UNIVERSITY OF WATERLOO

Daniel Lemire, Waterloo University, May 10th 2018.

Next Generation Indexes For Big Data Engineering

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Knuth on performance

> Premature optimization is the root of all evil

Knuth on performance

> Premature optimization is the root of all evil (...) After a programmer knows which parts of his routines are really important, a transformation like doubling up of loops will be worthwhile.

Constants matter

fasta benchmark:

	elapsed time	total time (all processors)
single-threaded	1.36 s	1.36 s

https://benchmarksgame-team.pages.debian.net/benchmarksgame/performance/fasta.html

Constants matter

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multicore (4 cores)	1.00 s	2.00 s

Constants matter

fasta benchmark:

	elapsed time	total time (all processors)
single-threaded	1.36 s	1.36 s
multicore (4 cores)	1.00 s	2.00 s
vectorized (1 core)	0.31 s	0.31 s

https://lemire.me/blog/2018/01/02/multicore-versus-simd-instructions-the-fasta-case-study/

> “One Size Fits All”: An Idea Whose Time Has Come and Gone (Stonebraker, 2005)

Rediscover Unix

In 2018, Big Data Engineering is made of several specialized and re-usable components:

- Calcite : SQL + optimization
- Hadoop
- etc.

> "Make your own database engine from parts"

We are in a Cambrian explosion, with thousands of organizations and companies building their custom high-speed systems.

- Specialized used cases
- Heterogeneous data (not everything is in your Oracle DB)

For high-speed in data engineering you need...

- Front-end (data frame, SQL, visualisation)
- High-level optimizations
- Indexes (e.g., Pilosa, Elasticsearch)
    - Great compression routines
    - Specialized data structures
- ....

Sets

A fundamental concept (sets of documents, identifiers, tuples...)

$\longrightarrow$ For performance, we often work with sets of integers (identifiers).

- tests : $x \in S$?
- intersections : $S_2 \cap S_1$, unions : $S_2 \cup S_1$, differences : $S_2 \setminus S_1$
- Similarity (Jaccard/Tanimoto): $|S_1 \cap S_1|/|S_1 \cup S_2|$
- Iteration

