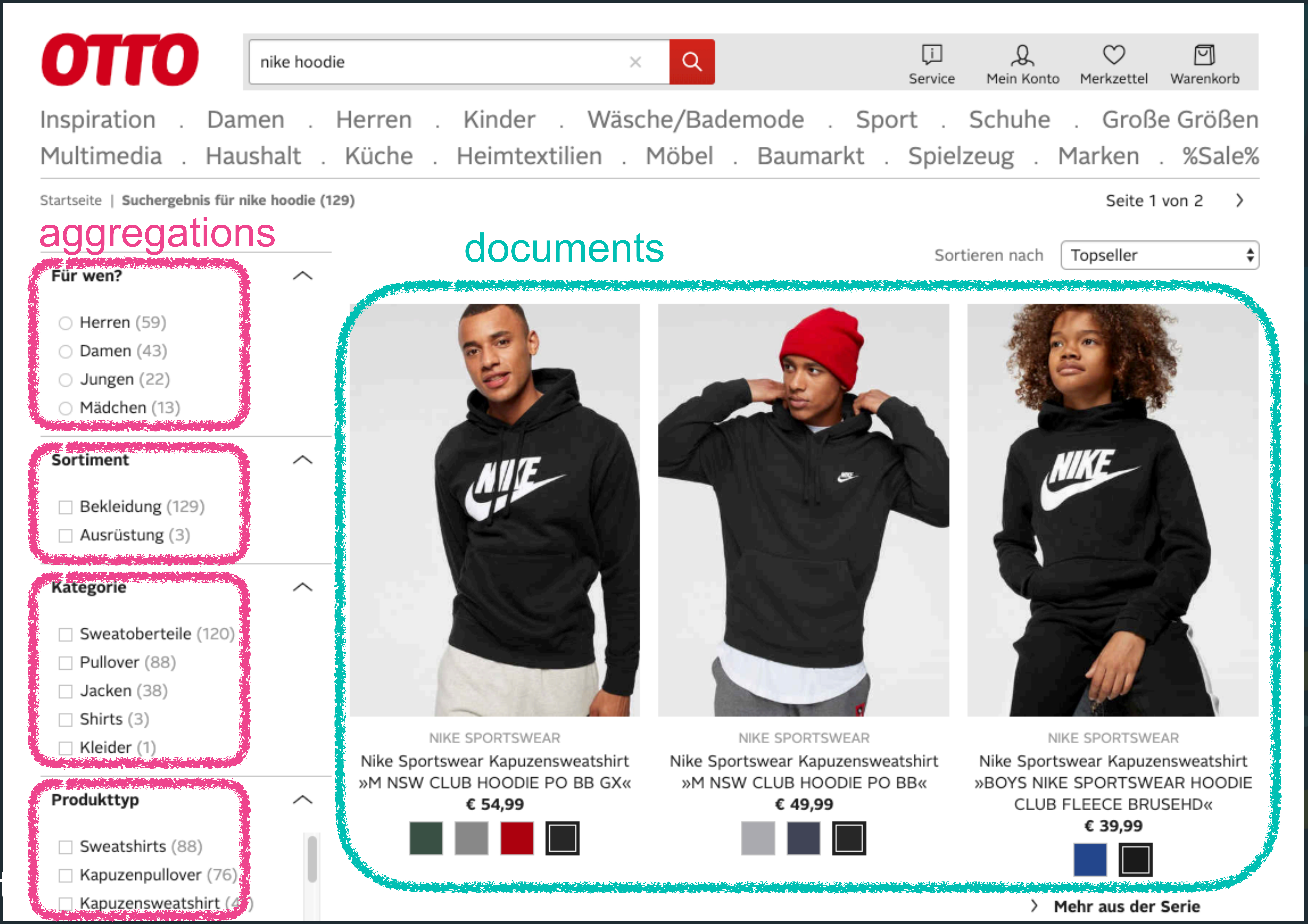
- □ Sweatshirts (88)
- □ Kapuzenpullover (76)
- □ Kapuzensweatshirt (41)

NIKE SPORTSWEAR
Nike Sportswear Kapuzensweatshirt »M NSW CLUB HOODIE PO BB GX«
€ 54,99

NIKE SPORTSWEAR
Nike Sportswear Kapuzensweatshirt »M NSW CLUB HOODIE PO BB«
€ 49,99

NIKE SPORTSWEAR
Nike Sportswear Kapuzensweatshirt »BOYS NIKE SPORTSWEAR HOODIE CLUB FLEECE BRUSEHD«
€ 39,99

› **Mehr aus der Serie**



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Startseite | **Suchergebnis für nike hoodie (129)**

Seite 1 von 2 ›

aggregations

documents

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🟩 ⬜ 🟥 ⬛

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⬜ 🟦 ⬛

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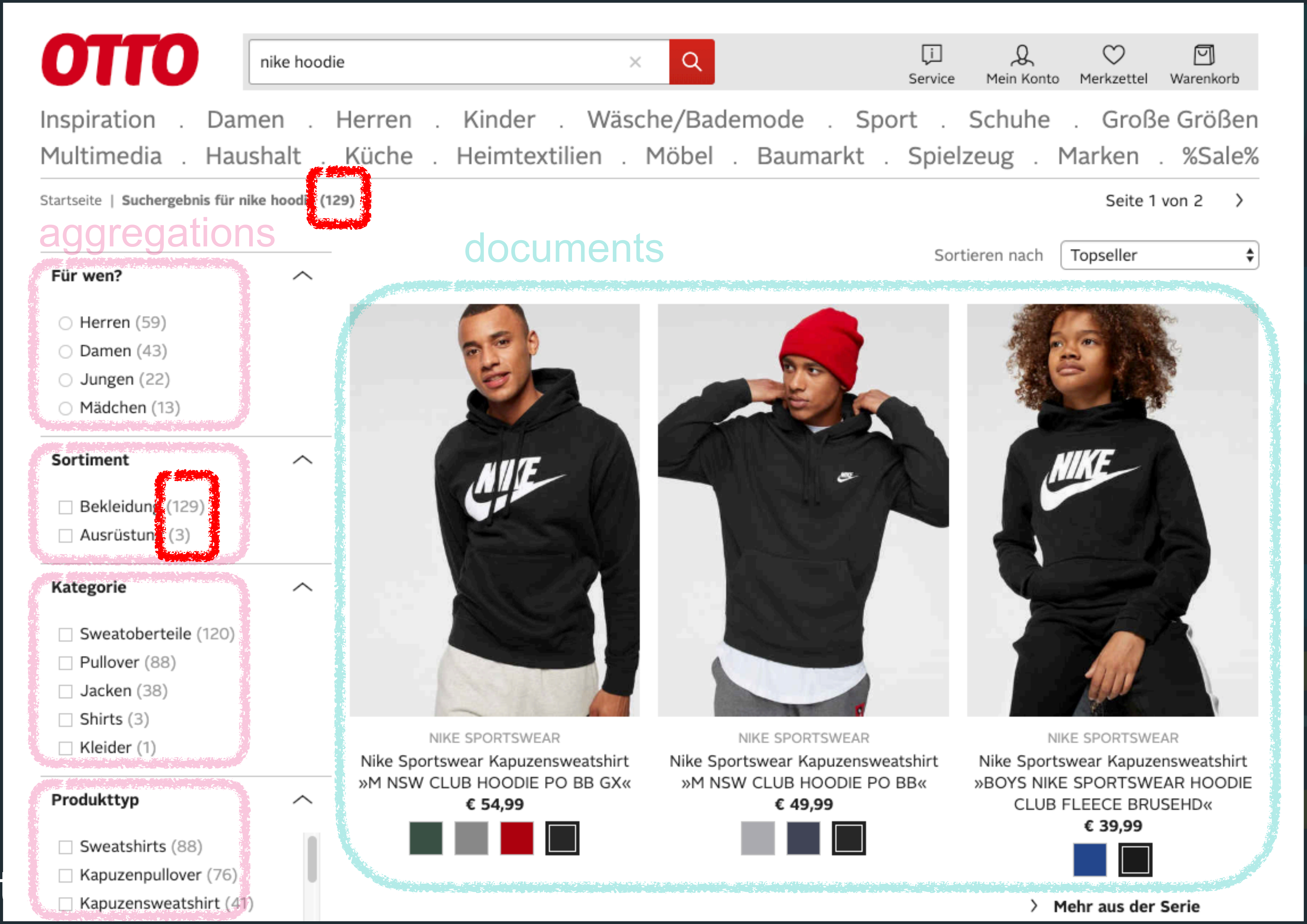
Nike Sportswear Kapuzensweatshirt »BOYS NIKE SPORTSWEAR HOODIE CLUB FLEECE BRUSEHD«
€ 39,99
🟦 ⬛

› **Mehr aus der Serie**

elast



OTTO

nike hoodie ×

Inspiration . Damen . Herren . Kinder . Wäsche/Bademode . Sport . Schuhe . Große Größen
Multimedia . Haushalt . Küche . Heimtextilien . Möbel . Baumarkt . Spielzeug . Marken . %Sale%

Startseite | Suchergebnis für nike hoodie (129)

