Chapter V: Indexing & Searching

Information Retrieval & Data Mining
Universität des Saarlandes, Saarbrücken
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Chapter V: Indexing & Searching

V.1 Indexing
Dictionary, Inverted Index, Forward Index,
Partitioning, Caching

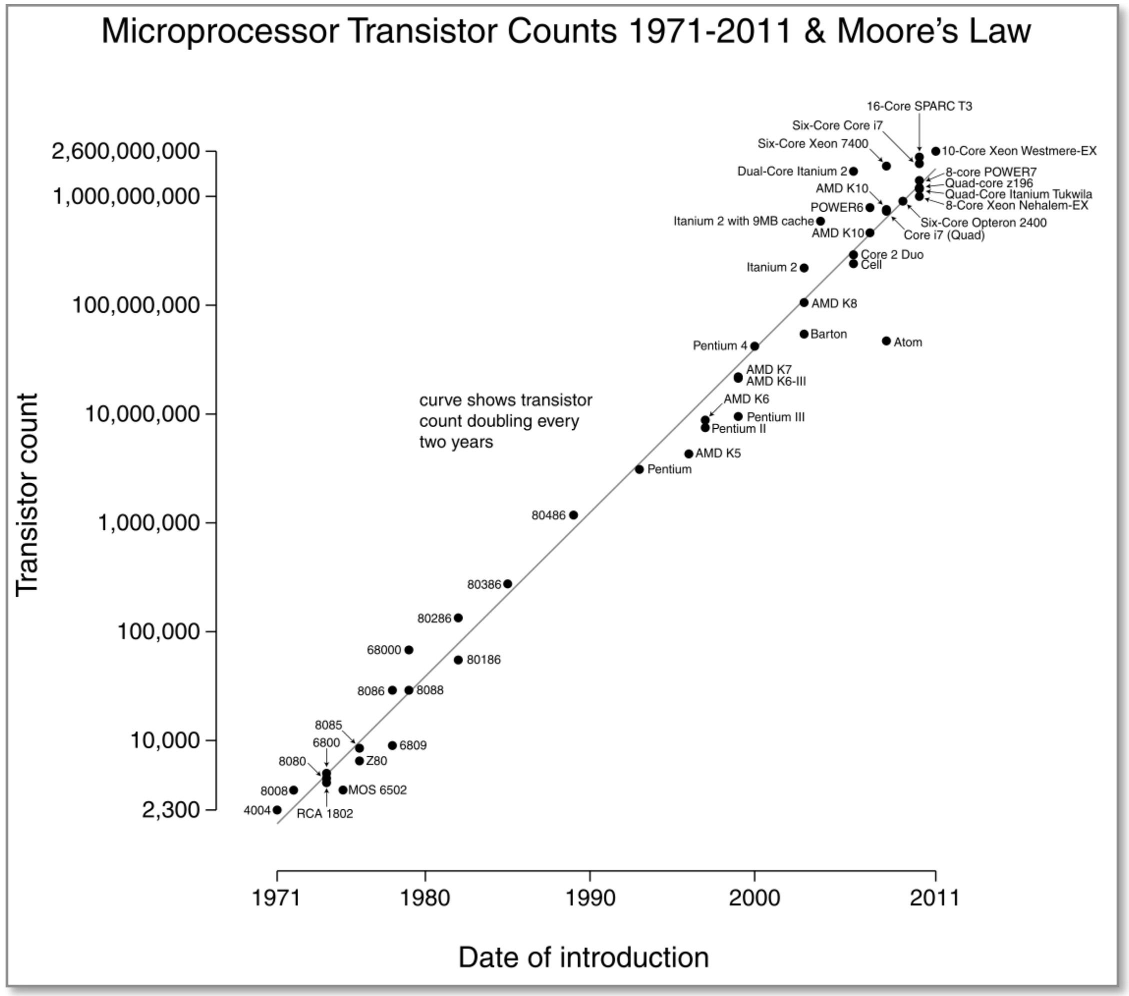
V.2 Compression
Huffman Coding, Ziv-Lempel, Variable-Byte Encoding,
Gap Encoding, Gamma Encoding, S9/S16, P-For-Delta

V.3 Query Processing
Term-at-a-Time, Document-at-a-Time,
Quit & Continue, WAND, Fagin's TA

V.4 MapReduce
Architecture, Programming Model, Hadoop

V.5 Near-Duplicate Detection
High-Dimensional Similarity Search, Shingling,
Min-Wise Independent Permutations, Locality Sensitive Hashing

Moore's Law



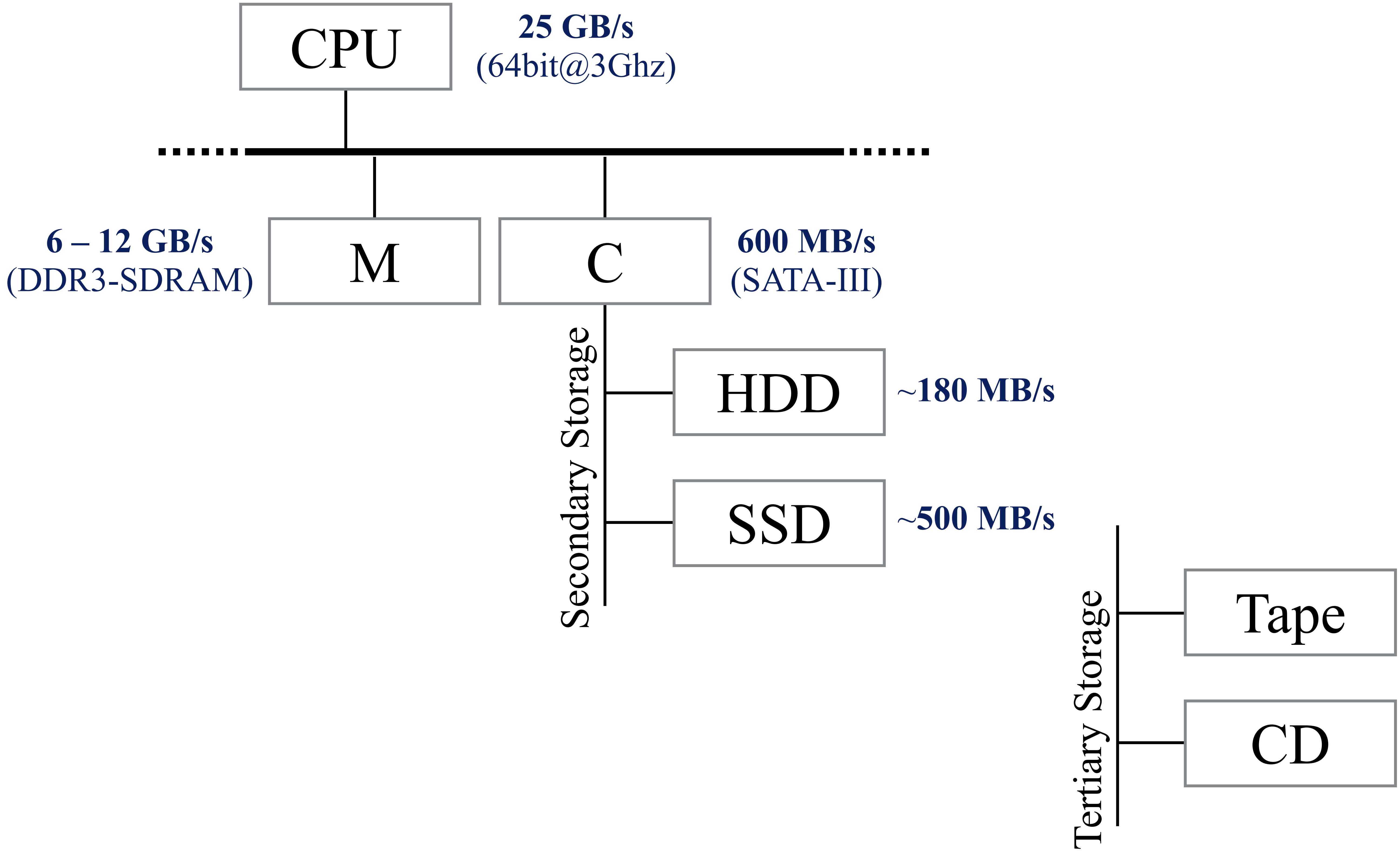
Source: http://en.wikipedia.org/wiki/Moore's_law

"The density of integrated circuits (transistors) will double every 18 months!"