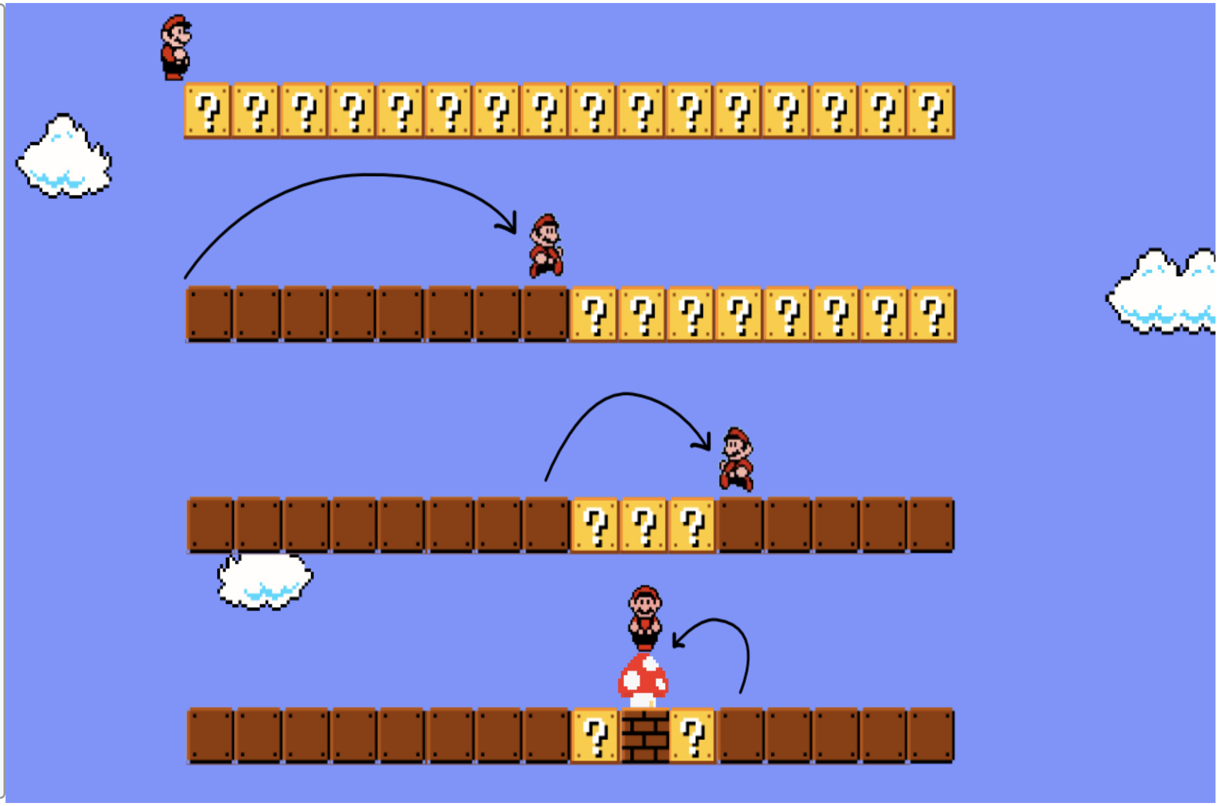
```
for x in S do
    print(x)
```

How to implement sets?

- sorted arrays (`std::vector<uint32_t>`)
- hash tables (`java.util.HashSet<Integer>` , `std::unordered_set<uint32_t>`)
- . . .
- bitmap (`java.util.BitSet`)
- ❤️ ❤️ ❤️ compressed bitmaps ❤️ ❤️ ❤️

Arrays are your friends

```
while (low <= high) {
   int mI =
   (low + high) >>> 1;
   int m = array.get(mI);
   if (m < key) {
     low = mI + 1;
   } else if (m > key) {
     high = mI - 1;
   } else {
     return mI;
   }
}
return -(low + 1);
```



Hash tables

- value x at index $h(x)$
- random access to a value in expected constant-time
  - much faster than arrays

in-order access is kind of terrible

- $[15, 3, 0, 6, 11, 4, 5, 9, 12, 13, 8, 2, {\color{red}1}, 14, 10, 7]$
- $[15, 3, 0, 6, 11, 4, 5, 9, 12, 13, 8, {\color{red}2}, 1, 14, 10, 7]$
- $[15, {\color{red}3}, 0, 6, 11, 4, 5, 9, 12, 13, 8, 2, 1, 14, 10, 7]$
- $[15, 3, 0, 6, 11, {\color{red}4}, 5, 9, 12, 13, 8, 2, 1, 14, 10, 7]$
- $[15, 3, 0, 6, 11, 4, {\color{red}5}, 9, 12, 13, 8, 2, 1, 14, 10, 7]$
- $[15, 3, 0, {\color{red}6}, 11, 4, 5, 9, 12, 13, 8, 2, 1, 14, 10, 7]$

(Robin Hood, linear probing, MurmurHash3 hash function)

Set operations on hash tables

```
h1 <- hash set
h2 <- hash set
...
for(x in h1) {
   insert x in h2 // cache miss?
}
```