Seite 1 von 2 ›

aggregations

documents

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€ 39,99

› Mehr aus der Serie

Bucketing documents

Pumps

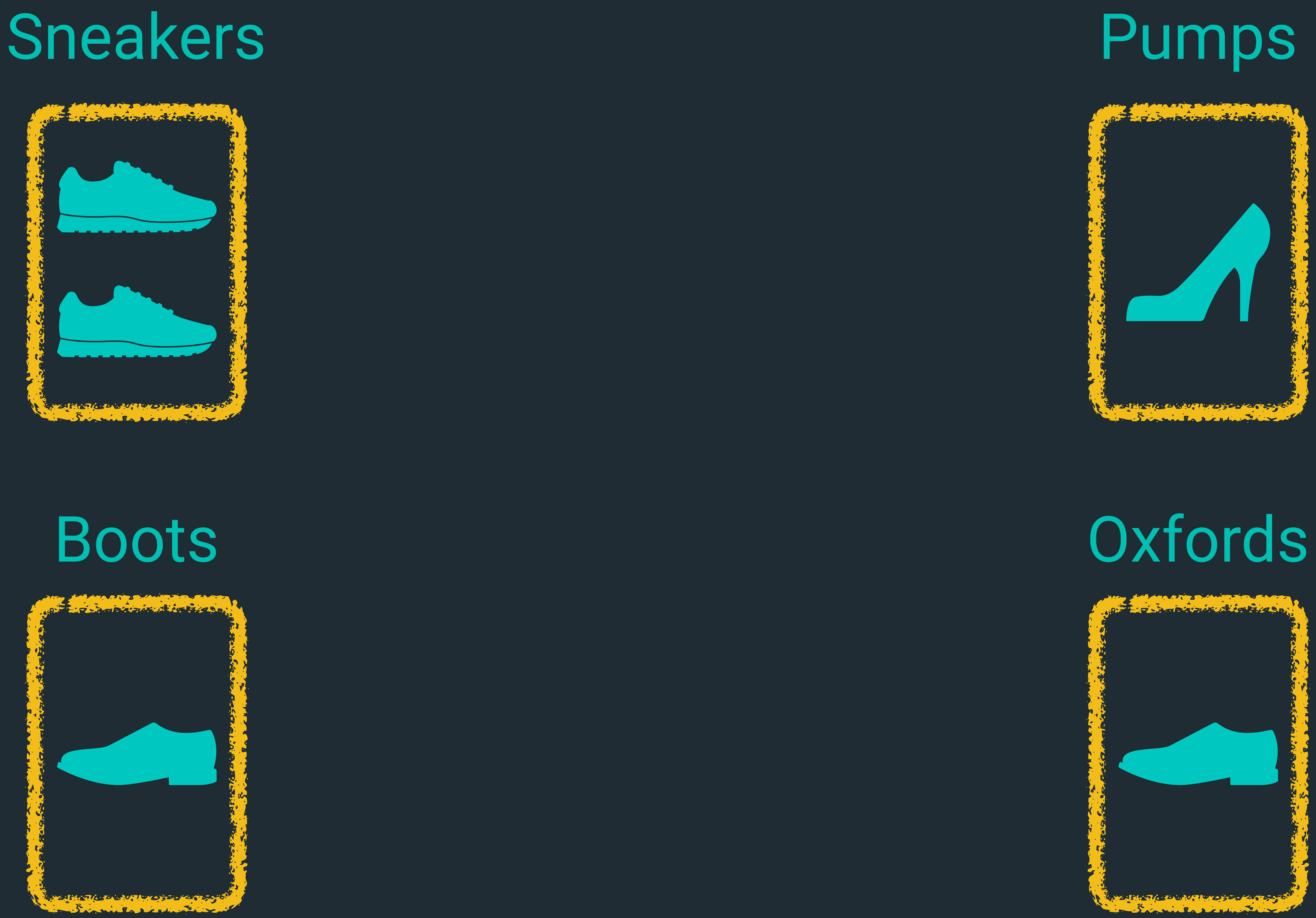
Sneakers

Oxfords

Sneakers

Boots

Bucketing documents



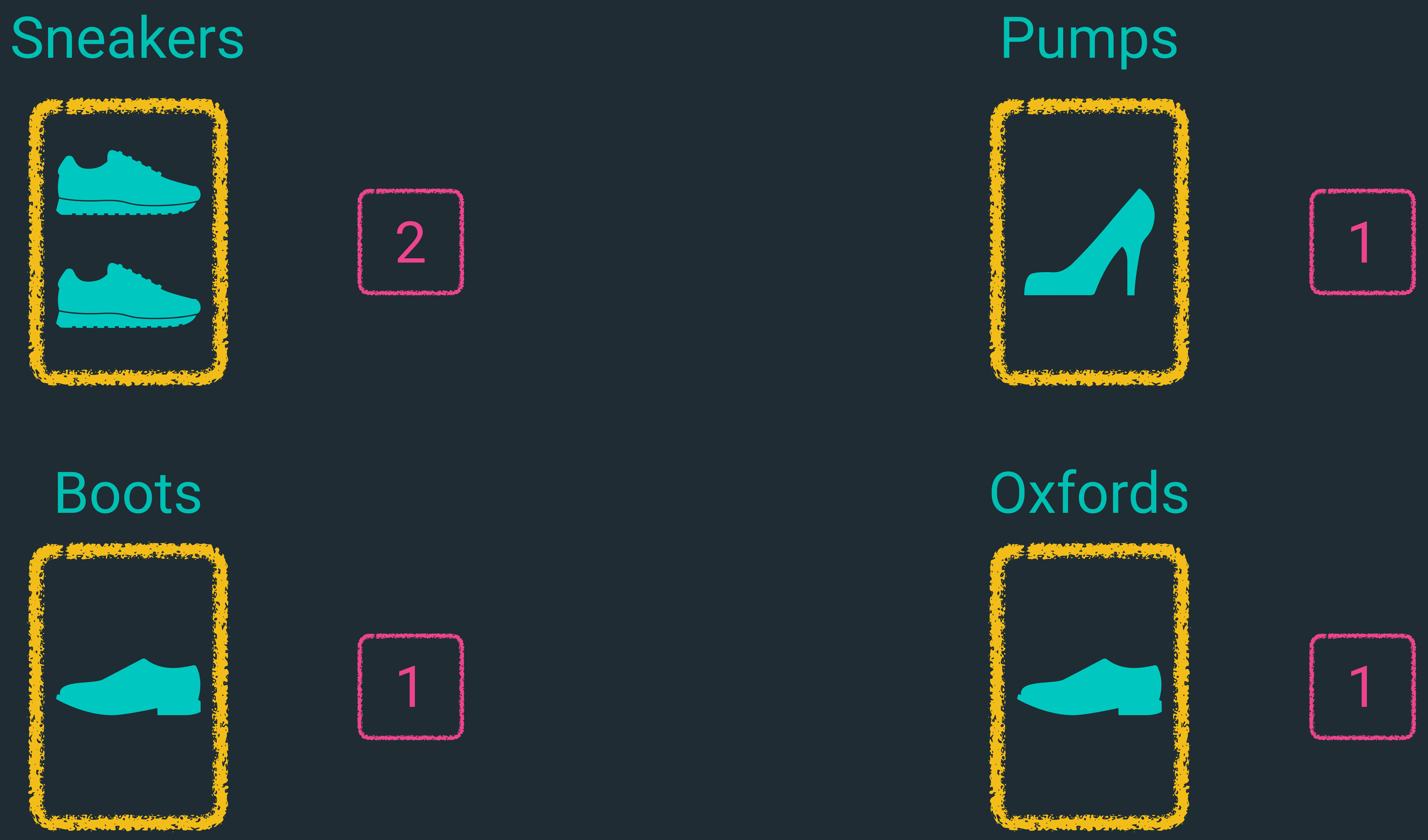
Sneakers

Pumps

Boots

Oxfords

Bucketing documents



Sneakers

2

Pumps

1

Boots

1

Oxfords

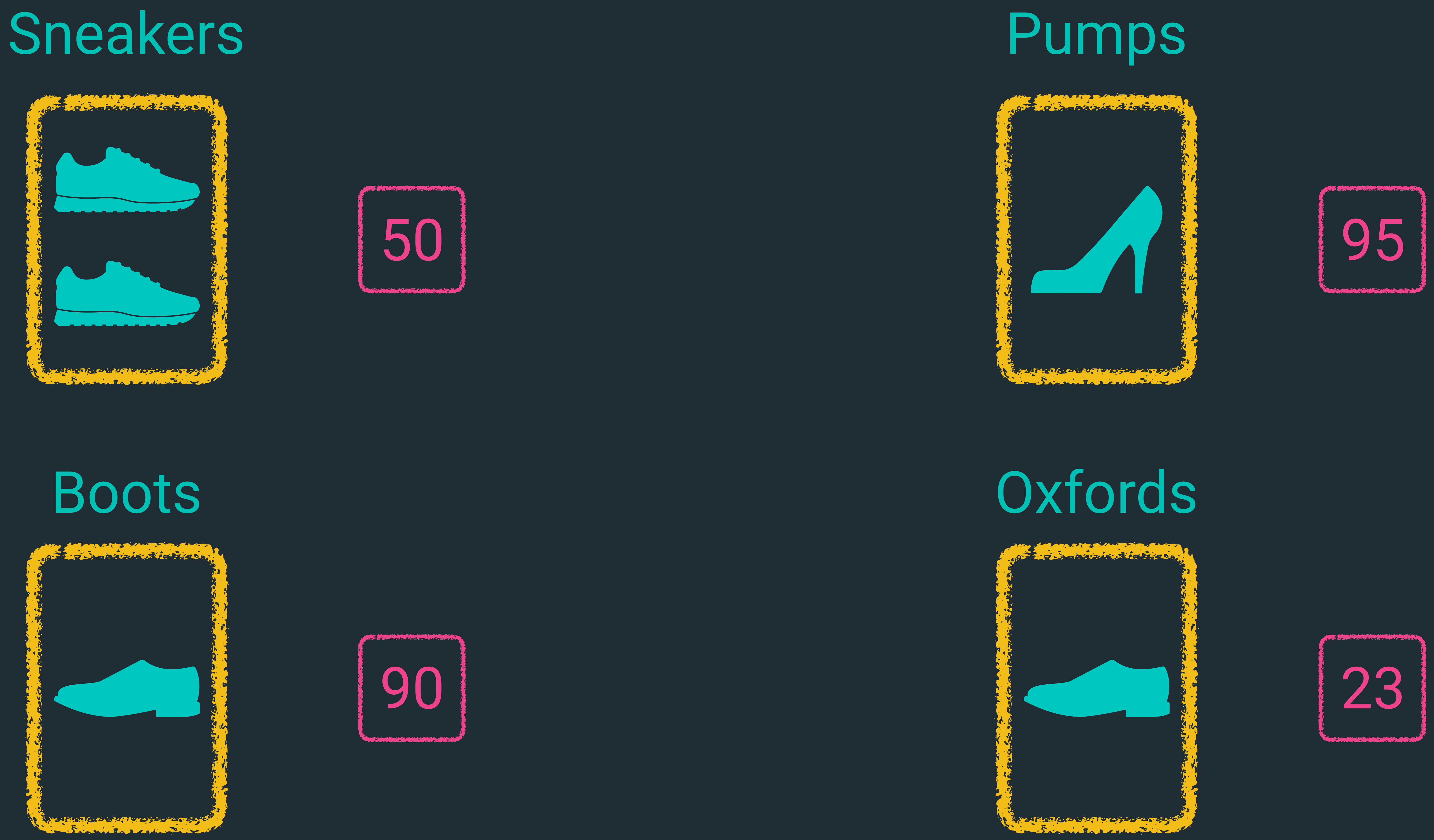
1

bucket agg

metric agg

doc_count

Bucketing documents



Sneakers

50

Pumps

95

Boots

90

Oxfords

23

bucket agg

metric agg

avg price

Aggregations

- bucket: terms, histogram, geo, range, sampler , significant text, nested
- metric: value_count, avg, min, max, sum, stats, median deviation, geo, percentile, cardinality,
- pipeline: min, max, sum, avg, derivative, stats, percentiles, cumulative sum, moving average, moving function, serial differencing

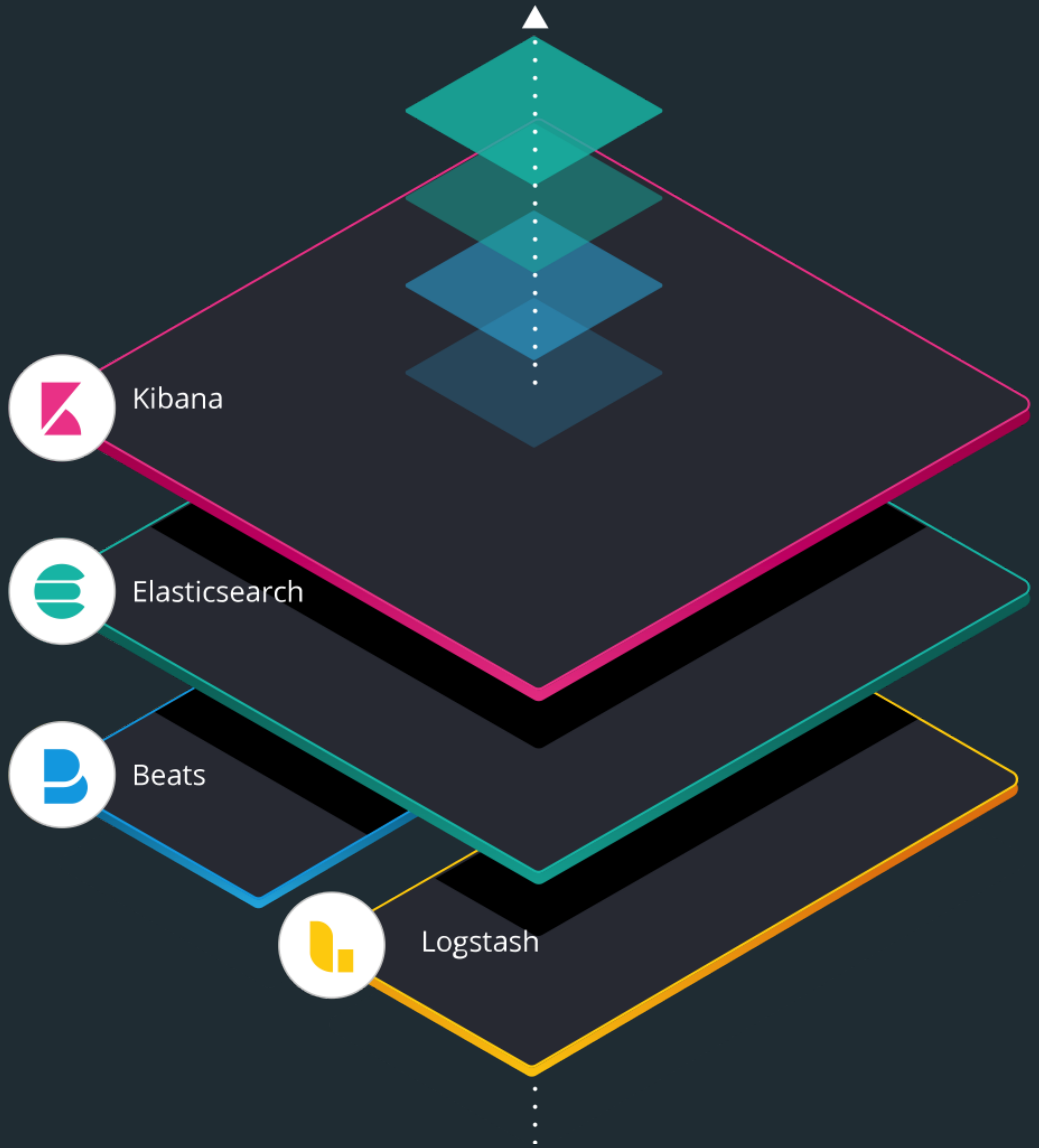
elastic

Distributed systems & search

Fanning out a search, reducing the results

Elasticsearch

elastic



elastic

Elasticsearch in 10 seconds

- Search Engine (FTS, Analytics, Geo), near real-time
- Distributed, scalable, highly available, resilient
- Interface: HTTP & JSON
- Centrepiece of the Elastic Stack
- Uneducated conservative guess: Tens of thousands of clusters worldwide, hundreds of thousands of instances

Distributed systems

elastic

Distributed systems

- How do nodes communicate with each other?
- Who is taking and executing decisions?
- Failure detection?
- Replication strategy?
- Consistency?
- Enter consensus algorithms...

> *A fundamental problem in distributed computing and multi-agent systems is to achieve overall system reliability in the presence of a number of faulty processes. This often requires processes to agree on some data value that is needed during computation*

https://en.wikipedia.org/wiki/Consensus_(computer_science)

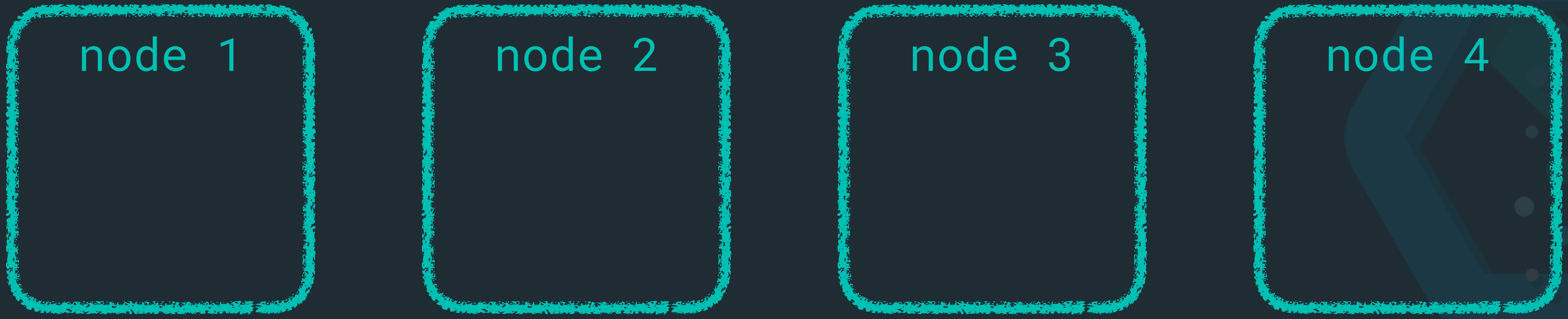
Consensus algorithms

- Leader based: Paxos, Raft
- Non leader based: BTC, gossip

Consensus in Elasticsearch

- Custom consensus algorithm, improving the existing one
- Formally verified
- Optimized for Elasticsearch use-case (rolling restarts, growing/shrinking clusters, log-of-operations vs. cluster state)

