Practical Implementations of Compressed RAM

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Problem Definition

Given a string S over alphabet $\Sigma=\{1,\ldots,\sigma\}$ of size n, consider a data structure that supports the following operations:

1. **access(i):** Return S[i].

3	7	**5**	2	6	3	1

access(3): Return 5

2. **replace(u, c):** replace S[i] with c.

3	7	5	**2**	6	3	1

→

3	7	5	**7**	6	3	1

replace(3, 7)

- These two operations are basic operations on standard RAM.
- We assume that word-RAM model with word size $\Theta(\log n)$, which means access operation can return any $\Theta(\log_\sigma n)$ consecutive symbols in $O(1)$ time.

Problem Definition

We also consider the following two additional operations on S

3. **insert (i, c):** Insert c between S[i-1] and S[i].

3	7	**5**	2	6	3	1

→

3	7	**6**	**5**	2	6	3	1

insert(3, 6)

4. **delete(i):** Delete S[i].

3	7	5	**2**	6	3	1

→

3	7	5	6	3	1

delete(4)

- Data structure which supports access, replace, insert, and delete is called dynamic RAM.

Problem: Construct dynamic RAM using small space while supporting the operations efficiently.

Here, the small space means close to $H_k(S)$ (the k-th entropy of S).

Previous Results

- Theoretically, there are several works ([Jansson et al. 12], [Grossi et al. 13], [Munro and Nekrich 15]). All of them support the queries efficiently while using o(H_k(S))-bit additional space from H_k(S).

- Also there are some practical implementations

SPSI (Searchable Partial Sums with Insert) [Prezza 17]

: Uncompressed, delete is not implemented

(input can be compressed, delete is implemented when σ =2).

KN [Klitzke and Nicholson 16]

: Based on the work of [Jansson et al. 12] with LZ compression.

Our Results

New Practical implementation of compressed dynamic RAM while supporting access/replace/insert/delete operations

- Based on [Jansson et al. 12] (CRAM) and [Grossi et al. 13] (DCRAM).
- Compressed S based on Huffman code (KN uses LZ-based compression).
- As in theory, the space changes based on the current input's entropy (this is not supported in SPSI and KN).
- Optimized for sequential operations.
- Compared our implementation with SPSI and KN.

The source is available at https://github.com/wyptcs/CRAM

[Jansson et al. 12] (CRAM)

Codetable(before)	
code	block
0	AA
1	AD
00	AB
01	AC
10	BA
11	CB

Codetable(after)	
code	block
0	AA
1	AB
00	AC
01	BA
10	CB
11	AD

r = 2, ε = 0.5, superblock size: r/ε = 4

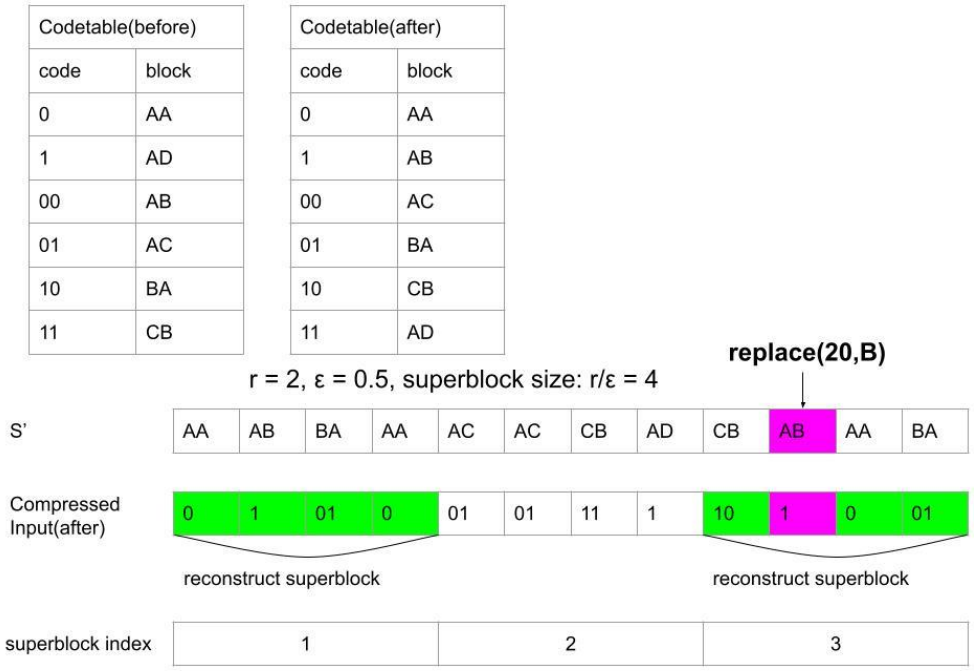
replace(20,B)