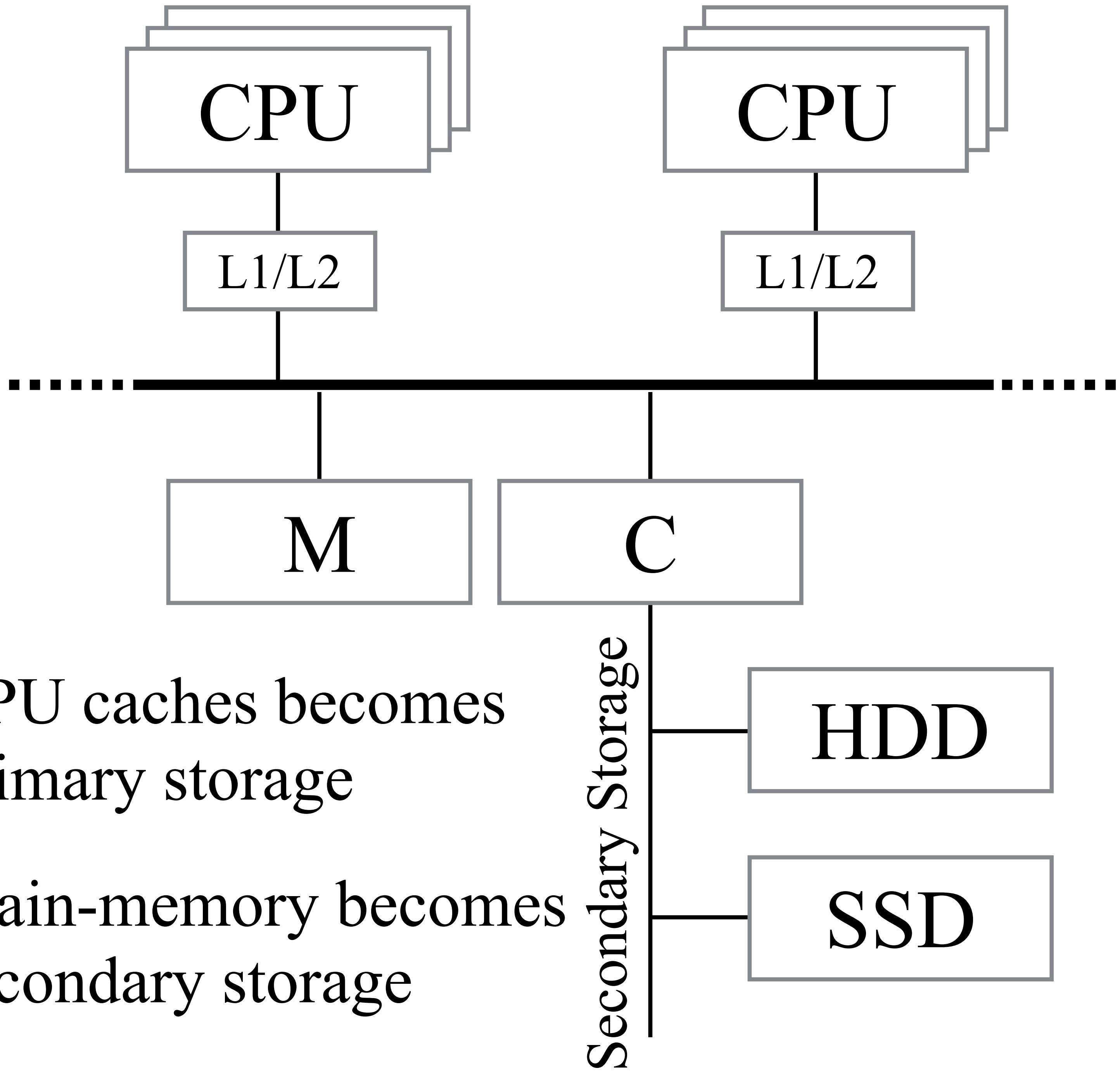
[Gordon Moore 1965]

- Has often been generalized to clock rates of CPUs, disk & memory sizes, etc.
- Still holds today for integrated circuits!

Traditional View on Hardware



More Modern View on Hardware



- CPU caches becomes primary storage
- Main-memory becomes secondary storage

- CPU-to-L1: ~3-5 cycles
- CPU-to-L2: ~15-20 cycles
- CPU-to-M: ~200 cycles

Random Access vs. Sequential Access

- **Locality** matters across all levels of the memory hierarchy
- Typical **latencies** of performing a **random access**:
  - Main memory: 10^{-8} s (~ 95MB/s assuming one byte is read)
  - Solid state drive: 10^{-5} s (~ 0.9 MB/s assuming one byte is read)
  - Hard disk drive: 10^{-2} s (~ 0.09 KB/s assuming one byte is read)
- High transfer rates only achievable through **sequential accesses**, i.e., by reading data that is stored contiguously, e.g., on disk

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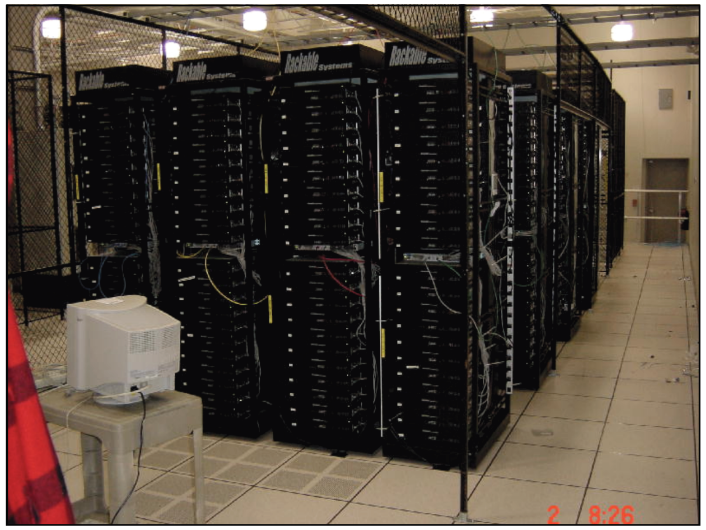
Data Centers

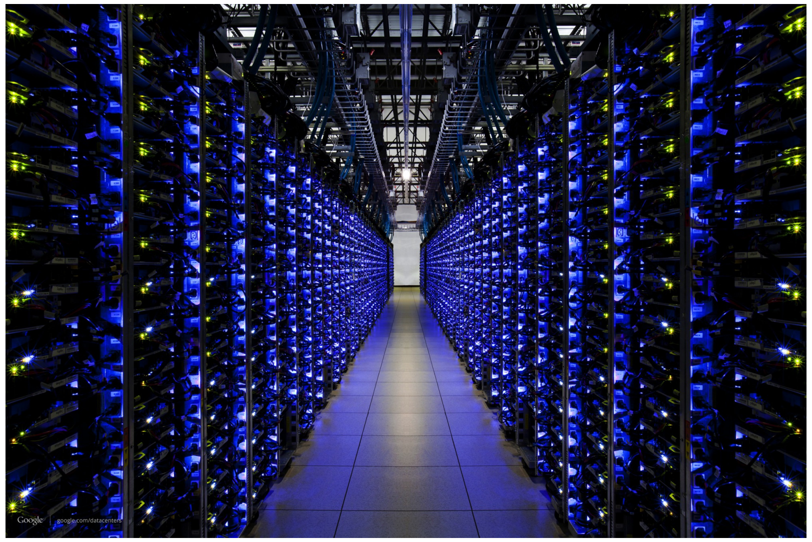
1996

Source: Stanford Infolab



2004

Source: [Dean '09]

