# Realtime Search with Lucene

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# Realtime Search with Lucene

## Agenda

- Introduction
- Near-realtime Search (NRT)
- Searching DocumentsWriter's RAM buffer
- Sequence IDs
- Twitter prototype
- Roadmap

# Introduction

# Introduction

- Lucene made great progress towards realtime search with the Near-realtime search feature (NRT) added in 2.9

- NRT reduces search latency (time it takes until a document becomes searchable) significantly, using the new **`IndexWriter.getReader()`**

- Drawback of NRT: If **`getReader()`** is called frequently, indexing performance decreases significantly

- New approach: Searching on IndexWriter's/DocumentsWriter's in-memory buffer directly

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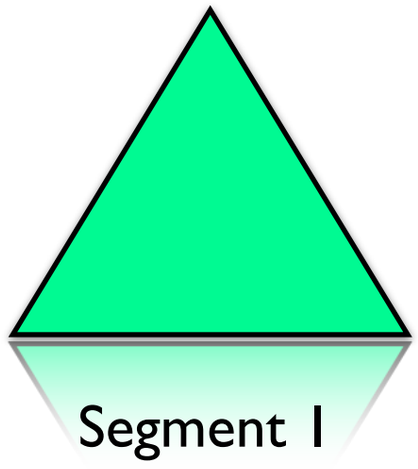
# Near-realtime Search (NRT)

# Incremental Indexing

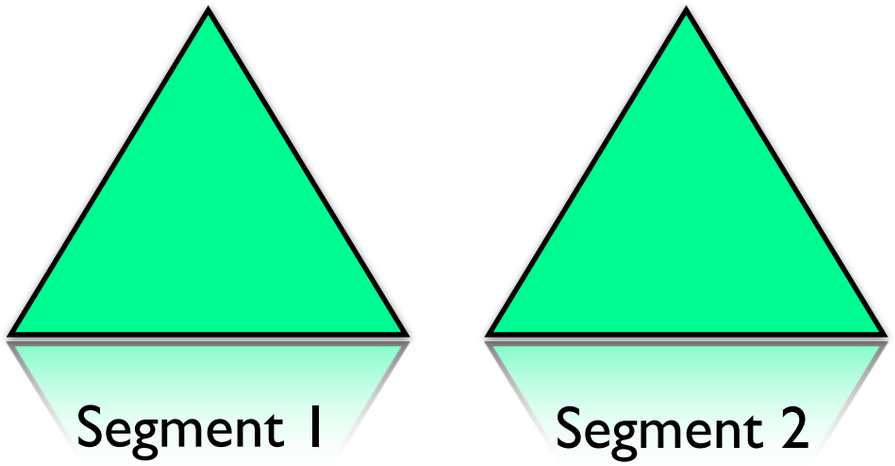
- Lucene is an incremental indexer - documents can be added to an existing, searchable index
- Lucene writes “segments”, which are small indexes itself
- A Lucene index consists of one or more segments
- Small segments are merged into larger ones to limit total number of segments per index

# Incremental Indexing




- After a segment is written and committed (triggered by **`IndexWriter.commit()`** or **`IndexWriter.close()`**) it is visible to IndexReaders

# Incremental Indexing

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- New segments can be written, while IndexReaders execute queries on older segments

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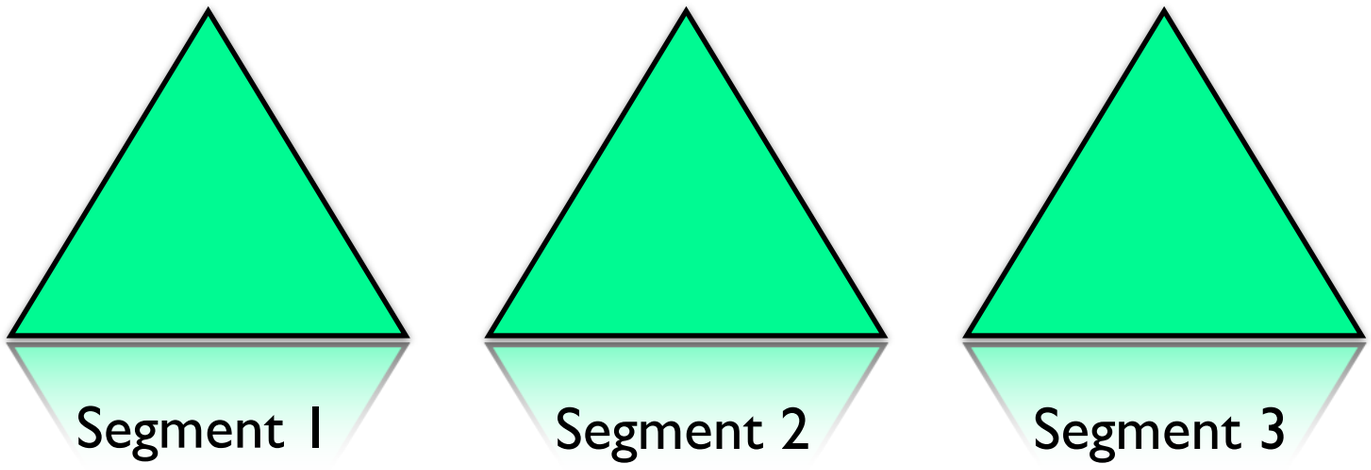


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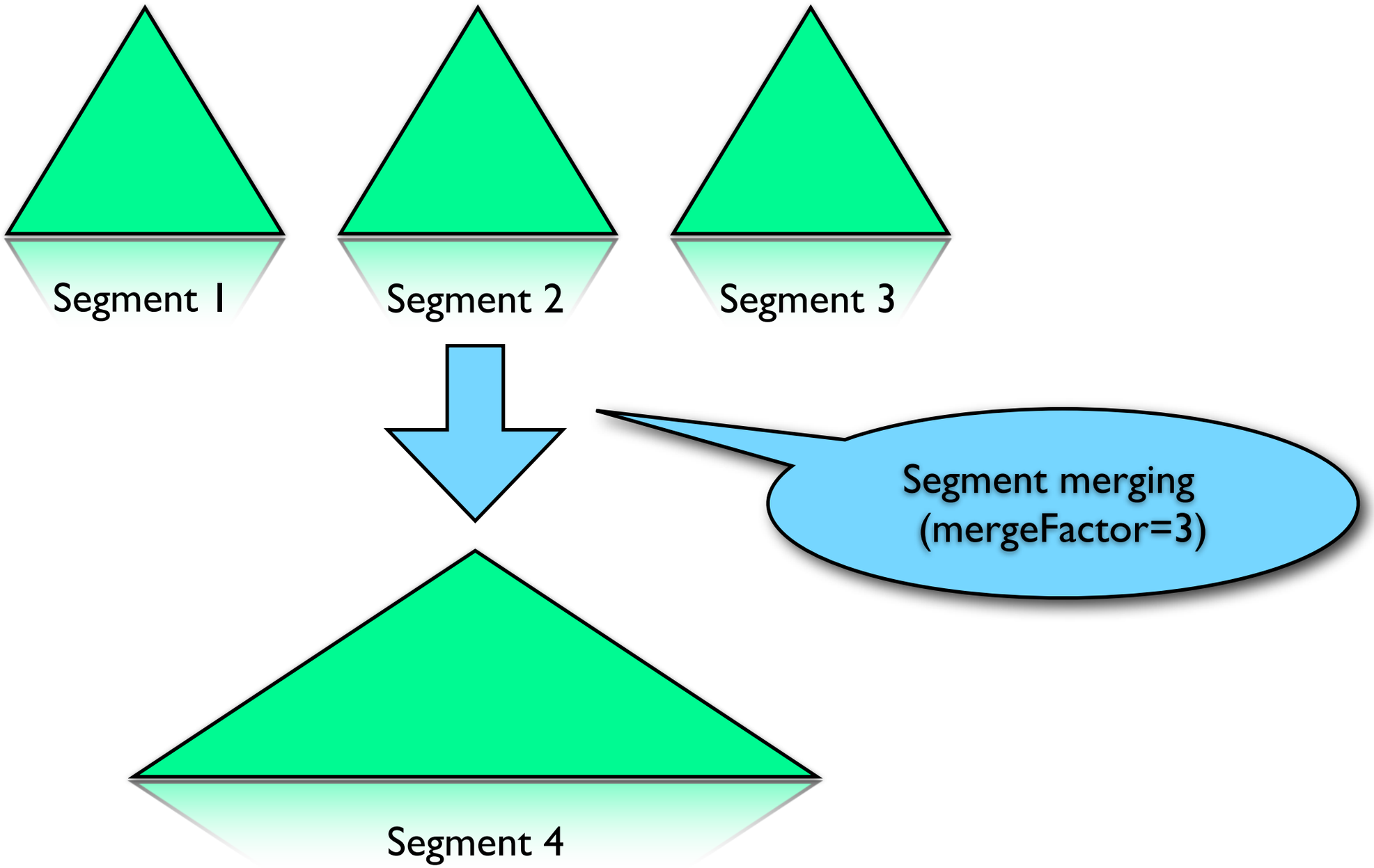

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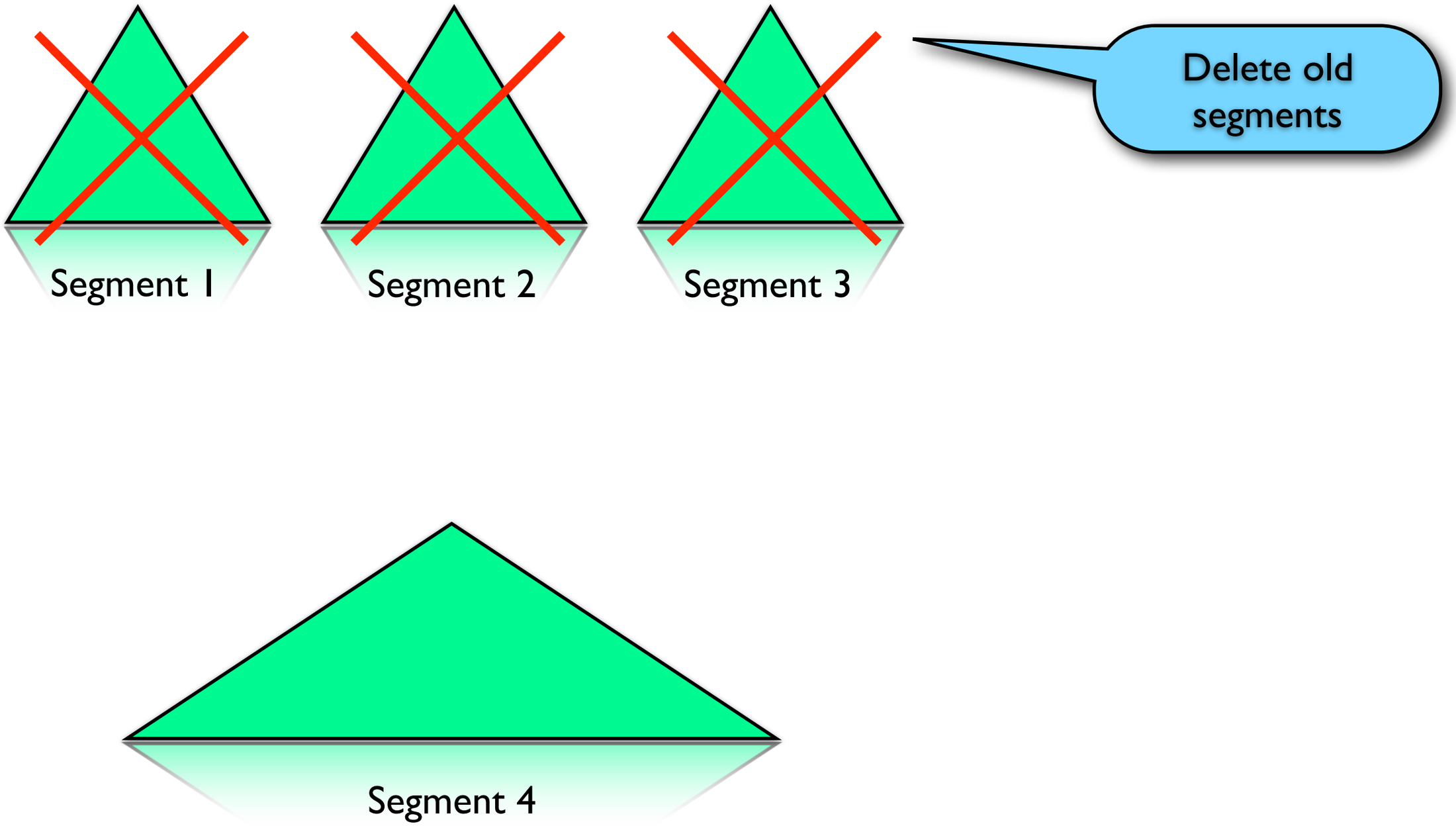

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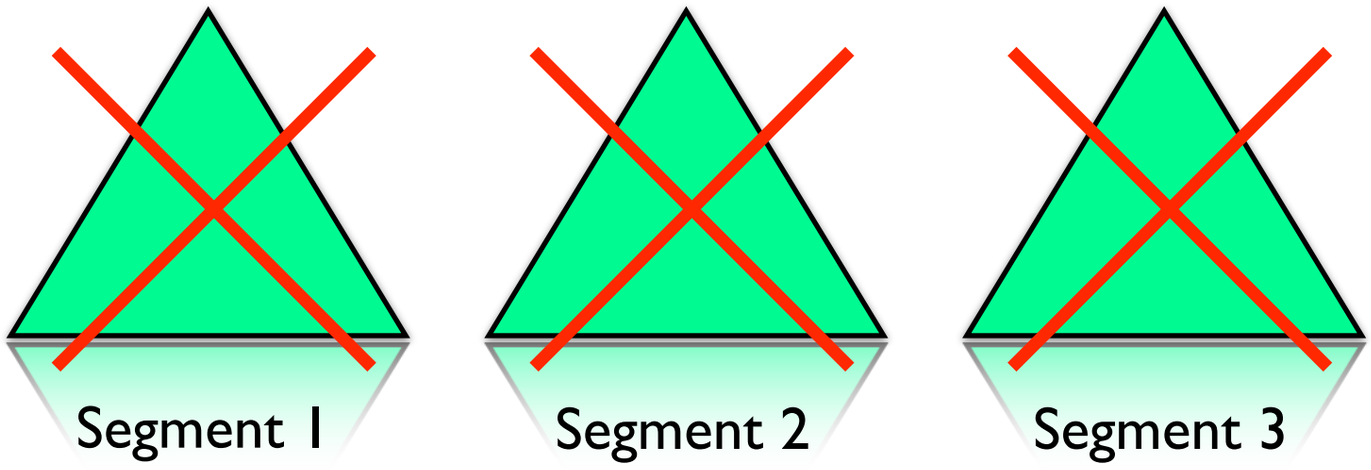