Consensus in Elasticsearch



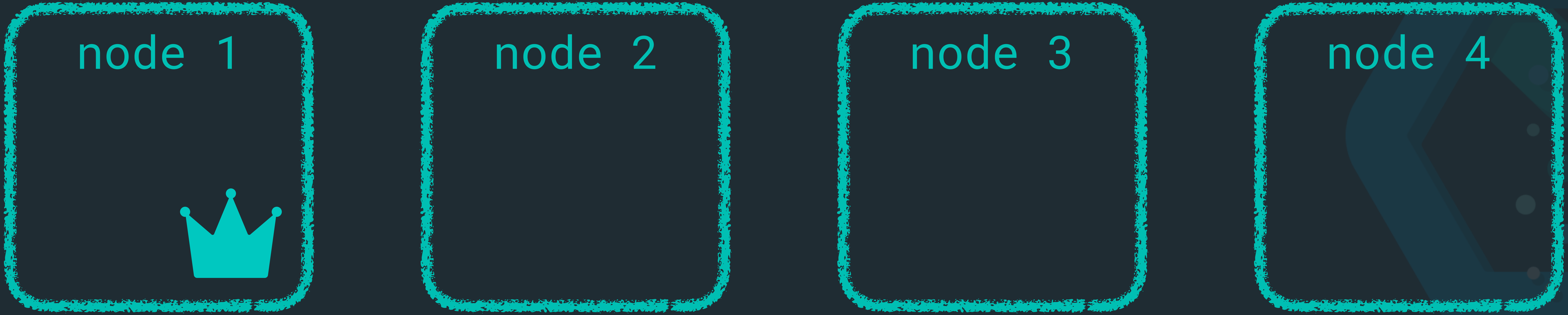
node 1

node 2

node 3

node 4

Consensus in Elasticsearch



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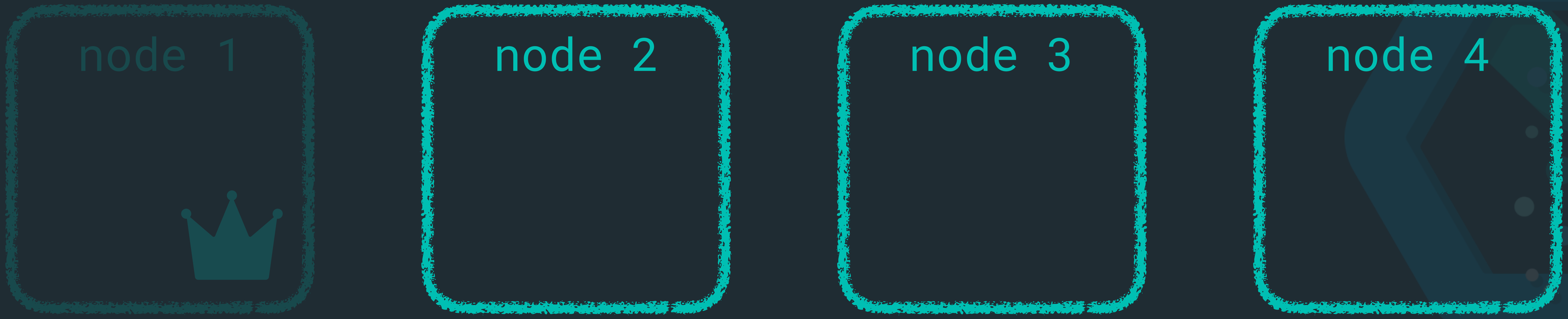
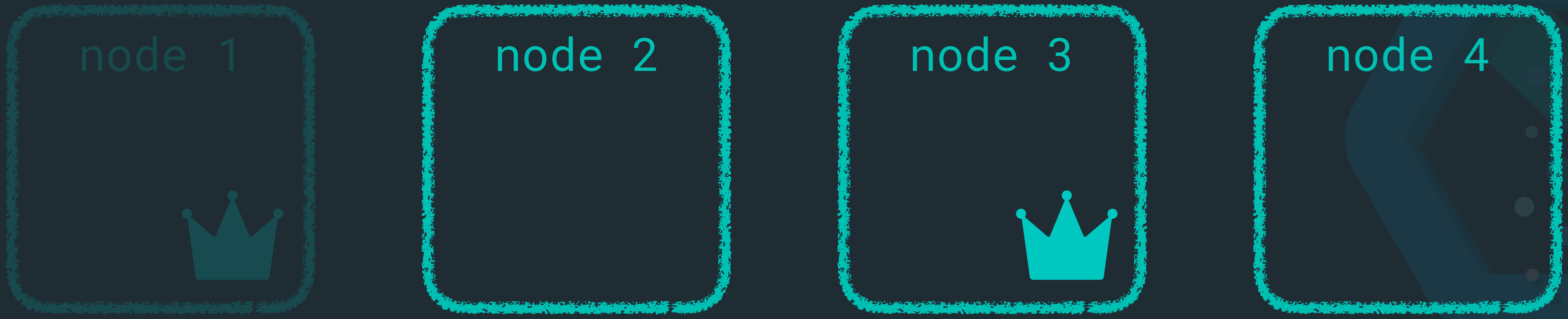
Consensus in Elasticsearch



Consensus in Elasticsearch

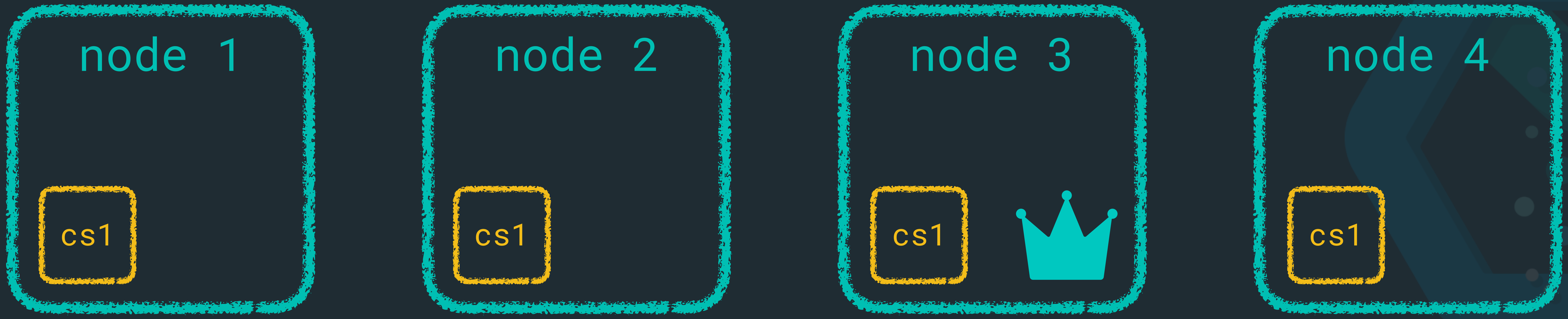


elastic

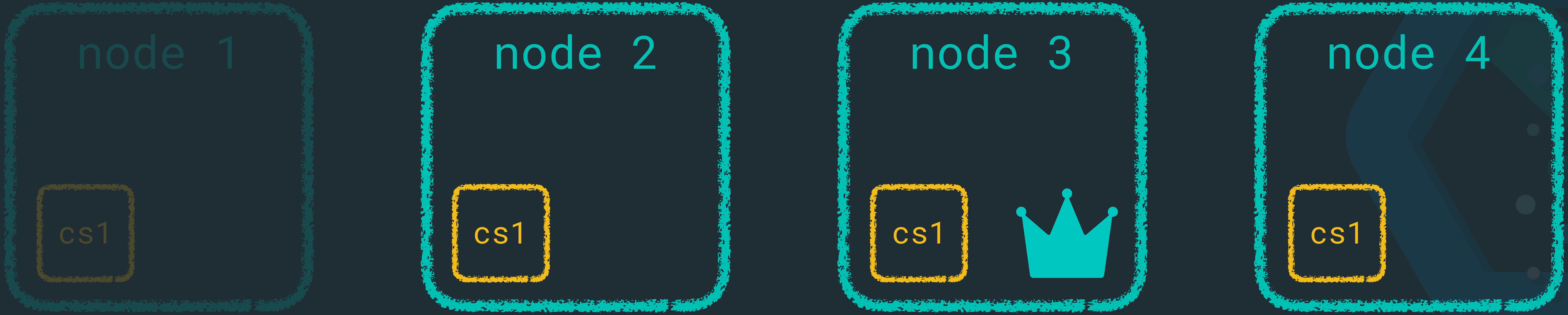
Master node tasks

- Deciding where data should be stored
- Pinging other nodes
- Reacting on node leaves/joins
- Updating cluster state
- Distributing cluster state

