Indexing and Searching

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References:

1. Modern Information Retrieval, chapter 9
2. Information Retrieval: Data Structures & Algorithms, chapter 5
3. G.H. Gonnet, R.A. Baeza-Yates, T. Snider, Lexicographical Indices for Text: Inverted files vs. PAT trees

Introduction

- The main purpose of an IR system is
  - To help users find information of their interest, achieving high **effectiveness** (maximizing the ratio of user satisfaction versus user effort)

- Here we look at the other side of the coin
  - Viz. the secondary issue, **efficiency**
    - To process user queries with minimal requirements of computational resources, network bandwidth, etc.
    - As we move to larger-scale applications, efficiency becomes more and more important

Introduction (cont.)

- **Sequential or online searching**
  - Find the occurrences of a pattern in a text when the text is not preprocessed
    - Only appropriate when:
      - The text is small
      - Or the text collection is **very volatile**
      - Or the index space overhead cannot be afforded

- **Indexed search**
  - Build data structures over the text (i.e., indices) to speed up the search
  - Appropriate for the larger or semi-static text collection
  - The system updated at reasonably regular intervals

Introduction (cont.)

- The efficiency of an indexed IR system can be measured by:
  - Indexing time:
    - The time needed to build the index
  - Indexing space:
    - Space used during the generation of the index
  - Index storage:
    - Space required to store the index
  - Query latency:
    - Time interval between the arrival of the query in the IR system and the generation of the answer
  - Query throughput:
    - Average number of query processed per second.

Introduction (cont.)

- Three **data structures** for indexing are considered
  - **Inverted files**
    - The best choice for most applications
  - **Signature files**
    - Popular in the 1980s
  - **Suffix arrays**
    - Faster but harder to build and maintain

Issues:
Search cost,
Space overhead,
Building/updating time

Inverted Files

- A word-oriented mechanism for indexing a text collection in order to speed up the searching task
  - Two elements:
    - A vector containing all the distinct words (called vocabulary) in the text collection
      - The space required for the vocabulary is rather small:

        $\sim O(n^{\beta})$, n: the text size, $0<\beta<1$ (Heaps' law)
    - For each vocabulary word, a list of all docs (identified by doc number in ascending order) in which that word occurs
      - Space overhead: 30~40% of the text size (for text position addressing)

- Distinction between inverted file or list
  - **Inverted file**: occurrence points to documents or file names (identities)
  - **Inverted list**: occurrence points to word positions

Inverted Files (cont.)

- **Example**

```
1     6  9 11   17 19  24  28    33     40    46  50    55   60
This is a text. A text has many words. Words are made from letters.
```

Text

Vocabulary	Occurrences
letter	60 ...
made	50 ...
many	28 ...
Text	11, 19, ...
word	33, 40, ...
....	....

<u>An inverted list</u>

Each element in a list points to a text position

<u>An inverted file</u>

Each element in a list points to a doc number

difference: indexing granularity

Inverted Files: Addressing Granularity

- Text (word/character) positions (full inverted indices)
- Documents
  - All the occurrences of a word inside a document are collapsed to one reference
- (Logical) blocks
  - The blocks can be of fixed or different size
  - All the occurrences of a word inside a single block are collapsed to one reference
  - Space overhead: ~5% of the text size for a large collection

Inverted Files: Some Statistics

- Size of an inverted file as approximate percentages of the size of the text collection

	Index	Small Collection (1 Mb)		Medium Collection (200 Mb)		Large Collection (2 Gb)	
4 bytes/pointer	Addressing Words	45%	73%	36%	64%	35%	63%
1,2,3 bytes/pointer	Addressing Documents	19%	26%	18%	32%	26%	47%
2 bytes/pointer	Addressing 64K blocks	27%	41%	18%	32%	5%	9%
1 byte/pointer	Addressing 256 blocks	18%	25%	1.7%	2.4%	0.5%	0.7%