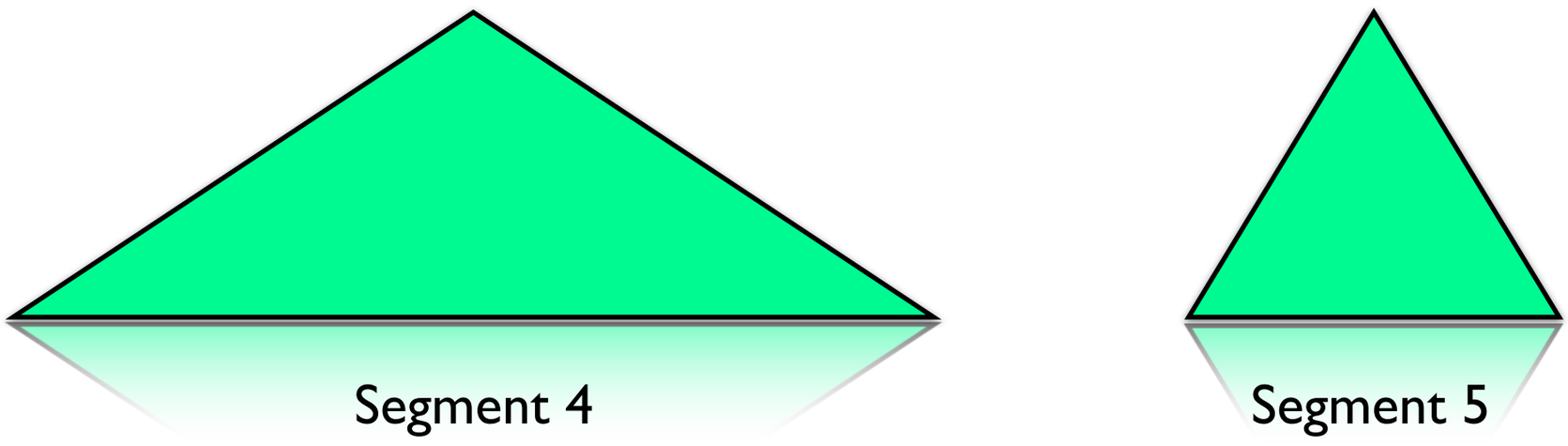

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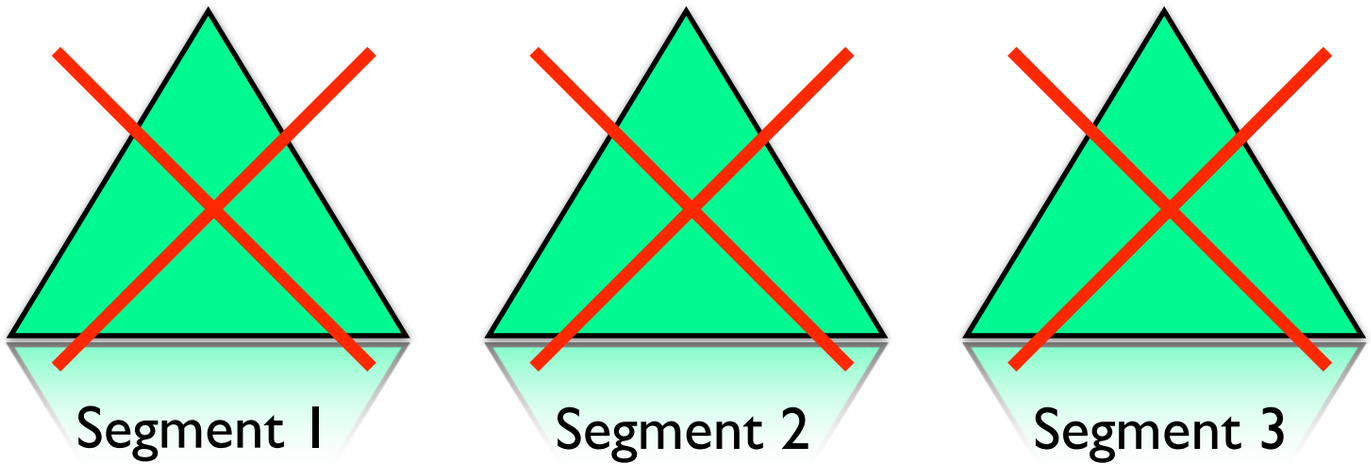


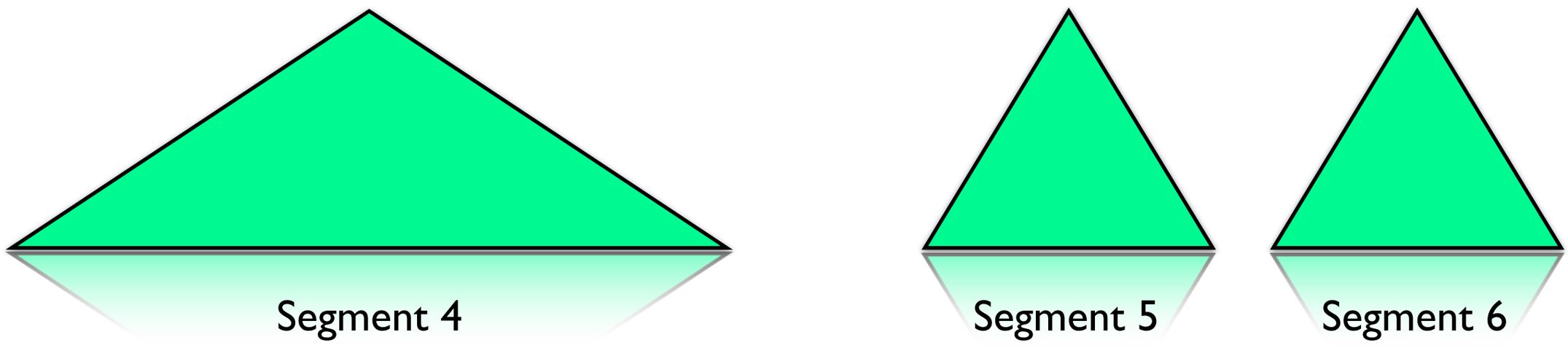

# Committing an index segment

- Flush in-memory data structures to index location (usually on disk)
- Possibly trigger a segment merge
- Synchronize segment files, which forces the OS to flush those files from the FS cache to the physical disk (this can be an expensive operation)
- Append an entry to segments_x file and write new segment_x+1 file
- **`IndexWriter.close()`** might have to wait for in-flight segment merges to complete (this can be **very** expensive)

# Near-realtime search (NRT)

- NRT tries to avoid the two most expensive aspects of segment committing: file handle sync calls and waiting for segment merge completion

- **`IndexWriter.getReader()`** can be called to obtain an IndexReader, that can query **flushed, not-yet-committed** segments

- Reduces indexing latency significantly, and IndexWriters don't have to be closed to (re)open IndexReaders

- Disadvantage: **`getReader()`** triggers a flush of the in-memory data structures

# A little bit Lucene history: LUCENE-843

- Indexer was rewritten with LUCENE-843 patch (released in 2.3)
- Indexing performance improved by 5x-10x (!!)
- Before, each document was inverted and encoded as its own segment
- These tiny single-doc segments were merged with Lucene's standard SegmentMerger
- LUCENE-843 introduced class DocumentsWriter, which can take a large number of docs and invert them into a single segment
- Dramatic improvements in memory consumption and indexing performance

# Near-realtime search (NRT)

- IndexWriter.getReader() triggers DocumentsWriter to flush its in-memory data structures into a segment every time it's called

- If called very frequently (desired in realtime search), it results in a similar behavior as before LUCENE-843

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# Searching DocumentsWriter's RAM buffer

# Goals

- **Goal 1:**
  Allow IndexReaders to search on DocumentsWriter's RAM buffer, while documents are being appended simultaneously to the same data structures

- **Goal 2:**
  Maintain high indexing performance with large RAM buffer, and independent of the query load

- **Goal 3:**
  Opening a RAM IndexReader should be so cheap, so that a new reader can be opened for every query (drops latency close to zero)

# LUCENE-2329: Parallel posting arrays

- Already committed to Lucene's trunk
- Changes how per-term data is stored in RAM

# Inverted Index

| | |
|---|---|
| 1 | The old night keeper keeps the keep in the town |
| 2 | In the big old house in the big old gown. |
| 3 | The house in the town had the big old keep |
| 4 | Where the old night keeper never did sleep. |
| 5 | The night keeper keeps the keep in the night |
| 6 | And keeps in the dark and sleeps in the light. |

## Table with 6 documents

Example from:
*Justin Zobel , Alistair Moffat,*
*Inverted files for text search engines,*
*ACM Computing Surveys (CSUR)*
*v.38 n.2, p.6-es, 2006*

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Table with 6 documents

| term | freq | |
|---|---|---|
| and | 1 | <6> |
| big | 2 | <2> <3> |
| dark | 1 | <6> |
| did | 1 | <4> |
| gown | 1 | <2> |
| had | 1 | <3> |
| house | 2 | <2> <3> |
| in | 5 | <1> <2> <3> <5> <6> |
| keep | 3 | <1> <3> <5> |
| keeper | 3 | <1> <4> <5> |
| keeps | 3 | <1> <5> <6> |
| light | 1 | <6> |
| never | 1 | <4> |
| night | 3 | <1> <4> <5> |
| old | 4 | <1> <2> <3> <4> |
| sleep | 1 | <4> |
| sleeps | 1 | <6> |
| the | 6 | <1> <2> <3> <4> <5> <6> |
| town | 2 | <1> <3> |
| where | 1 | <4> |

Dictionary and posting lists

# Inverted Index

# Query: keeper

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Dictionary and posting lists

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Table with 6 documents

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| **keeper** | **3** | **<1> <4> <5>** |
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Dictionary and posting lists

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Per term we store different kinds of metadata: text pointer, frequency, postings pointer, etc.

Dictionary and posting lists

# LUCENE-2329: Parallel posting arrays

```
class PostingList

int textPointer;
int postingsPointer;
int frequency;
...
```

- Term hashtable is an array of these objects: **`PostingList[] termsHash`**

- For each unique term in a segment we need an instance; this results in a very large number of objects that are long-living, i.e. the garbage collecter can't remove them quickly (they need to stay in memory until the segment is flushed)

- With a searchable RAM buffer we want to flush much less often and allow DocumentsWriter to fill up the available memory

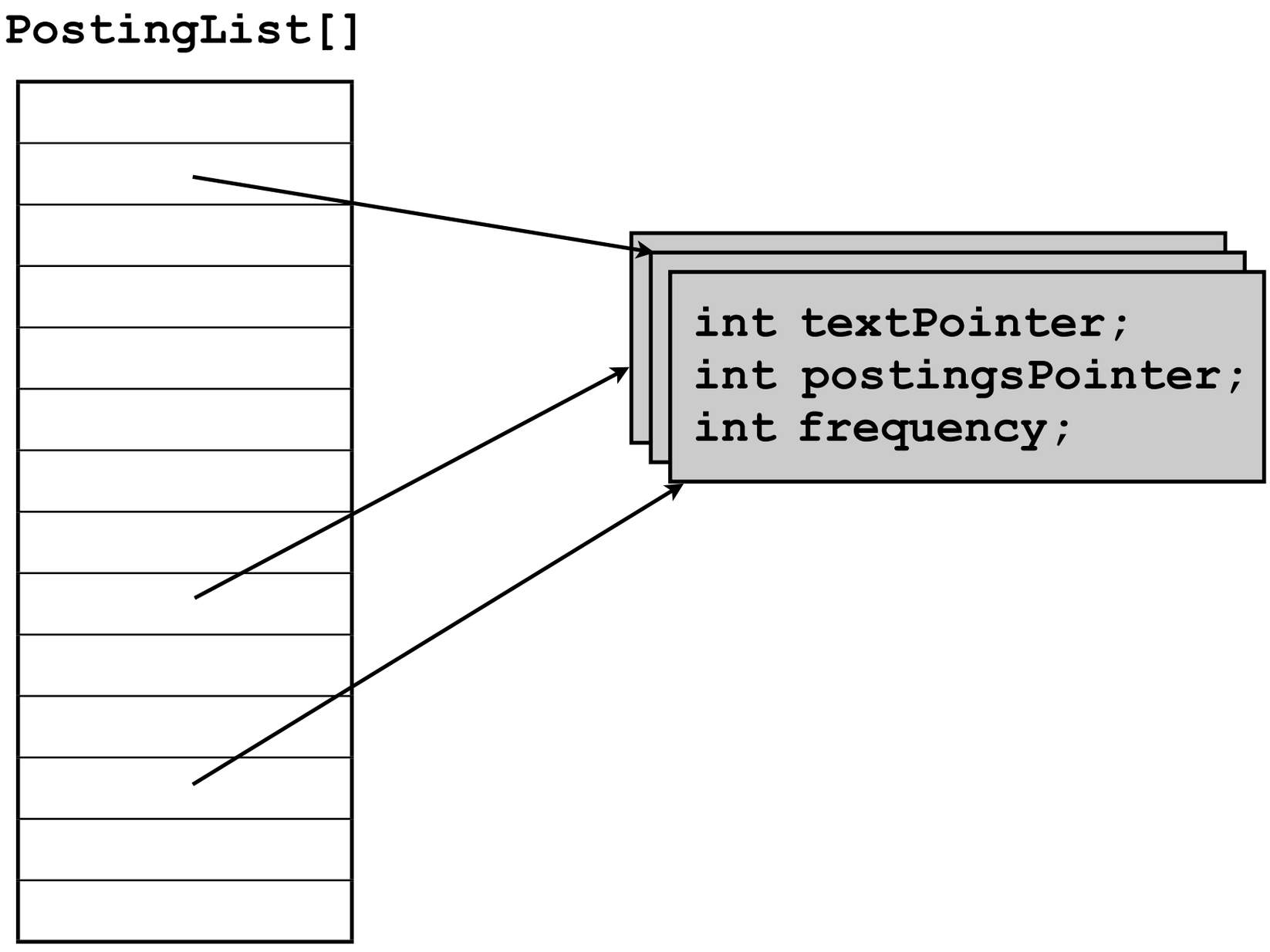
# LUCENE-2329: Parallel posting arrays

```
class PostingList

int textPointer;
int postingsPointer;
int frequency;
...
```

- Having a large number of long-living objects is very expensive in Java, especially when the default mark-and-sweep garbage collector is used
- The mark phase of GC becomes very expensive, because all long-living objects in memory have to be checked
- We need to reduce the number of objects to improve GC performance!
  -> Parallel posting arrays