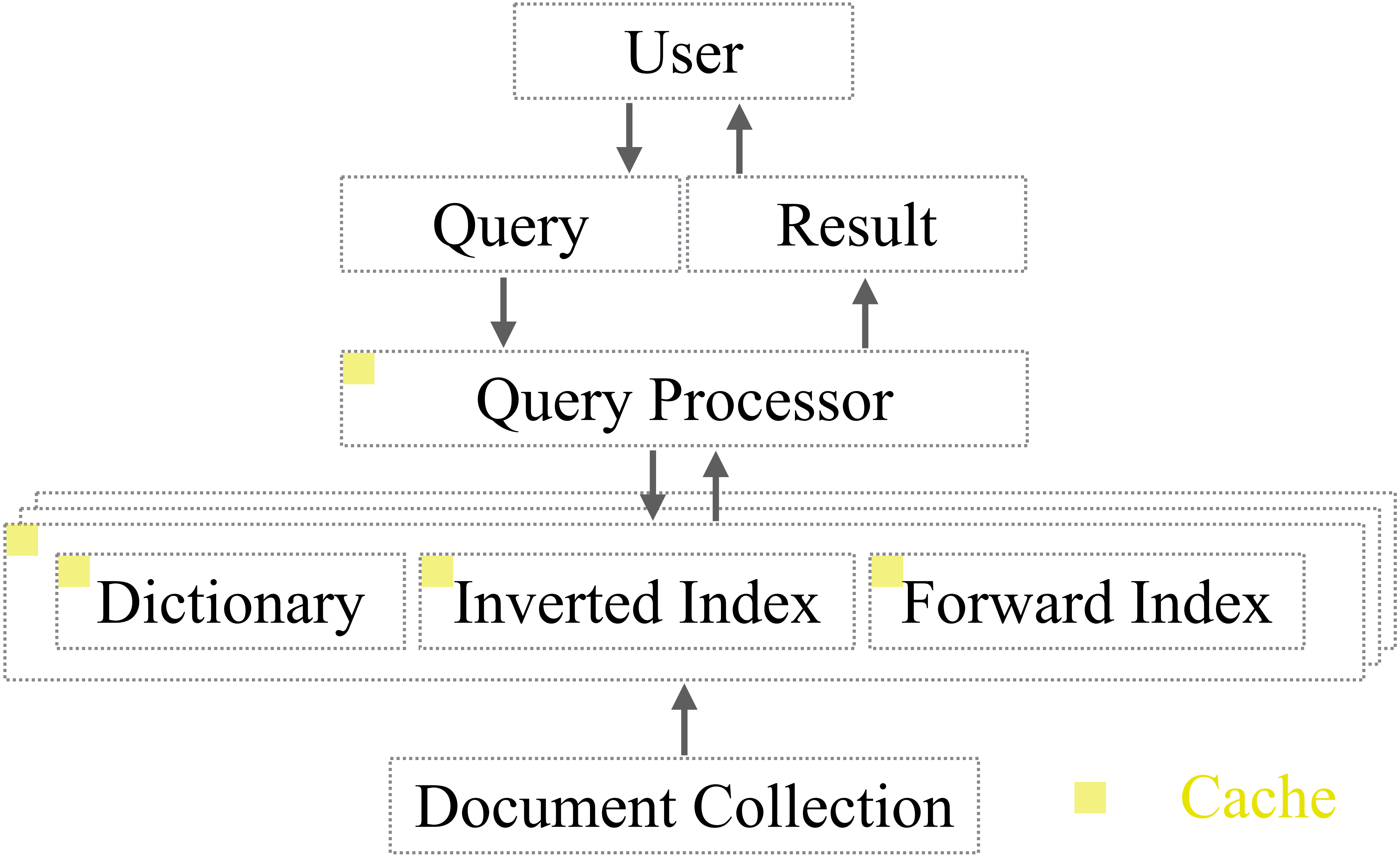


2013

Source: http://www.google.com/about

- Geographically distributed (i.e., bring data close to users)
- Indexes distributed and kept in main memory of many machines
- Energy consumption is an important cost factor

Overview of Modern IR System



V.1 Indexing

1. **Dictionary**
2. **Inverted Index**
3. **Forward Index**
4. **Partitioning**
5. **Caching**

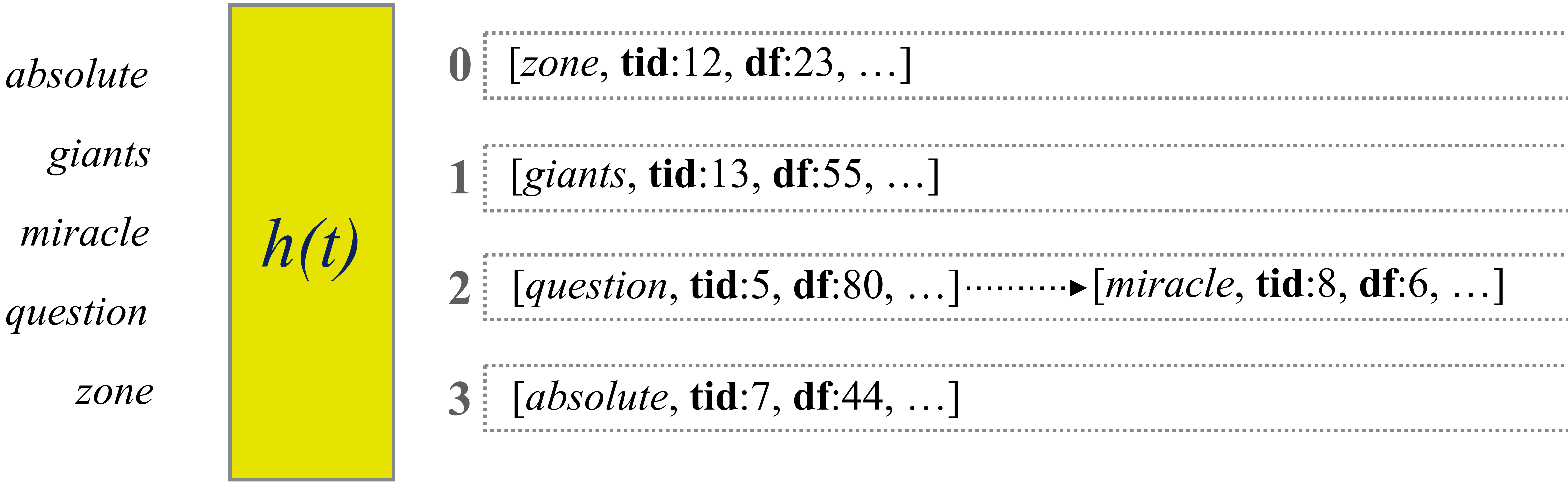
Based on **MRS Chapters 2, 3, 4** and **RBY Chapter 9**