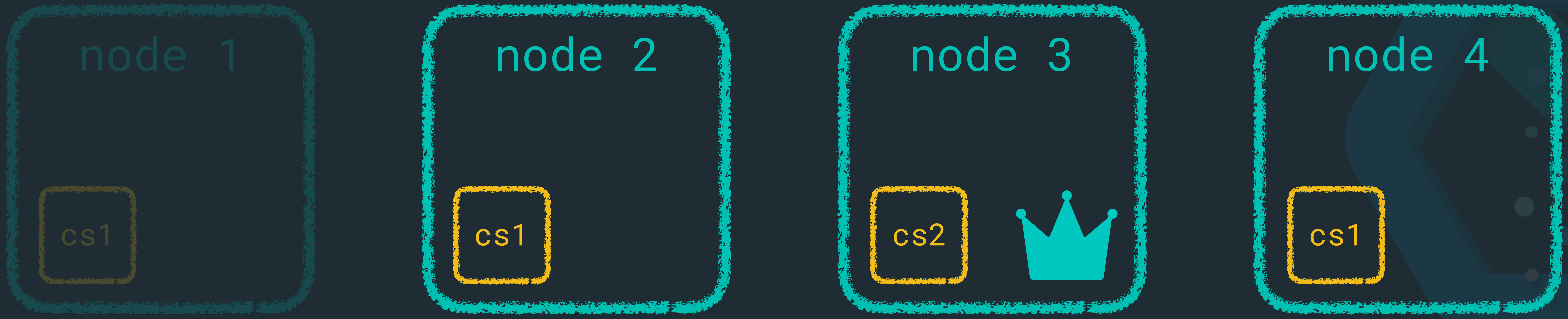
Consensus in Elasticsearch



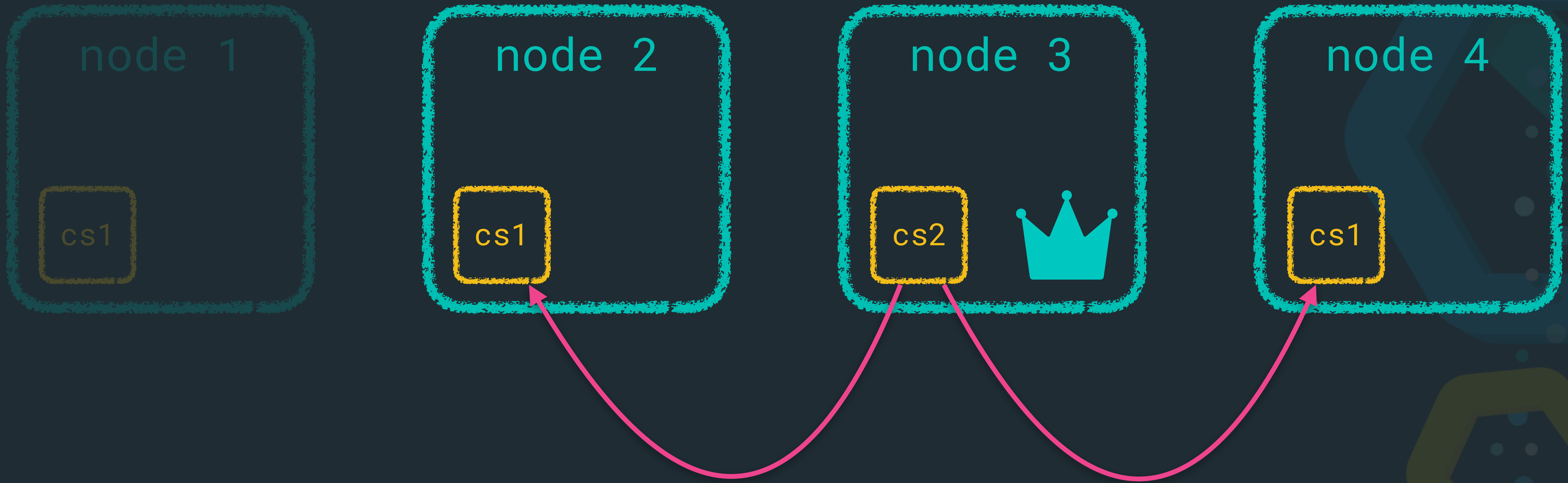
Consensus in Elasticsearch



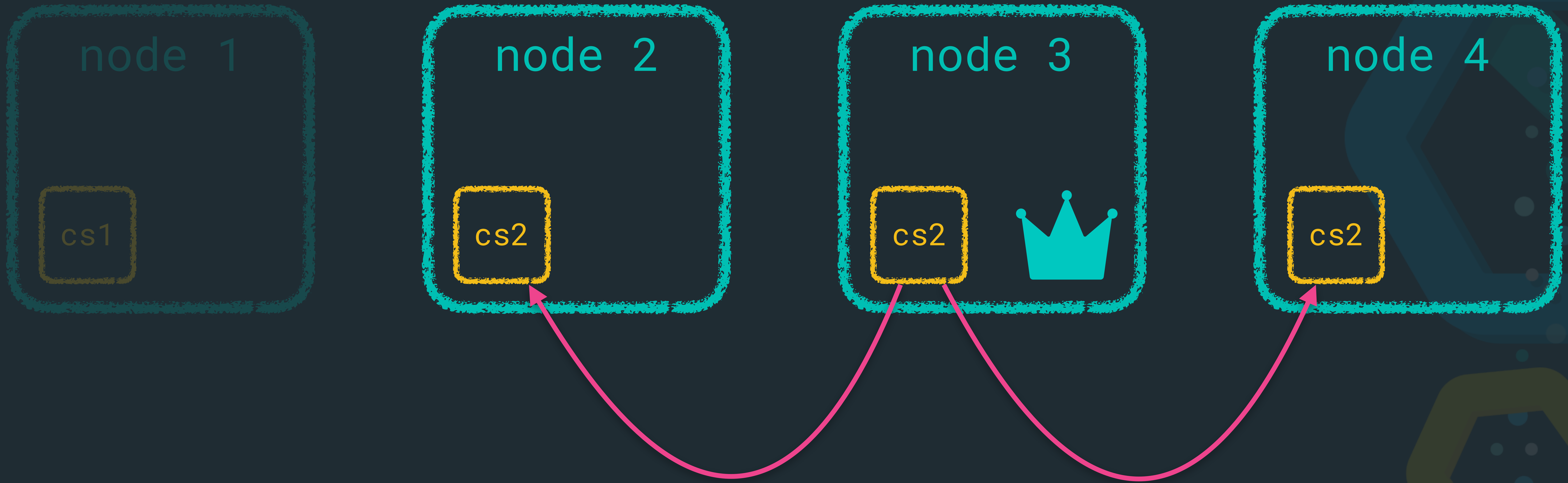
Consensus in Elasticsearch



Consensus in Elasticsearch

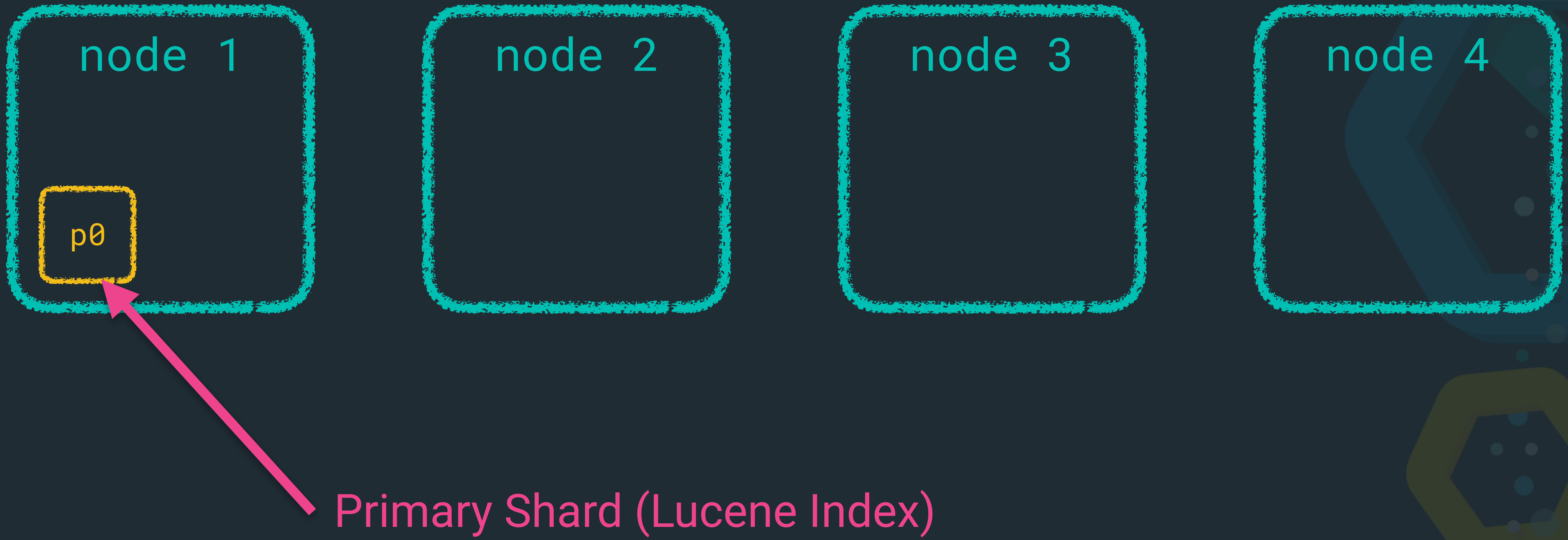


Consensus in Elasticsearch



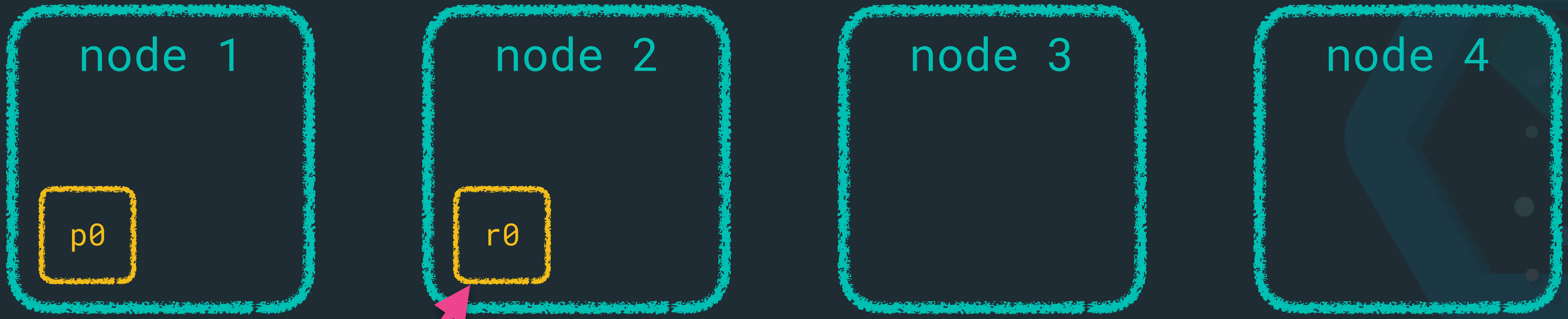
Distributed search

Distributed search in Elasticsearch



Primary Shard (Lucene Index)

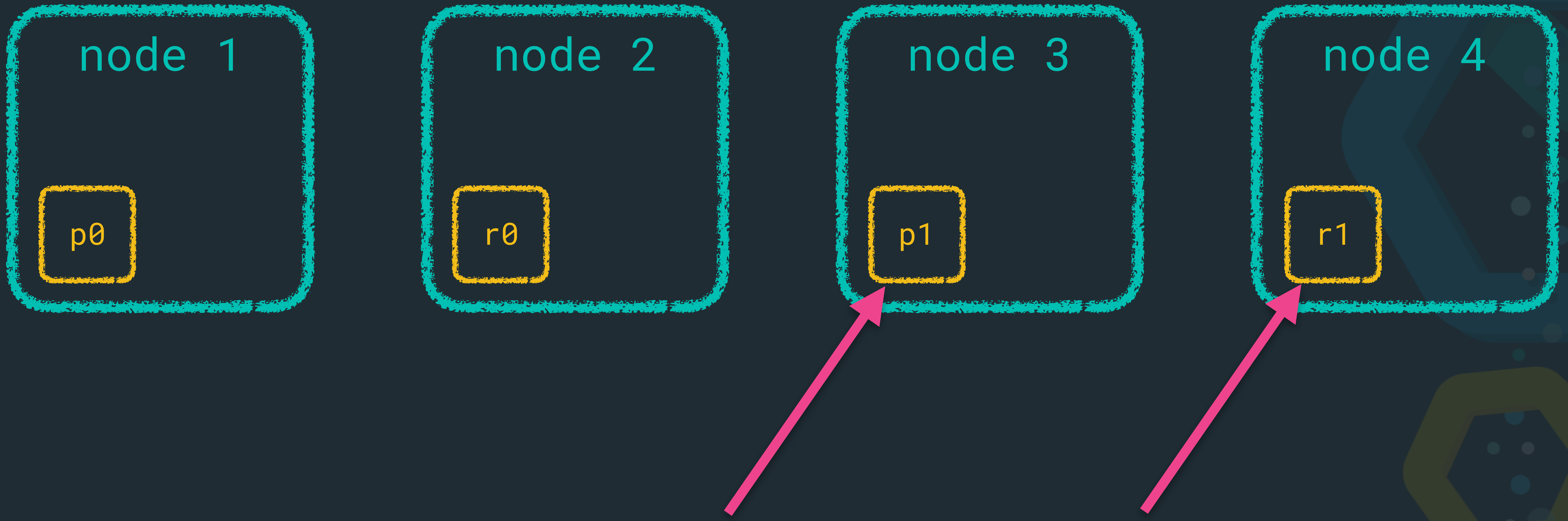
Distributed search in Elasticsearch



Replica shard (copy)

elastic

Distributed search in Elasticsearch



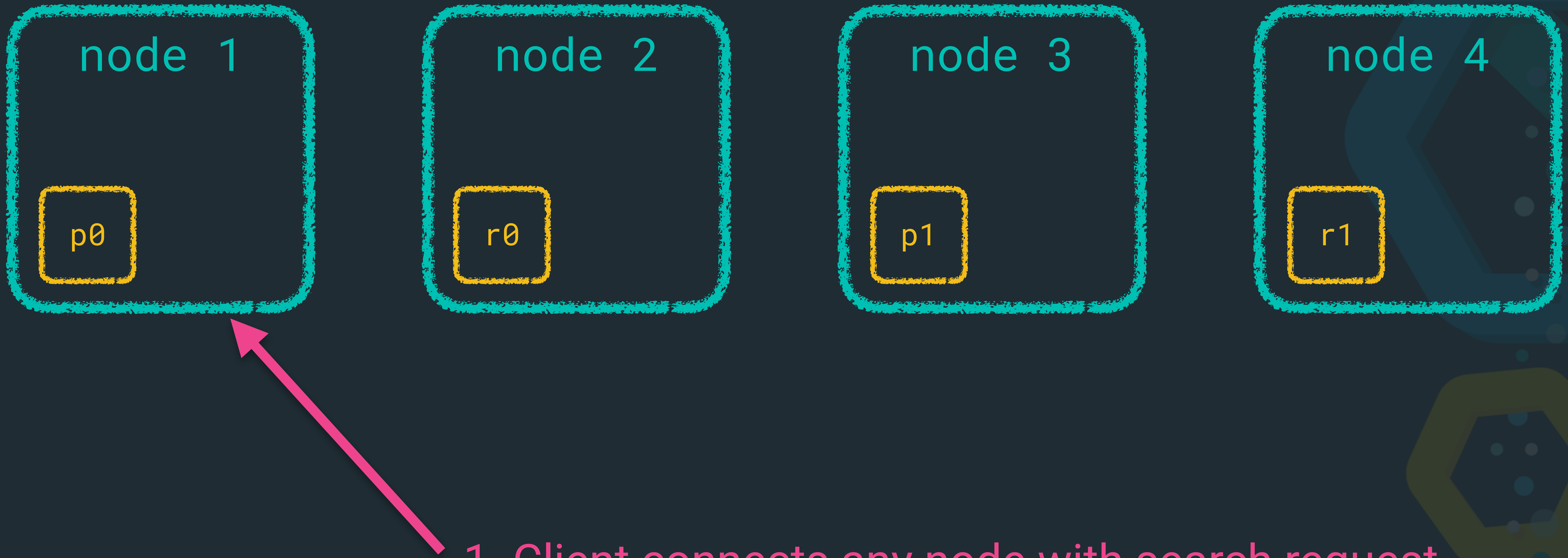
2nd Primary Shard

Replica shard (copy)

Distributed search in Elasticsearch

- Shard: Lucene index, unit of scale
- Primary shard: Write scalability
- Replica shard: Read scalability, availability

