Decoding billions of integers per second through vectorization

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Problem Statement: Optimize Space and Speed

- We would like to encode and decode large arrays of integers efficiently in terms of space and time, i.e., achieve good compression and high rate of processing.

- Focus on 32-bit integer sequences, often sorted.

- Main memory, rather than disk, often limits computation speed in modern algorithms.

- Applications in search engines and relational databases.
Aside to illustrate compression ideas

(Space optimization is a solved problem)

Suppose we have a 4-sided die. The probabilities of the sides are listed below. We would like to roll this die many times and communicate results to a friend using a sequence of bits. How to efficiently do this?

| Side | Probability |
|------|-------------|
| 0    | 1/4         |
| 1    | 1/4         |
| 2    | 1/4         |
| 3    | 1/4         |
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| Side | Probability | Bit representation |
|------|-------------|--------------------|
| 0    | 1/4         | 00                 |
| 1    | 1/4         | 01                 |
| 2    | 1/4         | 10                 |
| 3    | 1/4         | 11                 |
Aside to illustrate compression ideas
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| Side | Probability |
|------|-------------|
| 0    | 1/2         |
| 1    | 1/4         |
| 2    | 1/8         |
| 3    | 1/8         |
Aside to illustrate compression ideas (Space optimization is a solved problem)

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| Side | Probability | Bit representation |
|------|-------------|--------------------|
| 0    | 1/2         | 0                  |
| 1    | 1/4         | 10                 |
| 2    | 1/8         | 110                |
| 3    | 1/8         | 111                |
Aside to illustrate compression ideas

(Space optimization is a solved problem)

- Given a probability distribution $p_x(\cdot)$ over a set $\{x_1, \ldots, x_n\}$, the average number of bits required to encode i.i.d. symbols from this distribution is at least

  $$H[X] = \sum_x -p_x(x) \log_2(p_x(x))$$

- Furthermore, there are coding algorithms that can (with some nuance) achieve this bound
Binary and Unary

Binary:

1 -> 1
2 -> 10
3 -> 11

Unary:

1 -> 1
2 -> 01
3 -> 001
Elias gamma and delta coding

- Elias gamma: encode number of bits in unary, followed by binary representation of the number (without the MSB)

- Elias delta: encode number of bits using Elias gamma, followed by binary representation of the number (without the MSB)
Variable byte encoding

- Break integer into 7 bit chunks. Each 7 bit chunk is stored in a byte, with 0 as the 8th bit denoting “continue” and 1 denoting “end”

- E.g., 11001000 gets encoded as 10000001 01001000
Varint-GB and Varint-G8IU

Varint-GB

- Use one byte broken into four chunks of 2 bits each. Each 2 bit chunk encodes number of bytes used to describe an integer \{1, 2, 3, 4\}
- The integer encodings follow the descriptor byte

Varint-G8IU

- Use one byte descriptor that describes layout of 8 data bytes. A “0” indicates the end of an integer
- The integer encodings follow the descriptor byte
- Can be efficiently decoded using SIMD “pshufb” instruction
Idea 1: Differential Coding (Space)

- For sorted arrays, first pre-process elements into deltas

- \( \delta_j = x_j - x_{j-1} \)

- Recover original elements using prefix sum

- Compute differences in-place working from end of the array backwards toward the start
Idea 2: Utilize SIMD Operations (Speed)

- Many modern CPUs provide SIMD operations

- SIMD operations have been used to speedup varint-G8IU by 50% (decoding) and 300% (encoding) previously

- Use SIMD operations for encoding/decoding process AND prefix-sum
Idea 2: Utilize SIMD Operations (Speed)

- In particular, partition array into consecutive blocks of 4 elements each, take element-wise differences between blocks.

- This increases speed from 2 billion integers per second to 5 billion integers per second.

- Causes differences to be, on average, four times larger (costs 2 bits of storage)
Idea 3: Break large arrays into small arrays during processing (Speed)

- For arrays with more than 256 KB worth of data, break them into 256 KB chunks and process them independently.