Stopwords are removed — Stopwords are indexed

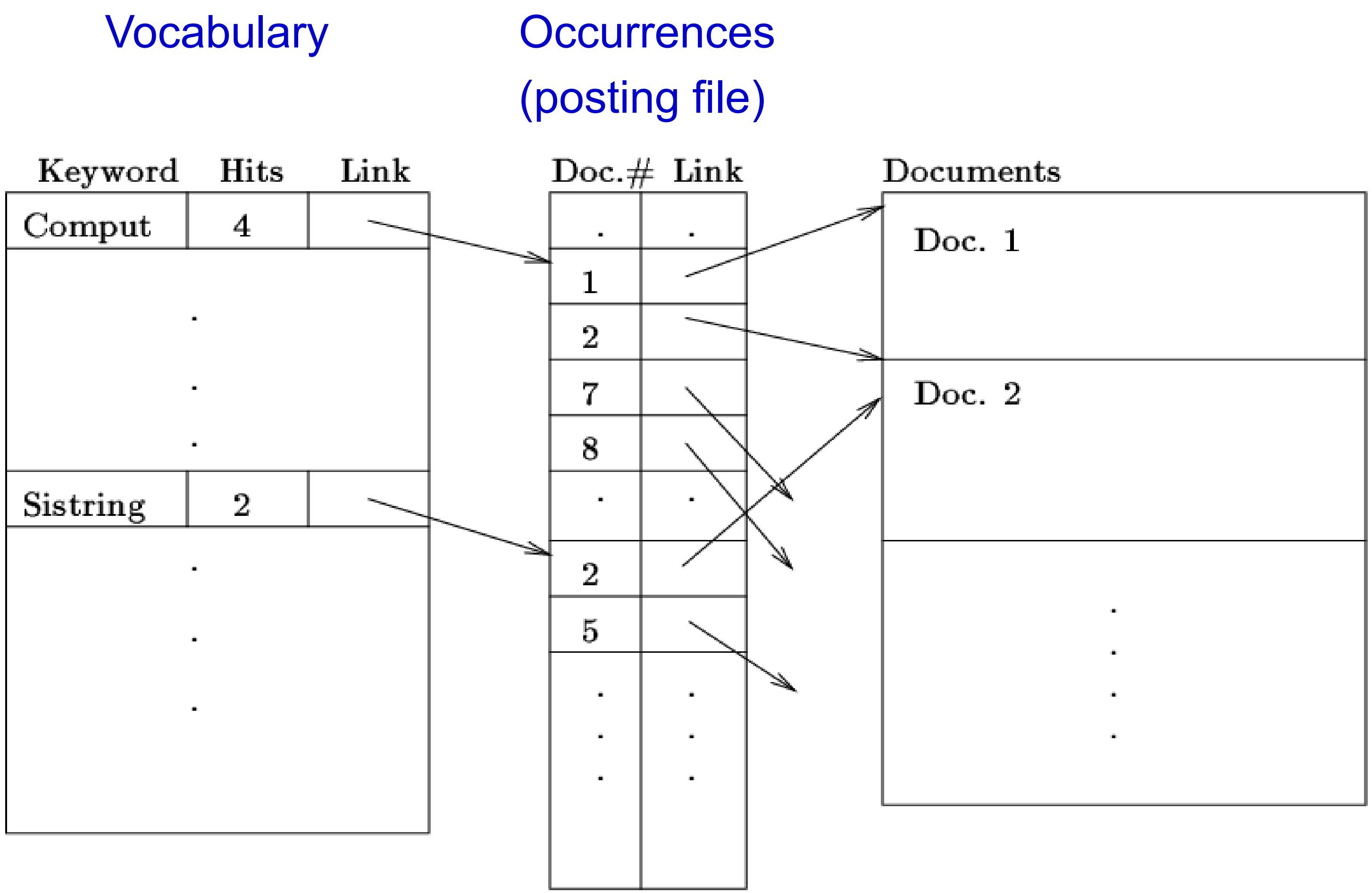
Inverted Files (cont.)

- **Document addressing**
  - Assume that the vocabulary (control dictionary) can be kept in main memory. Assign a sequential word number to each word
  - Scan the text database and output to a temporary file containing the record number and its word number
  - Sort the temporary file by word number and use record number as a minor sorting field
  - Compact the sorted file by removing the word number. During this compaction, build the inverted list from the end points of each word. This compacted file (posting file) becomes the main index

…..
$d_5\ w_3$
$d_5\ w_{100}$
$d_5\ w_{1050}$
…..
$d_9\ w_{12}$
…..

Inverted Files (cont.)

- **Document addressing** (count.)

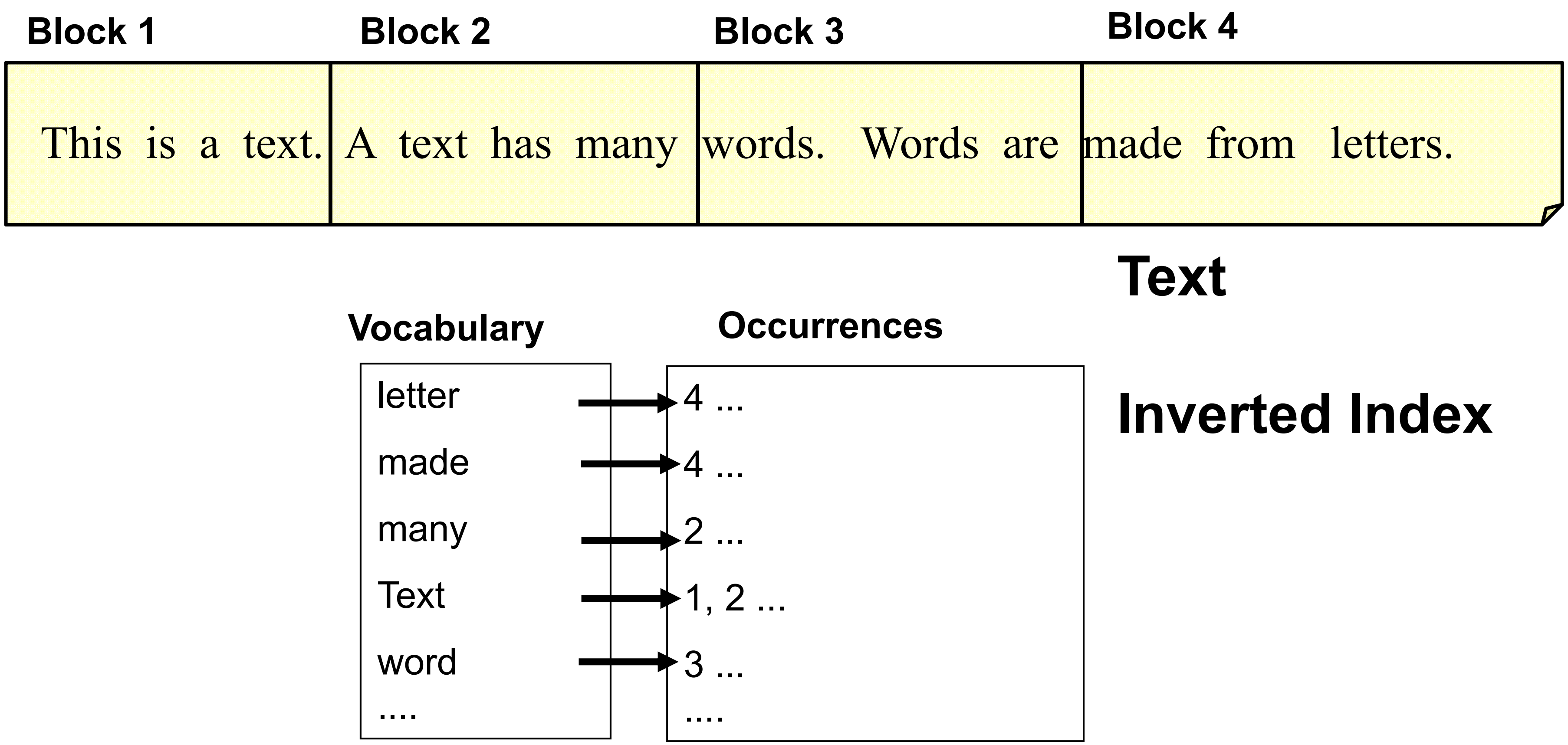


Inverted Files: Block Addressing

- Features
  - Text is divided into blocks
  - The occurrences in the invert file point to blocks where the words appear
  - Reduce the space requirements for recording occurrences