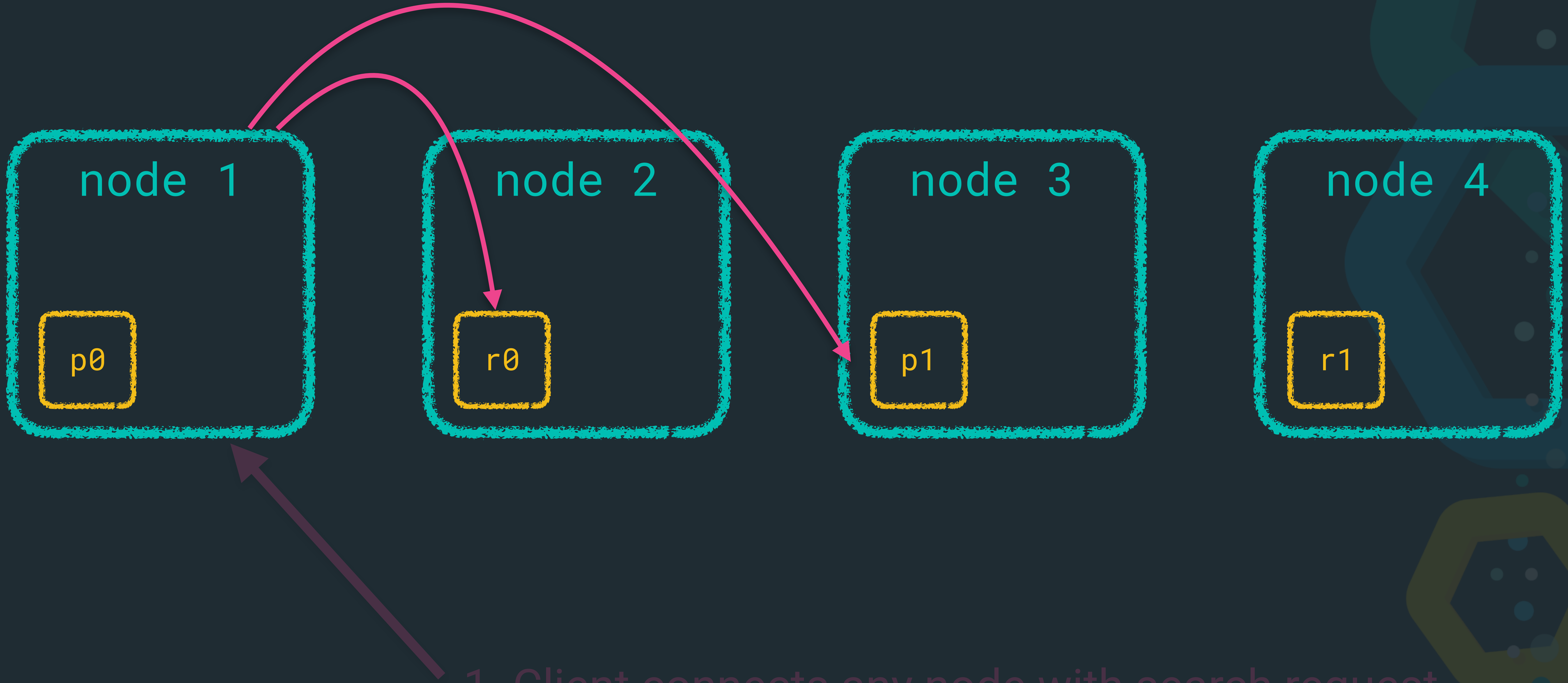
Distributed search in Elasticsearch



1. Client connects any node with search request

Distributed search in Elasticsearch

2. Execute query against shards

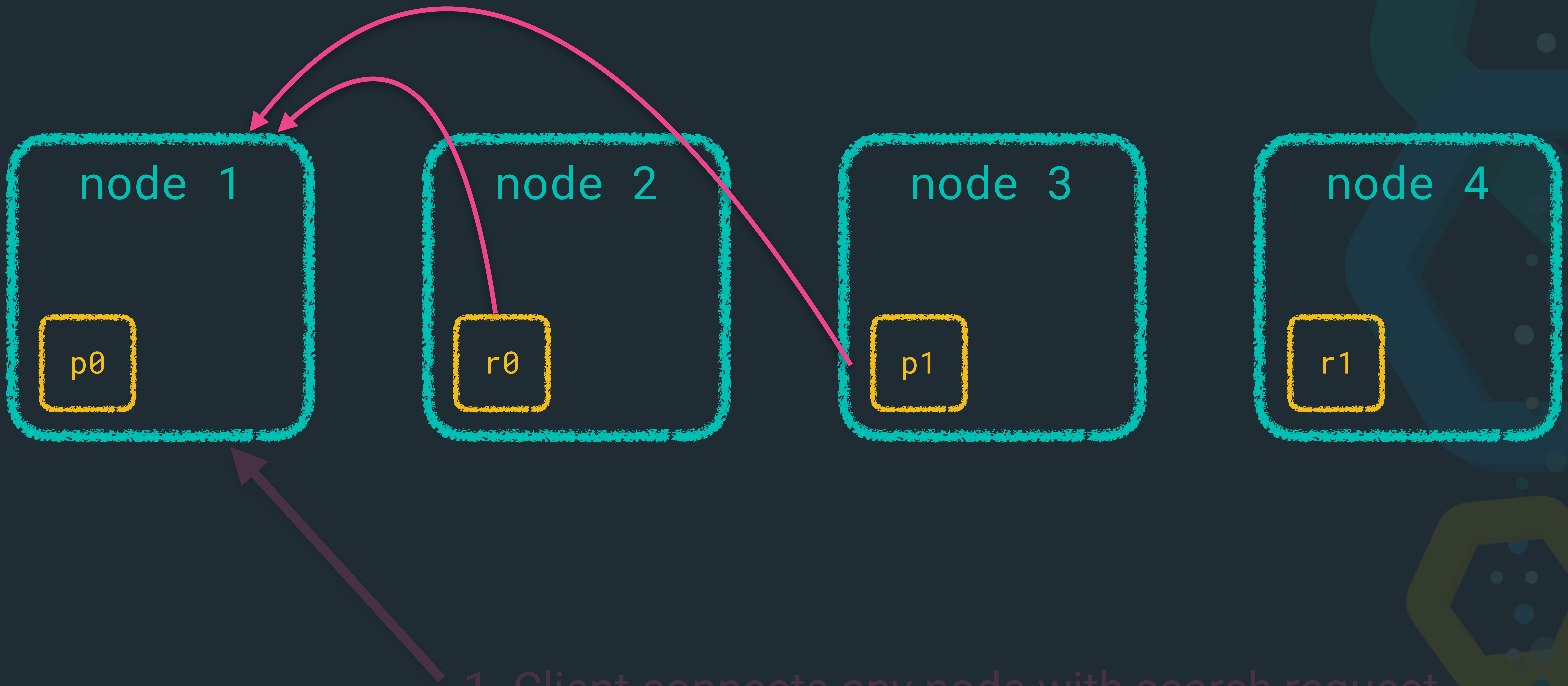


1. Client connects any node with search request

elastic

Distributed search in Elasticsearch

3. top-k search results are returned to coordinating node

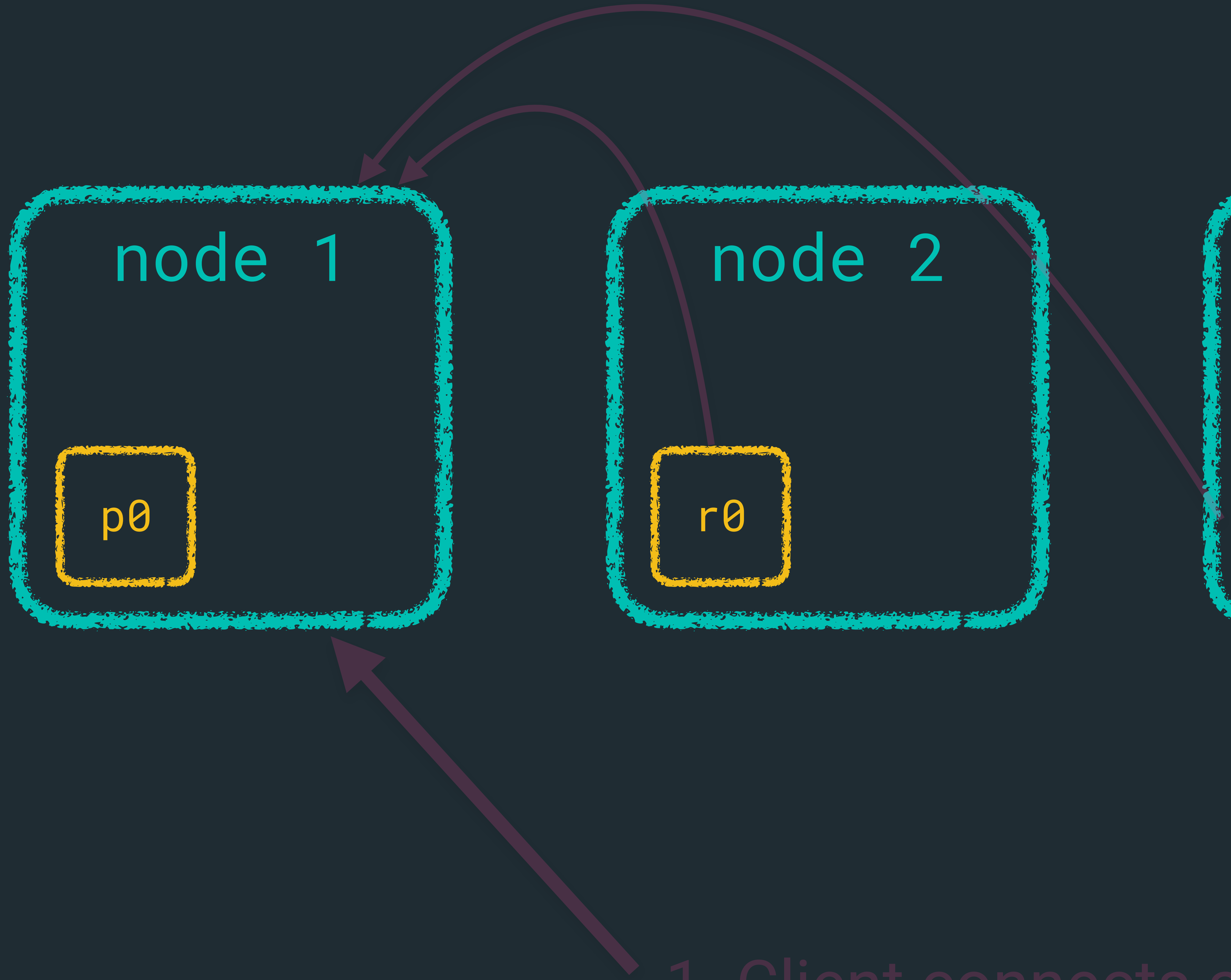


1. Client connects any node with search request

elastic

Distributed search in Elasticsearch

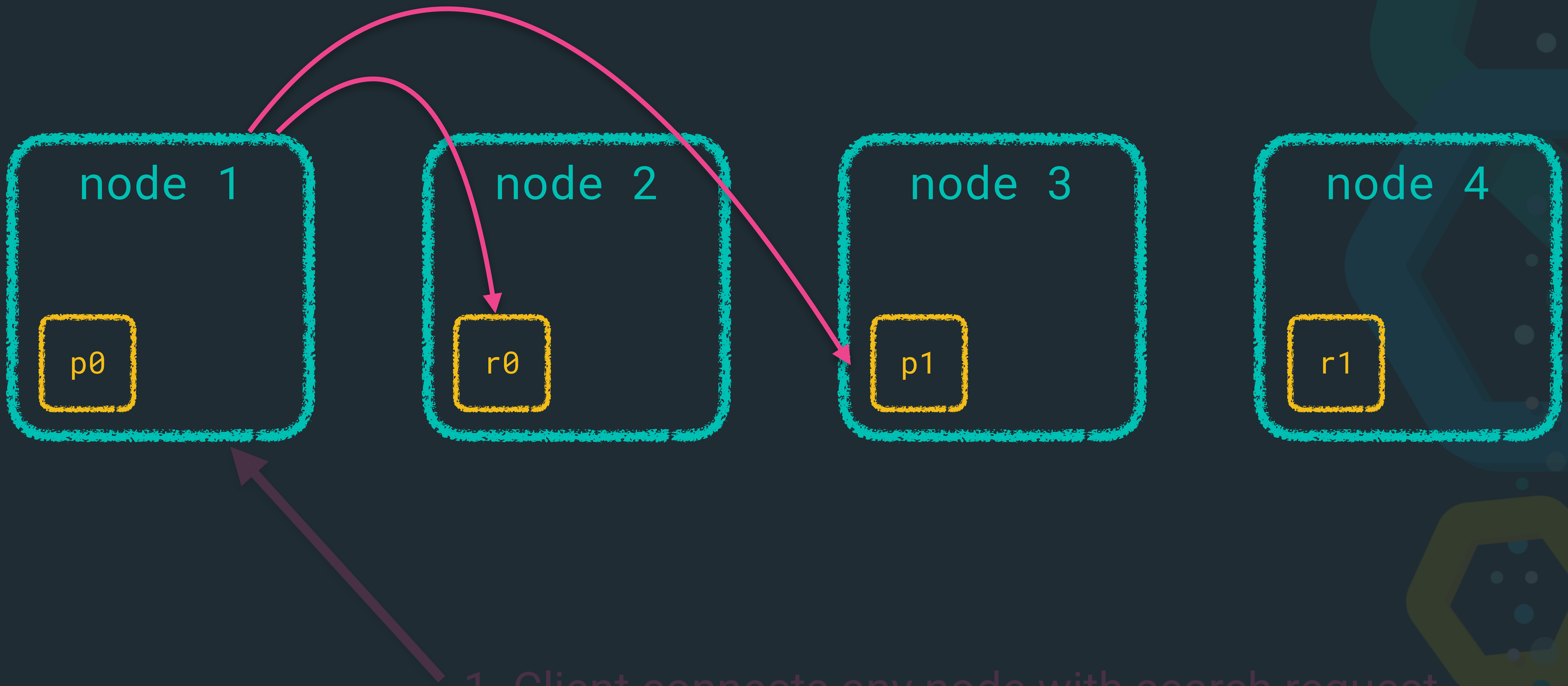
4. Create real top-k result list



1. Client connects any node with search request

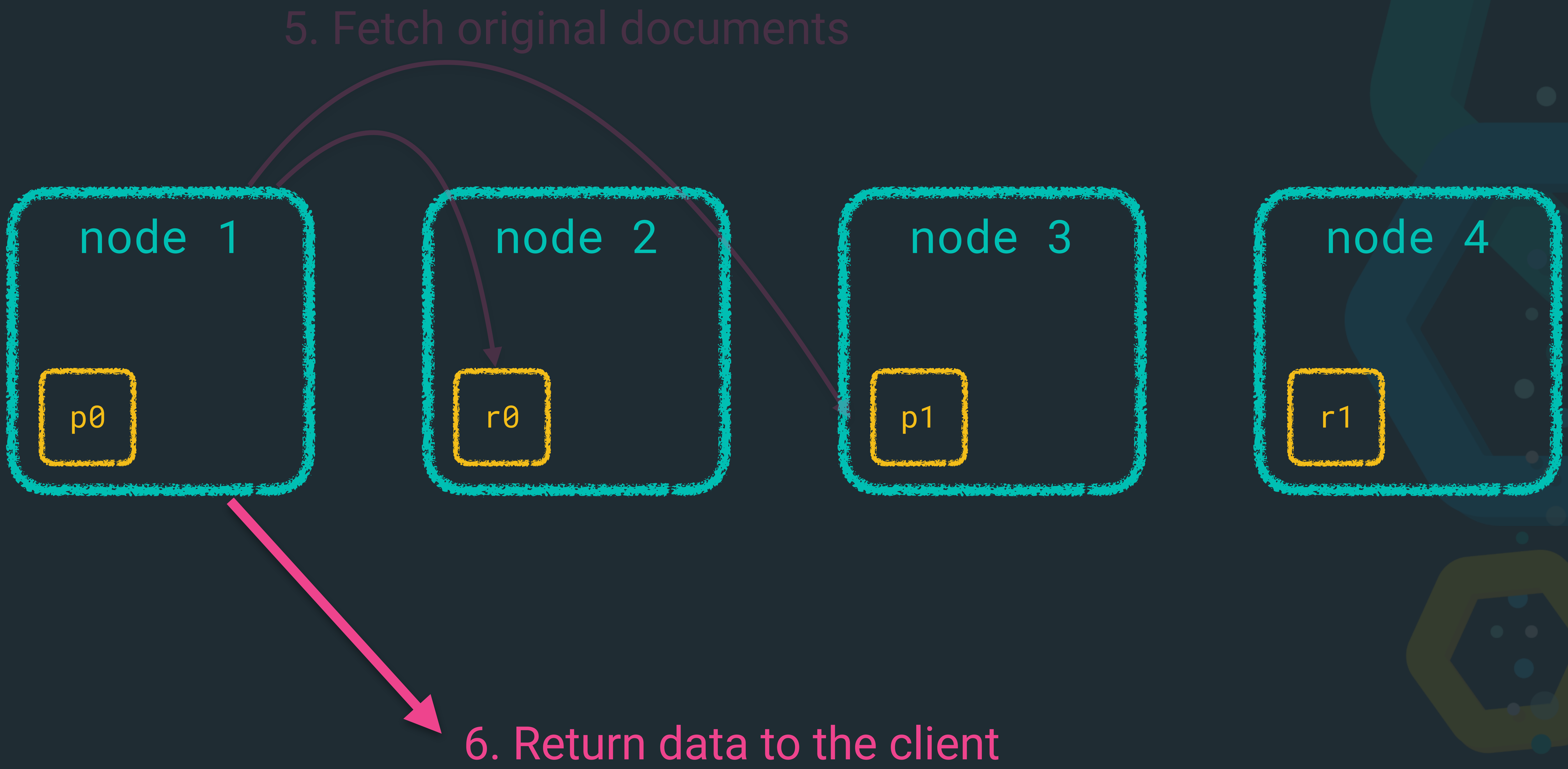
elastic

Distributed search in Elasticsearch


5. Fetch original documents
node 1
p0
node 2
r0
node 3
p1
node 4
r1
1. Client connects any node with search request

elastic

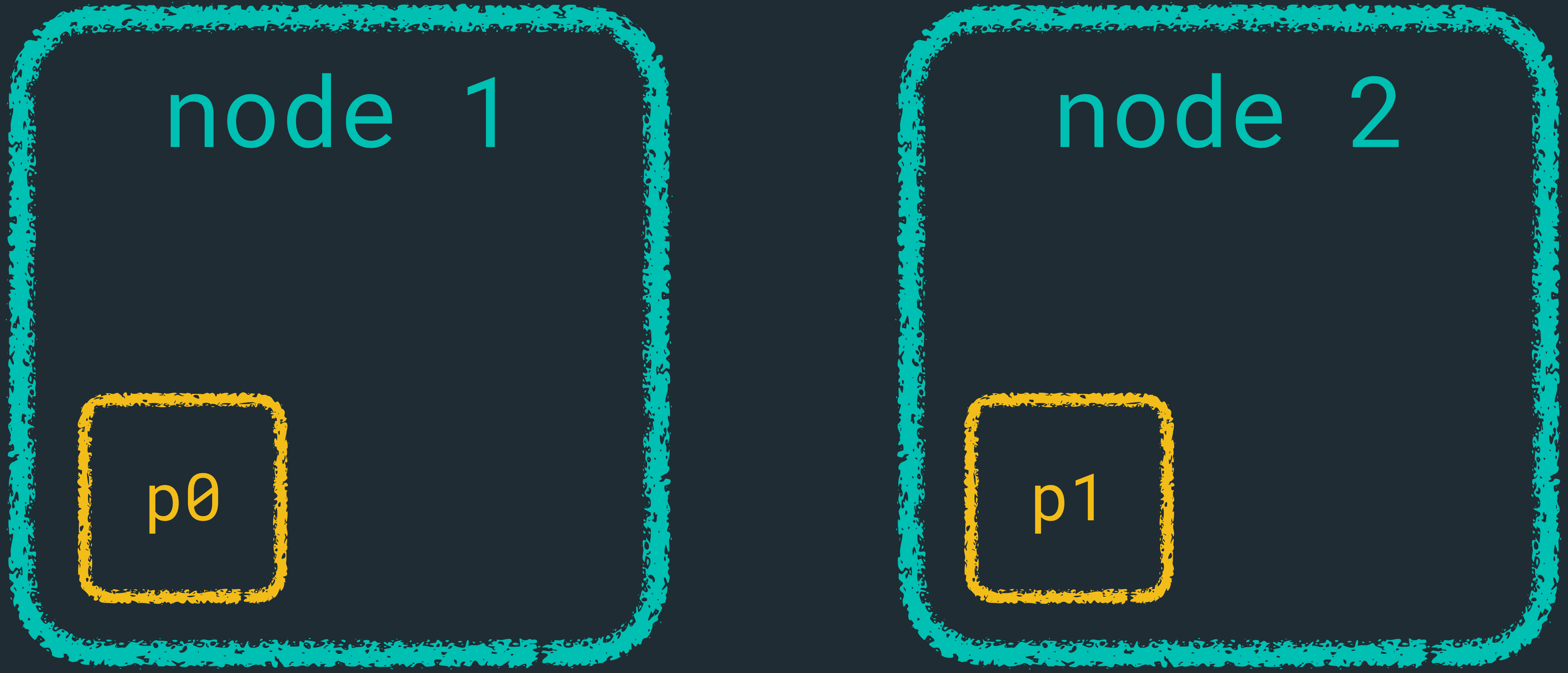
Distributed search in Elasticsearch



elastic

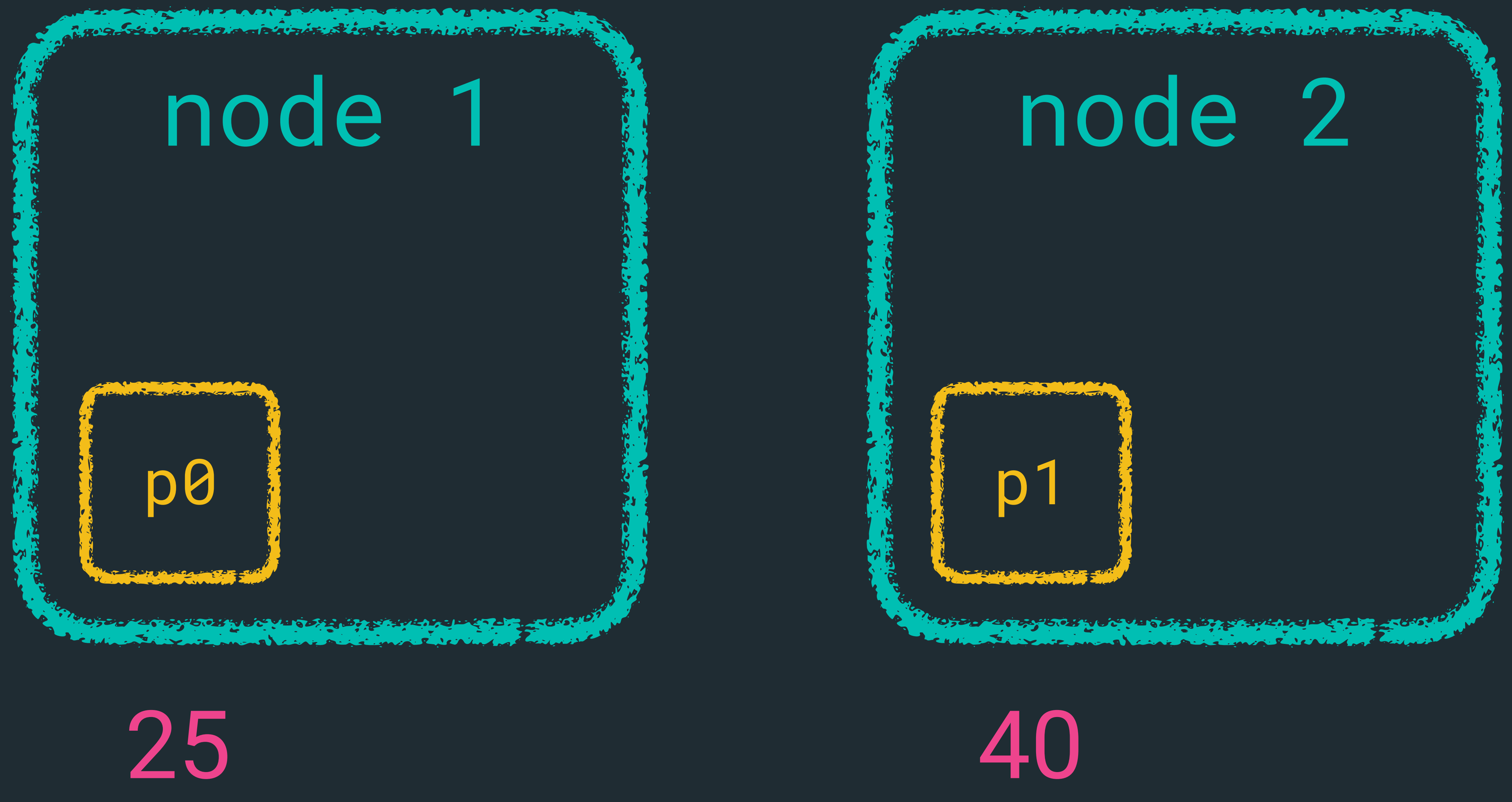
Aggregations

Aggregations - cardinality



```
POST /sales/_search?size=0
{
  "aggs" : {
    "type_count" : {
      "cardinality" : {
        "field" : "type"
      }
    }
  }
}
```

Aggregations - cardinality



How many distinct elements are in my index?

What is the total? 40? 65?

Naive solution: merge data to single dataset and count. Doesn't scale!

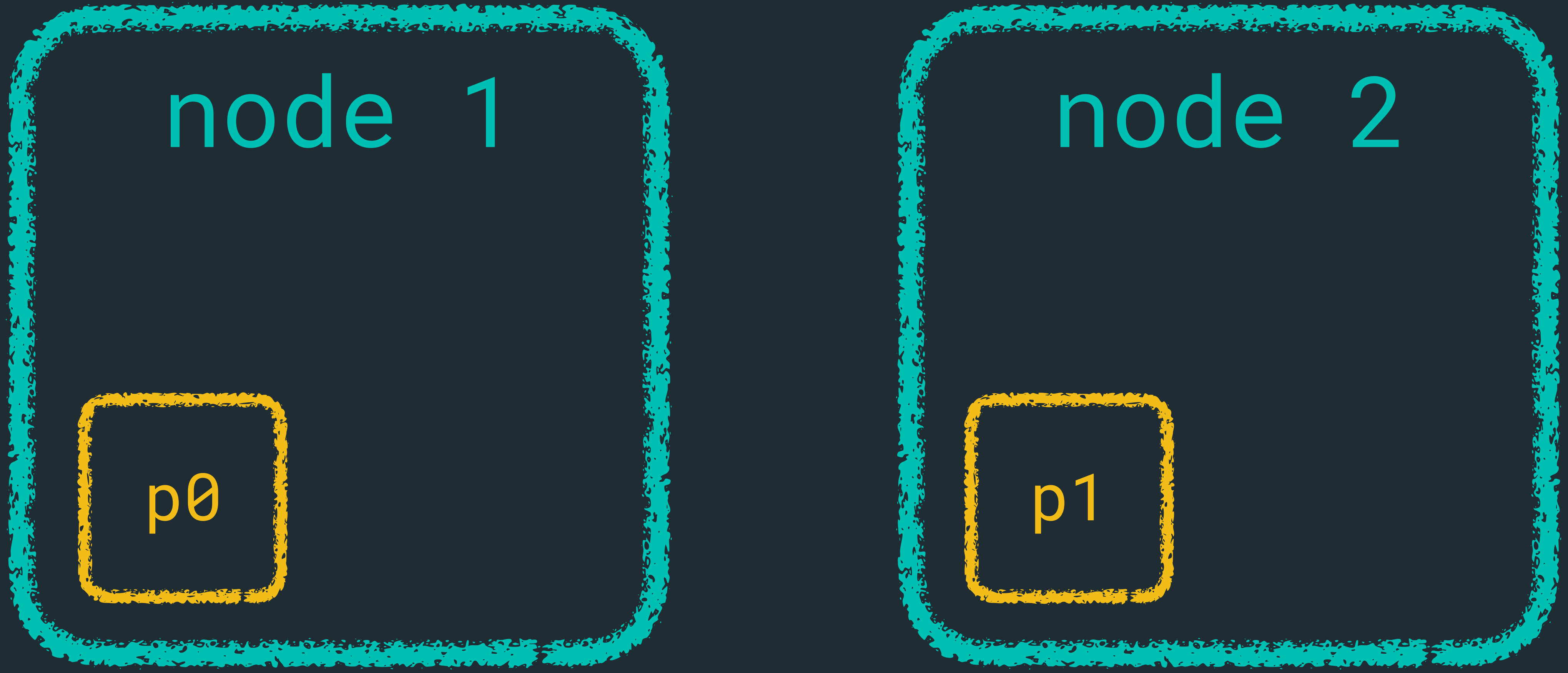
Solution: Use HyperLogLog++

elastic

HyperLogLog++

- Hash based counting
- Trades in memory for accuracy
- Fixed memory usage, based on configurable precision
- Result: Small mergeable data structure, can easily be sent over the network

Aggregations - percentile



```
GET latency/_search
{
  "size": 0,
  "aggs" : {
    "load_time_outlier" : {
      "percentiles" : {