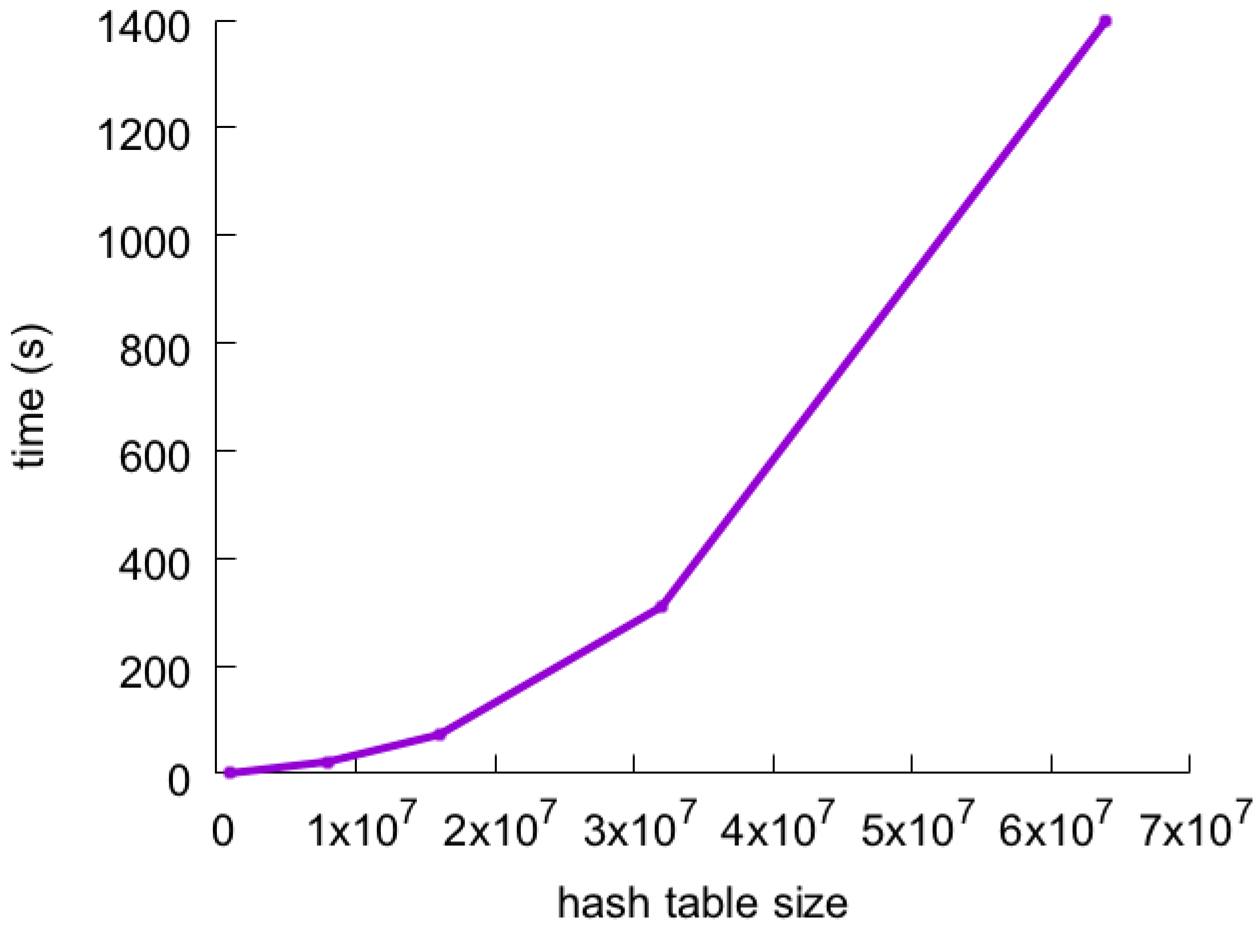
"Crash" Swift

```
var S1 = Set<Int>(1...size)
var S2 = Set<Int>()
for i in d {
    S2.insert(i)
}
```

Some numbers: half an hour for 64M keys

size	time (s)
1M	0.8
8M	22
64M	1400

- Maps and sets can have quadratic-time performance https://lemire.me/blog/2017/01/30/maps-and-sets-can-have-quadratic-time-performance/
- Rust hash iteration+reinsertion https://accidentallyquadratic.tumblr.com/post/153545455987/rust-hash-iteration-reinsertion


1400
1200
1000
800
600
400
200
0
time (s)
0
1x10^7
2x10^7
3x10^7
4x10^7
5x10^7
6x10^7
7x10^7
hash table size

Bitmaps

Efficient way to represent sets of integers.

For example, 0, 1, 3, 4 becomes `0b11011` or "27".

- $\{0\} \to$ `0b00001`
- $\{0,3\} \to$ `0b01001`
- $\{0,3,4\} \to$ `0b11001`
- $\{0,1,3,4\} \to$ `0b11011`

Manipulate a bitmap

64-bit processor.

Given `x`, word index is `x/64` and bit index `x % 64`.

```
add(x) {
  array[x / 64] |= (1 << (x % 64))
}
```

How fast is it?

```
index = x / 64          -> a shift
mask = 1 << ( x % 64)   -> a shift
array[ index ] |= mask -> a OR with memory
```

One bit every ≈ 1.65 cycles because of superscalarity

Bit parallelism

Intersection between {0, 1, 3} and {1, 3}
a single AND operation
between `0b1011` and `0b1010`.

Result is `0b1010` or {1, 3}.

No branching!