- Disadvantages
  - The occurrences of a word inside a single block are collapsed to one reference
  - Online search over qualifying blocks is needed if we want to know the exact occurrence positions
    - Because many retrieval units are packed into a single block

Inverted Files: Block Addressing (cont.)



Inverted Files: Searching

- Three general steps
  - **Vocabulary search**
    - Words and patterns in the query are isolated and searched in the vocabulary
    - Phrase and proximity queries are split into single words

      "white house" "network of computer" "computer network"
  - **Retrieval of occurrences**
    - The lists of the occurrences of all words found are retrieved
  - **Manipulation of occurrences** intersection, distance, etc.
    - For phrase, proximity or Boolean operations
    - Directly search the text if block addressing is adopted

Inverted Files: Searching (cont.)

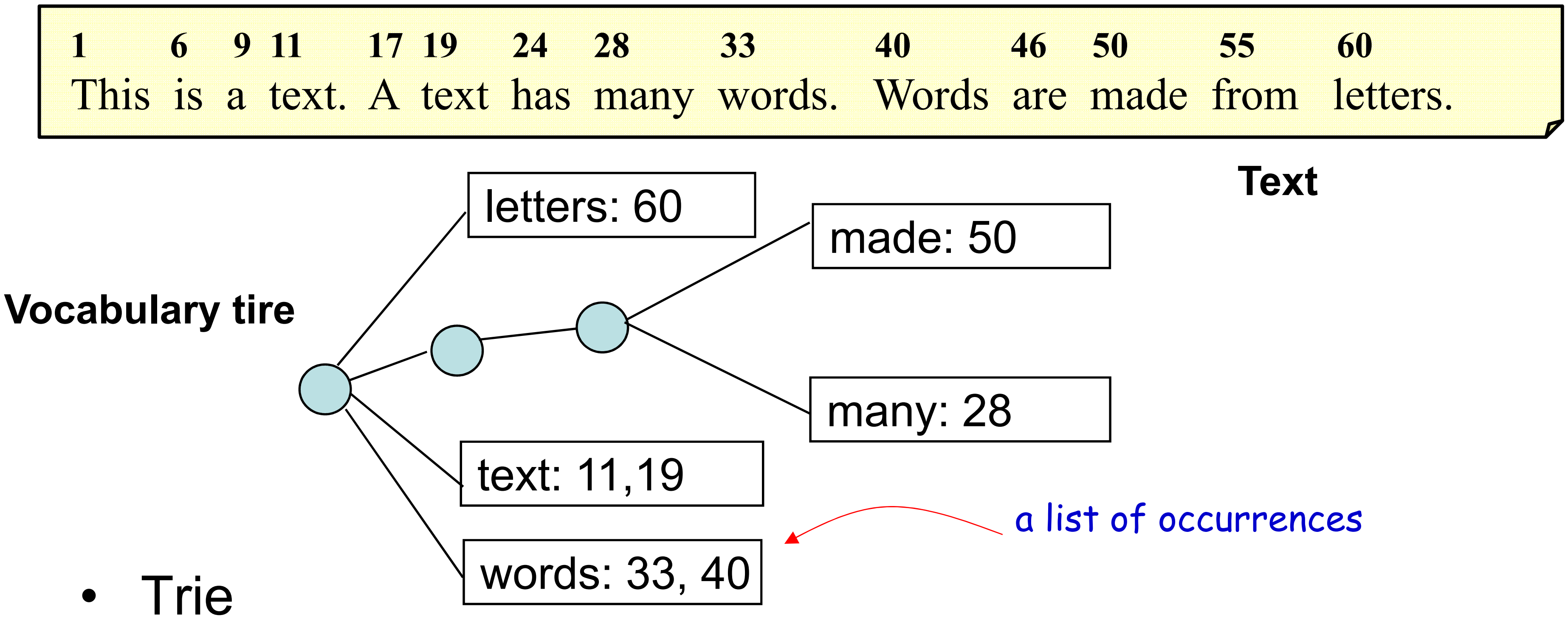
- Most time-demanding operation on inverted files is the merging or intersection of the lists of occurrences
  - E.g., **for the context queries**
    - Each element (word) searched separately and a list (occurrences for word positions, doc IDs, ..) generated for each

An expansive solution

    - The lists of all elements traversed in synchronization to find places where all elements appear in sequence (for a phrase) or appear close enough (for proximity)