        "field" : "load_time"
      }
    }
  }
}
```

elastic

T-Digest

- Extreme percentiles are more accurate than the Median
- Percentiles are divided into buckets
- When buckets grow over a boundary, approximation kicks in, saving memory in the process
- The exact level of inaccuracy is difficult to generalize
- Alternative: HDR histograms

Probabilistic data structures

- bloom/cuckoo/quotient filters (membership check)
- HyperLogLog++ (cardinality)
- T-Digest, DDSketch, HDR histogram (percentile)
- Count-Min sketch (frequency, top-k)
- Hashing (similarity)

elastic

Demo

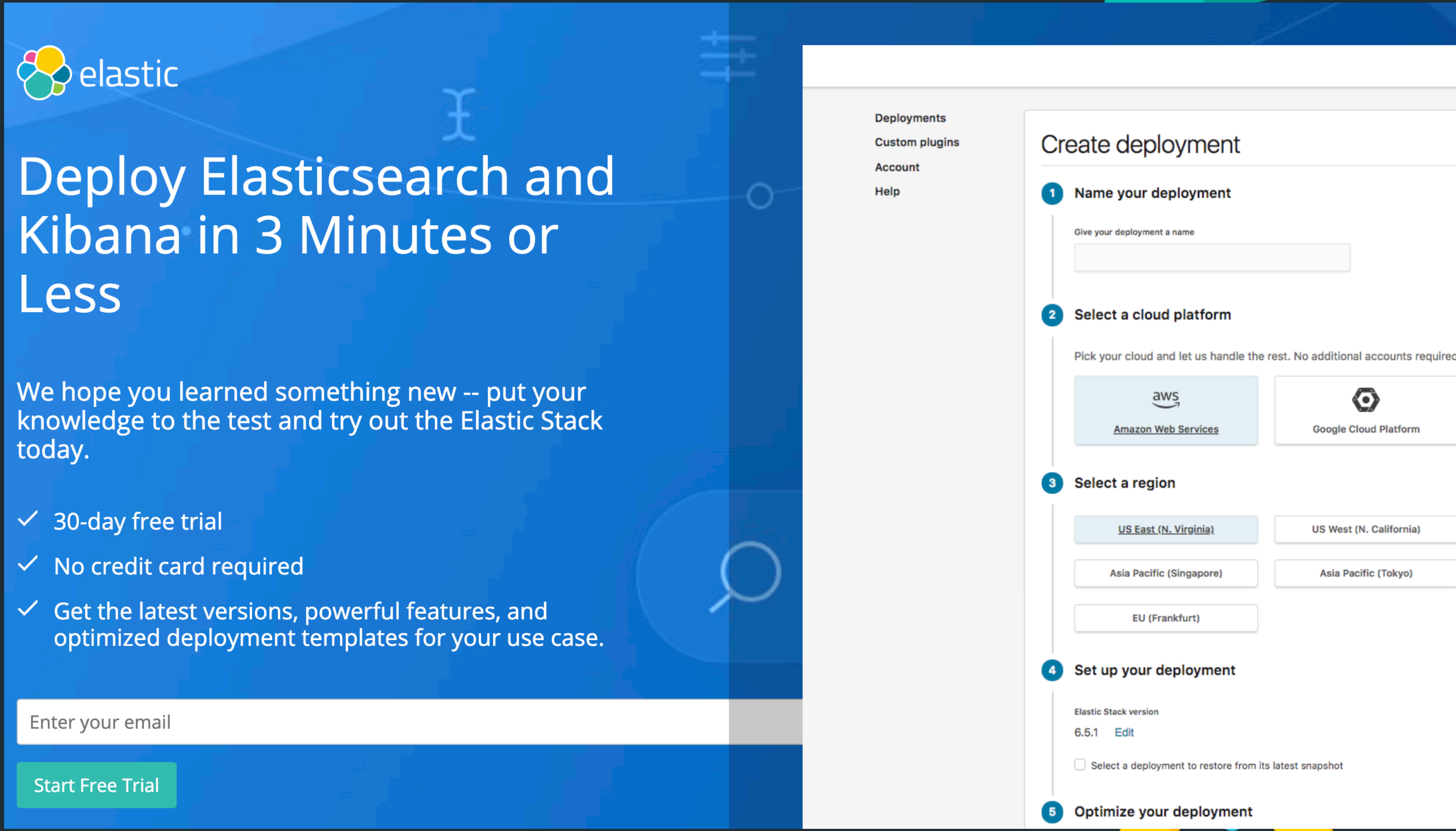
Try it out yourself!

https://ela.st/jade-hochschule-samples

elastic

Elastic Cloud

Free 30 day trial



elastic

Deploy Elasticsearch and Kibana in 3 Minutes or Less

We hope you learned something new -- put your knowledge to the test and try out the Elastic Stack today.

- ✓ 30-day free trial
- ✓ No credit card required
- ✓ Get the latest versions, powerful features, and optimized deployment templates for your use case.

Enter your email

Start Free Trial

Create deployment

1. Name your deployment

   Give your deployment a name

2. Select a cloud platform

   Pick your cloud and let us handle the rest. No additional accounts require

   aws Amazon Web Services | Google Cloud Platform

3. Select a region

   US East (N. Virginia) | US West (N. California)
   Asia Pacific (Singapore) | Asia Pacific (Tokyo)
   EU (Frankfurt)

4. Set up your deployment

   Elastic Stack version
   6.5.1 Edit

   □ Select a deployment to restore from its latest snapshot

5. Optimize your deployment

https://ela.st/university-wilhelmshaven

Upcoming trends & summary

... or why you should take a closer look at search

Search is not just google...