# LUCENE-2329: Parallel posting arrays



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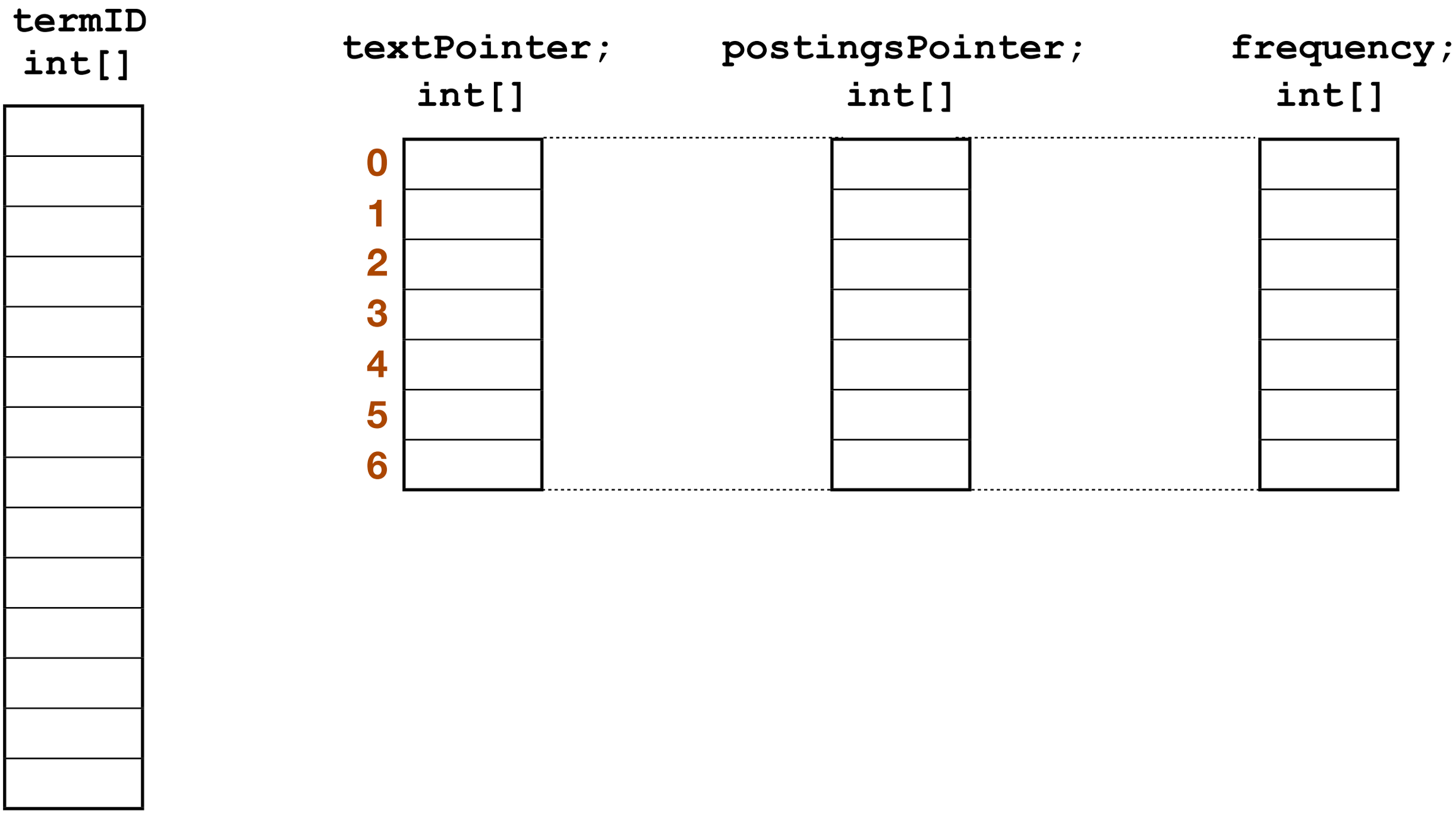

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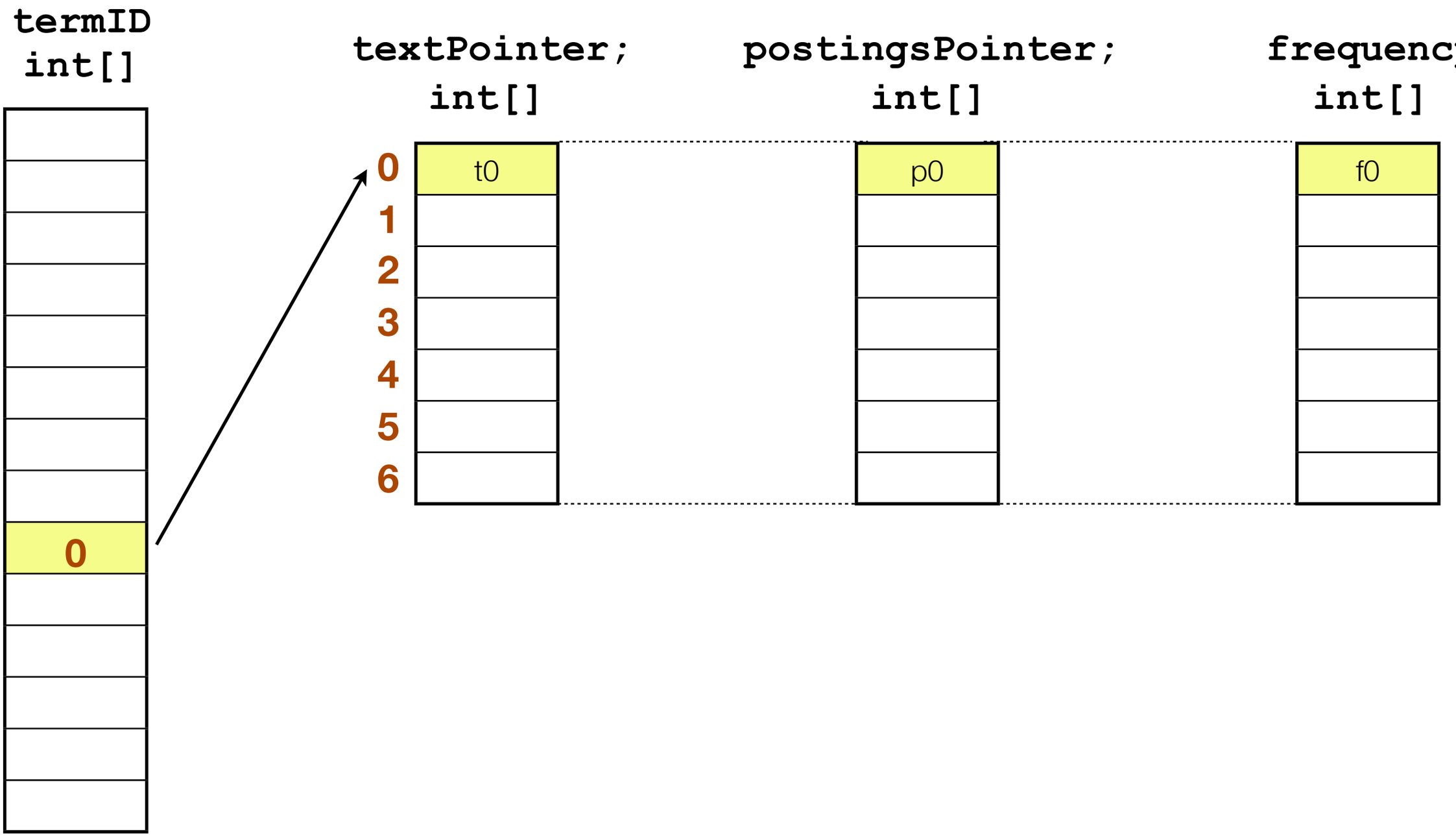

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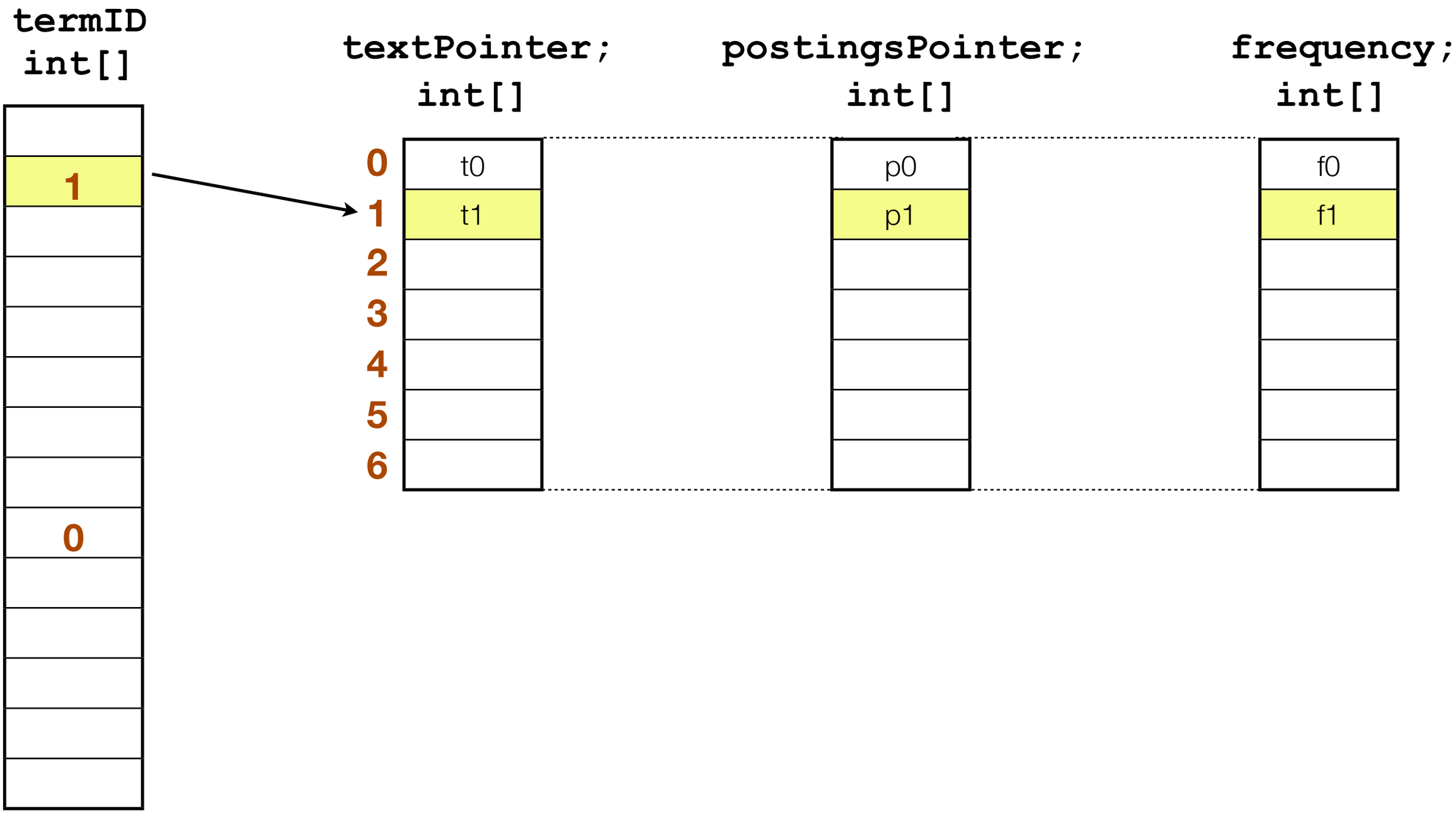

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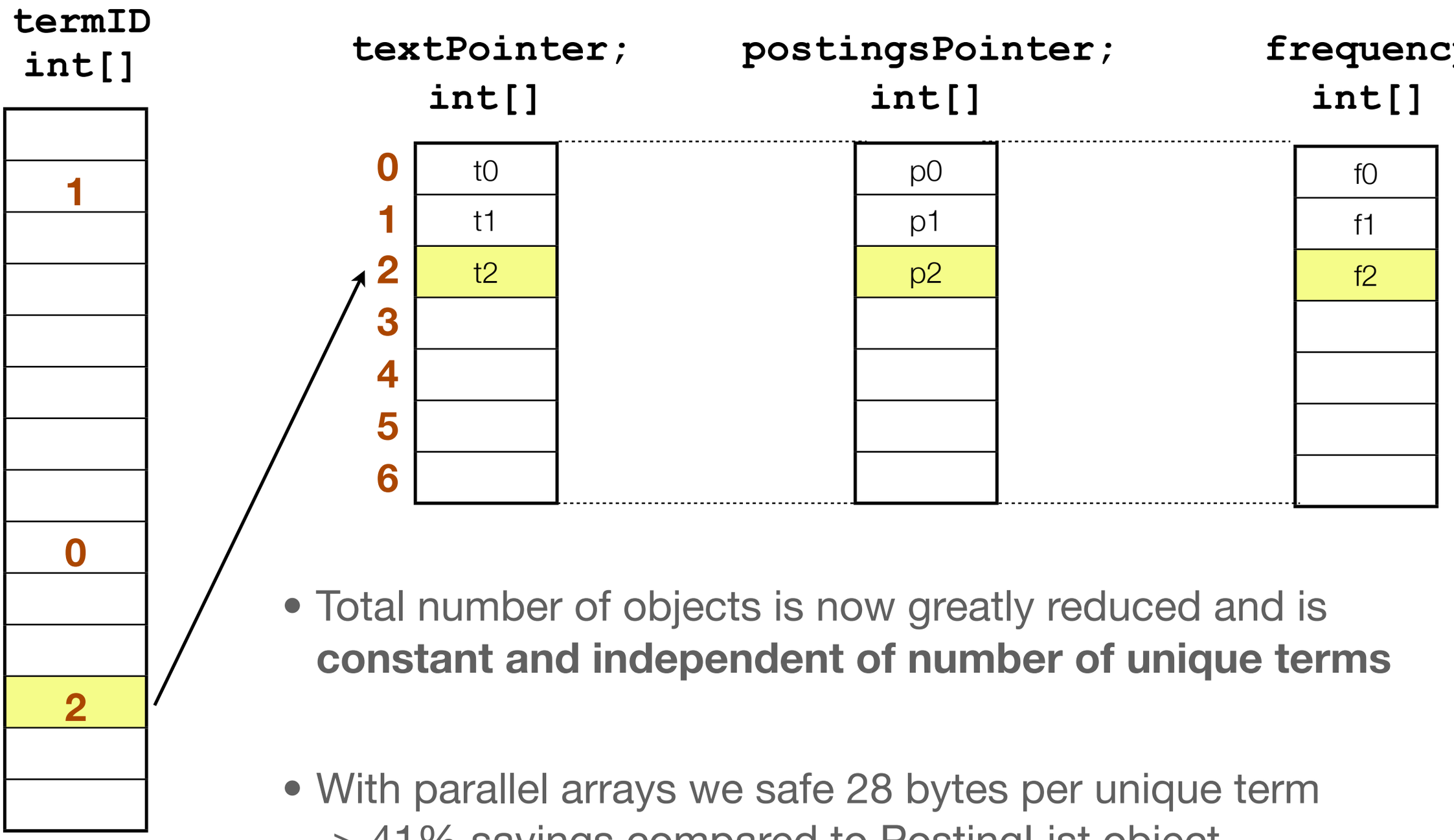



- Total number of objects is now greatly reduced and is **constant and independent of number of unique terms**

- With parallel arrays we safe 28 bytes per unique term
  -> 41% savings compared to PostingList object

# LUCENE-2329: Parallel posting arrays - Performance

- Performance experiments: Index 1M wikipedia docs

1) -Xmx**2048M**, indexWriter.setMaxBufferSizeMB(**200**)

**4.3%** improvement

2) -Xmx**256M**, indexWriter.setMaxBufferSizeMB(**200**)

