AES on Sharemind

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Motivation

- Common benchmarking test
- Can be used as a cryptographic primitive
  - E.g. Database JOIN operation

Advanced Encryption Standard

- Symmetric block cipher
  - Using 128-bit blocks
  - 128, 192 or 256-bit keys
    - We use 128-bit keys in our implementation

AES-128 on Sharemind

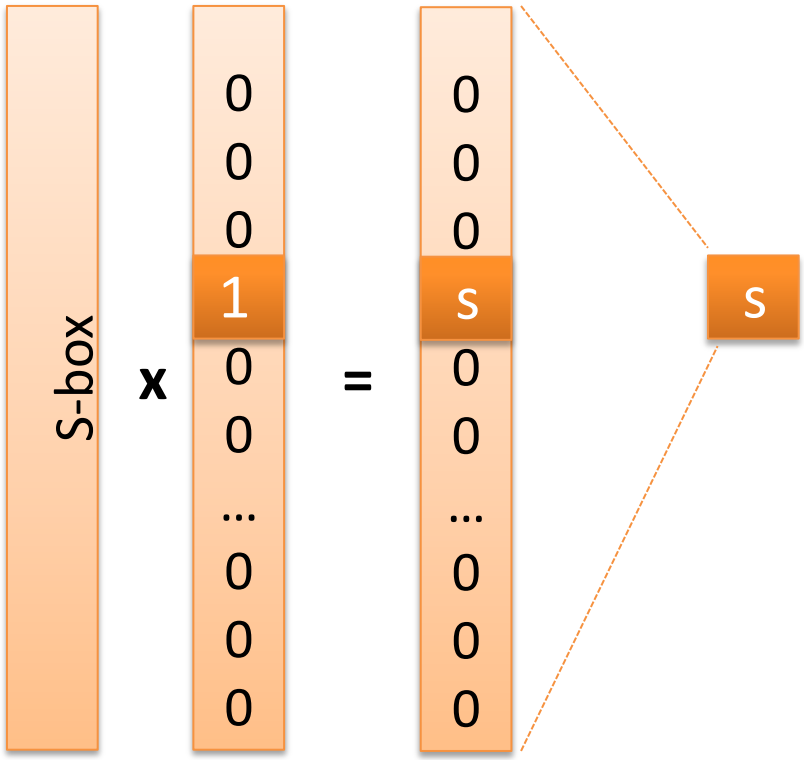
- Straightforward, following the NIST specification
- Plaintext and key are bitwise secret shared

  $s = s_1 \oplus s_2 \oplus s_3$, where $\oplus$ is XOR
- Four 8-bit bytes are packed into a single 32-bit integer (word)
- Most computations are local
  - Additions, bitshifts, multiplications by constant in $GF(2^8)$

AES-128 on Sharemind (2)

- **S-box**: non-linear byte-for-byte substitution table
  - Has algebraic definition
    - Usually pre-computed and given as a 16x16 byte table
    - We use it as a 256-byte vector
  - Byte `b` is replaced with `S-box[b]`
  - Requires communication

Computing S-box: characteristic vector



Computing S-box: characteristic vector (2)

- Substitute byte b = $b_7b_6b_5b_4b_3b_2b_1b_0$
- S-box[0] $(1-b_7)(1-b_6)(1-b_5)(1-b_4)(1-b_3)(1-b_2)(1-b_1)(1-b_0)$

  [1] $(1-b_7)(1-b_6)(1-b_5)(1-b_4)(1-b_3)(1-b_2)(1-b_1)b_0$

  [2] $(1-b_7)(1-b_6)(1-b_5)(1-b_4)(1-b_3)(1-b_2)b_1(1-b_0)$

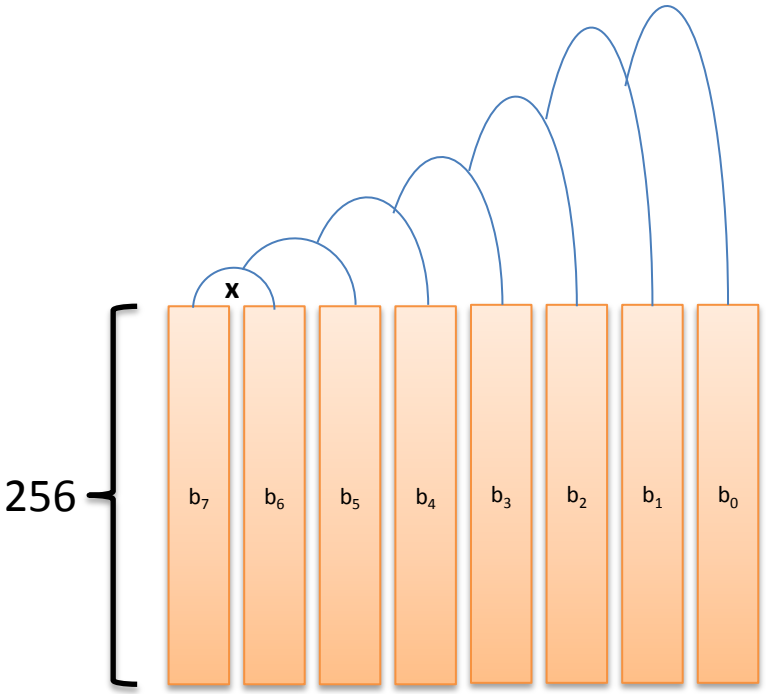
  ...