Bitmaps love ❤️ wide registers

- SIMD: Single Intruction Multiple Data
  - SSE (Pentium 4), ARM NEON 128 bits
  - AVX/AVX2 (256 bits)
  - AVX-512 (512 bits)

AVX-512 is now available (e.g., from Dell!) with Skylake-X processors.

Bitsets can take too much memory

{1, 32000, 64000} : 1000 bytes for three values

We use compression!

Git (GitHub) utilise EWAH

Run-length encoding

Example: 000000001111111100 est
$00000000 - 11111111 - 00$

Code long runs of 0s or 1s efficiently.

https://github.com/git/git/blob/master/ewah/bitmap.c

Complexity

- Intersection : $O(|S_1| + |S_2|)$ or $O(\min(|S_1|, |S_2|))$
- In-place union ($S_2 \leftarrow S_1 \cup S_2$): $O(|S_1| + |S_2|)$ or $O(|S_2|)$

Roaring Bitmaps

http://roaringbitmap.org/

- Apache Lucene, Solr et Elasticsearch, Metamarkets’ Druid, Apache Spark, Apache Hive, Apache Tez, Netflix Atlas, LinkedIn Pinot, InfluxDB, Pilosa, Microsoft Visual Studio Team Services (VSTS), Couchbase's Bleve, Intel’s Optimized Analytics Package (OAP), Apache Hivemall, eBay’s Apache Kylin.
- Java, C, Go (interoperable)

Hybrid model

Set of containers

- sorted arrays ({1,20,144})
- bitset (0b10000101011)
- runs ([0,10],[15,20])