Inverted Files: Construction

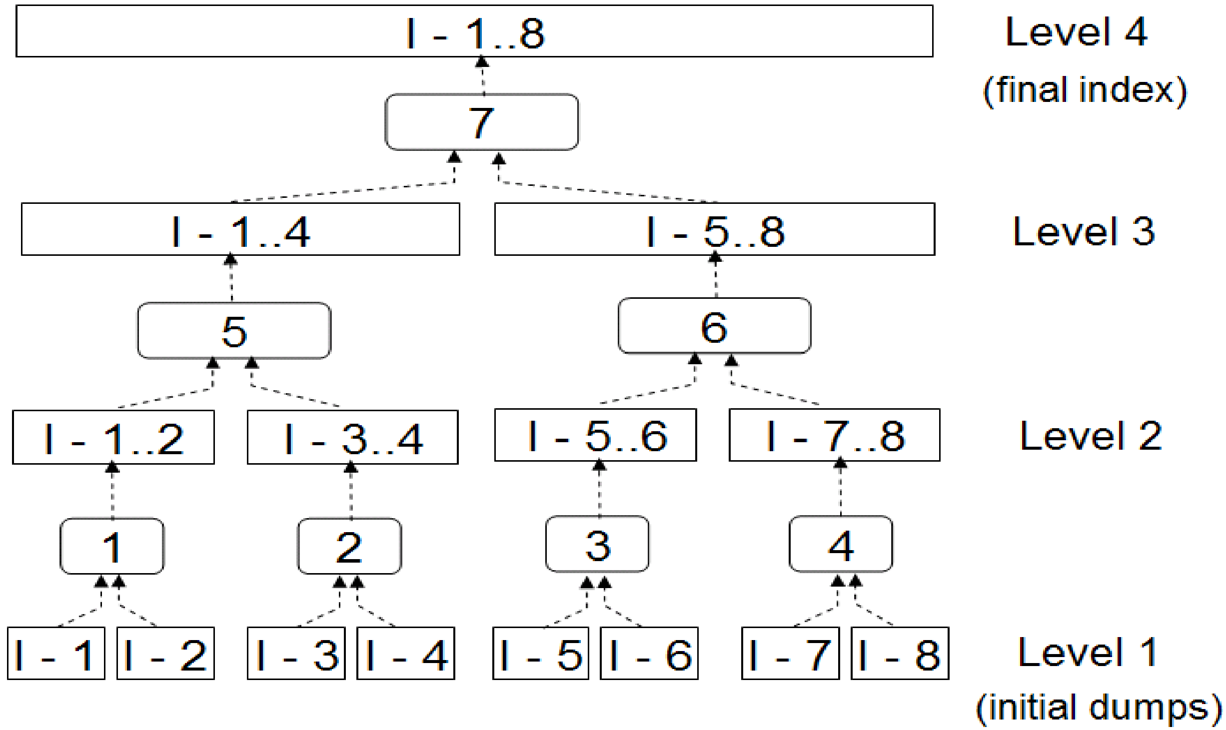
- The trie data structure to store the vocabulary



- Trie
  - A digital search tree
  - A multiway tree that stores set of strings and able to retrieve any string in time proportional to its length
  - A special character is added to the end of string to ensure that no string is a prefix of another (words appear only at leaf nodes)

Inverted Files: Construction (cont.)

- Merging of the partial indices
  - Merge the sorted vocabularies
  - Merge both lists of occurrences if a word appears in both indices



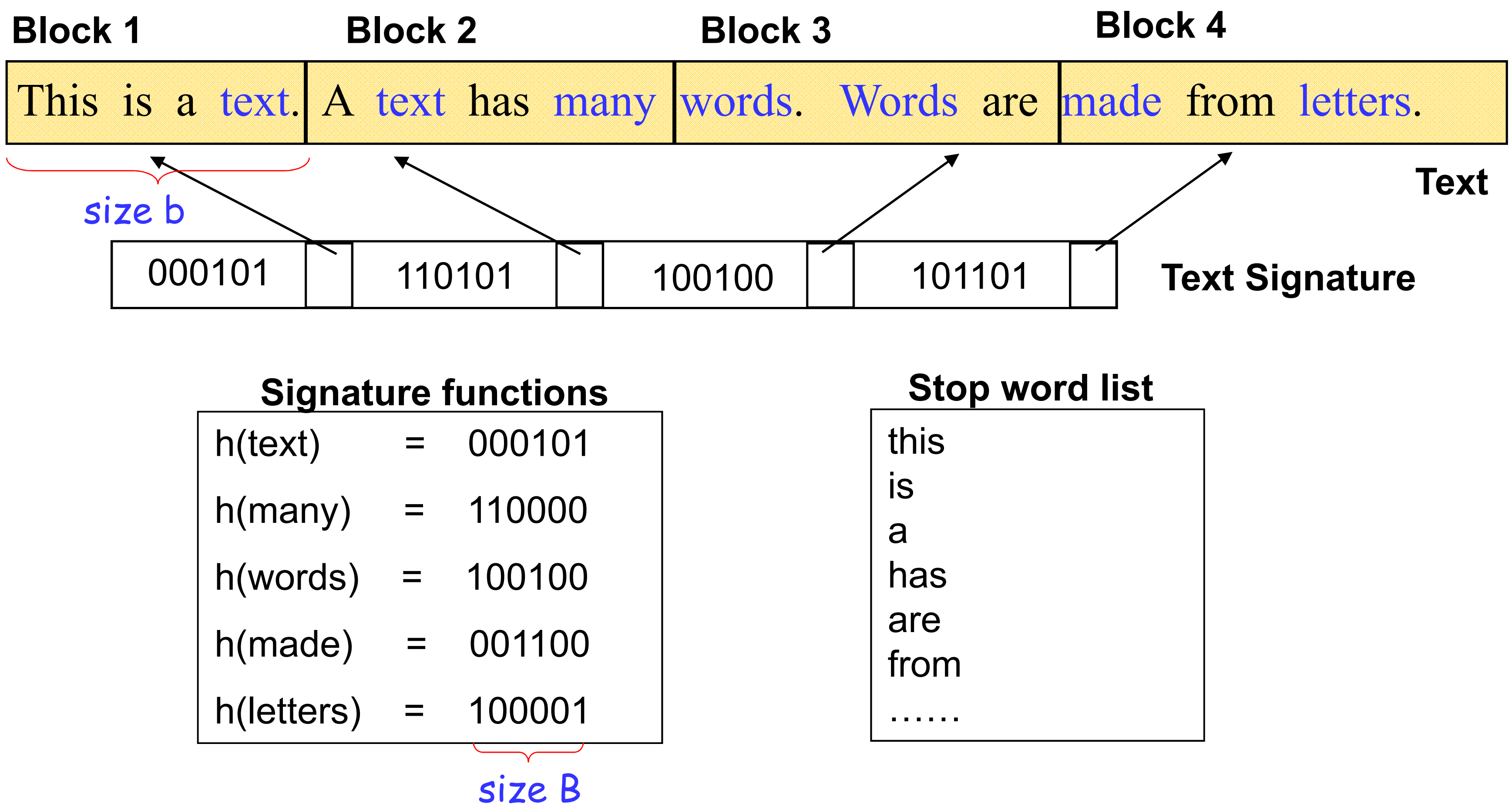
Inverted Files: Performance

- For a full index built on 250 Mb of text
  - Single word: 0.08 sec
  - Phrase (2~5 words): 0.25 to 0.35 sec