  [254] $b_7\ b_6\ b_5\ b_4\ b_3\ b_2\ b_1(1-b_0)$

  [255] $b_7\ b_6\ b_5\ b_4\ b_3\ b_2\ b_1\ b_0$

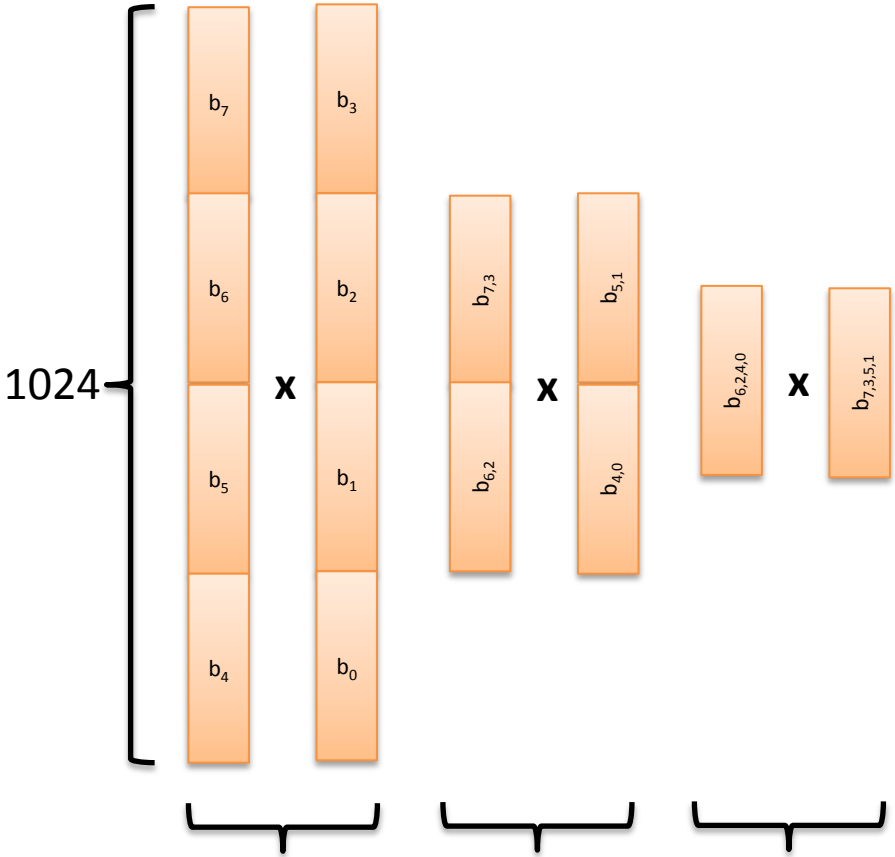
Characteristic vector: multiplication

Option 1:



Total: 7 rounds of multiplications

Option 2:



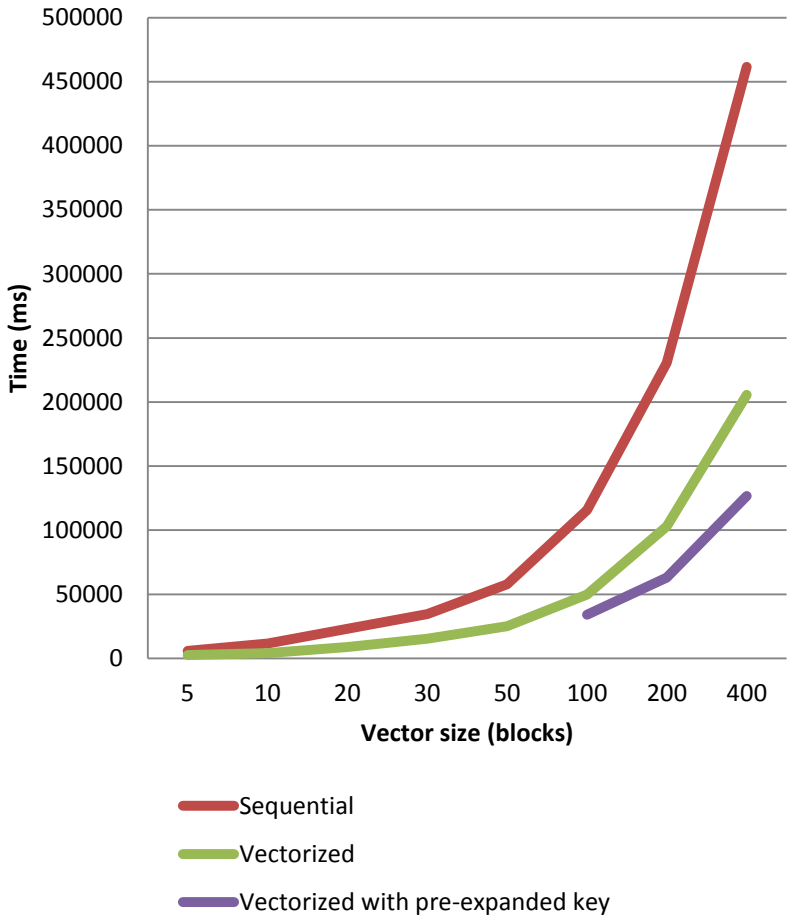
Vectorization

- Several plaintexts (128-bit blocks)
  - Each block encrypted separately
- Sharemind is highly optimized for vector operations
- Idea: Process several plaintext blocks in parallel
  - Vector lengths increase by the factor of #(blocks), but #(communication rounds) stays the same

Pre-expanded key

- S-box is used in key expansion phase:
  - Cipher key is used to generate ten 128-bit round keys
- Secret shared cipher key has to be known to miners before AES can be executed
- Idea: We can move key expansion to pre-processing phase and provide miners with the secret shared pre-expanded key instead

Benchmarking



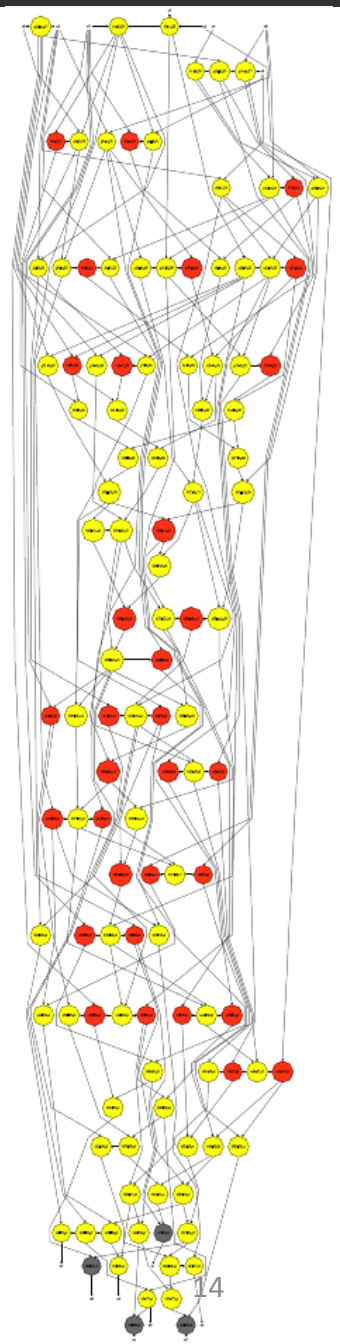
- 1 Gbit LAN
- Results:
  - 13.9 B/s
  - 33.2 B/s
  - 49.5 B/s
- Hoped for larger speedup :(

What happened?