**86.5%** improvement

# LUCENE-2329: Parallel posting arrays - Performance

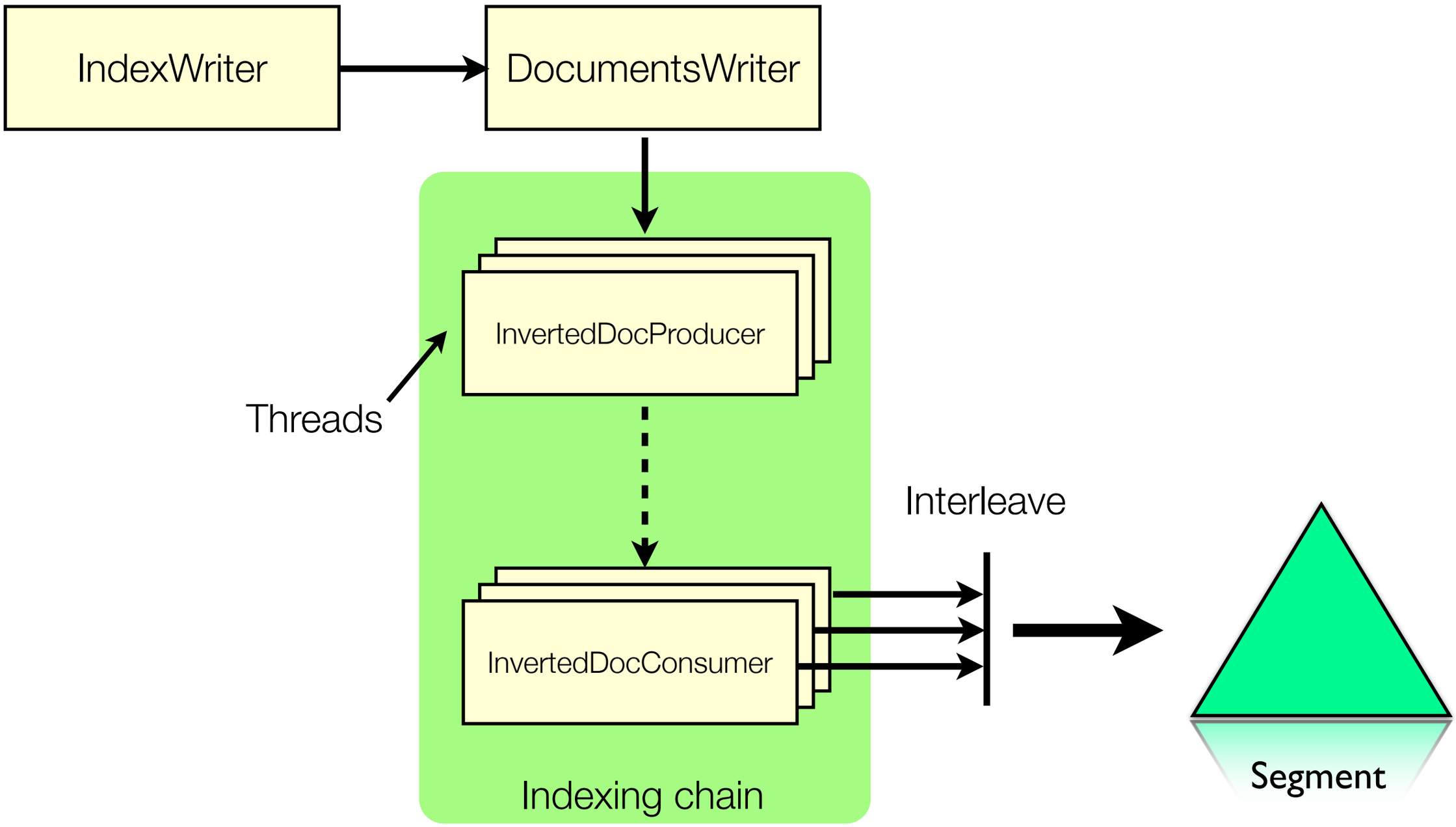
- With large heap there is a small improvement due to per-term memory savings

- With small heap the garbage collector is invoked much more often - huge improvement due to smaller number of objects (depending on doc sizes we have seen improvements of up to **400%**!)

- With searchable RAM buffers we want to utilize all the RAM we have; with parallel arrays we can maintain high indexing performance even if we get close to the max heap size

**Goal 2:**
Maintain high indexing performance with large RAM buffer, and independent of the query load

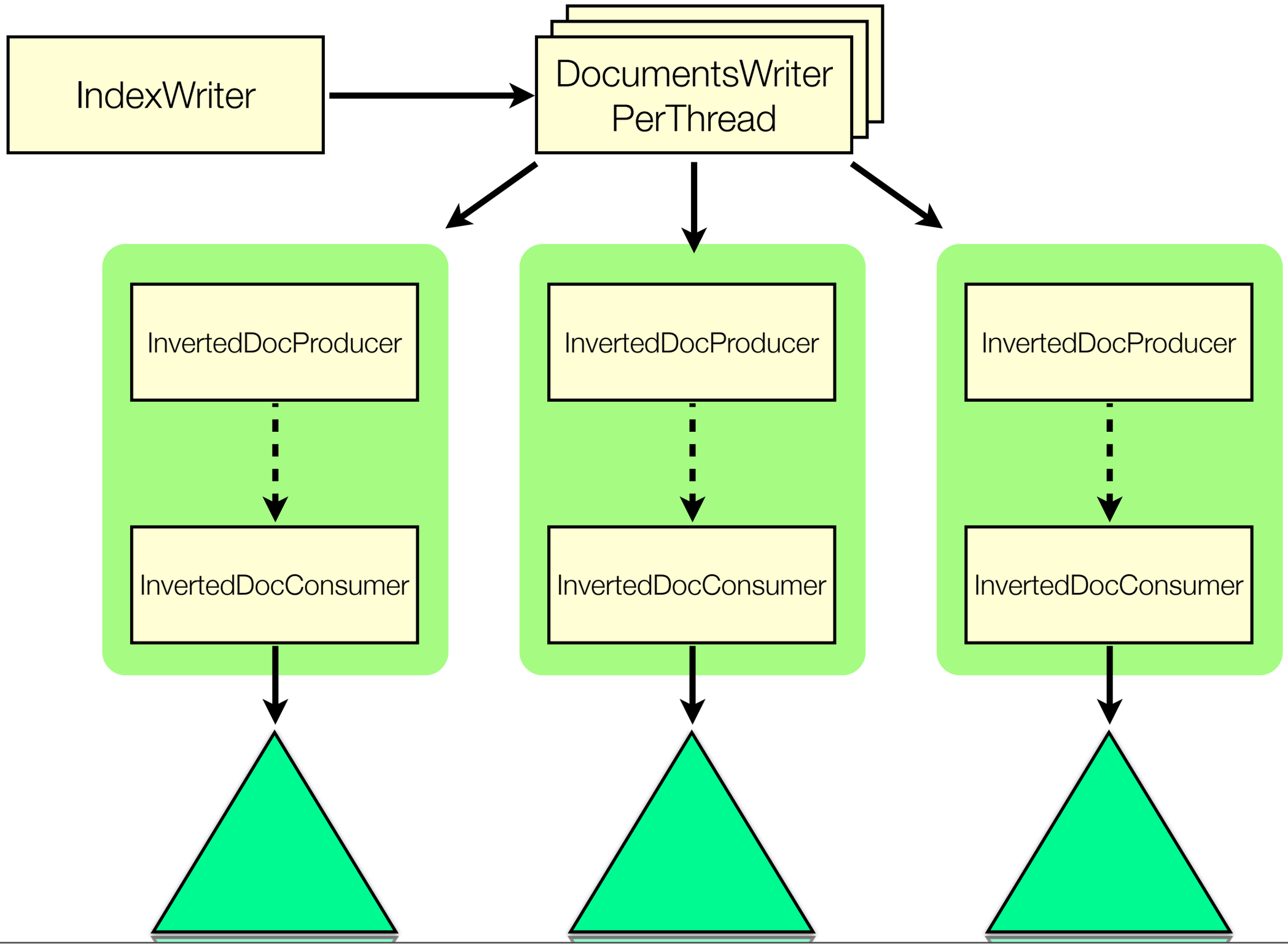
# Today: Multi-threaded Indexing chain



# Today: Multi-threaded Indexing chain

- The interleaving step is quite expensive
- Flushing “stops the world”: No documents can be added during flushing/ interleaving
- Multi-threaded code necessary in all IndexingChain classes, e.g. we have >10 *PerThread classes in the indexer package

# LUCENE-2324: Single threaded indexing chain



# LUCENE-2324: Single threaded indexing chain

- Multiple per-thread DocumentsWriters write their own private segments
- Great simplification, many perThread classes can be removed (see 2324 patch)
- DocumentsWriterPerThreads can flush independently without “stopping the world”; interleaving step not necessary anymore
- This change reduces the concurrency problem we need to solve for RAM IndexReaders to a single-writer, multi-reader problem -> lock-free algorithms are now possible

# Searching DocumentsWriter's RAM buffer

- Implement an IndexReader that shares the indexes data structures with DocumentsWriter
- Terms hashtable is used for fast term lookup
- TermDocs/TermPositions implementation for in-memory postinglists
- Sequence IDs for efficient deletes
- IndexReader needs to be able to switch automatically and on-the-fly from reader the RAM buffer to a flushed segment in case DocumentsWriter flushes its buffer while searches are in-flight

**Goal 1:**
Allow IndexReaders to search on DocumentsWriter's RAM buffer, while documents are being appended simultaneously to the same data structures

# Concurrency

- Having a single writer thread simplifies our problem: no locks have to be used to protect data structures from corruption (only one thread modifies data)

- But: we have to make sure that all readers **always** see a consistent state of **all** data structures -> this is much harder than it sounds!

- In Java, it is not guaranteed that one thread will see changes that another thread makes in program execution order, unless the same memory barrier is crossed by both threads -> **safe publication**

- Safe publication can be achieved in different, subtle ways.  Read the great book “Java concurrency in practice” by Brian Goetz for more information!

- Going through all details could easily fill an entire talk.  We’ll only look into a few examples here.

# Concurrency - Example: term lookup

- Each reader remembers the max. docID of the last completely indexed document at the time the reader was opened

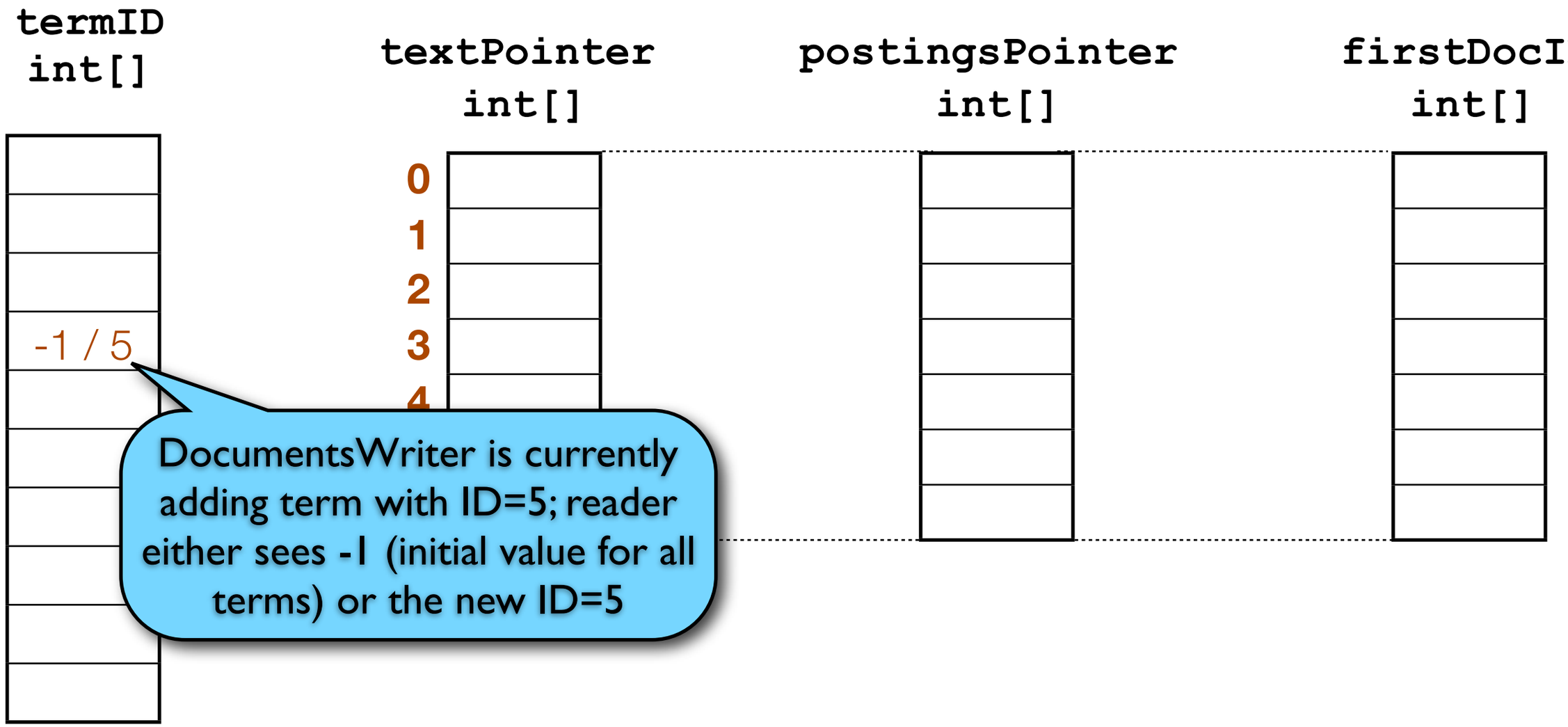
- For each term we store the first docIDs it occurred in.  We make sure the parallel array holding those first docIDs is properly initialized (visible to readers)

- When we lookup a term with an IndexReader, we compare the reader's maxDocID with the first docID of the term; the term is only returned if maxDocID(reader) >= firstDocID(term); otherwise the lookup method returns term_not_found

- There are not "dirty reads" on integers in Java, meaning a thread either gets the old or the new value of a variable that another thread is writing too in parallel

# Concurrency - Example: term lookup

- If a reader tries to lookup a term that a writer is at the same time writing for the first time (term has not yet occurred in earlier documents) different things can happen:



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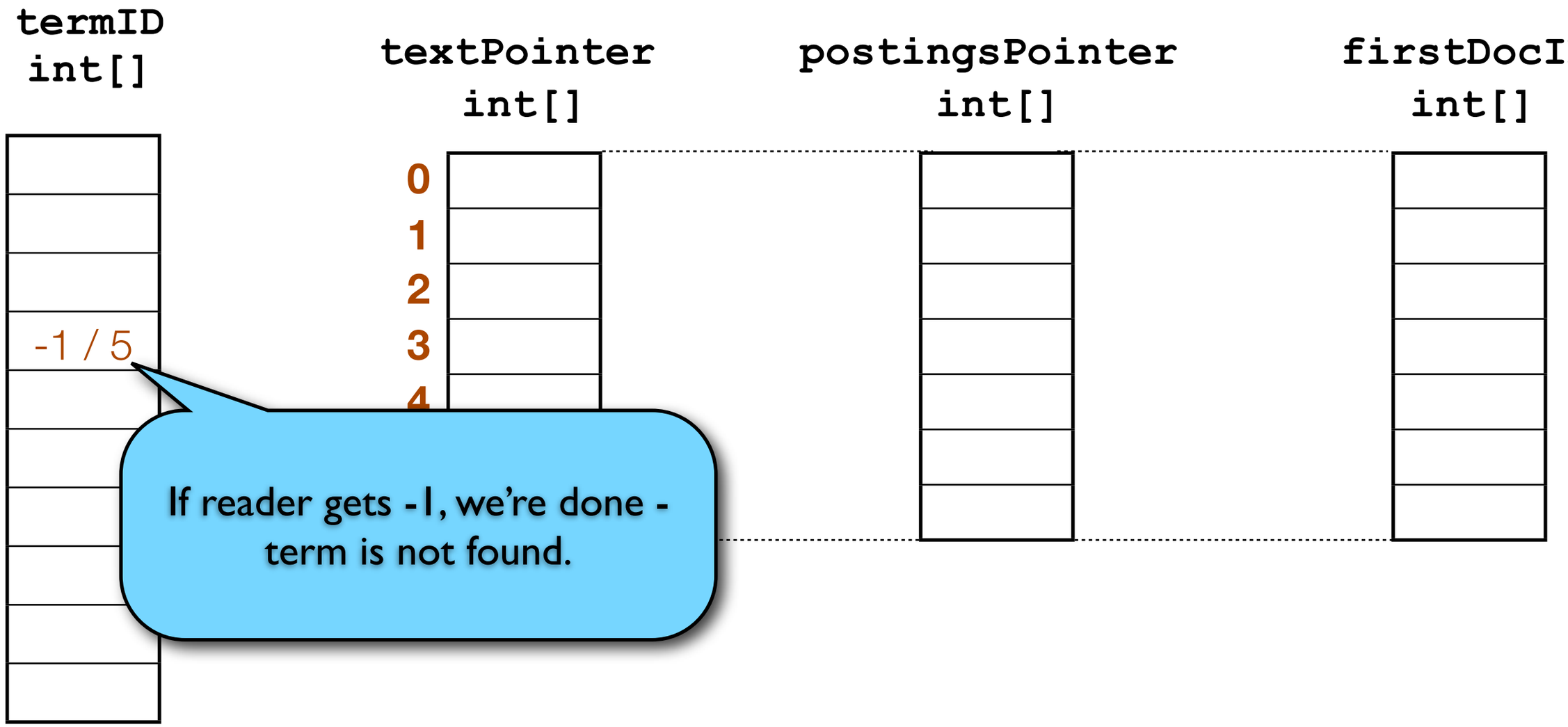

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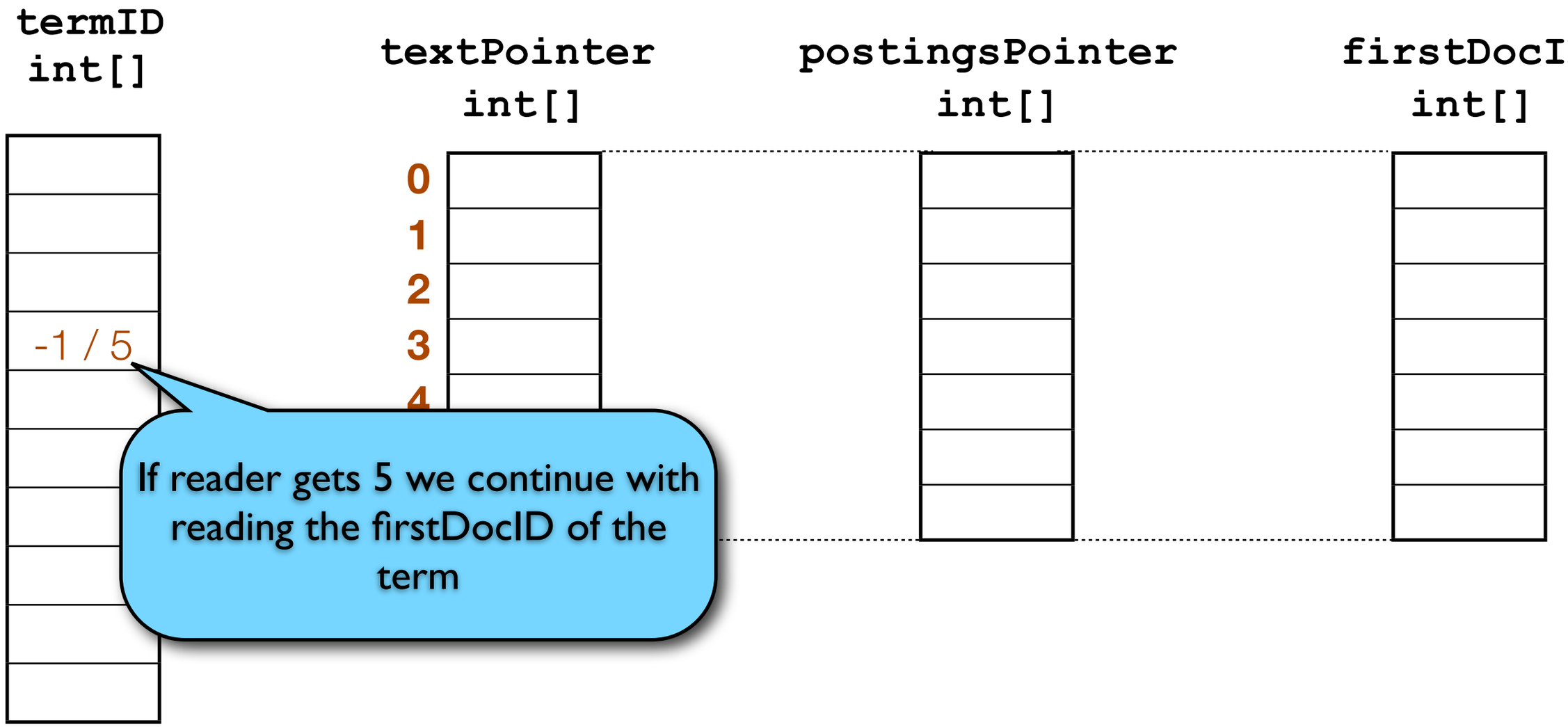

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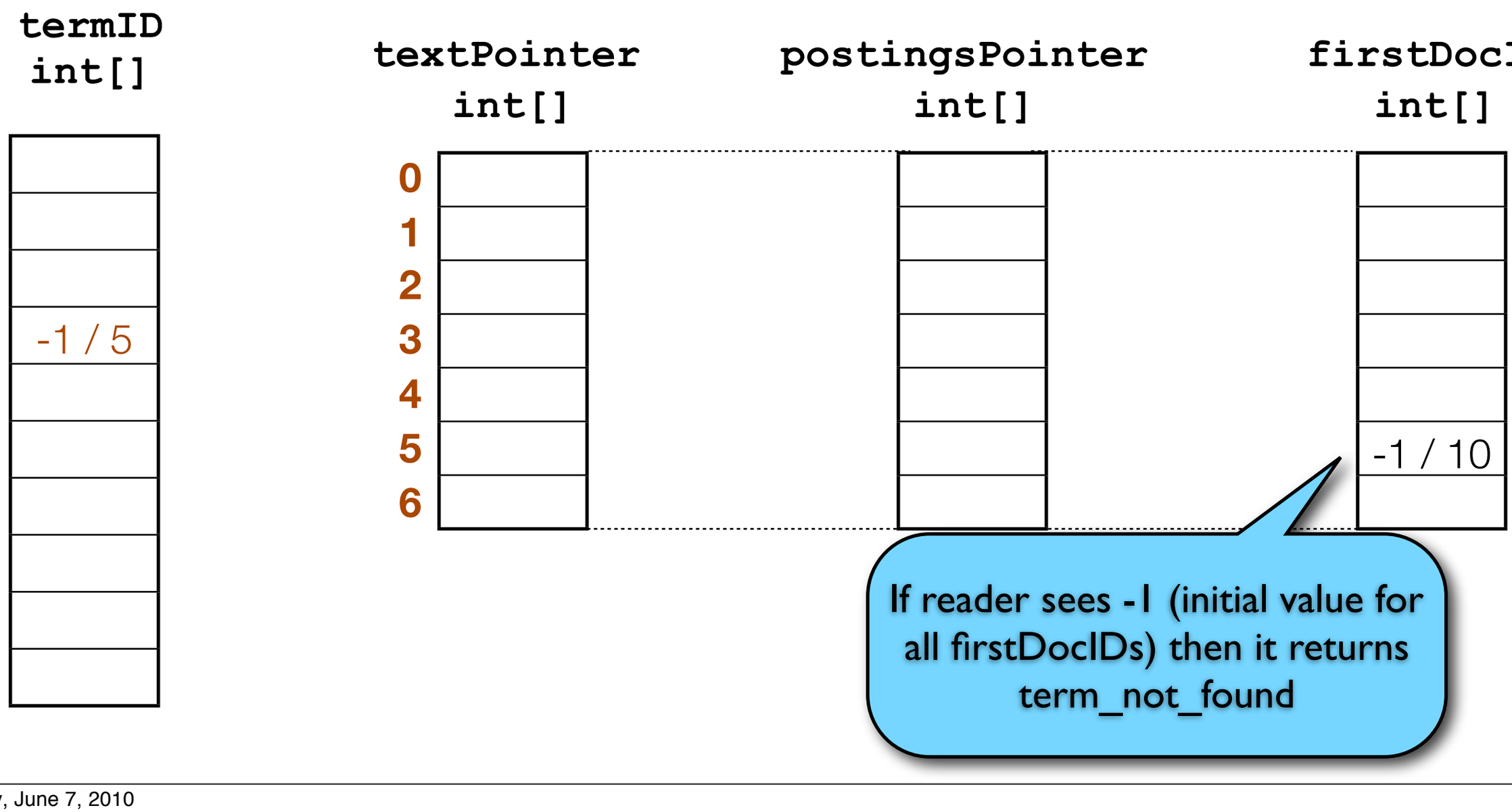

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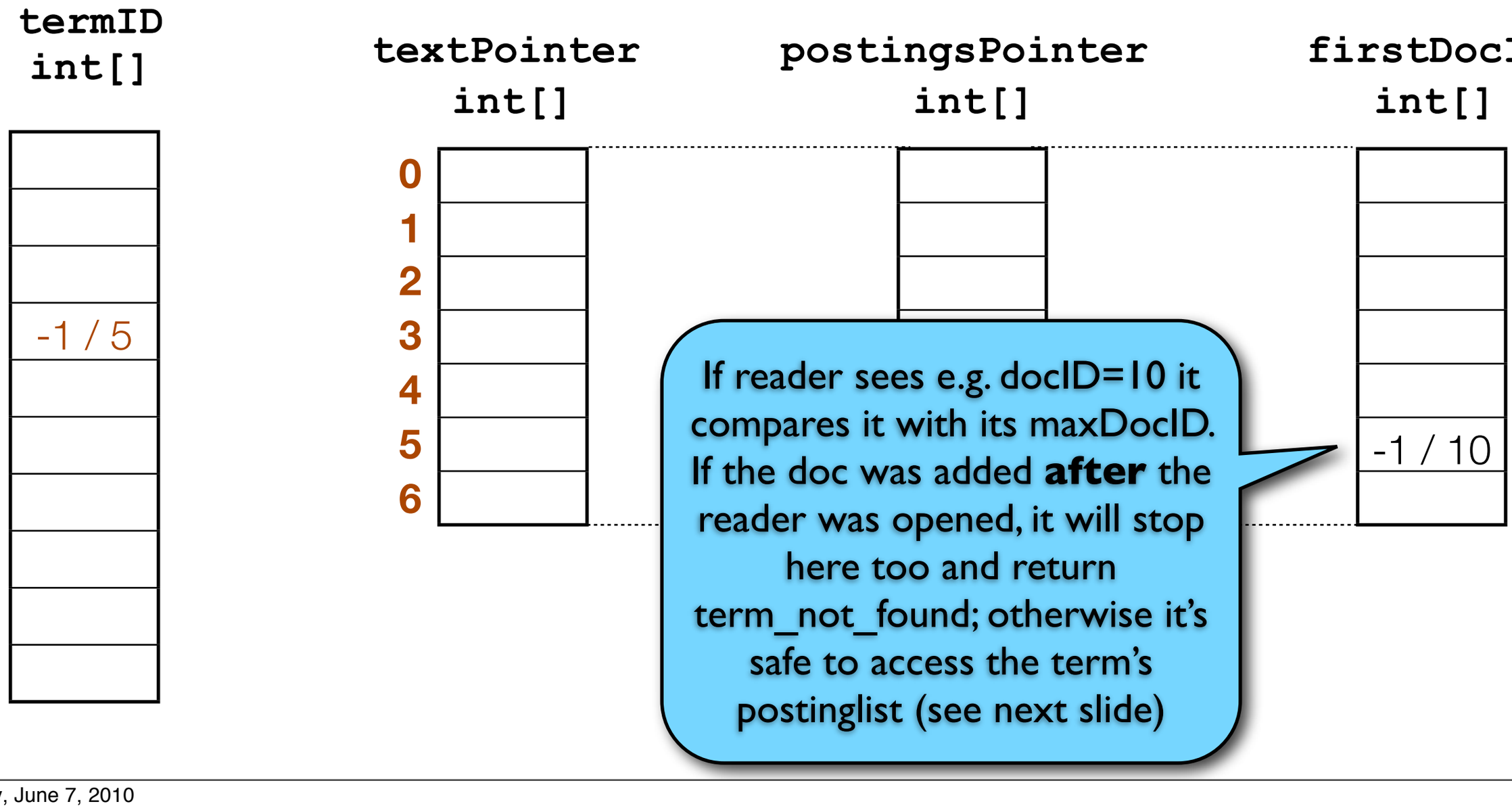

# Concurrency - Example: term lookup

- After each document is fully indexed the writer thread is forced to cross a memory barrier

- When a reader is opened the opening thread is also forced to cross the same memory barrier

- A memory barrier can be as simple as a single volatile variable that multiple threads access

- Hence, visibility for all documents older than maxDocID is ensured for an IndexReader

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- Sequence IDs
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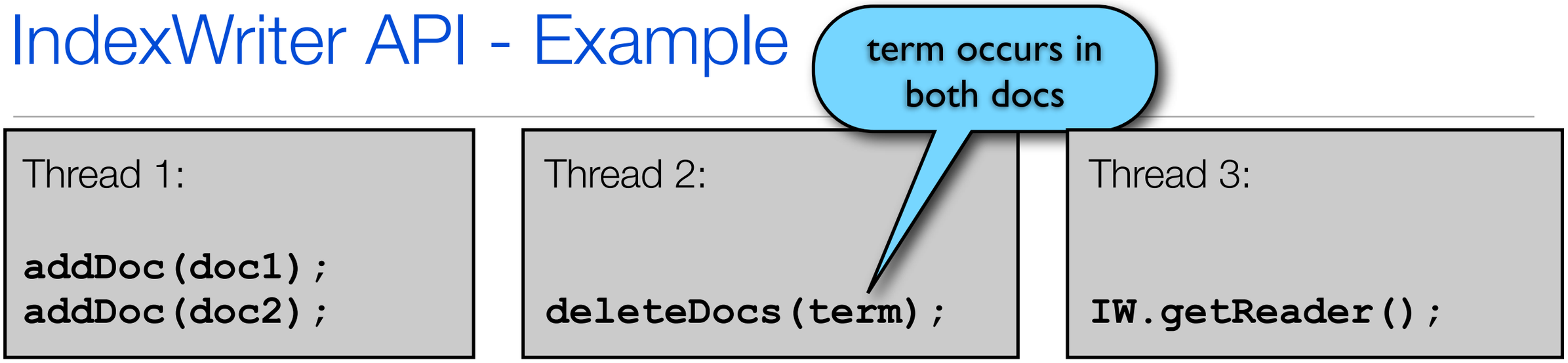
# Sequence IDs

# IndexWriter API

- `void addDocument(Document doc);`
- `void updateDocument(Term delTerm, Document doc);`
- `void deleteDocuments(Term delTerm);`
- `void commit();`
- All these methods are thread-safe
- But: in which order are they executed?