- "Just google it" does not cut it
- Enterprise search: Intranet/G-Drive/Dropbox
- Ecommerce search
- SIEM
- Observability: Logging, APM & Metrics

Search is not 'done'

- Constant improvement
- Data structures & algorithms (BKD tree for geo shapes)
- Academic research moves to industry thanks to Apache Lucene

Search is still tough

- Language specific analysis
- Smart query parsing (`nike red hoodie xl`)
- Geo based search
- Anomaly detection
- Incoporating feedback loops

Upcoming trends

- Learning-to-Rank
- Deep Learning
- Feedback loop

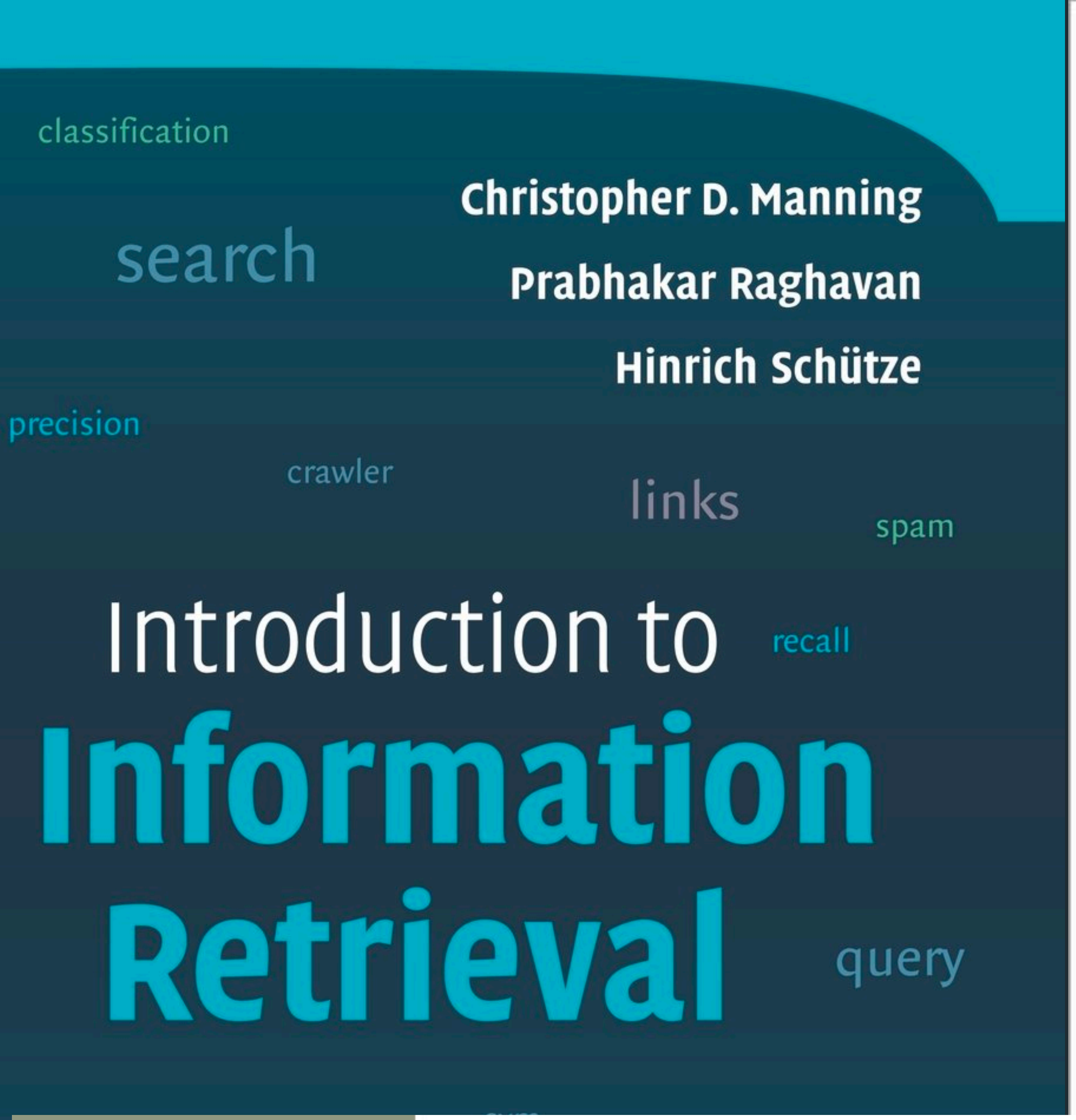
Summary

- Everything is a search problem!
- Search is hard... and interesting
- Distributed systems are hard... and interesting
- Domain knowledge required
- Data keeps exploding, good job chances!

elastic

Literature

Books, books, books


classification

search

precision

crawler

links

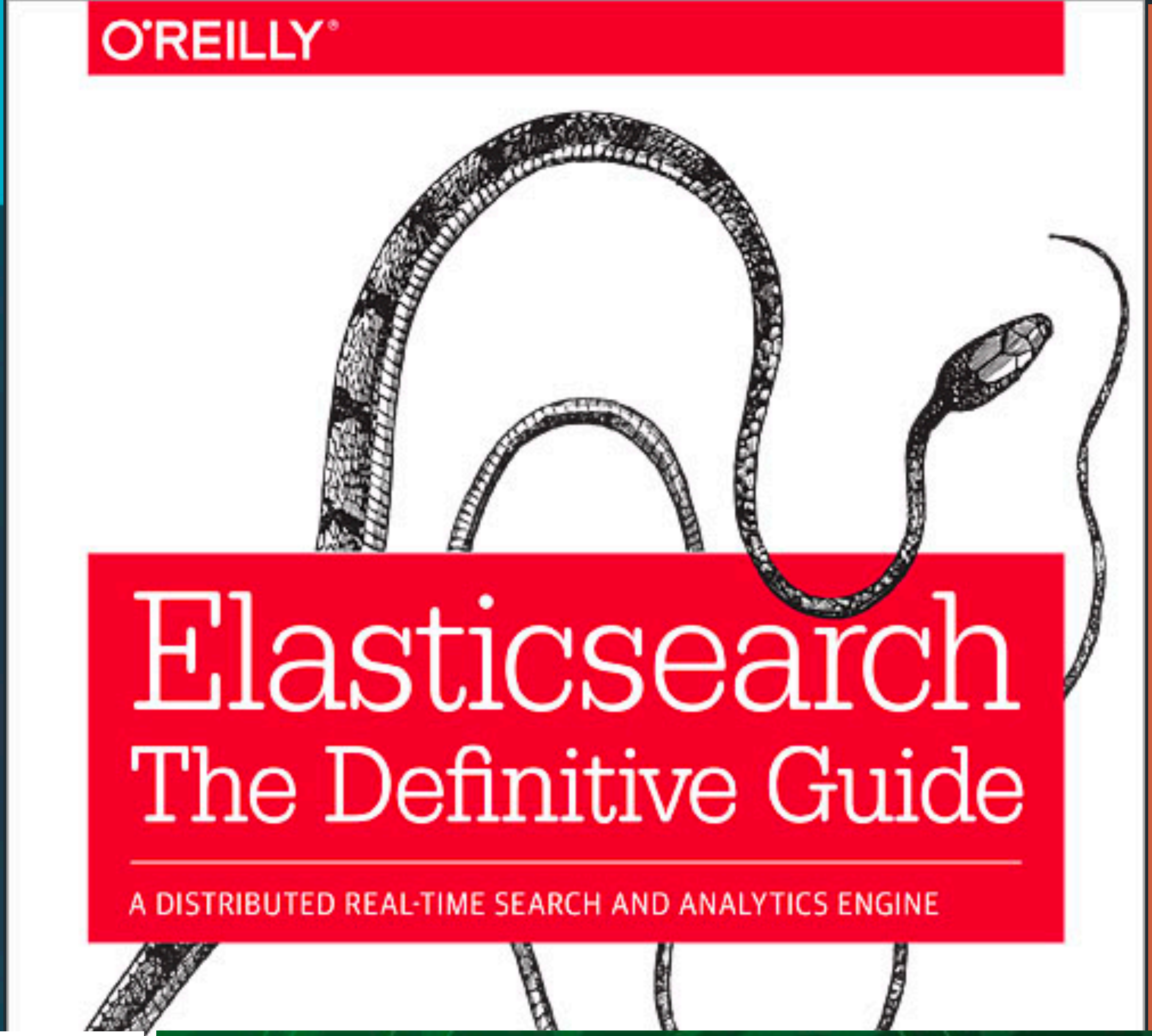
spam

recall

query

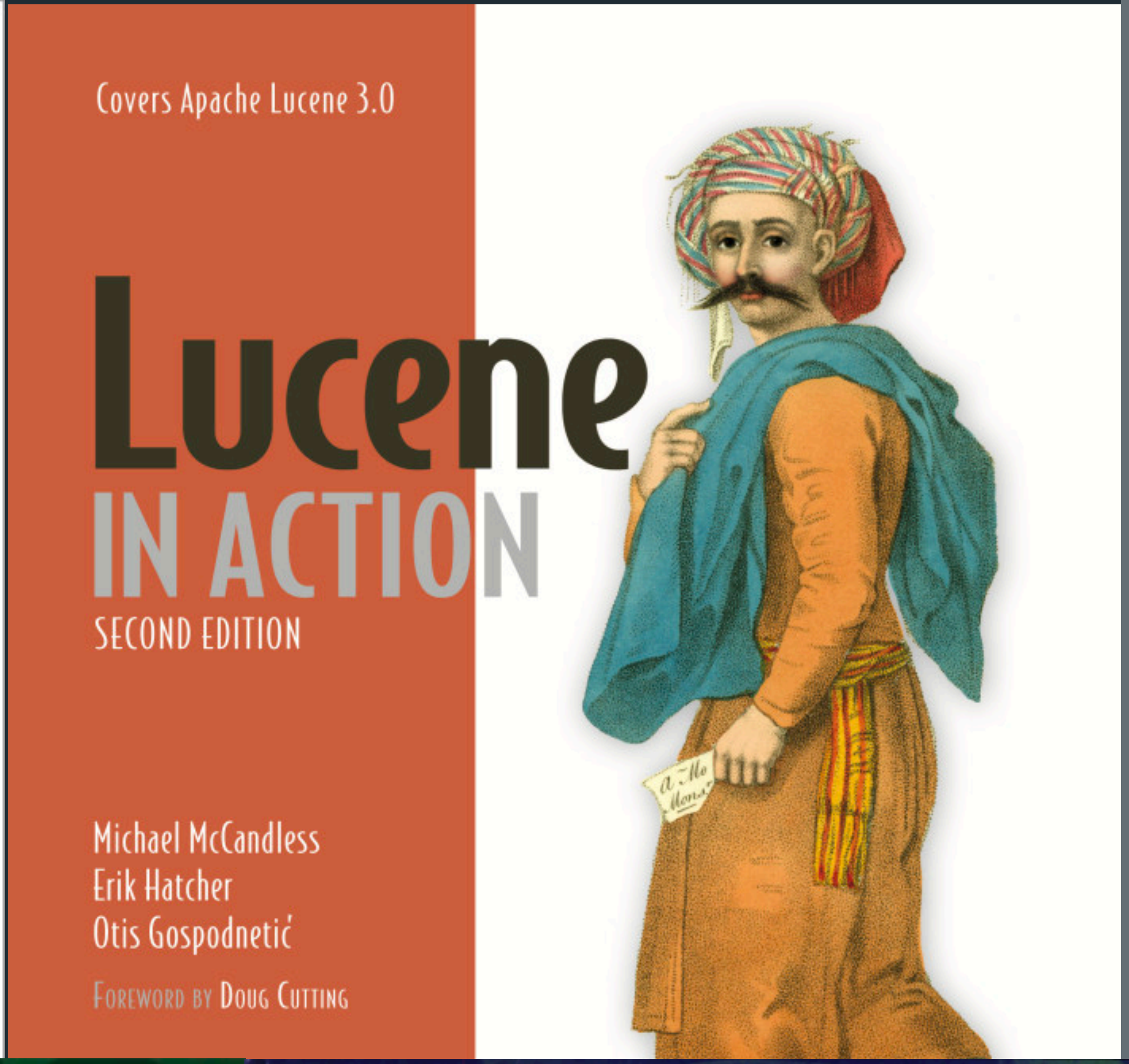
Christopher D. Manning
Prabhakar Raghavan
Hinrich Schütze

Introduction to
Information
Retrieval


O'REILLY

Elasticsearch
The Definitive Guide

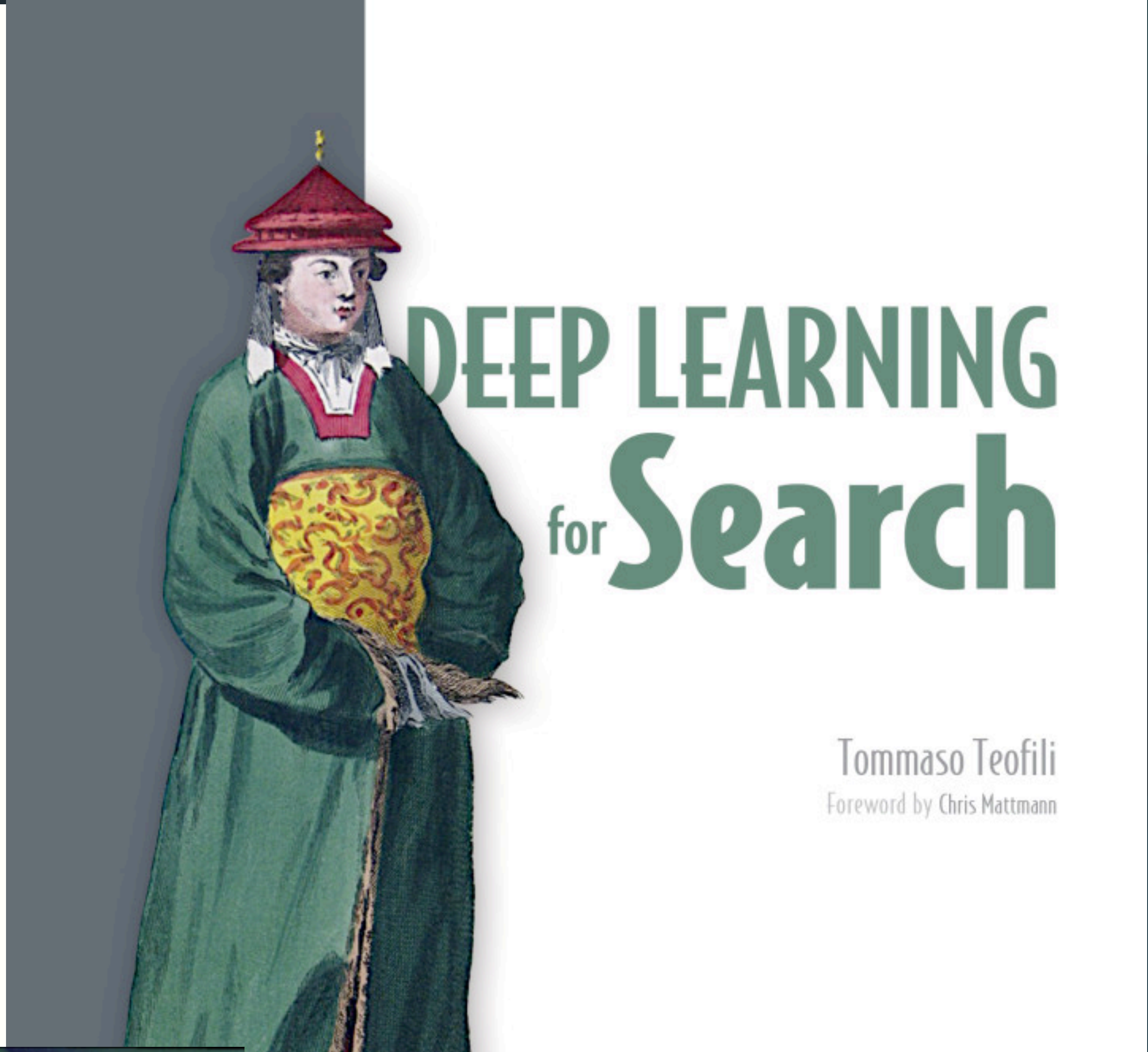
A DISTRIBUTED REAL-TIME SEARCH AND ANALYTICS ENGINE


