ENGINEERING FAST INDEXES (DEEP DIVE)

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Joint work with lots of super smart people

SPARK SUMMIT EAST 2017

Roaring : Hybrid Model

A collection of containers...

- array: sorted arrays ({1,20,144}) of packed 16-bit integers
- bitset: bitsets spanning 65536 bits or 1024 64-bit words
- run: sequences of runs ([0,10],[15,20])

Keeping track

E.g., a bitset with few 1s need to be converted back to array.

→ we need to keep track of the cardinality!

In Roaring, we do it 🌠 🌠 🌠 automagically 🌠 🌠 🌠

Setting/Flipping/Clearing bits while keeping track

Important : avoid mispredicted branches

Pure C/Java:

```
q = p / 64
ow = w[ q ];
nw = ow | (1 << (p % 64) );
cardinality += (ow ^ nw) >> (p % 64) ; // EXTRA
w[ q ] = nw;
```

In x64 assembly with BMI instructions:

```
shrx %[6], %[p], %[q]  //  q = p / 64
mov (%[w],%[q],8), %[ow]  // ow = w [q]
bts %[p], %[ow] //  ow |= ( 1<< (p % 64)) + flag
sbb $-1, %[cardinality] // update card based on flag
mov %[load], (%[w],%[q],8) // w[q] = ow
```

`sbb` is the extra work

For each operation

- union
- intersection
- difference
- ...

Must specialize by container type:

	array	bitset	run
array	?	?	?
bitset	?	?	?
run	?	?	?

High-level API or Sipping Straw?

Bitset vs. Bitset...

- Intersection:
  - First compute the cardinality of the result.
  - If low, use an array for the result (slow), otherwise generate a bitset (fast).
- Union: Always generate a bitset (fast).
  - (Unless cardinality is high then maybe create a run!)

We generally keep track of the cardinality of the result.

Cardinality of the result

How fast does this code run?

```
int c = 0;
for (int k = 0; k < 1024; ++k) {
  c += Long.bitCount(A[k] & B[k]);
}
```

We have 1024 calls to `Long.bitCount`.

This counts the number of 1s in a 64-bit word.

Population count in Java

```java
// Hacker`s Delight
int bitCount(long i) {
        // HD, Figure 5-14
        i = i - ((i >>> 1) & 0x5555555555555555L);
        i = (i & 0x3333333333333333L)
           + ((i >>> 2) & 0x3333333333333333L);
        i = (i + (i >>> 4)) & 0x0f0f0f0f0f0f0f0fL;
        i = i + (i >>> 8);
        i = i + (i >>> 16);
        i = i + (i >>> 32);
        return (int)i & 0x7f;
}
```

Sounds expensive?

Population count in C

How do you think that the C compiler `clang` compiles this code?

```
#include <stdint.h>
int count(uint64_t x) {
  int v = 0;
  while(x != 0) {
    x &= x - 1;
    v++;
  }
  return v;
}
```

Compile with `-O1 -march=native` on a recent x64 machine:

```
popcnt  rax, rdi
```

Why care for `popcnt`?

`popcnt` : throughput of 1 instruction per cycle (recent Intel CPUs)

Really fast.

Population count in Java?

```
// Hacker`s Delight
int bitCount(long i) {
        // HD, Figure 5-14
        i = i - ((i >>> 1) & 0x5555555555555555L);
        i = (i & 0x3333333333333333L)
           + ((i >>> 2) & 0x3333333333333333L);
        i = (i + (i >>> 4)) & 0x0f0f0f0f0f0f0f0fL;
        i = i + (i >>> 8);
        i = i + (i >>> 16);
        i = i + (i >>> 32);
        return (int)i & 0x7f;
}
```

Population count in Java!

Also compiles to `popcnt` if hardware supports it

```
$ java  -XX:+PrintFlagsFinal
  | grep UsePopCountInstruction

bool UsePopCountInstruction   = true
```

But only if you call it from `Long.bitCount`

Java intrinsics

- `Long.bitCount`, `Integer.bitCount`
- `Integer.reverseBytes`, `Long.reverseBytes`
- `Integer.numberOfLeadingZeros`, `Long.numberOfLeadingZeros`
- `Integer.numberOfTrailingZeros`, `Long.numberOfTrailingZeros`
- `System.arraycopy`
- …

Cardinality of the intersection

How fast does this code run?

```
int c = 0;
for (int k = 0; k < 1024; ++k) {
  c += Long.bitCount(A[k] & B[k]);
}
```

A bit over ≈ 2 cycles per pair of 64-bit words.