Related to: O'Neil's RIDBit + BitMagic

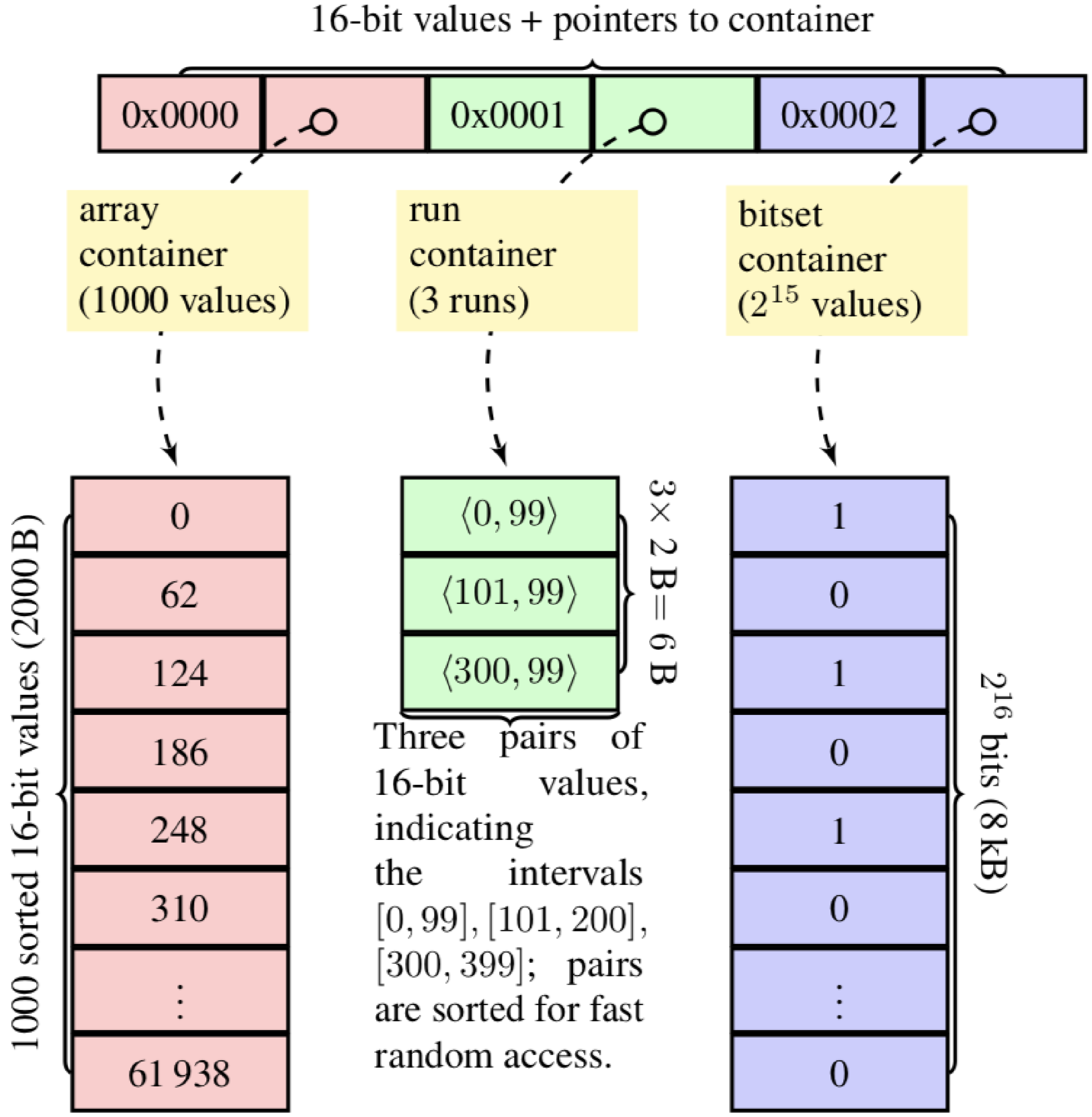


Figure 1. Roaring bitmap containing the first 1000 multiples of 62, all integers in the intervals $[2^{16}, 2^{16} + 100)$, $[2^{16} + 101, 2^{16} + 201)$, $[2^{16} + 300, 2^{16} + 400)$ and all even integers in $[2 \times 2^{16}, 3 \times 2^{16})$.

Roaring

- All containers are small (8 kB), fit in CPU cache
- We predict the output container type during computations
- E.g., when array gets too large, we switch to a bitset
- Union of two large arrays is materialized as a bitset...
- Dozens of heuristics... sorting networks and so on

> Use Roaring for bitmap compression whenever possible. Do not use other bitmap compression methods (Wang et al., SIGMOD 2017)

Unions of 200 bitmaps

bits per stored value

	bitset	array	hash table	Roaring
census1881	524	32	195	15.1
weather	15.3	32	195	5.38

cycles per input value:

	bitset	array	hash table	Roaring
census1881	9.85	542	1010	2.6
weather	0.35	94	237	0.16

Sometimes you do want arrays!!!

- But you'd like to compress them up.
- *Not always*: compression can be counterproductive.
- Still, if you must compress, you want to do it *fast*

Integer compression

- "Standard" technique: VByte, VarInt, VInt
- Use 1, 2, 3, 4, ... byte per integer
- Use one bit per byte to indicate the length of the integers in bytes
- Lucene, Protocol Buffers, etc.

varint-GB from Google

- VByte: one branch per integer
- varint-GB: one branch per 4 integers
- each 4-integer block is preceded byte a *control byte*

Vectorisation

- Stepanov (STL in C++) working for Amazon proposed varint-G8IU
- Use vectorization (SIMD)
- *Patented*
- Fastest byte-oriented compression technique (until recently)