Signature Files

- **Basic Ideas**
  - **Word-oriented index structures based on hashing**
    - A hash function (signature) maps words to bit masks of *B* bits
  - Divide the text into **blocks of *b* words** each
    - **A bit mask of *B* bits** is assigned to each block by bitwise **OR**ing the signatures of all the words in the text block
  - A word is presented in a text block if all bits set in its signature are also set in the bit mask of the text block

Signature Files (cont.)



- The text signature contains
  - Sequences of bit masks
  - Pointers to blocks

Signature Files (cont.)

- **False Drops** or False Alarms
  - All the corresponding bits are set in the bit mask of a text block, but the query word is not there
  - E.g., a false drop for the index “letters” in block 2
- **Goals** of the design of signature files
  - Ensure the probability of a false drop is low enough
  - Keep the signature file as short as possible

tradeoff

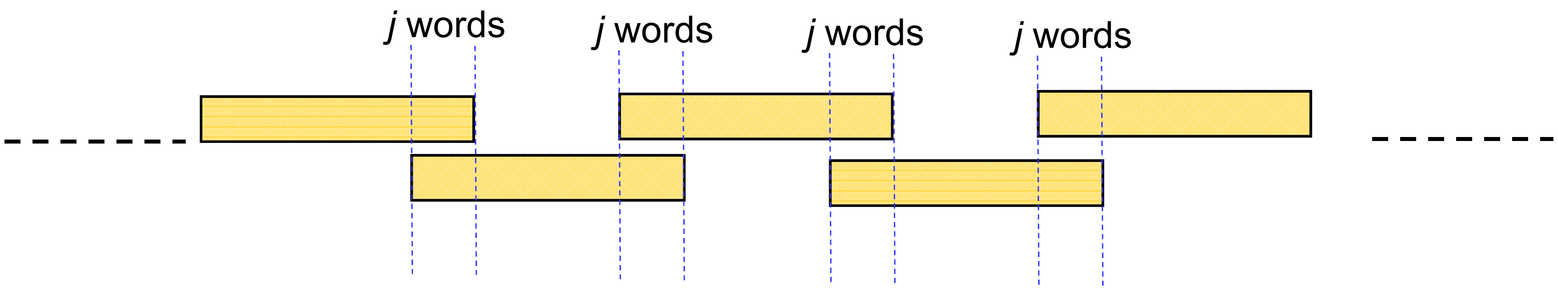
Signature Files: Searching

- **Single word queries**
  - Hash each word to a bit mask W
  - Compare the bit mask B_i of all text block (linear search) if they contain the word ($W \& B_i == W$?)
    - **Overhead**: online traverse candidate blocks to verify if the word is actually there

- **Phrase or Proximity queries**
  - The bitwise OR of all the query (word) masks is searched
  - The candidate blocks should have the same bits presented "1" as that in the composite query mask
  - Block boundaries should be taken care of
    - For phrases/proximities across two blocks

Signature Files: Searching (cont.)

- **Overlapping blocks**



- **Other types of patterns** (e.g., prefix/suffix strings,...) are not supported for searching in this scheme

- **Construction**
  - Text is cut in blocks, and for each block an entry of the signature file is generated
    - Bitwise OR of the signatures of all the words in it
  - Adding text and deleting text are easy

Signature Files: Searching (cont.)

- **Pros**
  - Pose a low overhead (10-20% text size) for the construction of text signature
  - Efficient to search phrases and reasonable proximity queries (the only scheme improving the phrase search)
- **Cons**
  - Only applicable to index words
  - Only suitable for not very large texts
    - Sequential search (check) in the text blocks to avoid false drops
    - Inverted files outperform signature files for most applications

Signature Files: Performance

- For a signature file built on 250 Mb of text
  - Single word (or phrase?): 12 sec

Suffix Trees

- **Premise**
  - Inverted files or signature files treat the text as a sequence of words
    - For collections that the concept of word does not exit, they would be not feasible (like genetic databases)

- **Basic Ideas**
  - Each position (character or bit) in the text considered as a text suffix
    - A string going from that text position to the end of the text (arbitrarily far to the right)
  - Each suffix (or called **semi-infinite string**, *sistring*) uniquely identified by its position
    - Two suffixes at different positions are lexicographical different

A special null character is added to the strings' ends

Suffix Trees (cont.)

- **Basic Ideas** (cont.)
  - **Index points**: not all text positions indexed
    - Word beginnings
    - Or, beginnings of retrievable text positions
  - Queries are based on prefixes of sistrings, i.e., on any substring of the text

1	6	9	11	17	19	24	28	33	40	46	50	55	60
This	is	a	text.	A	text	has	many	words.	Words	are	made	from	letters.

sistring 11: text. A text has many words. Words are made from letters.
sistring 19: text has many words. Words are made from letters.
sistring 28: many words. Words are made from letters.
sistring 33: words. Words are made from letters.
sistring 40: Words are made from letters.
sistring 50: made from letters.
sistring 60: letters.