- load A, load B
- bitwise AND
- `popcnt`

Take away

Bitset vs. Bitset operations are fast

even if you need to track the cardinality.

even in Java

e.g., `popcnt` overhead might be negligible compared to other costs like cache misses.

Array vs. Array intersection

Always output an array. Use galloping $O(m \log n)$ if the sizes differs a lot.

```
int intersect(A, B) {
    if (A.length * 25 < B.length) {
      return galloping(A,B);
    } else if (B.length * 25 < A.length) {
      return galloping(B,A);
    } else {
      return boring_intersection(A,B);
    }
  }
```

Galloping intersection

You have two arrays a small and a large one...

```
while (true) {
  if (largeSet[k1] < smallSet[k2]) {
    find k1 by binary search such that
    largeSet[k1] >= smallSet[k2]
  }
  if (smallSet[k2] < largeSet[k1]) {
    ++k2;
  } else {
    // got a match! (smallSet[k2] == largeSet[k1])
  }
}
```

If the small set is tiny, runs in $O(\log(\text{size of big set}))$

Array vs. Array union

Union: If sum of cardinalities is large, go for a bitset. Revert to an array if we got it wrong.

```
union (A,B) {
    total = A.length + B.length;
    if (total > DEFAULT_MAX_SIZE) {//  bitmap?
      create empty bitmap C and add both A and B to it
      if (C.cardinality <= DEFAULT_MAX_SIZE) {
        convert C to array
      } else if (C is full) {
        convert C to run
      } else {
         C is fine as a bitmap
      }
    }
    otherwise merge two arrays and output array
}
```

Array vs. Bitmap (Intersection)...

Intersection: Always an array.

Branchy (3 to 16 cycles per array value):

```
answer = new array
for value in array {
  if value in bitset {
    append value to answer
  }
}
```

Branchless (3 cycles per array value):

```
answer = new array
pos = 0
for value in array {
  answer[pos] = value
  pos += bit_value(bitset, value)
}
```

Array vs. Bitmap (Union)...

Always a bitset. Very fast. Few cycles per value in array.

```
answer = clone the bitset
for value in array { // branchless
  set bit in answer at index value
}
```

Without tracking the cardinality ≈ 1.65 cycles per value

Tracking the cardinality ≈ 2.2 cycles per value

Parallelization is not just multicore + distributed

In practice, all commodity processors support Single instruction, multiple data (SIMD) instructions.

- Raspberry Pi
- Your phone
- Your PC

Working with words $x \times$ larger has the potential of multiplying the performance by x.

- No lock needed.
- Purely deterministic/testable.

SIMD is not too hard conceptually

Instead of working with $x + y$ you do

$(x_1, x_2, x_3, x_4) + (y_1, y_2, y_3, y_4)$.

Alas: it is messy in actual code.

With SIMD small words help!

With scalar code, working on 16-bit integers is *not* $2\times$ faster than 32-bit integers.

But with SIMD instructions, going from 64-bit integers to 16-bit integers can mean $4\times$ gain.

Roaring uses arrays of 16-bit integers.

Bitsets are vectorizable

Logical ORs, ANDs, ANDNOTs, XORs can be computed *fast* with Single instruction, multiple data (SIMD) instructions.

- Intel Cannonlake (late 2017), AVX-512
  - Operate on 64 bytes with ONE instruction
  - $\rightarrow$ Several 512-bit ops/cycle 💘
  - Java 9's Hotspot can use AVX 512
- ARM v8-A to get Scalable Vector Extension...
  - up to 2048 bits!!!

Java supports advanced SIMD instructions

```
$ java  -XX:+PrintFlagsFinal  -version |grep "AVX"
     intx UseAVX                = 2
```

Vectorization matters!

```
for(size_t i = 0; i < len; i++) {
  a[i] |= b[i];
}
```

- using scalar : 1.5 cycles per byte
- with AVX2 : 0.43 cycles per byte ($3.5\times$ better)

With AVX-512, the performance gap exceeds $5\times$

- Can also vectorize OR, AND, ANDNOT, XOR + population count (AVX2-Harley-Seal)

Vectorization beats `popcnt`

```
int count = 0;
for(size_t i = 0; i < len; i++) {
  count += popcount(a[i]);
}
```

- using fast scalar (popcnt): 1 cycle per input byte
- using AVX2 Harley-Seal: 0.5 cycles per input byte
- even greater gain with AVX-512

Sorted arrays

- sorted arrays are vectorizable:
  - array union
  - array difference
  - array symmetric difference
  - array intersection
- sorted arrays can be compressed with SIMD

Bitsets are vectorizable... sadly...