SIMD-Based Decoding of Posting Lists, CIKM 2011

https://stepanovpapers.com/SIMD_Decoding_TR.pdf

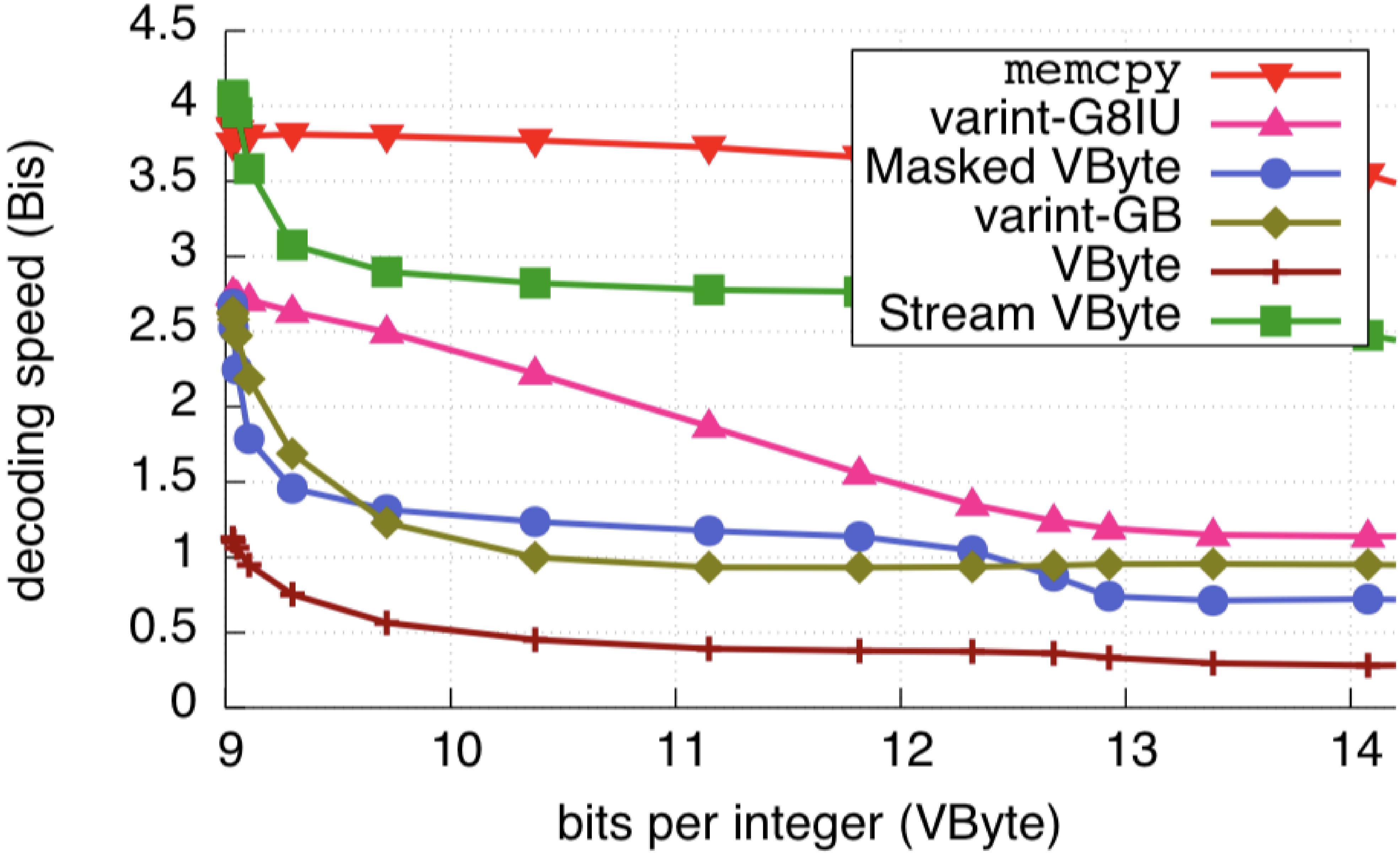
Observations from Stepanov et al.

- We can vectorize Google's varint-GB, but it is not as fast as varint-G8IU

Stream VByte

- Reuse varint-GB from Google
- But instead of mixing control bytes and data bytes, ...
- We store control bytes separately and consecutively...

> Daniel Lemire, Nathan Kurz, Christoph Rupp
> Stream VByte: Faster Byte-Oriented Integer Compression
> Information Processing Letters 130, 2018


4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
decoding speed (Bis)
9
10
11
12
13
14
bits per integer (VByte)
memcpy
varint-G8IU
Masked VByte
varint-GB
VByte
Stream VByte

Stream VByte is used by...

- Redis (within RediSearch) https://redislabs.com
- upscaledb https://upscaledb.com
- Trinity https://github.com/phaistos-networks/Trinity

Dictionary coding

Use, e.g., by Apache Arrow

Given a list of values:

- "Montreal", "Toronto", "Boston", "Montreal", "Boston"...

Map to integers

- 0, 1, 2, 0, 2

Compress integers:

- Given 2^n distinct values...
- Can use n-bit per values (binary packing, patched coding, frame-of-reference)

Dictionary coding + SIMD

dict. size	bits per value	scalar	AVX2 (256-bit)	AVX-512 (512-bit)
32	5	8	3	1.5
1024	10	8	3.5	2
65536	16	12	5.5	4.5

(cycles per value decoded)

https://github.com/lemire/dictionary

To learn more...

- Blog (twice a week) : https://lemire.me/blog/
- GitHub: https://github.com/lemire
- Home page : https://lemire.me/en/
- CRSNG : *Faster Compressed Indexes On Next-Generation Hardware* (2017-2022)
- Twitter @lemire

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