# IndexWriter API - Example




- Problem: Will Thread 2 only delete doc1 or also doc2? Which state will the reader that Thread 3 opens “see”?

- Answer: It depends on Java’s thread scheduling which thread acquires the mutex first.

- It’s currently hard to write code that can track the order of calls and answer the question above.

# IndexWriter API

- `long addDocument(Document doc);`
- `long updateDocument(Term delTerm, Document doc);`
- `long deleteDocuments(Term delTerm);`
- `long commit();`
- All methods will return a sequence ID, which unambiguously indicate the order the operations were executed in
- An RAM IndexReader will also have a sequence ID that defines which snapshot of the index it can “see”

# IndexWriter API - Example

Thread 1:

```
addDoc(doc1);   1
addDoc(doc2);     3
```

Thread 2:

```
deleteDocs(term); 2
```

Thread 3:

```
IW.getReader();  1
```

- doc1 is added before delete; delete happens before doc 2 is added

- Thread 3's reader will see doc 1

# IndexWriter API - Example

Thread 1:

```
addDoc(doc1);   1
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Thread 2:

```
deleteDocs(term); 2
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Thread 3:

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```

- doc1 is added before delete; delete happens before doc 2 is added

- Thread 3's reader will only see doc 2 (doc 1 will appear as deleted)

# IndexWriter API - Example

Thread 1:

```
addDoc(doc1);   1
addDoc(doc2);     2
```

Thread 2:

```
deleteDocs(term);3
```

Thread 3:

```
IW.getReader();  2
```

- doc1 is added before doc2; delete happens after both docs are added

- Thread 3's reader will see both docs

# IndexWriter API - Example

Thread 1:

```
addDoc(doc1);   1
addDoc(doc2);     2
```

Thread 2:

```
deleteDocs(term);3
```

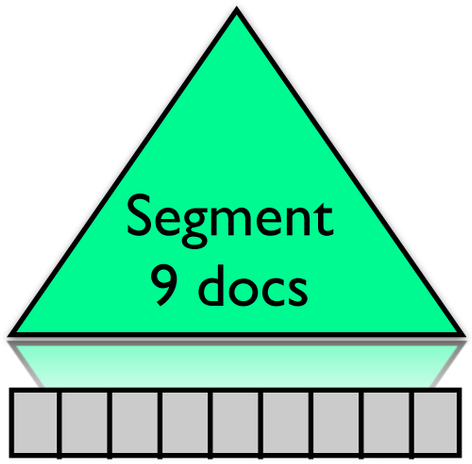
Thread 3:

```
IW.getReader();  3
```

- doc1 is added before doc2; delete happens after both docs are added
- Thread 3's reader will not see any docs (both will appear as deleted)

# Deletes

- Today deletes are stored as BitSets



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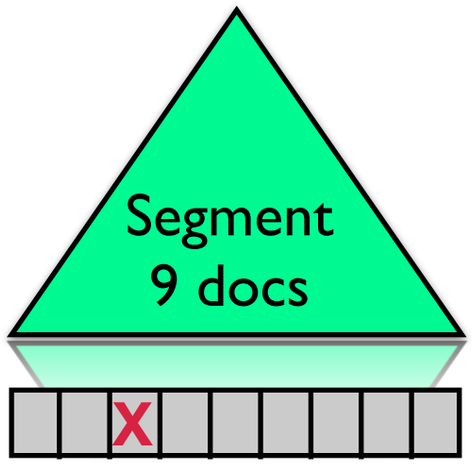
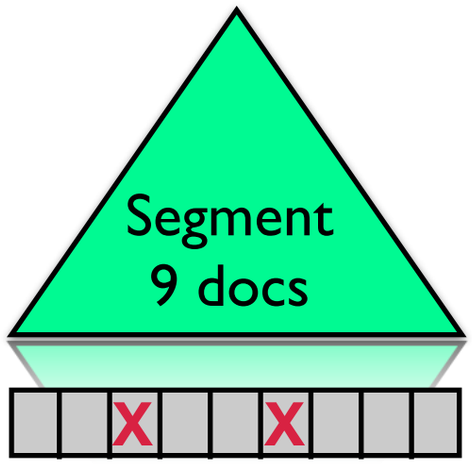



```
deleteDoc(2);
```

# Deletes

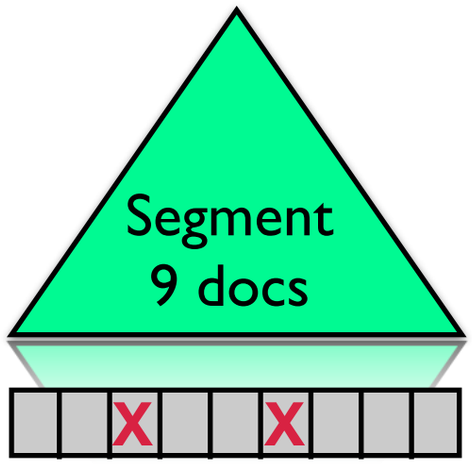
- Today deletes are stored as BitSets



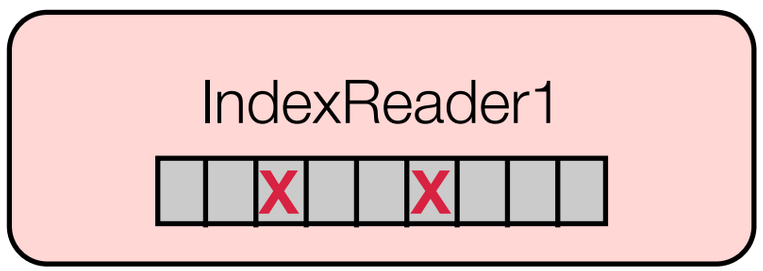

```
deleteDoc(2);
deleteDoc(5);
```

# Deletes

- Today deletes are stored as BitSets




```
deleteDoc(2);
deleteDoc(5);
open IndexReader1
```



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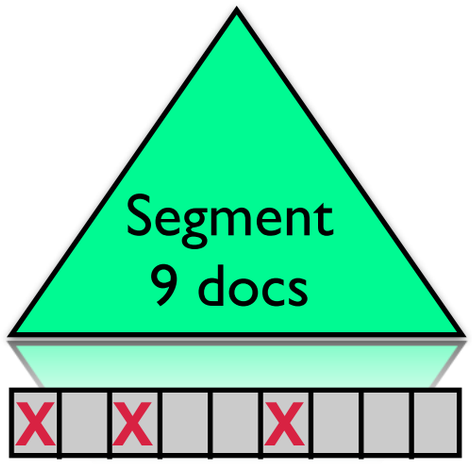
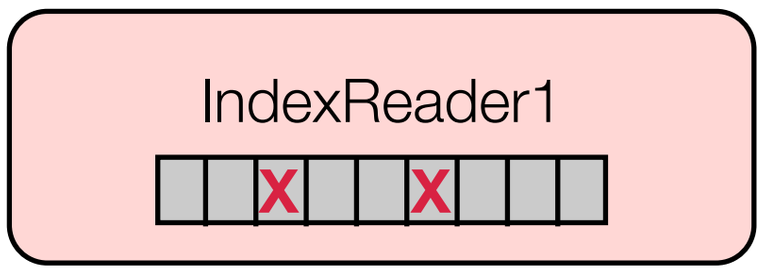
- Today deletes are stored as BitSets




```
deleteDoc(2);
deleteDoc(5);
open IndexReader1
deleteDoc(0);
```



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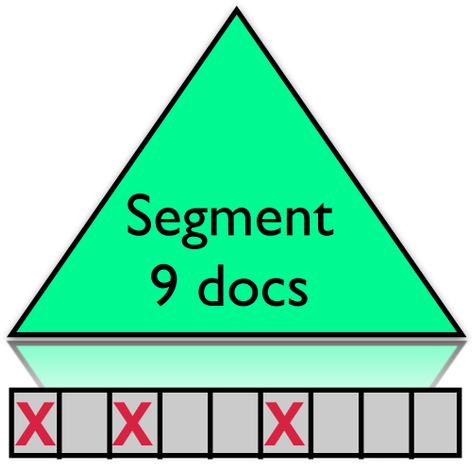
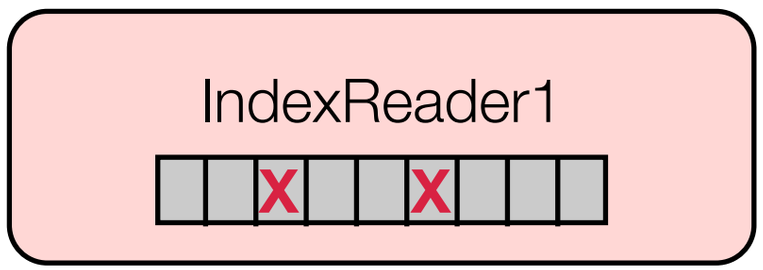
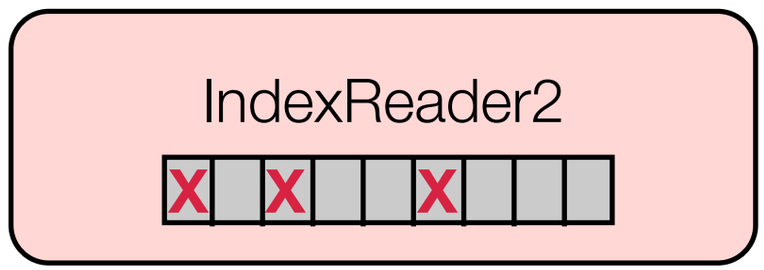
- Today deletes are stored as BitSets



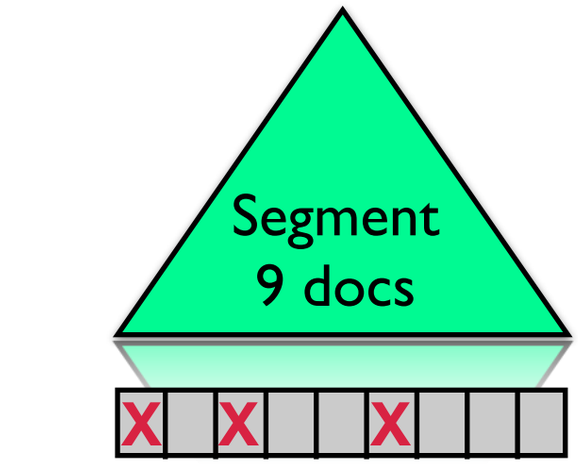

```
deleteDoc(2);
deleteDoc(5);
open IndexReader1
deleteDoc(0);
open IndexReader2
```