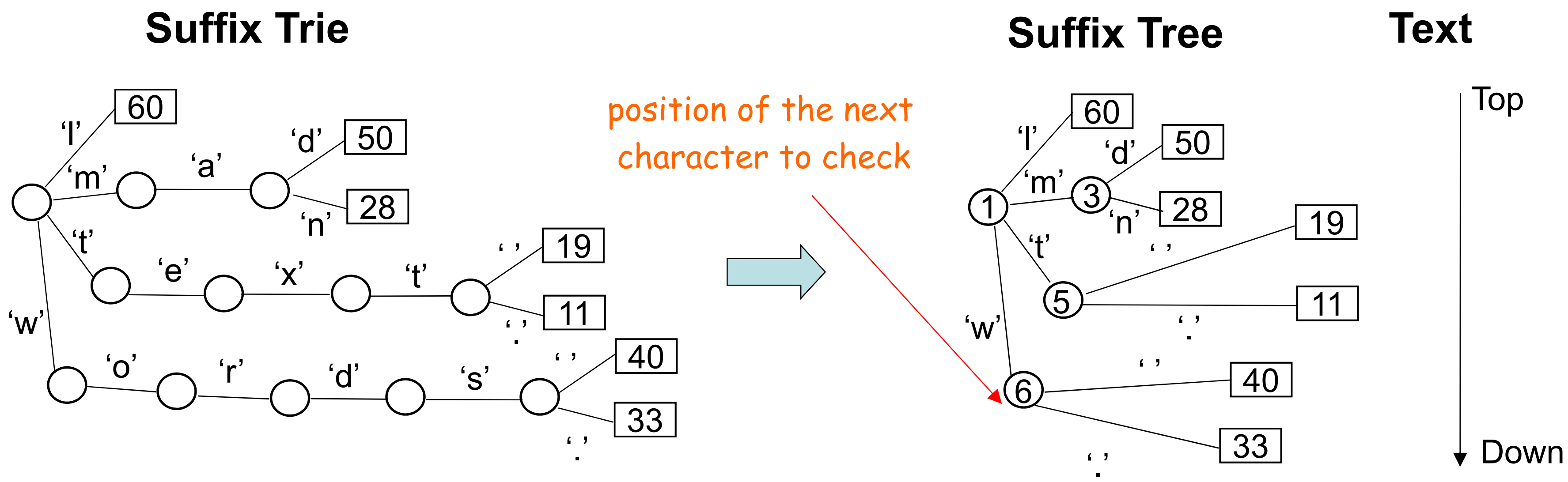
Suffix Trees (cont.)

- **Structure**
  - The suffix tree is a trie structure built over all the suffixes of the text
    - Points to text are stored at the leaf nodes
  - The suffix tree is implemented as a **Patricia tree** (or **PAT tree**), i.e., **a compact suffix tree**
    - Unary paths (where each node has just one child) are compressed
    - An indication of next character (or bit) position to consider/check are stored at the internal nodes
      - Each node takes 12 to 24 bytes
      - A space overhead of 120%~240% over the text size

Suffix Trees (cont.)

- PAT tree over a sequence of characters

1	6	9	11	17	19	24	28	33	40	46	50	55	60
This	is	a	text.	A	text	has	many	words.	Words	are	made	from	letters.

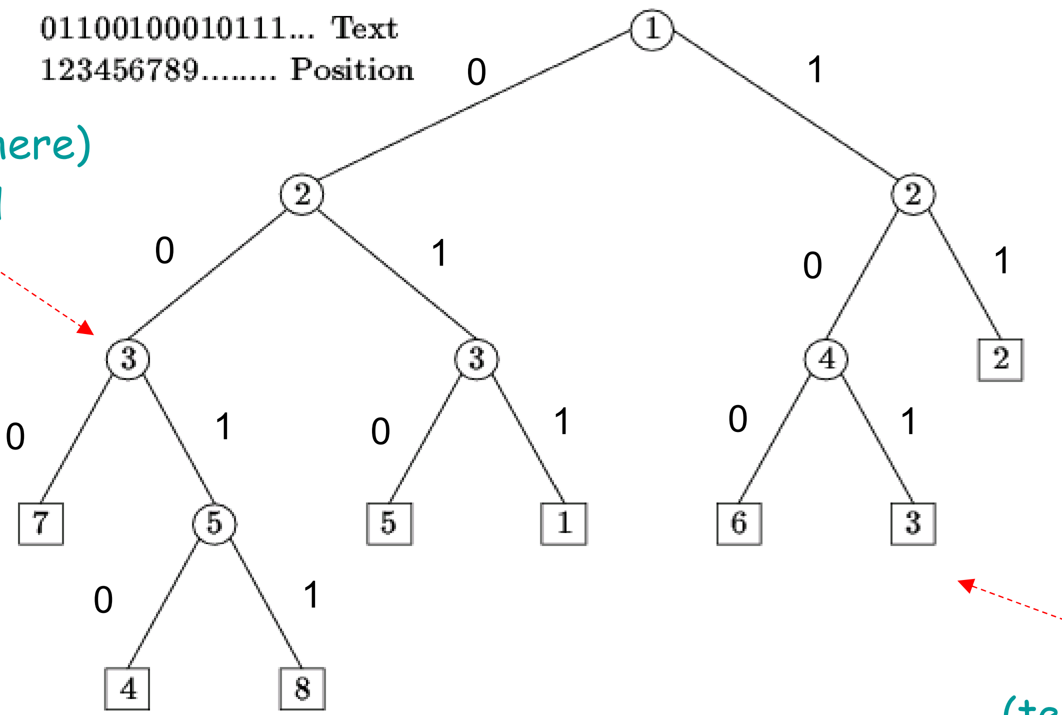


What if the query is "mo" or "modulation"?

Suffix Trees (cont.)