- Improves cache efficiency by reducing the number of cache misses
Idea 4: Bit packing (Space)

```c
struct Fields4_8 {
    unsigned Int1: 4;
    unsigned Int2: 4;
    unsigned Int3: 4;
    unsigned Int4: 4;
    unsigned Int5: 4;
    unsigned Int6: 4;
    unsigned Int7: 4;
    unsigned Int8: 4;
};

struct Fields5_8 {
    unsigned Int1: 5;
    unsigned Int2: 5;
    unsigned Int3: 5;
    unsigned Int4: 5;
    unsigned Int5: 5;
    unsigned Int6: 5;
    unsigned Int7: 5;
    unsigned Int8: 5;
};
```

(a) 4-bit integers

(b) 5-bit integers
Terminology

- Page: Group of thousands/millions of integers
- Block: Group of 128 integers

In particular, an array of integers comprises many pages, and each page comprises many blocks.
Idea 6: Store Exceptions at the page level (Space)
Idea 7: Choose different bit widths for each block (Space)

- An exception is an unusually large integer within a block

- The bit width of a block is chosen to match the “typical” integer bit width within the block. Any integers that exceed this bit width are stored as an exception.
Example

- Can choose \( b = 6 \) bits, but would like \( b \) to be smaller
- Heuristic of cost for each exception: \( 8 + (6 - b) = 14 - b \)
- Choose \( b \) to minimize \( 128* b + (14 - b) * c \) (in this example, replace 128 with 16)
- Here, choose \( b = 2 \) to minimize cost

10, 10, 1, 10, 100110, 10, 1, 11, 10, 100000, 10, 110100, 10, 11, 11, 1

10, 10, 1, 10, 10, 10, 1, 11, 10, 00, 10, 00, 10, 11, 11, 1.
Example

- Compressed page starts with 32 bit integer describing the total size of the truncated sequence
- Skip the truncated sequence to reach the byte array
- Byte array contains b, maximal bit width, number of exceptions, locations of exceptions, all using one byte each.
- Exceptions follow the byte array and are further compressed
  - SimplePFOR compresses using Simple-8b
  - FastPFOR has 32 arrays, one for each possible exception bit-width
- Exceptions are the first component decoded and are decoded in bulk

| Data to be compressed: | … 10, 10, 10, 10, 100110, 10, 1, 11, 10, 100000, 10, 110100, 10, 11, 11, 1… |
|------------------------|---------------------------------------------------------------------------------|
| Truncated data:        | … 10, 10, 01, 10, 10, 10, 01, 11, 10, 00, 10, 00, 10, 11, 11, 01 …               |
| (16 × 2 = 32 bits)     |                                                                                  |
| Byte array:            | … 2, 6, 3, 4, 9, 11 …                                                            |
| (6 × 8 = 48 bits)      |                                                                                  |
| Exception data:        | … 1001, 1000, 1101 …                                                             |
| (to be compressed)     |                                                                                  |
Experiments

- “Linux server equipped with Intel Core i7 2600 (3.40 GHz, 8192 KB of L3 CPU cache) and 16 GB of RAM. The DDR3-1333 RAM with dual channel has a transfer rate of 20,000 MB/s or 5300 mis.”
Experiments

- Test on ClusterData and Uniform model synthetic datasets
- Test on real datasets: ClueWeb09 (Category B) data set and GOV2 data set
- Test against other state-of-the-art algorithms like PFOR and varint-G8IU
- End up with the fastest coding and decoding speeds, with competitive compression ratios
- SIMD-BP128 works very well across test cases
Experiments
Evaluation of paper and comparison to previous work

- Strong speed increase over previous methods
- Utilizes binary packing and vectorizes it (not done previously, at least not nearly as effectively)
- Strength: Comprehensive analysis, many other compression schemes are introduced and the authors did extensive testing to compare their ideas to previous work
- Strength: Good examples.
- Weakness: Many acronyms to keep track of, and many variants of the compression schemes. This makes it harder (at least for me) to develop general “take away” ideas from the paper.
- Future work: data-based adaptive compression schemes, and probabilistic analysis of the algorithms proposed here