1. Dictionary

- Dictionary maintains information about **terms**, e.g.:
  - **unique term identifier** (e.g., *house* → 3,141)
  - **location of corresponding posting list** on disk or in memory
  - **statistics** such as document frequency and collection frequency

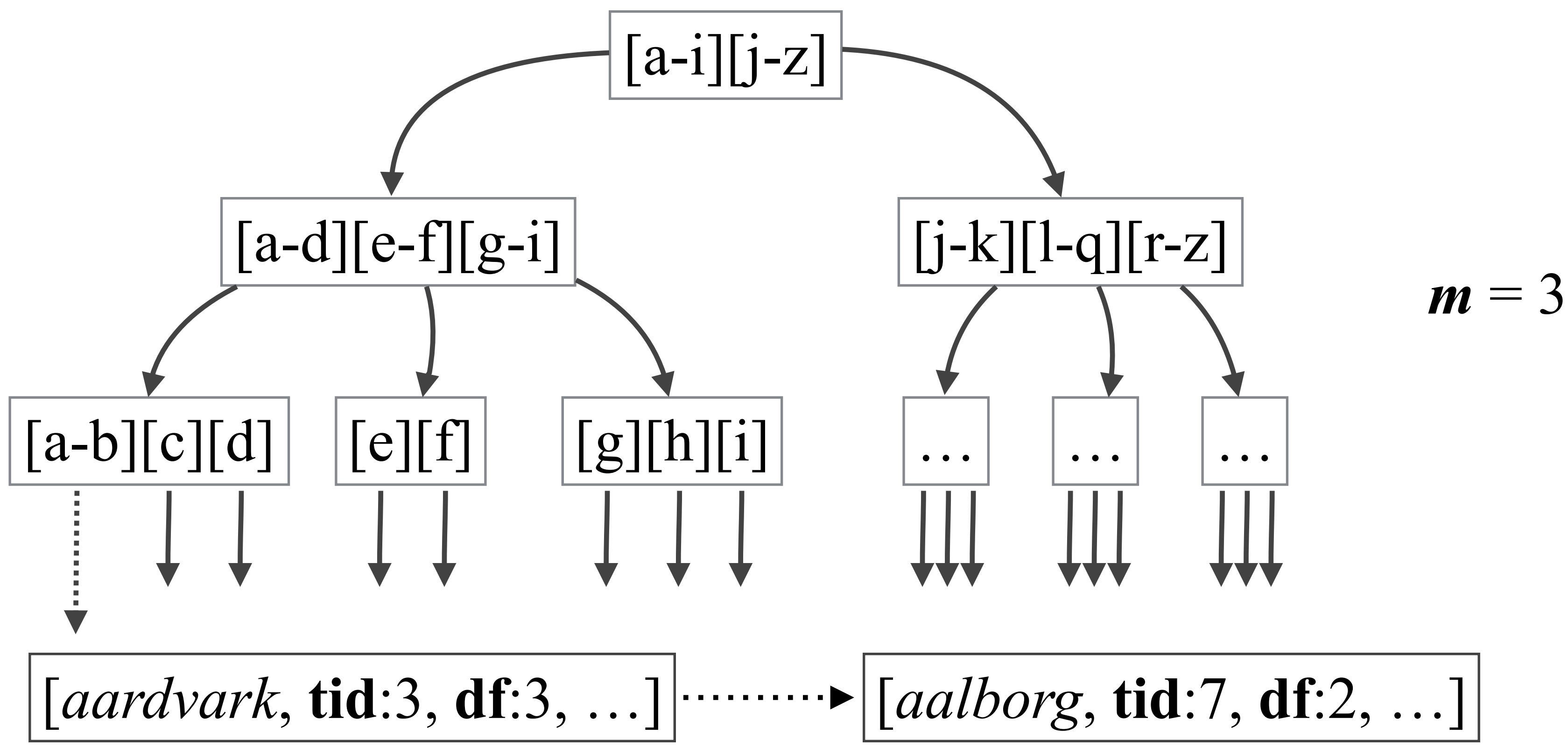
- Operations supported by the dictionary
  - **lookups by term**
  - **range searches** (e.g., for prefix and suffix queries like *hous** and **ing*)
  - **substring matching** (e.g., for wildcard queries like *ho*e*lly*)
  - **lookups by term identifier**

Hash-Based Dictionary



- Supports lookups in $O(1)$ but no other operations
- Vocabulary dynamics (i.e., new or removed terms) problematic
- Works best in **main memory**

B+-Tree-Based Dictionary



- **B-Tree**: Balanced tree with internal nodes having fan-out m
- **B+-Tree**: Leaf nodes additionally linked for efficient range search
- Supports lookups in $O(\log n)$ and range searches in $O(\log n + k)$
- Vocabulary dynamics (i.e., new or removed terms) no problem
- Works on **secondary storage**

Permuterm Index

- Indexes all permutations of each term with delimiter symbol $

		absolute$		*absolute$*
		bsolute$a		*bsolute$a*
		solute$ab		*e$absolut*
		olute$abs		*lute$abso*
absolute	⋯⋯▸	*lute$abso*	⋯⋯▸	*olute$abs*
		ute$absol		*solute$ab*
		te$absolu		*te&absolu*
		e$absolut		*ute&absol*

- Supports **arbitrary wildcard queries** (e.g., *ho*e*lly* is mapped to prefix query *lly*$*ho** with post-filtering of matching terms)
- Works on-top of dictionary supporting range searches
- Space blowup proportional to average term length

k-Gram Index

- Indexes all *k*-grams for each term with delimiter symbol $

absolute ⋯⋯▸ *\$ab*, *abs*, *bso*, *sol*, *olu*, *lut*, *ute*, *te\$* **k** = 3

- Supports **arbitrary wildcard queries** (e.g., *ho*e*lly* is mapped to lookups $*ho*, *lly*, *ly*$ with intersection and post-filtering of terms)
- Works on-top of dictionary supporting lookups
- Space blowup proportional to parameter *k*

2. Inverted Index

- Inverted index keeps a **posting list** for each term, which usually reside on secondary storage, with each **posting** capturing information about term's **occurrences in a specific document**
  - **document identifier** (e.g., d_{123}, d_{234}, …)
  - **term frequency** (e.g., $tf(house, d_{123}) = 2$, $tf(house, d_{234}) = 4$)
  - **score impacts** (e.g., $tf(house, d_{123}) * idf(house) = 3.75$)
  - **offsets** (i.e., absolute positions at which the term occurs in the document)

giants ………… [d_{123}, 2, [4, 14]] [d_{133}, 1, [47]] [d_{266}, 3, [1, 9, 20]] - - - - -

Posting

Posting list

- Posting lists are usually **compressed** for time and space efficiency

Posting Payloads

- Posting payloads depend on the **kind of queries** and the **retrieval models** to be supported
  - **document identifier** (always required, sufficient for Boolean retrieval)

    d_{123}

  - **term frequency** (for ranked retrieval, possibly different retrieval models)

    d_{123}, 2

  - **score impacts** (if the retrieval model has been fixed)

    d_{123}, 3.75

  - **offsets** (for proximity constraints or phrase queries)

    d_{123}, 2, [4, 14]