- Another representation
  - PAT tree over a sequence of bits

The bit position of query used for comparison
- Absolute bit position (used here)
- Or the count of bits skipped (skip counter)



Pat tree when the sistrings 1 through 8 have been inserted.

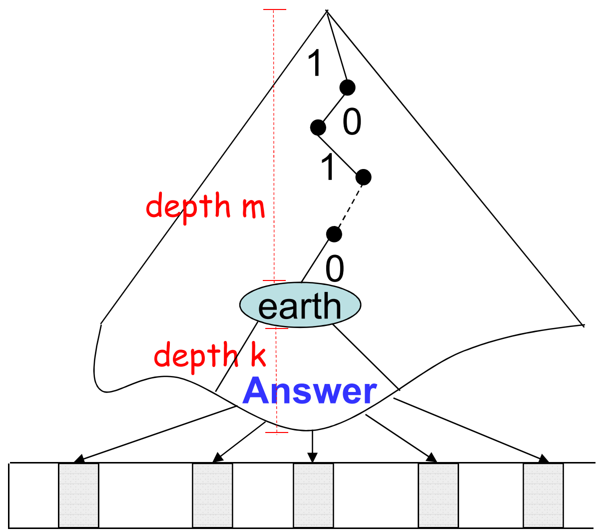
The key (text position)

Internal nodes with single descendants are eliminated !

Example query: 00101

Suffix Trees: Search

- Prefix searching
  - Search the prefix in the tree up to the point where the prefix is exhausted or an external node reached   O(m), m is the length in bits of the search pattern
  - Verification is needed
    - A single comparison of any of the sistrings in the subtree
  - If the comparison is successful, then all the sistrings in the substree are the answer   O(klogk)
  - The results may be further sorted by text order



Suffix Trees: Search (cont.)

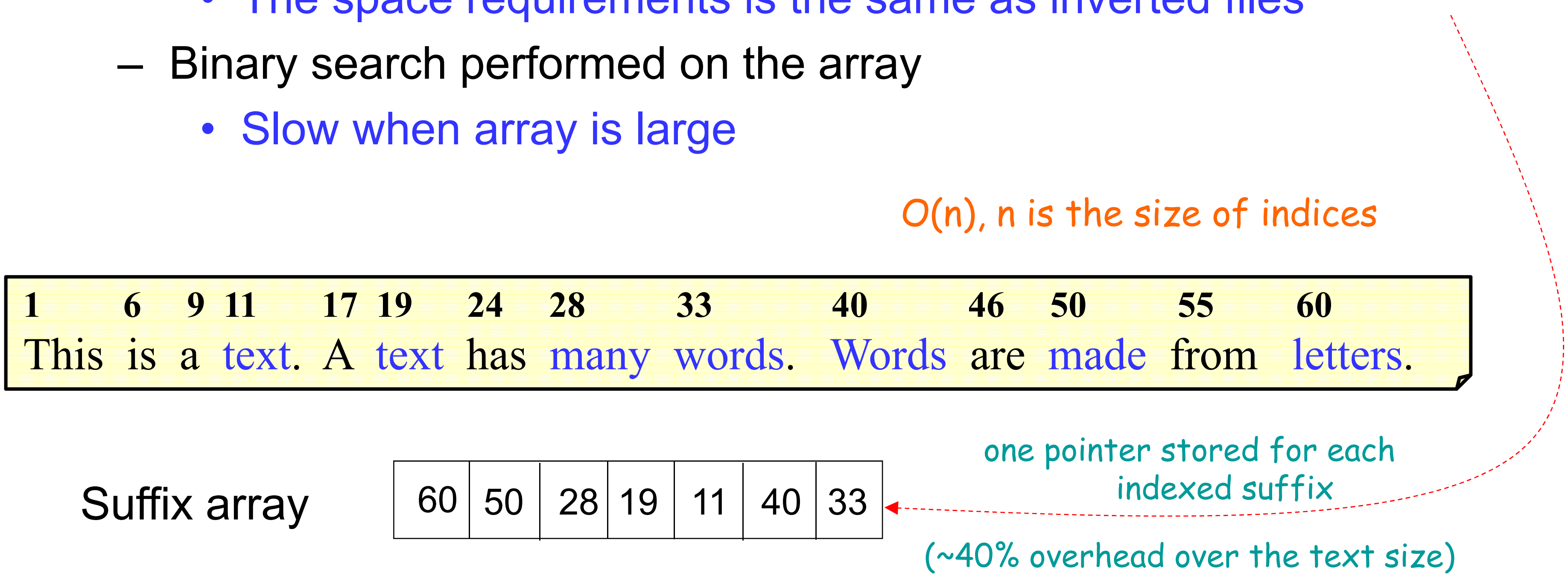
- Range searching
- Longest repetition searching
- Most significant or most frequent searching
  - Key-pattern/-word extraction

Suffix Trees: Performance

- For a suffix tree built on 250 Mb of text
  - Single word or phrase (without supra-indices): 1 sec
  - Single word or phrase (with supra-indices): 0.3 sec