Java's hotspot is limited in what it can autovectorize:

1. Copying arrays
2. String.indexOf
3. ...

And it seems that `Unsafe` effectively disables autovectorization!

There is hope yet for Java

> One big reason, today, for binding closely to hardware is to process wider data flows in SIMD modes. (And IMO this is a long-term trend towards right-sizing data channel widths, as hardware grows wider in various ways.) AVX bindings are where we are experimenting, today
> (John Rose, Oracle)

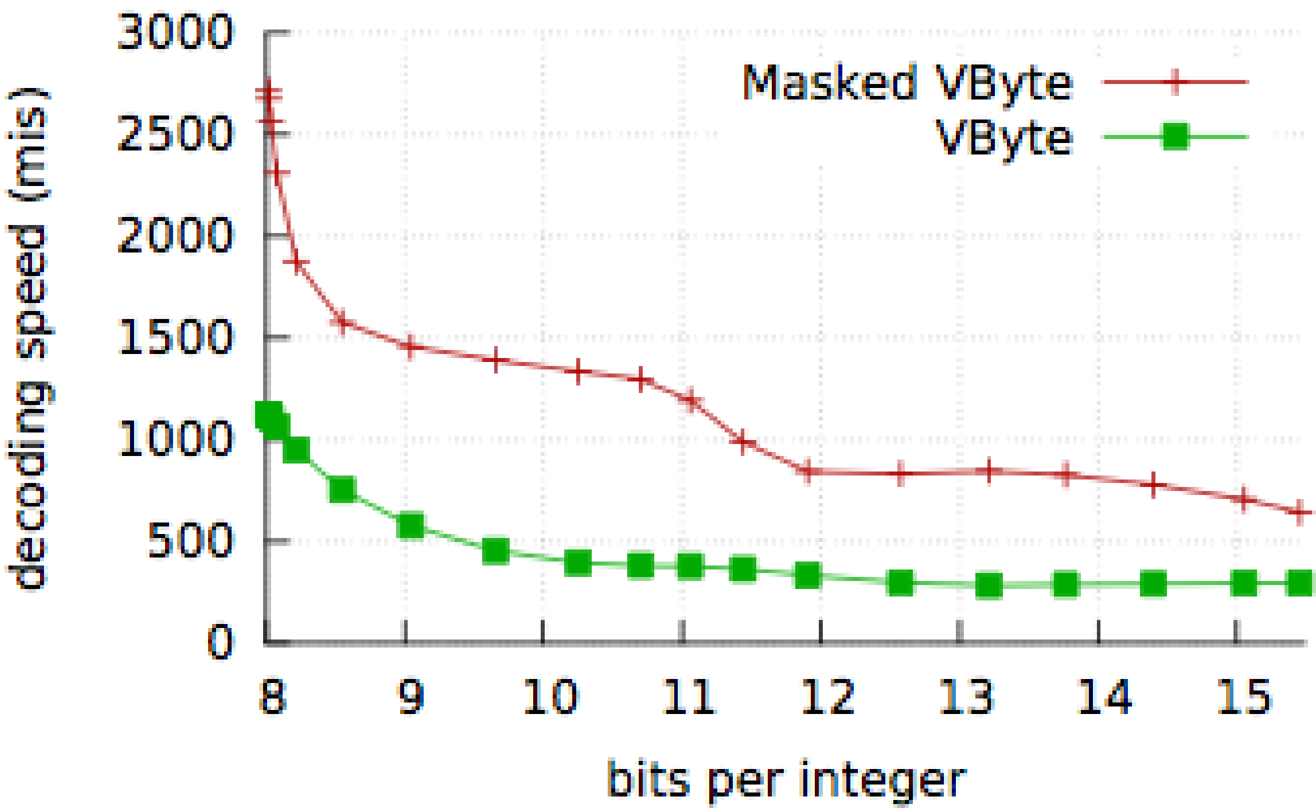
Fun things you can do with SIMD: Masked VByte

Consider the ubiquitous VByte format:

- Use 1 byte to store all integers in $[0, 2^7)$
- Use 2 bytes to store all integers in $[2^7, 2^{14})$
- ...

Decoding can become a bottleneck. Google developed Varint-GB. What if you are stuck with the conventional format? (E.g., Lucene, LEB128, Protocol Buffers...)

Masked VByte



Joint work with J. Plaisance (Indeed.com) and N. Kurz.

http://maskedvbyte.org/

Go try it out!

- Fully vectorized Roaring implementation (C/C++): https://github.com/RoaringBitmap/CRoaring
- Wrappers in Python, Go, Rust...