Posting-List Order

- Posting-list order depends on the **kinds of queries** to be supported

- **Document-ordered posting lists** for more efficient intersections (e.g., required for Boolean queries and phrase queries)

d_{123}, 2, [4, 14]	d_{133}, 1, [47]	d_{266}, 3, [1, 9, 20]	- - - - -

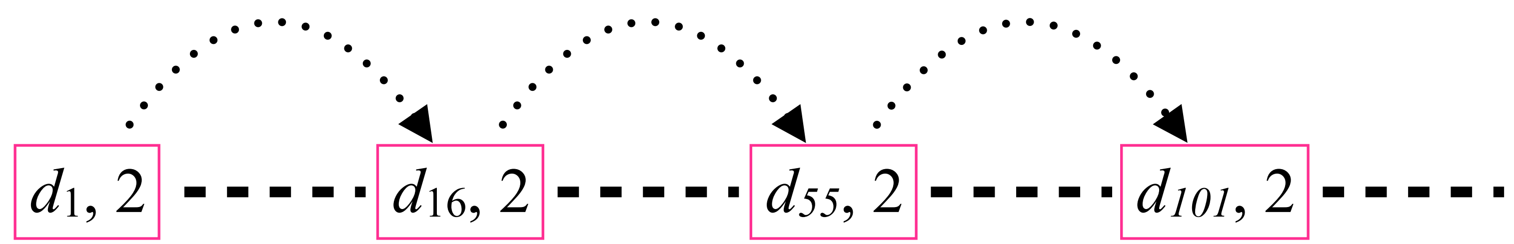
- **Impact-ordered posting lists** for more efficient top-k queries (i.e., terminate query processing as soon as top-k results known)

d_{231}, 1.0	d_{12}, 0.9	d_{662}, 0.8	d_{3}, 0.5	- - - - -

Skip Pointers

- Posting lists can be equipped with **additional structure**

- **Skip pointers** allow “fast forwarding” in a posting list
  - <u>common heuristic</u>: evenly spaced at $df(term)^{1/2}$
  - can be embedded into postings or kept together in posting-list header



3. Forward Index

- Forward index maintains information about **documents**
  - compact representation of **content** (e.g., as sequence of term identifiers)
  - **document length**

d_{123} *the giants played a fantastic season. it is not clear …*

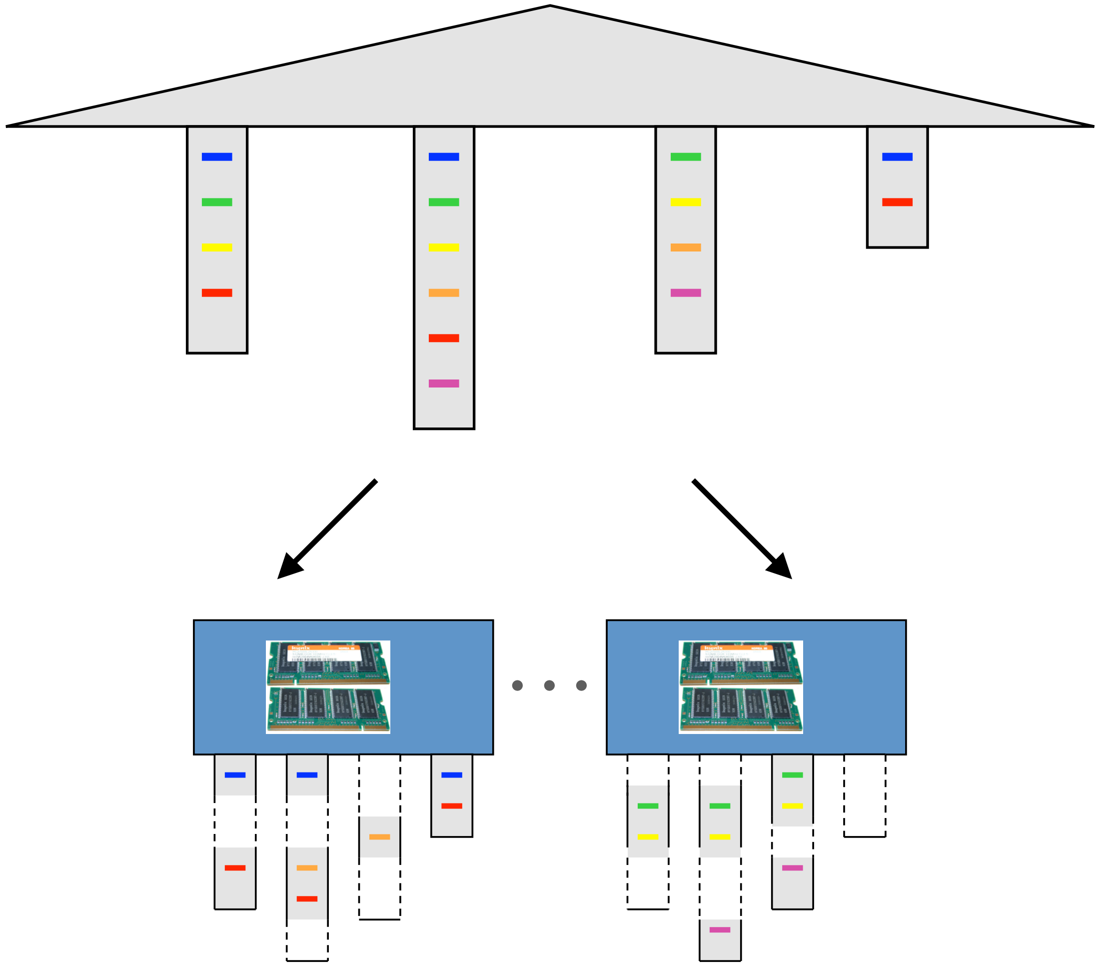
↓

d_{123} **dl**:428 **content**:< 1, 222, 127, 3, 897, 233, 0, 12, 6, 7, 123, … >

- Forward index can be used for tasks, e.g.:
  - **result-snippet generation** (i.e., show context of query terms)
  - computation of **proximity features** for advanced ranking (e.g., width of smallest window that contains all query terms)