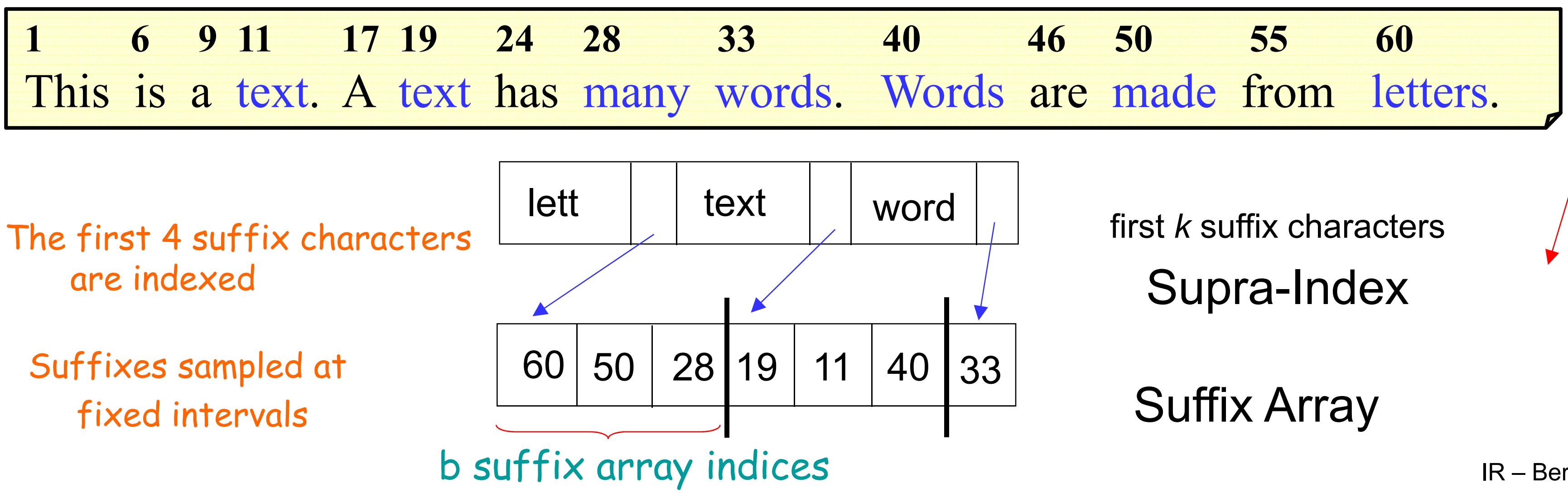
Suffix Arrays

- **Basic Ideas**
  - Provide the same functionality as suffix trees with much less space requirements
  - The leaves of the suffix tree are traversed in left-to-right (or top-to-down here) order, i.e. lexicographical order, to put the points to the suffixes in the array
    - The space requirements is the same as inverted files
  - Binary search performed on the array
    - Slow when array is large



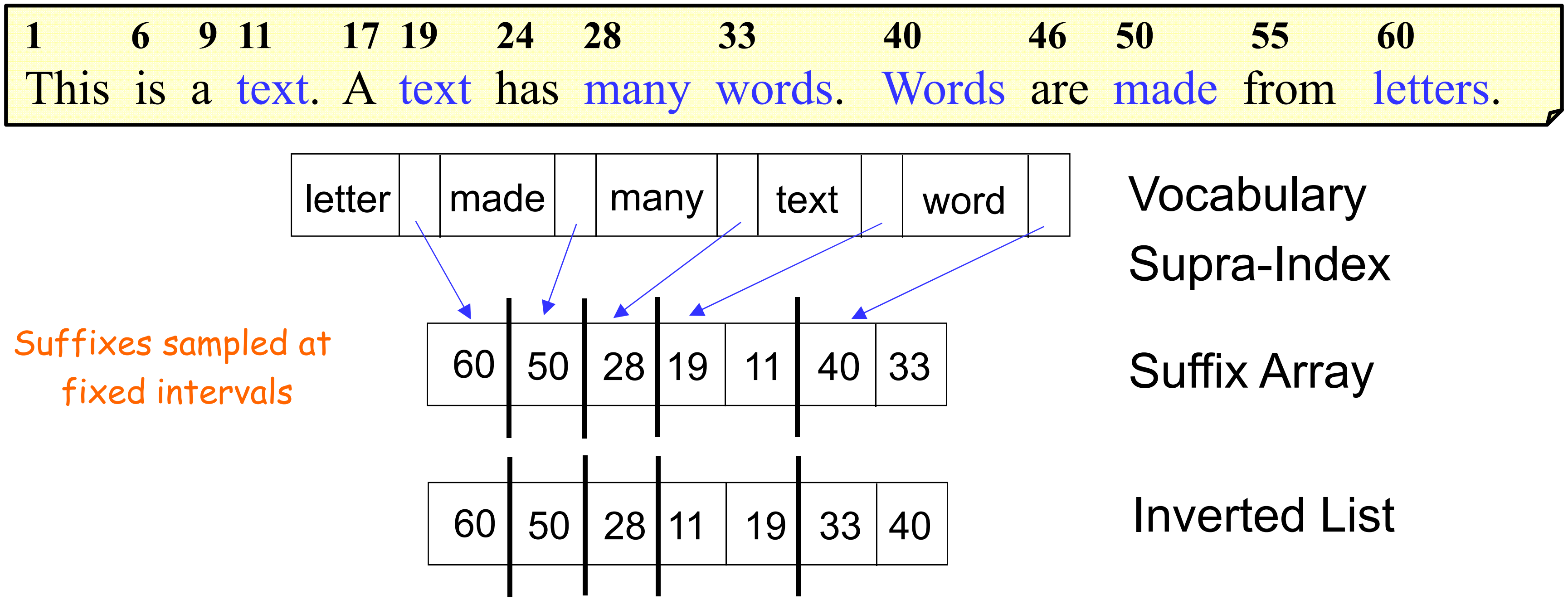
Suffix Arrays: Supra indices

- Divide the array into blocks (may with variable length) and make a sampling of each block
  - Use the **first *k* suffix characters**
  - Use the **first word of suffix changes** (e.g., “text ” (19) in the next example for nonuniformly sampling)
- Act as a first step of search to reduce external accesses (supra indices kept in memory!)



Suffix Arrays: Supra indices (cont.)

- Compare word (vocabulary) supra-index with inverted list



major difference
  - Word occurrences in suffix array are sorted lexicographically
  - Word occurrences in inverted list are sorted by text positions

Suffix Trees and Suffix Arrays

- **Pros**
  - Efficient to search more complex queries (phrases)
    - The query can be any substring of the text
- **Cons**
  - Costly construction process
  - Not suitable for approximate text search
  - Results are not delivered in text position order, but in a lexicographical order