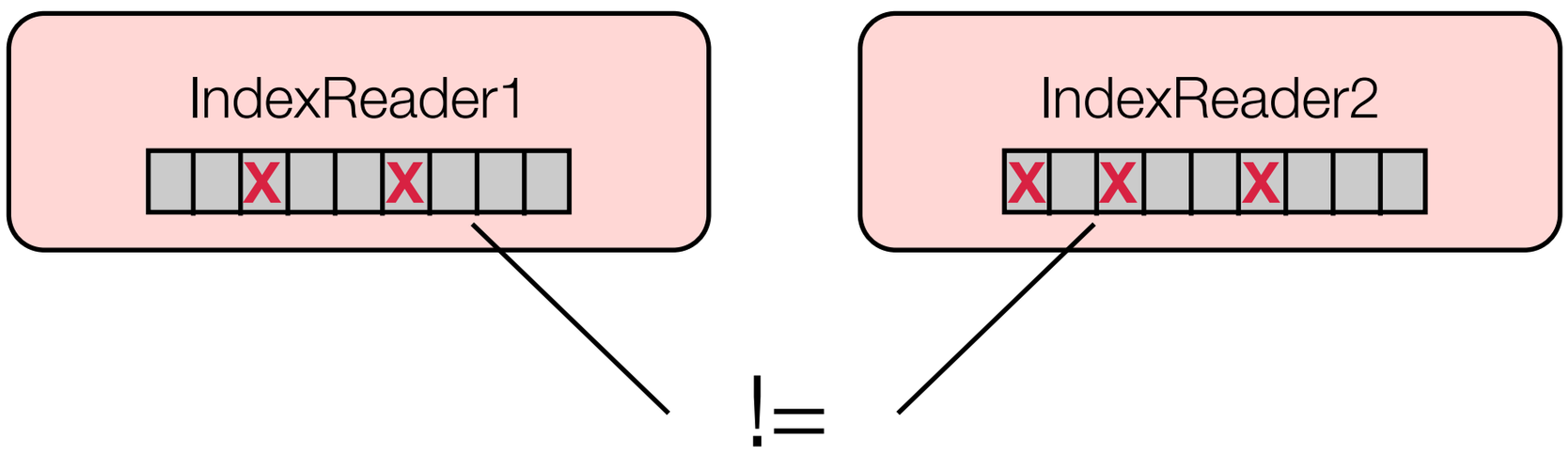



# Deletes

- Today deletes are stored as BitSets

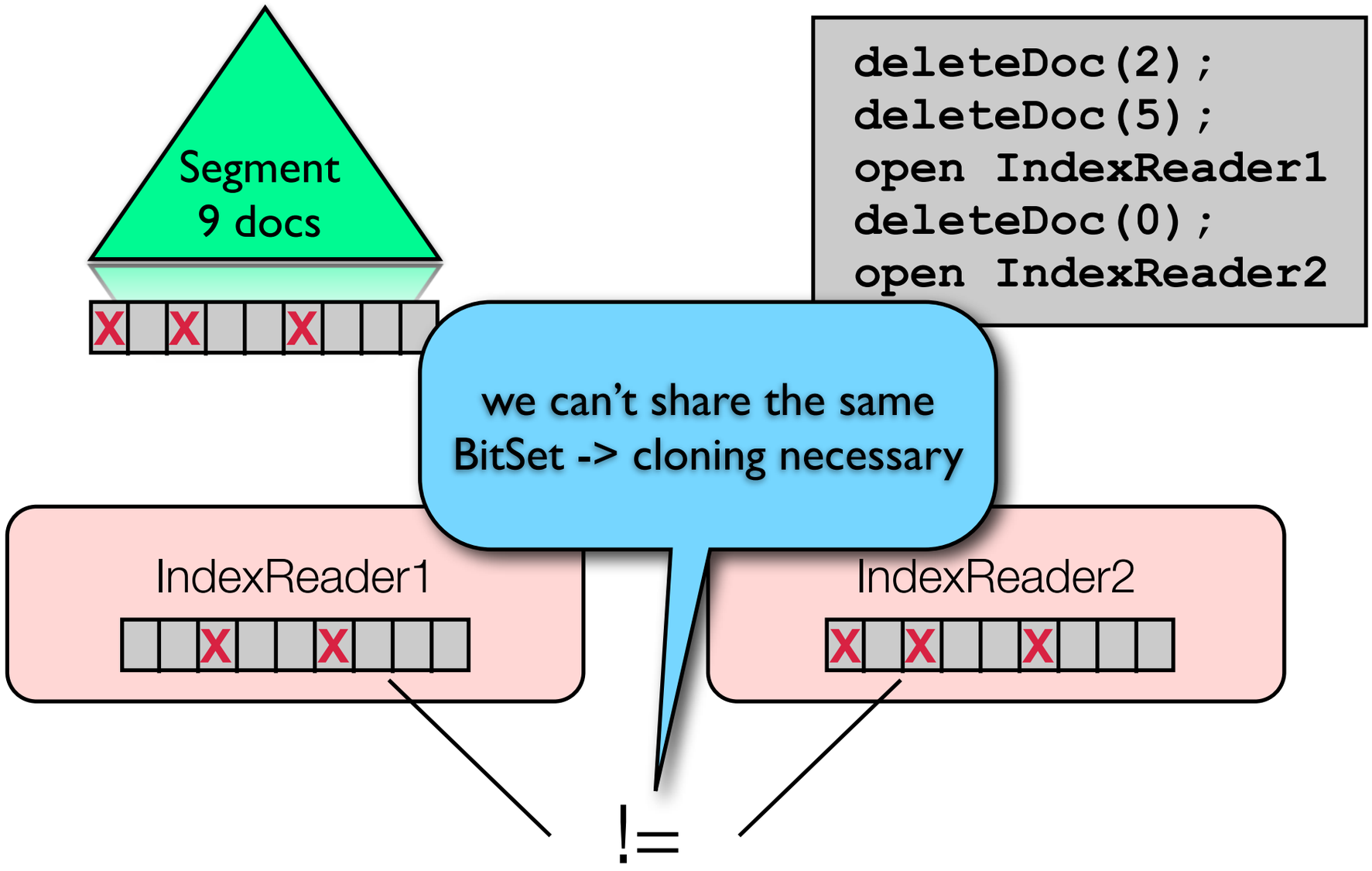



```
deleteDoc(2);
deleteDoc(5);
open IndexReader1
deleteDoc(0);
open IndexReader2
```



# Deletes

- Today deletes are stored as BitSets

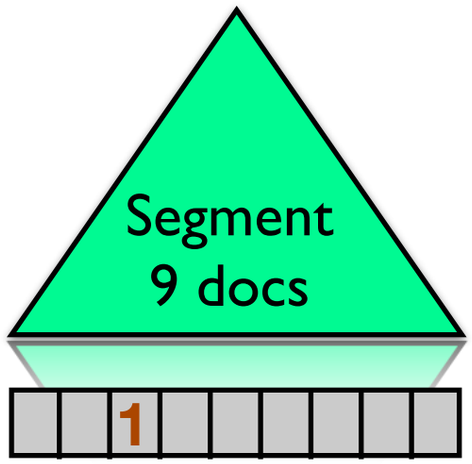


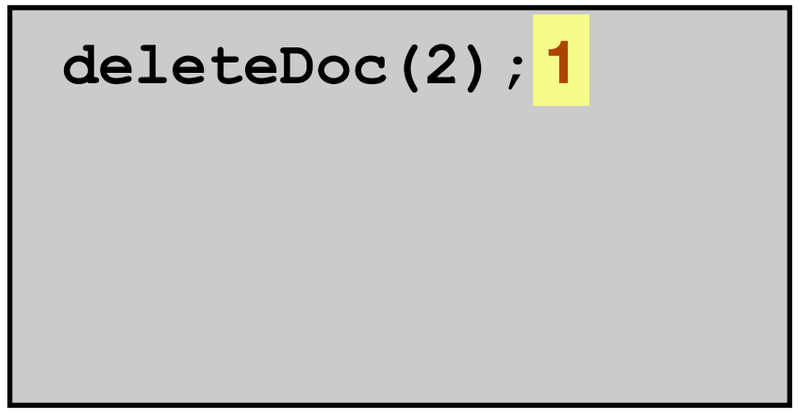
# Deletes

- Each IndexReader may need its own copy of the BitSet
- Especially for large segments the cloning quickly becomes very inefficient, if deletes and IndexReader (re)opens are frequent
- Solution: Utilize sequence IDs instead of BitSets

# Utilizing Sequence IDs for memory efficient deletes

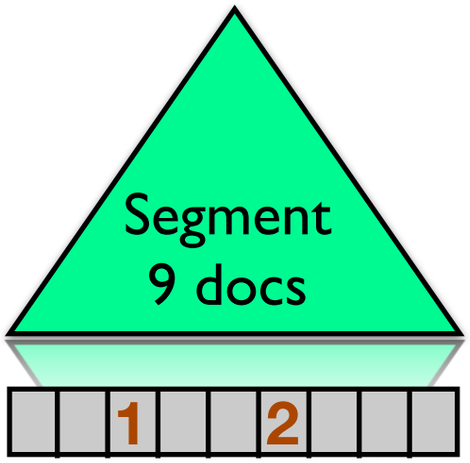
- LUCENE-2324: Use array of sequence IDs instead of BitSets



# Utilizing Sequence IDs for memory efficient deletes

- LUCENE-2324: Use array of sequence IDs instead of BitSets



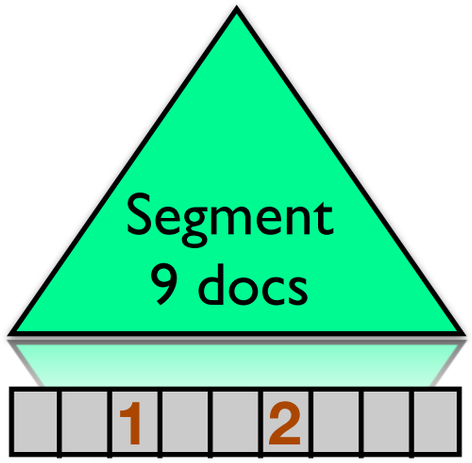

```
deleteDoc(2);
deleteDoc(5);
```

1

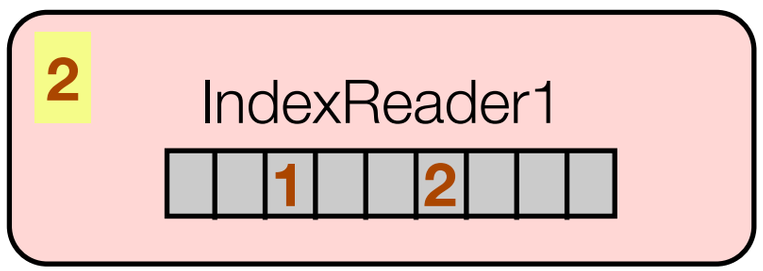
2

# Utilizing Sequence IDs for memory efficient deletes

- LUCENE-2324: Use array of sequence IDs instead of BitSets




```
deleteDoc(2); 1
deleteDoc(5);   2
open IndexReader1
```



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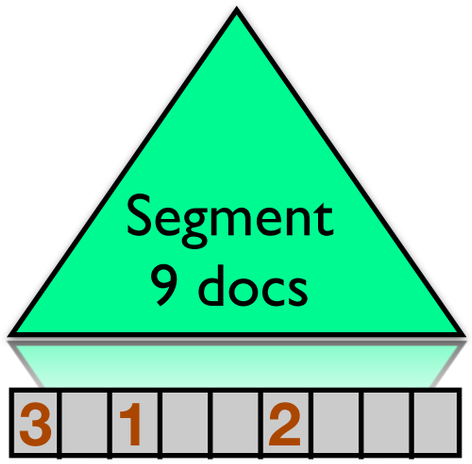
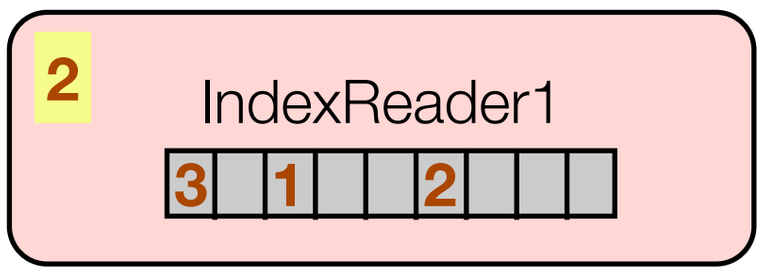



```
deleteDoc(2); 1
deleteDoc(5);   2
open IndexReader1
deleteDoc(0); 3
```



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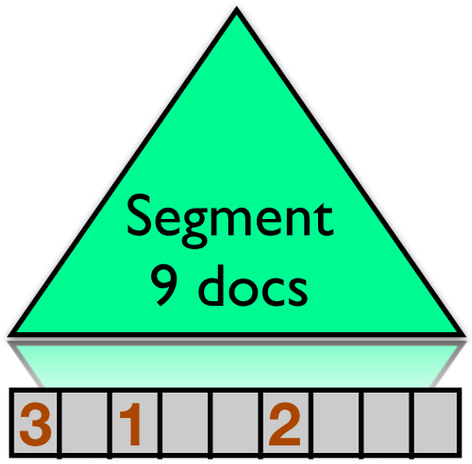
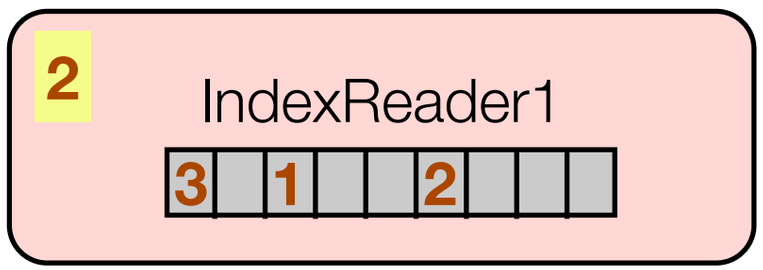
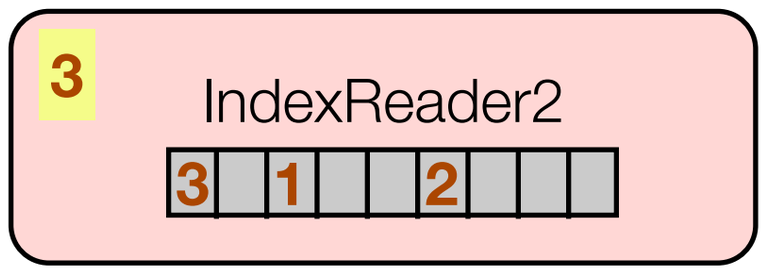



```
deleteDoc(2); 1
deleteDoc(5);   2
open IndexReader1
deleteDoc(0); 3
open IndexReader2
```



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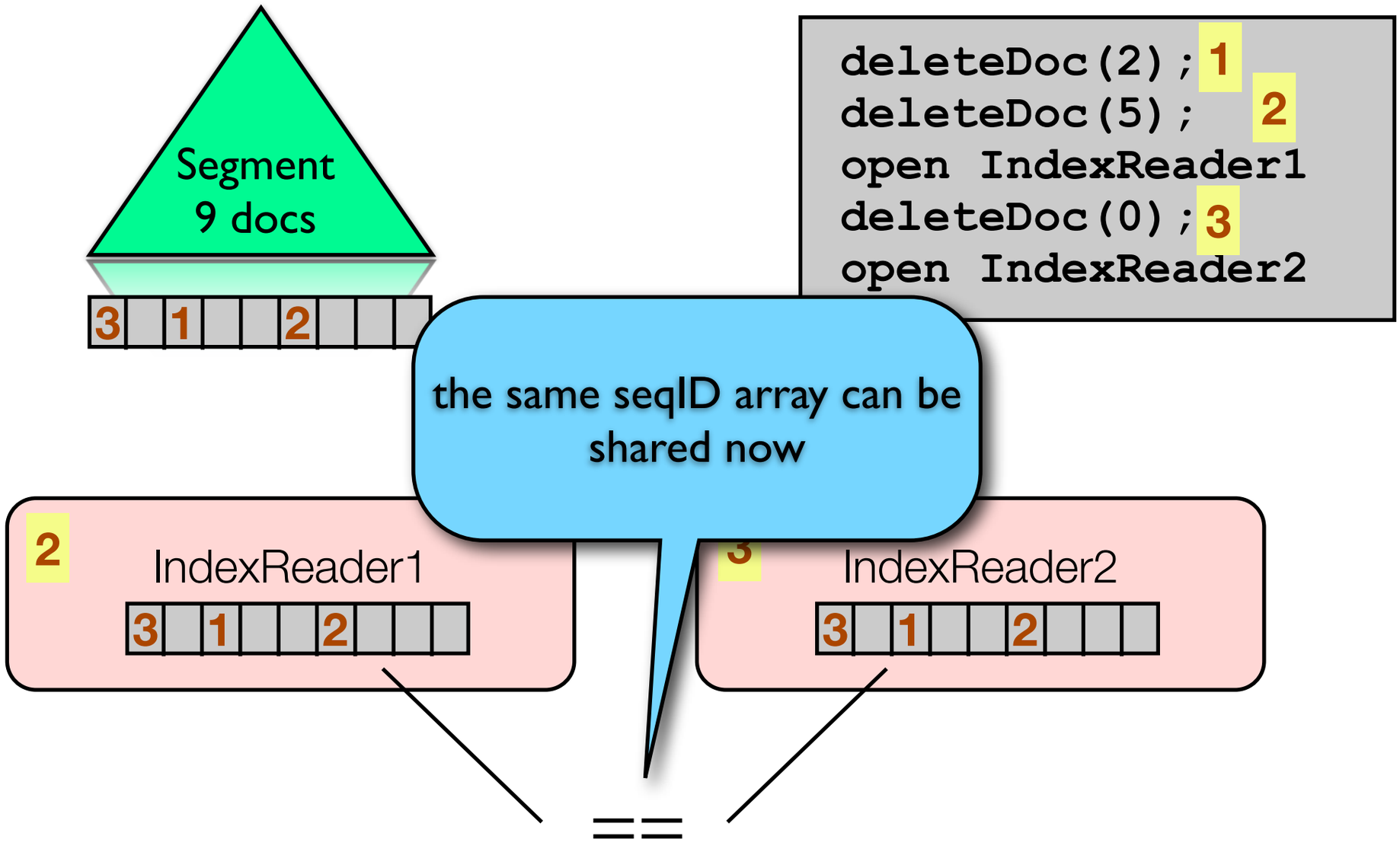