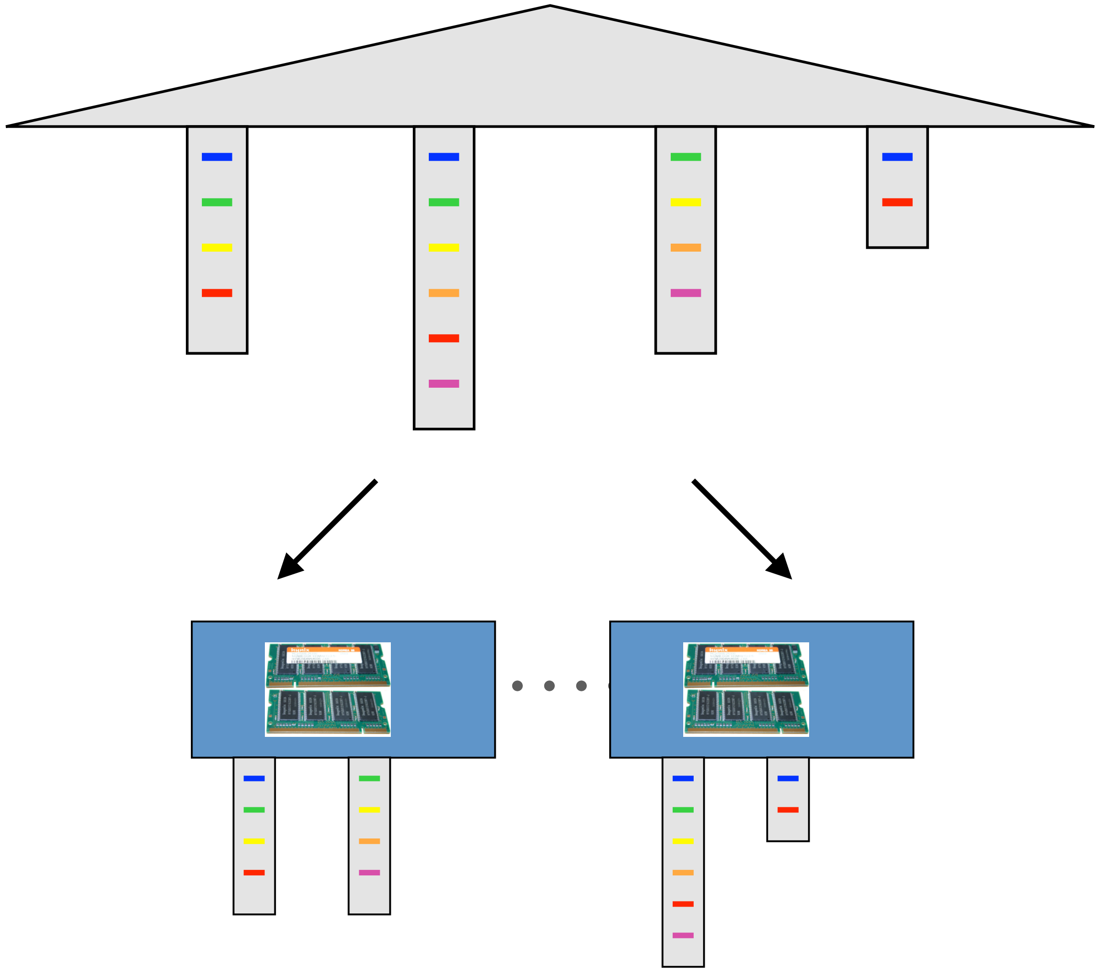
4. Partitioning

- **Document-partitioned** inverted index
  - each compute node indexes **a subset of the document collection**
  - **each query** is processed by **every compute node**
  - perfect load balance, embarrassingly scalable, easy maintenance



Partitioning (cont'd)

- **Term-partitioned** inverted index
  - each compute node holds posting lists for a **subset of terms**
  - queries are **routed to compute nodes with relevant terms**
  - lower resource consumption, susceptible to imbalance (because of skew in the data or query workload), index maintenance non-trivial



Back-of-the-Envelope Cost Comparison

- 20 billion web pages, 100 terms each ⟶ 2 x 10^{12} postings
- 10 million distinct terms ⟶ 2 x 10^{5} entries per posting list
- 5 bytes per posting ⟶ 1 MB per posting list, 10 TB total

- Query throughput: typical 1,000 q/s; peak 10,000 q/s
- Response time: all queries in ≤ 100 ms
- Reliability and redundancy: 10-fold redundancy

- Execution cost per query:
  - 1 ms initial latency + 1 ms per 1,000 postings
  - 2 terms per query

- Cost per compute node (4 GB RAM): $ 1,000
- Cost per disk (1 TB): $ 500 with 5 ms per RA, 20 MB/s for SAs

Back-of-the-Envelope Cost Comparison (cont'd)

- **Document-partitioned inverted index in RAM**
- 3,000 compute nodes to hold one copy of the index in RAM
  - 3,000 x 4 GB RAM = 12 TB (10 TB total index size + workspace RAM)
- Query processing:
  - each query executed on 3,000 computers in parallel:
    1 ms + (2 x 200 ms / 3,000) ≈ 1 ms
  - each cluster can sustain ~ 1,000 q/s
- 10 clusters = 30,000 compute nodes to sustain peak load and guarantee reliability & availability
- **$ 30 million** = 30,000 x $ 1,000 (no "big" disks)

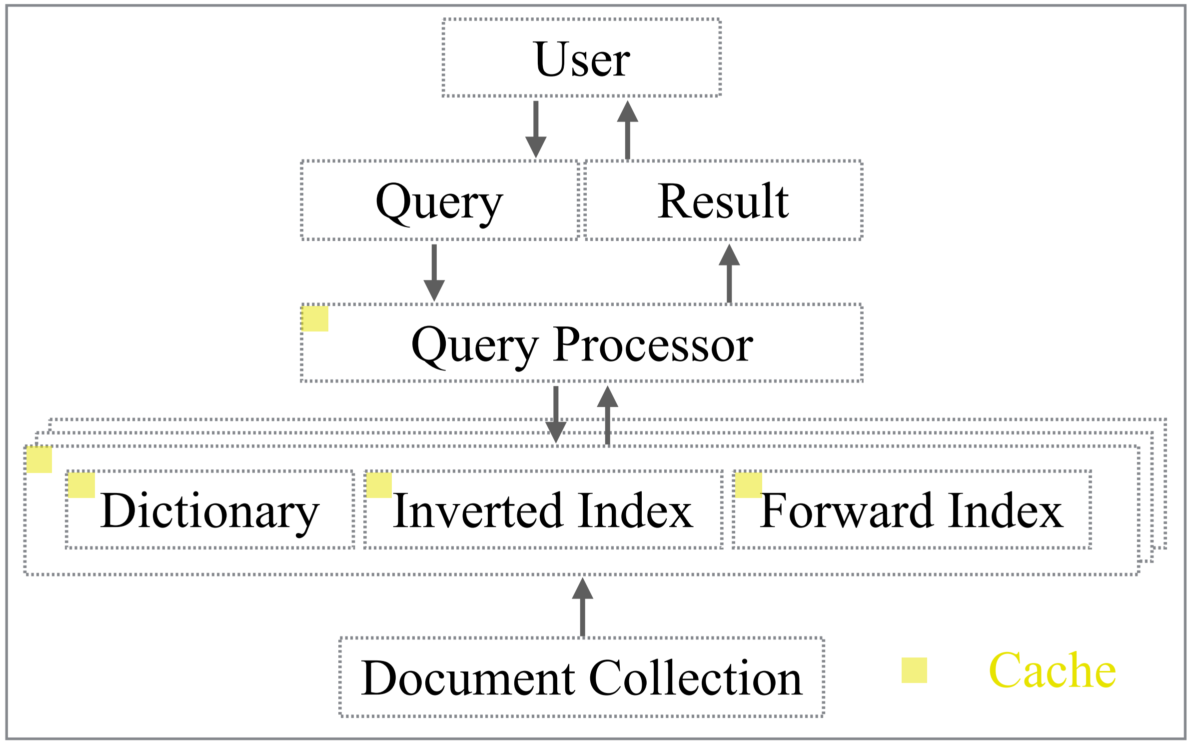
Back-of-the-Envelope Cost Comparison (cont'd)

- **Term-partitioned inverted index on disk**
- 10 compute nodes each with 1 TB disk to hold entire index
- Query processing:
  - max(1 MB / 20 MB/s, 1 ms + 200 ms)
  - limited throughput: 5 q/s per compute node for 1-term queries
- 1 cluster = 400 nodes to sustain 1,000 q/s for 2-term queries
- 10 clusters = 4,000 nodes to sustain peak load and guarantee reliability & availability

- **\$ 6 million** = 4,000 x (\$ 1,000 + \$ 500)

5. Caching

- What is cached?
  - Query results
  - Posting lists
  - Posting-list intersections
  - Documents
  - Snippets



- Where is it cached?
  - in RAM of responsible compute node
  - in dedicated front-end accelerators or proxy nodes
  - in RAM of all (many) compute nodes

Caching Strategies

- **Least recently used** (LRU)
  - when space is needed, evict the item that was least recently used
- **Least frequently used** (LFU)
  - when space is needed, evict the item that was least frequently used
- **Cost-aware** (Landlord algorithm)
  - estimate for each item: *temperature* = *access-rate* / *cost*
  - when space is needed, evict item with lowest temperature
  - prefetch item if its predicted temperature is higher than the temperature of the corresponding replacement victims
  - Full details: [Cao and Irani '97][Young '02]

Caching Effectiveness

- Query frequencies follow **Zipf distribution** ($s \approx 1$)

- [Baeza-Yates et al. '07] analyzed one-year query log of Yahoo!
  - **88%** of queries are issued only once
  - account for **44%** of overall query volume
  - query-result caching achieves **cache-hit ratios** < 50% in practice

Summary of V.1

- **Dictionary**
  holds information about terms
- **Inverted Index**
  holds information about word occurrences in documents
- **Forward Index**
  holds compact representations of documents
- **Partitioning**
  distribute inverted index by-document or by-term
- **Caching**
  query results, posting lists, posting-list intersection, etc.