Covers Apache Lucene 3.0

Lucene
IN ACTION
SECOND EDITION

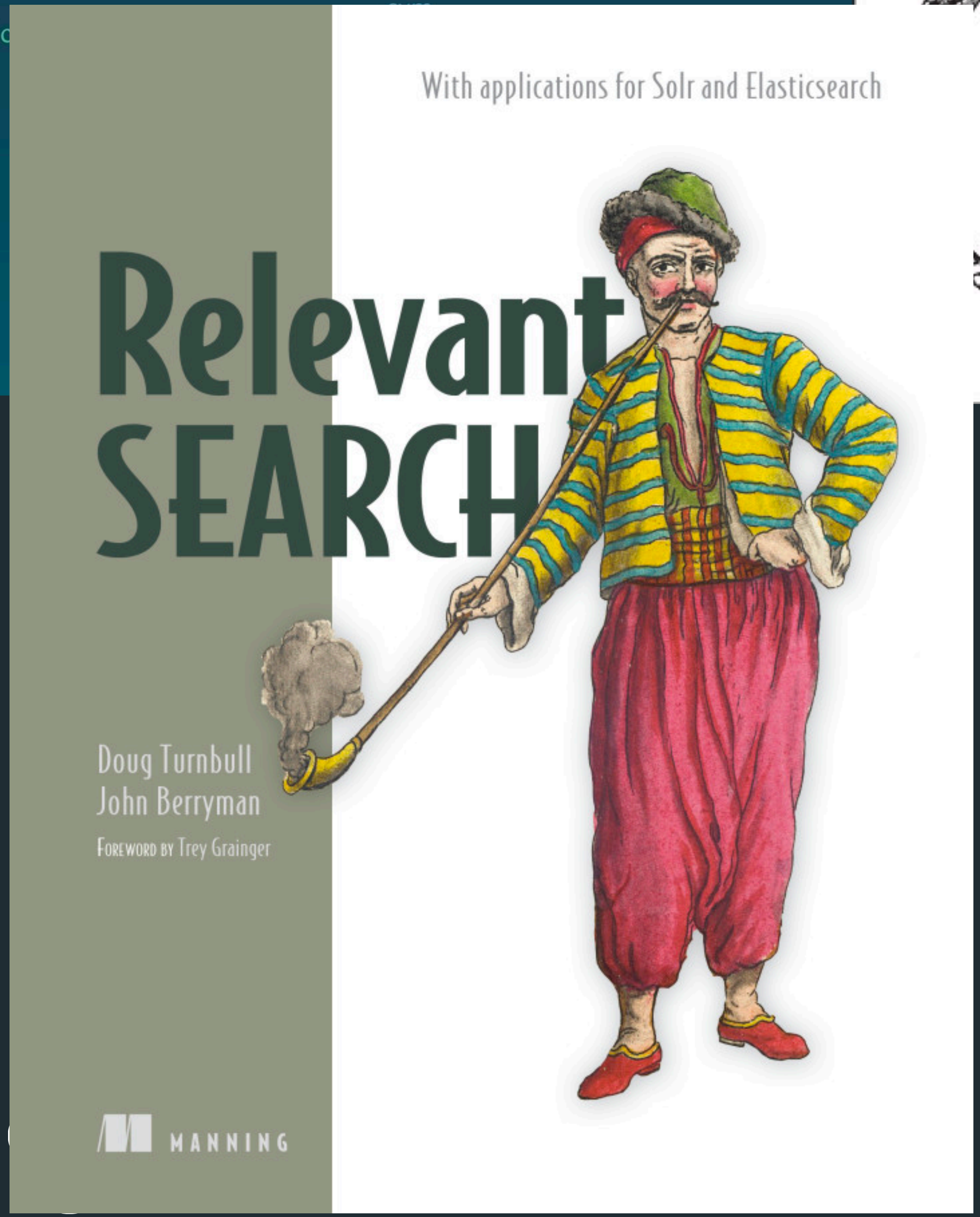
Michael McCandless
Erik Hatcher
Otis Gospodnetić

Foreword by Doug Cutting


DEEP LEARNING
for Search

Tommaso Teofili
Foreword by Chris Mattmann

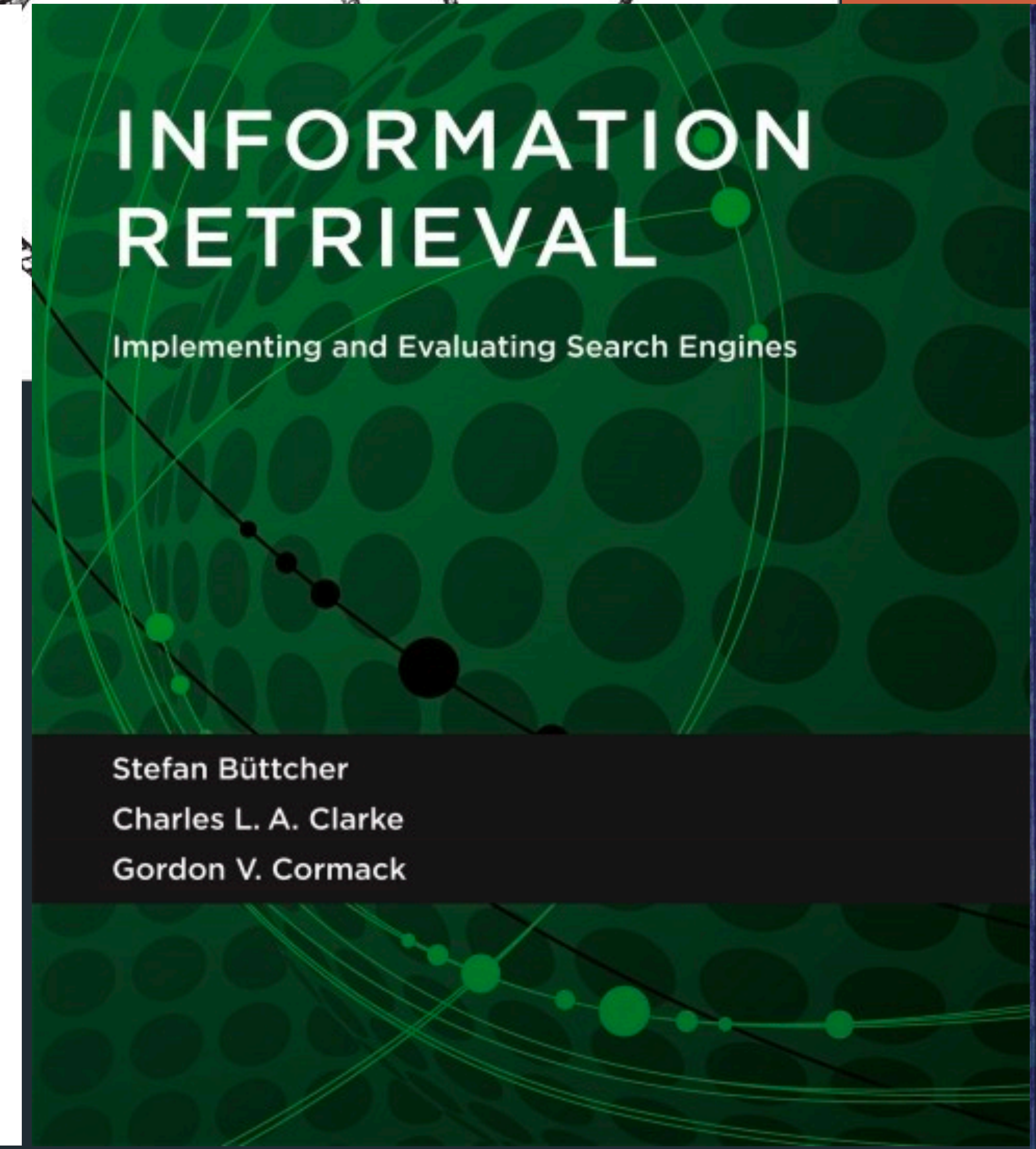
MANNING


With applications for Solr and Elasticsearch

Relevant
SEARCH

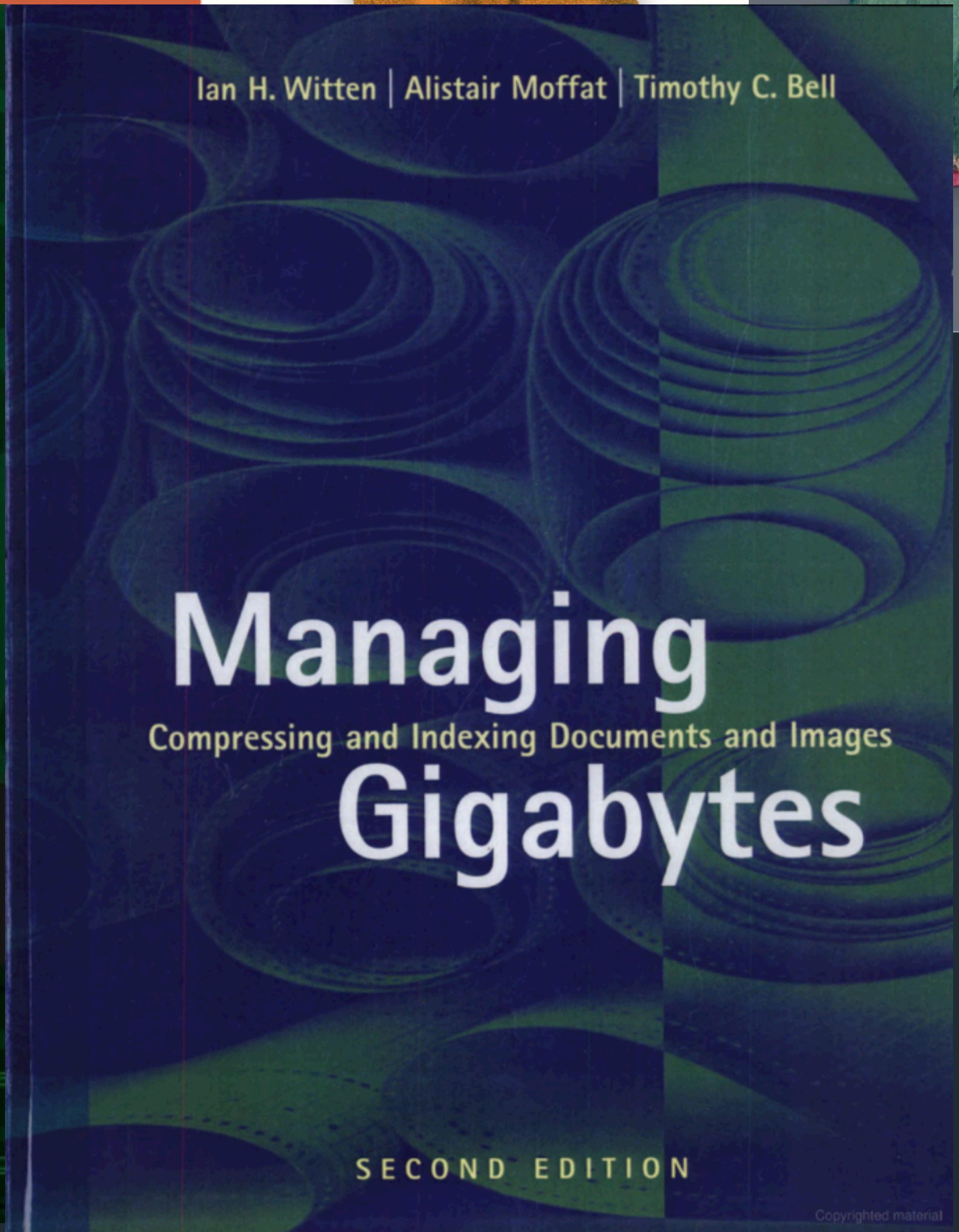
Doug Turnbull
John Berryman
Foreword by Trey Grainger

MANNING


INFORMATION
RETRIEVAL

Implementing and Evaluating Search Engines

Stefan Büttcher
Charles L. A. Clarke
Gordon V. Cormack


Ian H. Witten | Alistair Moffat | Timothy C. Bell

Managing
Compressing and Indexing Documents and Images
Gigabytes

SECOND EDITION

elastic

Resources

Links, links, links

Links

https://lucene.apache.org/core/8_2_0/core/org/apache/lucene/search/similarities/TFIDFSimilarity.html

https://www.elastic.co/blog/whats-new-in-lucene-8

https://www.elastic.co/blog/faster-retrieval-of-top-hits-in-elasticsearch-with-block-max-wand

https://speakerdeck.com/elastic/amusing-algorithms-and-data-structures

https://www.elastic.co/blog/index-sorting-elasticsearch-6-0

https://raft.github.io/

https://github.com/elastic/elasticsearch-formal-models

https://gist.github.com/spinscale/b62c8b357fae7db3f14b7d3127758951

Links - probabilistic data structures

https://github.com/addthis/stream-lib

https://github.com/DataDog/sketches-java

https://github.com/HdrHistogram/HdrHistogram

https://github.com/JohnStarich/java-skip-list

https://github.com/addthis/stream-lib

https://static.googleusercontent.com/media/research.google.com/fr/pubs/archive/40671.pdf

elastic

Q & A

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