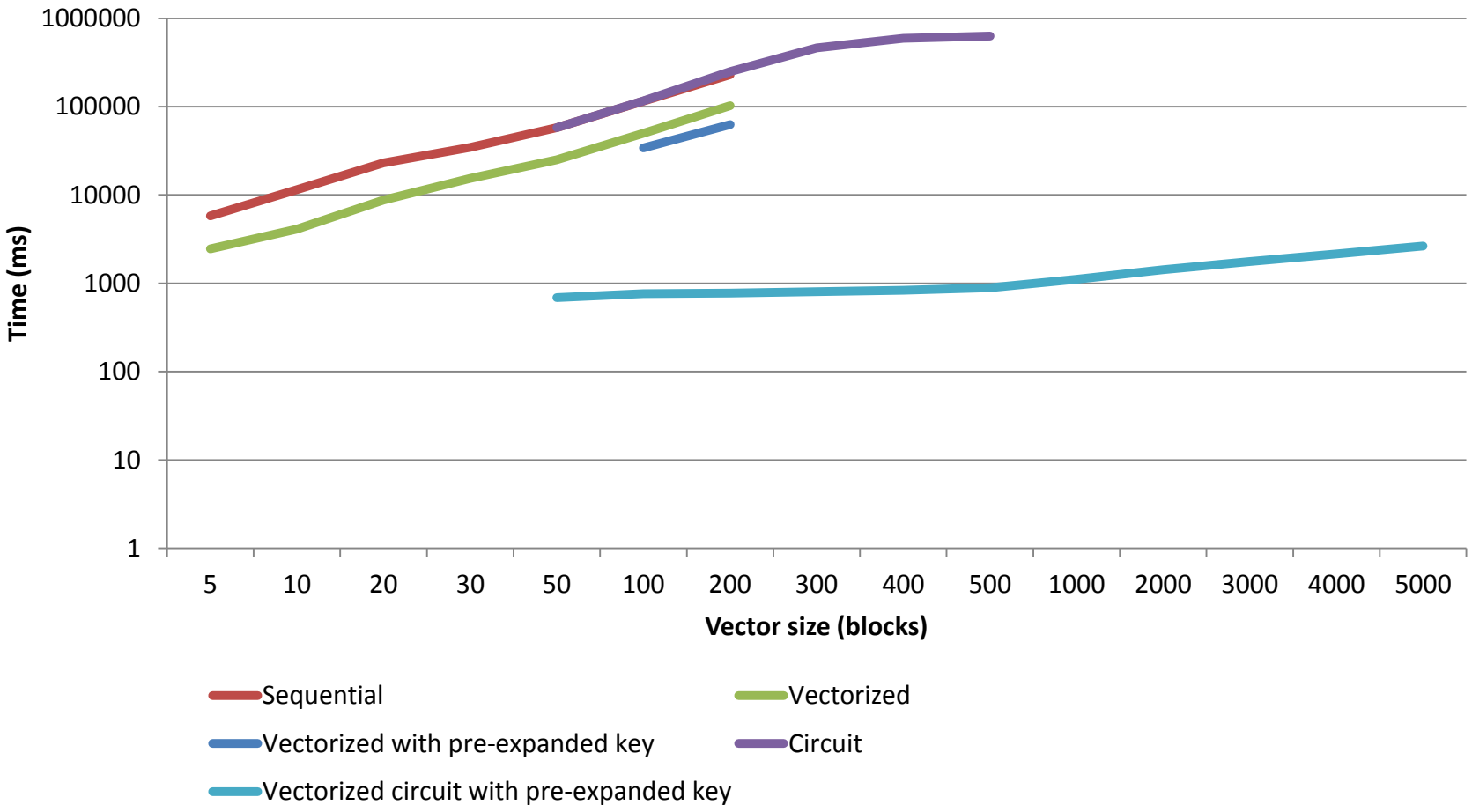
- Vectors are too large for the network layer
  - E.g. SubBytes() multiplies vectors of size up to #(blocks)×4096 words
  - Saturation point for multiplication protocol depends on bandwidth
    - In our scenario, it is ca. 10 000
  - Hence, encrypting more than 2 blocks at once, clogs the network layer!
- Optimizing only communication rounds is wrong
  - Large amount of data kills parallelization

S-box with circuits

- Boyar and Peralta [2010, 2011] have come up with several circuits for AES S-box
  - Using only AND, XOR, XNOR
  - Minimal depth
- In multi-party computing, XOR is free (local), AND (multiplication) costs
  - We want minimal number of AND gates



Benchmarking, again



Benchmarking, again (2)

- Vectorized circuit with pre-expanded key
  - Maximum vector length: #(blocks)×18 words
  - Reach saturation point with ca. 550 blocks
  - Average throughput: 12.6 kB/s

Compare to others

Team	Model	sec/ block
Damgård, Keller [2009]	3-party, w/o pre-expanded key, 10 blocks in parallel	2
Huang et al. [2011]	2-party, pre-expanded key	0.06
Launchbury et al. [2011]	3-party, 1 block, no pipelining	0.015
	3-party, 64 blocks in parallel, pipelined	0.007
Us [2011]	3-party, pre-expanded key, 10 blocks in parallel	0.07
	3-party, pre-expanded key, 100 blocks in parallel	0.007
	3-party, pre-expanded key, 1000 blocks in parallel	0.001
	3-party, pre-expanded key, 5000 blocks in parallel	0.0005

Conclusions

- AES on secret shared data can be done
- Optimizing only communication rounds is wrong
  - Large amount of data kills parallelization
- Circuits help to lower the amount of data
- In future, we use it to implement oblivious database JOIN operation