Additional Literature for V.1

- **R. Baeza-Yates, A. Gionis, F. Junqueira, V. Murdock, V. Plachouras, and F. Silvestri**: *The Impact of Caching on Search Engines*, SIGIR 2007
- **S. Brin and L. Page**: *The anatomy of a large-scale hypertextual Web search engine*, Computer Networks 30:107-117, 1998
- **P. Cao and S. Irani**: *Cost-Aware WWW Proxy Caching Algorithms,* USENIX 1997
- **R. Ozcan, I. S. Altingovde, B. B. Cambazoglu, F. P. Junqueira, O. Ulusoy**: *A five-level static cache architecture for web search engines*, IP&M 48(5):828-840, 2012
- **N. E. Young**: *On-Line File Caching*, Algorithmica 33(3):371-383, 2002
- **J. Zobel and A. Moffat**: *Inverted Files for Text Search Engines*, ACM Computing Surveys 38(2):6, 2006

V.2 Compression

1. **Huffman Coding**
2. **Ziv-Lempel Compression**
3. **Variable-Byte Encoding**
4. **Gamma Encoding**
5. **Gap Encoding**
6. **Run-Length Encoding**
7. **S9/S16 Encoding**
8. **P-FoR-Delta Encoding**

Why Compression?

- **Zipf's law** and **Heaps' law** suggest opportunities for compression due to frequent terms or terms occurring repeatedly in documents

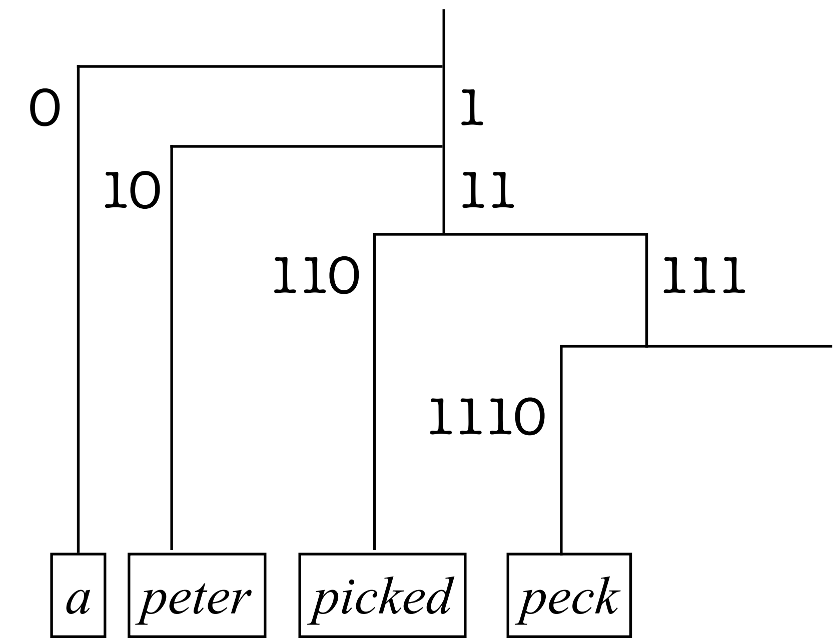
- **Compression of posting lists** is attractive for several reasons
  - **reduced space consumption** on disk or in main memory
  - **faster query processing**, since **reading and decompressing data** is nowadays **often faster** than **reading uncompressed data**
  - **improved cache effectiveness**, since more posting lists fit into cache

1. Huffman Coding

- **Variable-length unary code** based on frequency analysis of the underlying distribution of symbols (e.g., terms) in a text
- Key idea: Choose shortest unary code for most frequent symbol

Symbol x	**Frequency $f(x)$**	**Huffman Encoding**
a	0.8	0
peter	0.1	10
picked	0.07	110
peck	0.03	1110

Huffman tree



Entropy

- Let $f(x)$ be the probability (or relative frequency) of the symbol x in some text d. The **entropy** of the text (or the underlying probability distribution) is defined as

$$H(d) = \sum_{x} f(x) \log_2 \frac{1}{f(x)}$$

- The entropy $H(d)$ is a **lower bound** on the average (i.e., expected) **number of bits per symbol** needed with optimal compression.

- Huffman codes come close to the optimum $H(d)$

2. Ziv-Lempel Compression

- **LZ77** (Adaptive Dictionary) and further variants:
  - Scan text and identify in a **lookahead window** the longest string that occurs repeatedly and is contained in **backwards window**
  - Replace this string by a **pointer** to its previous occurrence
- Encode text into list of **triples < back, count, new >** where
  - **back** is the backward distance to a prior occurrence of the string that starts at the current position
  - **count** is the length of this repeated string
  - **new** is the next symbol that follows the repeated string
- Triples themselves can be further encoded (with variable length)
- Variants use explicit dictionary with statistical analysis of text but need to scan text twice (for statistics and compression)

Ziv-Lempel Compression (Example)

- Example: *peter_piper_picked_a_peck_of_pickled_peppers*

< 0, 0, *p* >	*for character 1:*	*p*
< 0, 0, *e* >	*for character 2:*	*e*
< 0, 0, *t* >	*for character 3:*	*t*
< -2, 1, *r* >	*for characters 4-5:*	*er*
< 0, 0, _ >	*for character 6:*	_
< -6, 1, *i* >	*for characters 7-8:*	*pi*
< -8, 2, *r* >	*for characters 9-11:*	*per*
< -6, 3, *c* >	*for characters 12-13:*	*_pic*
< 0, 0, *k* >	*for character 16*	*k*
< -7,1, *d* >	*for characters 17-18*	*ed*

…

- Great for text but **not appropriate** for compressing posting lists

3. Variable-Byte Encoding

- 32-bit binary code represents 12,038 using 4 bytes as

00000000	00000000	00101111	00000110

- **Variable-byte encoding** (aka. 7-bit encoding) uses one bit per byte as a continuation bit indicating whether the current number expands into the next bytes

- Variable-byte encoding represents 12,038 using only 2 bytes as

01011110	10000110

1 continuation bit

7 data bits

- **Byte-aligned**, i.e., each number corresponds to sequence of bytes

4. Gamma Encoding

- Gamma (γ) encoding represents an integer x as
  - $length = floor(\log_2 x)$ in **unary**
  - $offset = x - 2^{length}$ in **binary**

  results in $(1 + \log_2 x + \log_2 x)$ bits for integer x

- **Not byte-aligned**, i.e., needs to be packed into bytes or words

- Useful when **distribution** of numbers is **not known** ahead of time or when **small numbers** (e.g., gaps, tf) are **frequent**

Gamma Encoding (Examples)

x	**Gamma Encoding**	
$1 = 2^0$	**u**:0	
$4 = 2^2$	**u**:110	**b**:00
$24 = 2^4 + 2^3$	**u**:11110	**b**:1000
$131 = 2^7 + 3$	**u**:11111110	**b**:0000011