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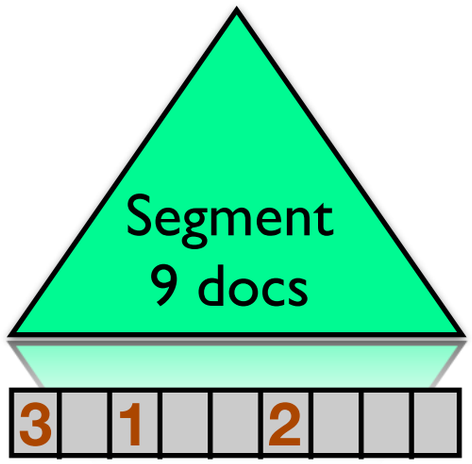
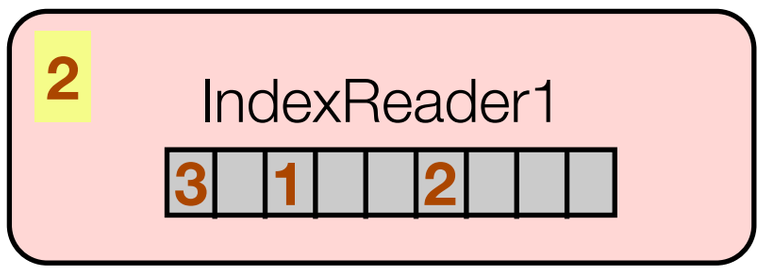
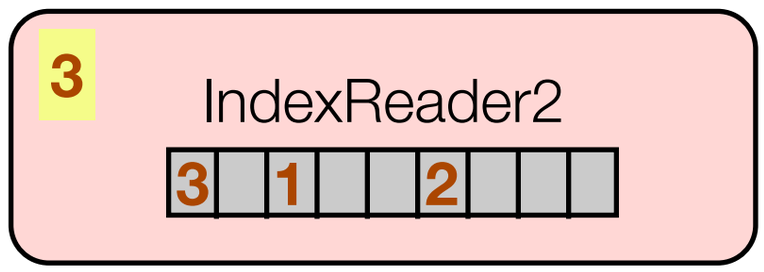



```
deleteDoc(2); 1
deleteDoc(5);   2
open IndexReader1
deleteDoc(0); 3
open IndexReader2
```




```
boolean isDeleted = (seqId[doc] <= readerSeqID);

Reader1: seqId[0] = 3, readerSeqID = 2 -> isDeleted = false
Reader2: seqId[0] = 3, readerSeqID = 3 -> isDeleted = true
```

# Utilizing Sequence IDs for memory efficient deletes

- No cloning necessary anymore
- Memory consumption for deletes does not increase when many IndexReaders are opened

**Goal 3:**

Opening a RAM IndexReader should be so cheap, so that a new reader can be opened for every query (drops latency close to zero)

# Using sequence IDs for document tracking

- Lucene's IndexWriter handles two kinds of exceptions: Aborting exceptions (e.g. OutOfMemoryError) and non-aborting exceptions (e.g. document encoding problem)

- When an aborting exception occurs, then the IndexWriter tries to commit all docs to the index that were successfully flushed before the error occurred

- Problem: Today it's not possible to know which documents made it into the index and which ones were dropped due to the error. **Which docs do I have to reindex?**

- Solution: **`IndexWriter.commit()`** will also return the sequence ID of the last write operation (add, delete, update) that was committed

# Using sequence IDs for document tracking

- An external log can be used to replay all operations that were lost due to the aborting exception

- It's easy to find out which write operations need to be replayed by checking the sequence ID that `commit()` returns

# Realtime Search with Lucene

## Agenda

- Introduction
- Near-realtime Search (NRT)
- Searching DocumentsWriter's RAM buffer
- Sequence IDs
- Twitter prototype
- Roadmap

# Twitter prototype

# Postinglist format

- Tweets are only 140 chars long

- Use 32-bit integers for postings:  24 bits for the docID (max segment size is 16.7M docs), 8 bits for the position (position can only have values 0-255; enough for tweets)

- Decoding speed significantly improved compared to delta and VInt decoding (early experiments suggest 5x improvement compared to vanilla Lucene with FSDirectory)

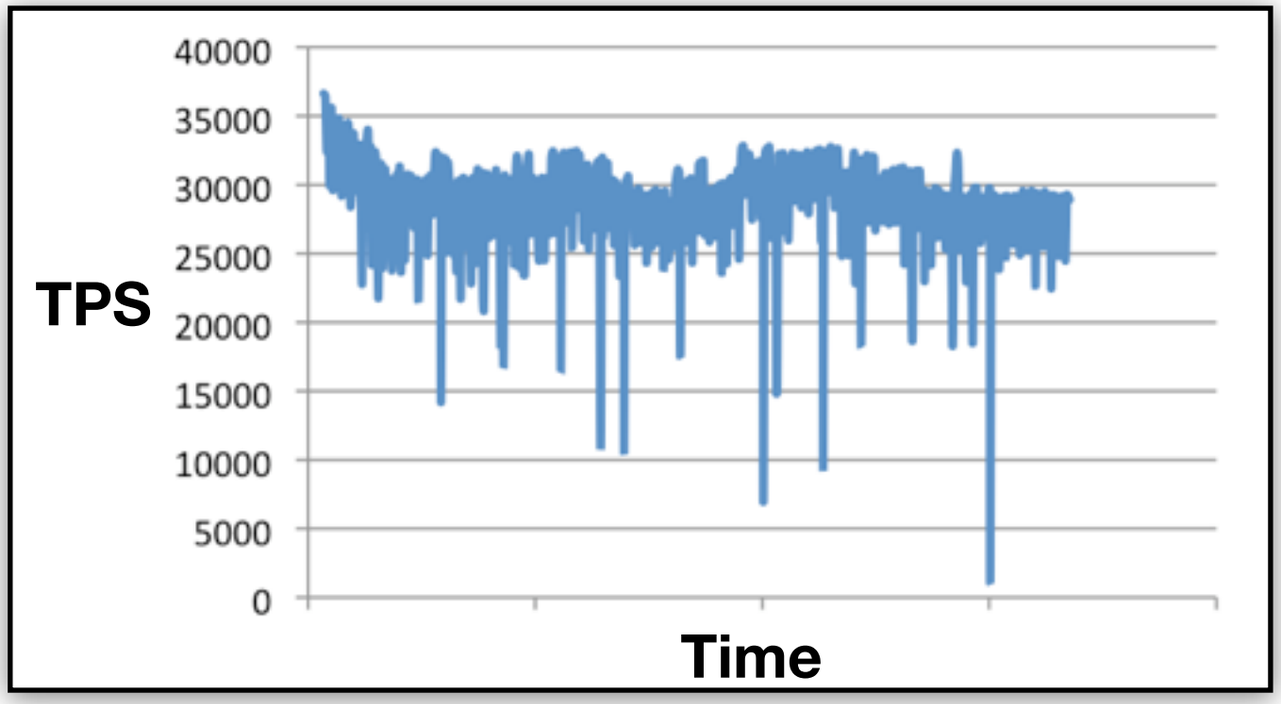
- In-memory postinglists can be traversed in reverse order -> early termination if time is a dominant factor of ranking score (as it usually is in realtime search)

# Early performance experiments

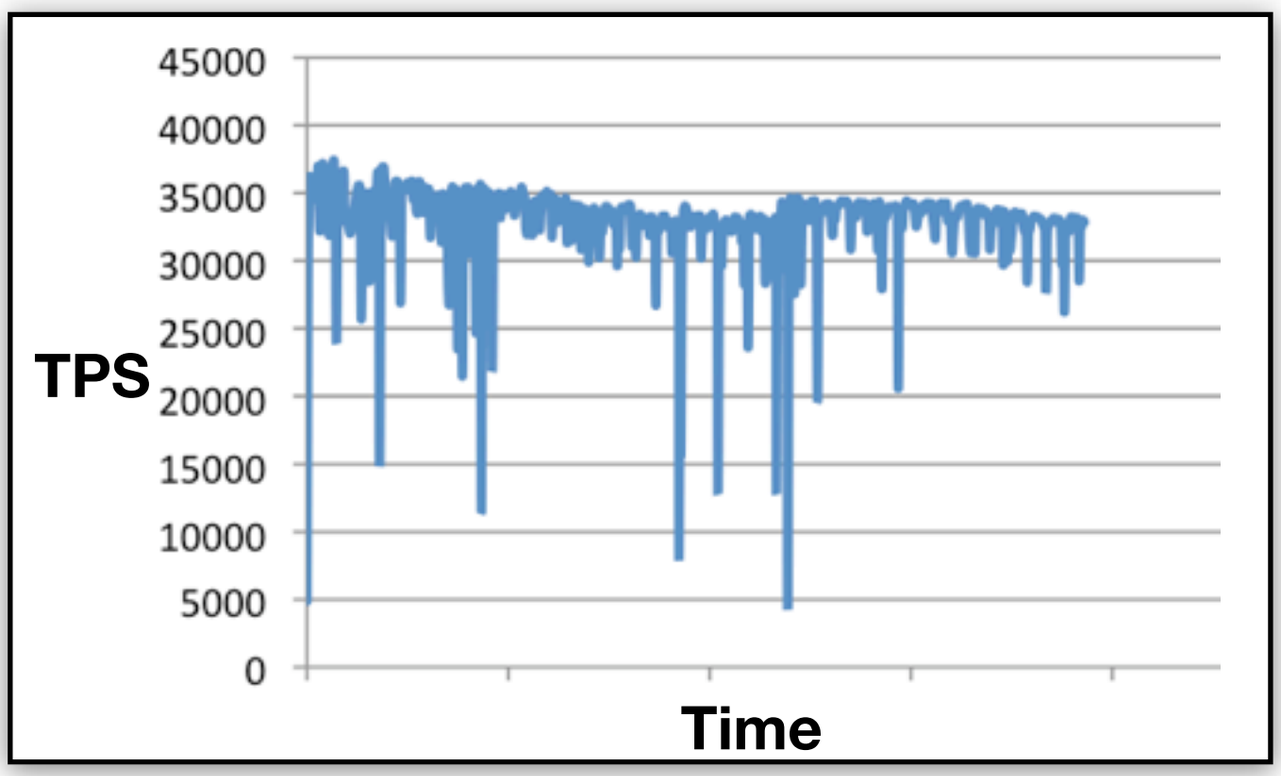
- On a single machine we can (without much tuning yet):
    - Index ~60,000 tweets/sec (very simple text analysis in the prototype)
    - Search with ~15,000-20,000 queries/sec
    - Lock-free algorithm: Results show, that indeed indexing and search performance are independent

# Early performance experiments

Indexing with one thread **while querying with multiple threads**

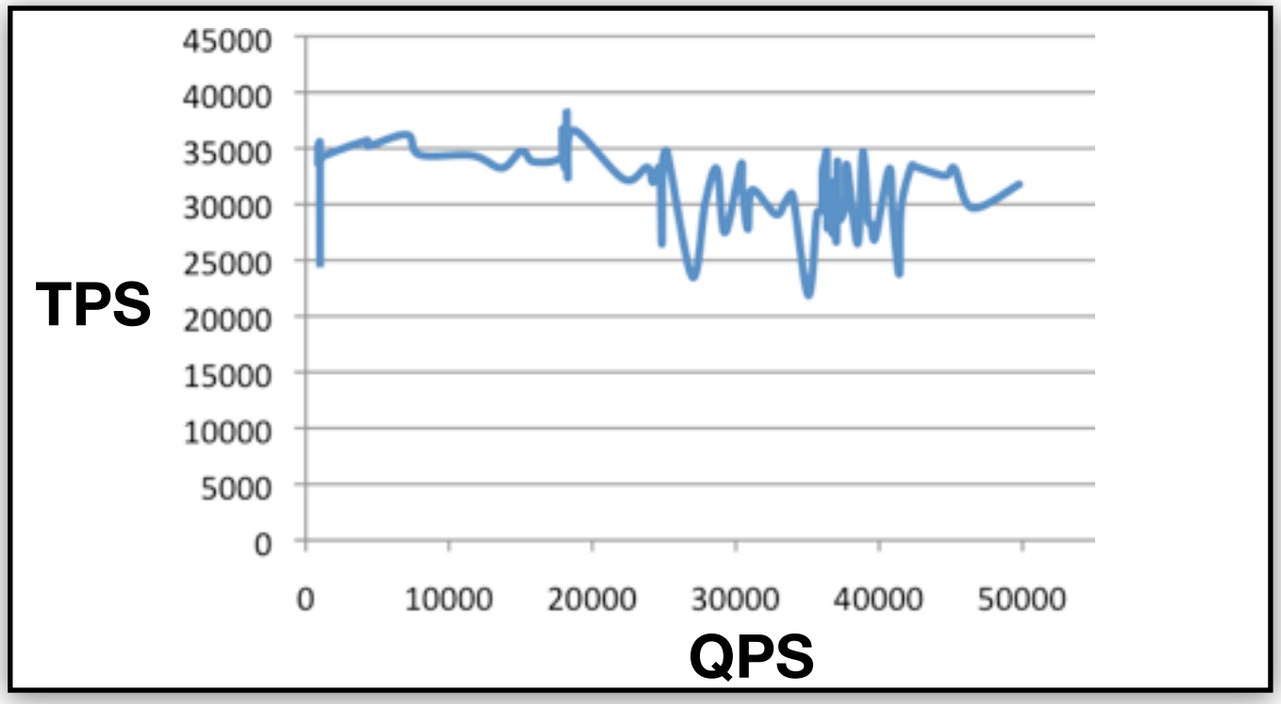



**Only indexing** with one thread



# Early performance experiments

Indexing performance over varying query load




- No “trend” here: indexing performance pretty much independent of query load

- TPS goes down only if more threads are used than CPU cores are present, because thread scheduling becomes expensive

**Goal 2:**
Maintain high indexing performance with large RAM buffer, and independent of the query load

# Realtime Search with Lucene

## Agenda

- Introduction
- Near-realtime Search (NRT)
- Searching DocumentsWriter's RAM buffer
- Sequence IDs
- Twitter prototype
- Roadmap

# Roadmap

# Roadmap

- ~~LUCENE-2329: Parallel posting arrays~~
- LUCENE-2324: Per-thread DocumentsWriter and sequence IDs
- LUCENE-2346: Change in-memory postinglist format
- LUCENE-2312: Search on DocumentsWriters RAM buffer
- IndexReader, that can switch from RAM buffer to flushed segment on-the-fly
- Sorted term dictionary (wildcards, numeric queries)
- Stored fields, TermVectors, Payloads (Attributes)

# Questions?

## Realtime Search with Lucene

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buschmi@apache.org