ECE459: Programming for Performance Winter 2019

Lecture 19 — Single-Thread Performance

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Single-Thread Performance

"Can you run faster just by trying harder?"

The performance improvements we've seen to date have been leveraging parallelism to improve throughput. Decreasing latency is trickier—it often requires domain-specific tweaks. We'll look at one example of decreasing latency today, Stream VByte [LKR18]. Even this example leverages parallelism—it uses vector instructions. But there are some sequential improvements, e.g. Stream VByte takes care to be predictable for the branch predictor.

Context. We can abstract the problem to that of storing a sequence of small integers. Such sequences are important, for instance, in the context of inverted indexes, which allow fast lookups by term, and support boolean queries which combine terms.

Here is a list of documents and some terms that they contain:

docid	terms
1	dog, cat, cow
2	cat
3	dog, goat
4	cow, cat, goat

The inverted index looks like this:

term	docs
dog	1, 3
cat	1, 2, 4
cow	1, 4
goat	3, 4

Inverted indexes contain many small integers in their lists: it is sufficient to store the delta between a doc id and its successor, and the deltas are typically small if the list of doc ids is sorted. (Going from deltas to original integers takes time logarithmic in the number of integers).

VByte is one of a number of schemes that use a variable number of bytes to store integers. This makes sense when most integers are small, and especially on today's 64-bit processors.

VByte works like this:

- x between 0 and $2^7 - 1$, e.g. $17 = 0b10001$: $0xxxxxxx$, e.g. 00010001;
- x between 2^7 and $2^{14} - 1$, e.g. $1729 = 0b11011000001$: $1xxxxxxx/0xxxxxxx$, e.g. $11000001/00001101$;
- x between 2^{14} and $2^{21} - 1$: $0xxxxxxx/1xxxxxxx/1xxxxxxx$;
- etc.

That is, the control bit, or high-order bit, is 0 if you have finished representing the integer, and 1 if more bits remain. (UTF-8 encodes the length, from 1 to 4, in high-order bits of the first byte.)

It might seem that dealing with variable-byte integers might be harder than dealing fixed-byte integers, and it is. But there are performance benefits: because we are using fewer bits, we can fit more information into our limited

RAM and cache, and even get higher throughput. Storing and reading 0s isn't an effective use of resources. However, a naive algorithm to decode VByte also gives lots of branch mispredictions.

Stream VByte is a variant of VByte which works using SIMD instructions. Science is incremental, and Stream VByte builds on earlier work—masked VByte as well as VARINT-GB and VARINT-G8IU. The innovation in Stream VByte is to store the control and data streams separately.

Stream VByte's control stream uses two bits per integer to represent the size of the integer:

00	1 byte	10	3 bytes
01	2 bytes	11	4 bytes

Each decode iteration reads a byte from the control stream and 16 bytes of data from memory. It uses a lookup table over the possible values of the control stream to decide how many bytes it needs out of the 16 bytes it has read, and then uses SIMD instructions to shuffle the bits each into their own integers. Note that, unlike VByte, Stream VByte uses all 8 bits of each data byte as data.

For instance, if the control stream contains $0b1000\ 1100$, then the data stream contains the following sequence of integer sizes: $3, 1, 4, 1$. Out of the 16 bytes read, this iteration will use 9 bytes; it advances the data pointer by 9. It then uses the SIMD "shuffle" instruction to put the decoded integers from the data stream at known positions in the 128-bit SIMD register; in this case, it pads the first 3-byte integer with 1 byte, then the next 1-byte integer with 3 bytes, etc. Let's say that the input is `0xf823 e127 2524 9748 1b.. .... .... .....` The 128-bit output is `0x00f8 23e1/0000 0027/2524 9748/0000/001b`, with the /s denoting separation between outputs. The shuffle mask is precomputed and, at execution time, read from an array.

The core of the implementation uses three SIMD instructions:

```
uint8_t C = lengthTable[control];
__m128i Data = _mm_loadu_si128 ((__m128i *) databytes);
__m128i Shuf = _mm_loadu_si128(shuffleTable[control]);
Data = _mm_shuffle_epi8(Data, Shuf);
databytes += C; control++;
```

Discussion. The paper [LKR18] includes a number of benchmark results showing how Stream VByte performs better than previous techniques on a realistic input. Let's discuss how it achieves this performance.

- control bytes are sequential: the processor can always prefetch the next control byte, because its location is predictable;
- data bytes are sequential and loaded at high throughput;
- shuffling exploits the instruction set so that it takes 1 cycle;
- control-flow is regular (executing only the tight loop which retrieves/decodes control and data; there are no conditional jumps).

We're exploiting SIMD, so this isn't quite strictly single-threaded performance. Considering branch prediction and caching issues, though, certainly improves single-threaded performance.

References

[LKR18] Daniel Lemire, Nathan Kurz, and Christoph Rupp. Stream vbyte: Faster byte-oriented integer compression. *Information Processing Letters*, 130(Supplement C):1 – 6, 2018. URL: `http://www.sciencedirect.com/science/article/pii/S0020019017301679`.