5. Golomb/Rice Encoding

- For **tunable parameter** M, split the number x into
  - **quotient** $q = floor(x / M)$ stored in **unary code** (using $q + 1$ bits)
  - **remainder** $r = (x \bmod M)$ stored in **binary code**
- If M chosen as 2^n then r needs $\log_2(M)$ bits (**Rice encoding**)
- Otherwise for $b = ceil(\log_2(M))$
  - If $r < 2^b - M$ then r is stored in binary code using $b - 1$ bits
  - Otherwise $r + 2^b - M$ is stored in binary code using b bits
- **Not byte-aligned**, i.e., needs to be packed into bytes or words
- Useful when **distribution** of numbers is **known ahead of time** (e.g., optimal for geometrically distributed numbers)

Golomb/Rice Encoding (Examples)

Golomb Encoding (*M* = 10, *b* = 4*)*

x	***q***	***bits*(*q*)**	***r***	***bits*(*r*)**
0	0	**u**:0	0	**b**:000
33	3	**u**:1110	3	**b**:011
57	5	**u**:111110	7	**b**:1101
99	9	**u**:1111111110	9	**b**:1111

5. Gap Encoding

- Variable-byte encoding, Gamma encoding, and Golomb/Rice encoding represent **smaller numbers using fewer bytes**

- Note: Posting lists contain **sequences of increasing integers**
  - **document identifiers** of postings in document-ordered posting list
  - **offsets** in posting payload if phrase queries need to be supported

- **Gap encoding** (aka. *d*-gaps) represents sequences of increasing integers as their first element followed by gaps

<7, 12, 20, 25, 33, 78, … > ⟶ <7, 5, 8, 5, 8, 45, … >

6. Run-Length Encoding

- Run-length encoding (e.g., used in early image formats like PCX) targets sequences of integers having **long runs of the same number** (i.e., many repetitions of that number in a row)
- Run-length encoding represents integer sequences as (number, frequency) pairs

<7, 7, 7, 8, 8, 1, 1, 1, 1, … > ⟶ < (7, 3), (8, 2), (1, 4), …>

7. S9/S16 Encoding

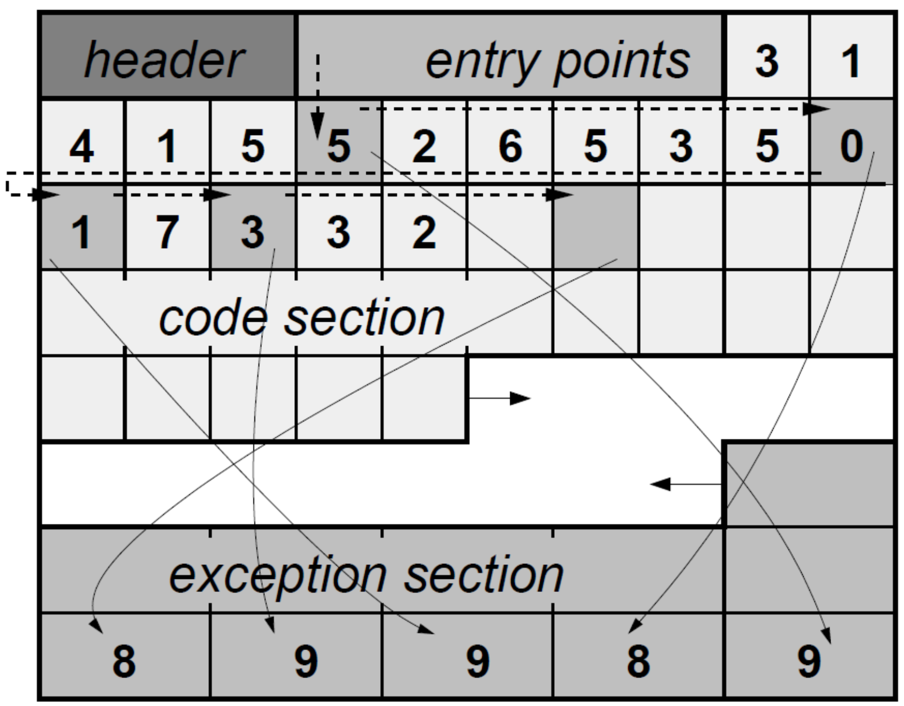
- Byte-aligned encoding (32-bit integer words of fixed length)
- 4 status bits encode 9/16 cases for partitioning 28 data bits

10011000	10111100	00101111	01011110

- Example: If 1001 above denotes 4 x 7 bits for the data part, then the data part encodes the decimal numbers: 69, 112, 47, 47
- Decompression by case table or by hardcoding all cases
- High cache locality of decompression code/table
- Fast CPU support for bit shifting integers on modern platforms
- Full details: [Zhang et al. '08]

8. P-FoR-Delta Encoding

- **P**atched **F**rame-**of**-**R**eference w/ **D**elta-encoded Gaps
- Key idea: Encode individual numbers such that "most" numbers fit into ***b* bits**
- Focuses on encoding an entire block at a time by choosing a value of ***b* bits** such that $[\mathbf{high}_{\mathbf{coded}}, \mathbf{low}_{\mathbf{coded}}]$ is small
- Outliers ("exceptions") stored in extra **exception section** at the end of the block in reverse order



Encoding of **31415926535897932** using ***b***=3 bitwise coding blocks for the code section.

- Full details: [Zukowski et al. '06]

Posting-List Layout & Compression (Example)

Skip Table | **Block 1** | Block 2 | - - - - - - - - - - - - - - - - - - | Block N

Block 1 (contain n postings)

- delta to last document identifier in block
- # documents in block (most often n)
- n - 1 deltas: Rice_M encoded
- tf values: Gamma encoded
- term attributes: Huffman encoded
- term positions: Huffman encoded

- Layout allows **incremental decoding**
- Full details: [Dean ’09]

Open Source Search Engines

- **Apache Lucene / Apache Solr**
  - implemented in Java, widely used in practice
  - http://lucene.apache.org/core/ http://lucene.apache.org/solr/
- **Indri**
  - implemented in C++, academic IR system developed at CMU & U Mass
  - http://www.lemurproject.org
- **Terrier**
  - implemented in Java, academic IR system developed at U Glasgow
  - http://terrier.org/
- **MG4J**
  - implemented in Java, academic IR system developed at U Milano
  - http://mg4j.dsi.unimi.it

Summary of V.2

- **Compression**
  is essential for performance in modern IR systems
- **Ziv-Lempel compression**
  as a dictionary-based encoding scheme that is great for text
- **Variable-byte encoding**
  as a byte-aligned non-parameterized encoding
- **Gamma encoding** and **Golomb/Rice encoding**
  as bit-aligned non-parameterized/parameterized encodings
- **Gap encoding** and **Run-length encoding**
  for transforming integer sequences
- **S9/S16** and **P-FoR-Delta**
  as methods that encode entire blocks of integers

Additional Literature for V.2

- **S. Brin and L. Page**: *The anatomy of a large-scale hypertextual Web search engine*, Computer Networks 30:107-117, 1998
- **J. Dean**: *Challenges in Building Large-Scale Information Retrieval Systems*, WSDM 2009, http://videolectures.net/wsdm09_dean_cblirs/
- **A. Moffat and L. Stuiver**: *Binary Interpolative Coding for Effective Index Compression,* Inf. Retr. 3(1): 25-47 (2000)
- **H. Yan, S. Ding, T. Suel**: *Compressing Term Positions in Web Indexes*, SIGIR 2009
- **H. Yan, S. Ding, T. Suel**: *Inverted index compression and query processing with optimized document ordering,* WWW 2009
- **I. Witten, A. Moffat, and T. Bell**: *Managing Gigabytes (2nd Edition)*, Morgan Kaufmann, 1999
- **J. Zhang, X. Long, T. Suel**: *Performance of compressed inverted list caching in search engines,* WWW 2008
- **M. Zukowski, S. Héman, N. Nes, P. A. Boncz**: *Super-Scalar RAM-CPU Cache Compression,* ICDE 2006