S	AA	AB	BA	AA	AC	AC	CB	AD	CB	AD	AA	BA
Compressed Input(before)	0	00	10	0	01	01	11	1	11	1	0	10
superblock index	1				2				3			

CRAM in theory (for access and replace)

- Divide S into blocks of size $r = 1/2 \log_\sigma n$
- Consider S as a string S′ of length n′= n/r over an alphabet 2^r, and construct a code table for S′ based on the frequency of the symbols in S′.
- Consecutive r/ε (0 < ε <1) blocks form a single superblock.
- Special DS (darray) for answering the end position of the i-th superblock while supporting updates, access can be answered in O(1) time using darray.

[Jansson et al. 12] (CRAM)



CRAM in theory (for access and replace)

- For replace, maintain two encode and decode tables (old and new).
- When i-th replace operation occurs, re-encode the superblock that contains the cor. Position, and update the frequency table.
- In addition, we update (i mod n') superblock using new encode table.
- After n' updates, reconstruct the tables based on the current frequencies of the symbols.
- In overall, supporting replace in O(1/ε) time.

[Grossi et al. 13] (DCRAM)

Codetable	
code	block
0000	AA
0001	AC
0010	unused
0011	unused
….	unused
1111	unused

Codetable	
code	block
00000	BA
00001	CB
00010	AD
00011	AB

r = 2

replace(20,B)

S	AA	AB	BA	AA	AC	AC	CB	AD	CB	AD	AA	BA
Compressed Input(before)	0000	00011	00000	0000	0001	0001	00001	00010	00001	00010	0000	00000

DCRAM in theory (for access and replace)

- S′ and darray structures on the blocks.
- Each symbol c in S′ is divided into class C_j based iff their frequency is between n′/2^j and n′/2^{j+1}, and we assign a code of length j+3 for the symbols in C_j (Hence, we have **some unused codes** for each class).
- access can be supported in O(1) time, similar as CRAM.

[Grossi et al. 13] (DCRAM)

Codetable	
code	block
0000	AA
0001	AC
0010	AB
0011	unused
....	unused
1111	unused

Codetable	
code	block
00000	BA
00001	CB
00010	AD
00011	AB

r = 2

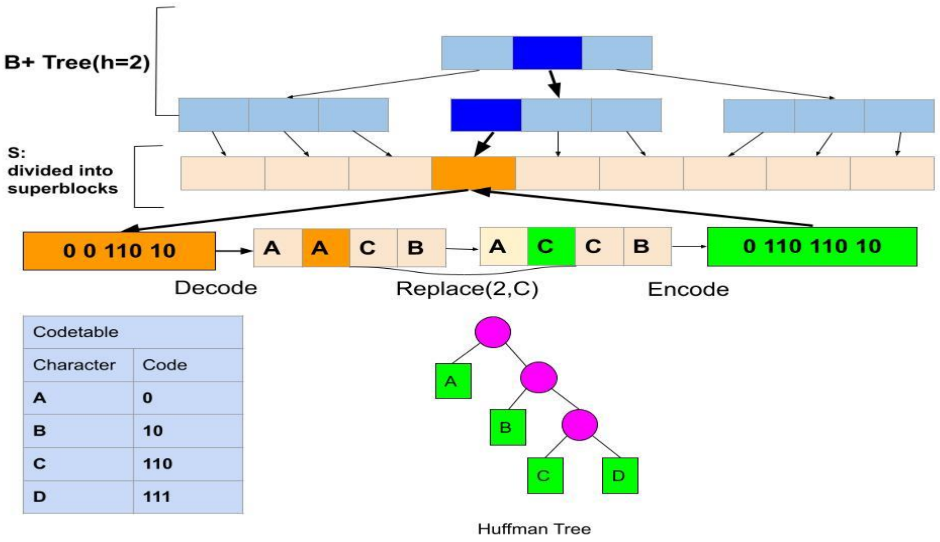
replace(20,B)

S'	AA	AB	BA	AA	AC	AC	CB	AD	CB	AB	AA	BA
Compressed Input(after)	0000	00011	00000	0000	0001	0001	00001	00010	00001	0010	0000	00000

DCRAM in theory (for access and replace)

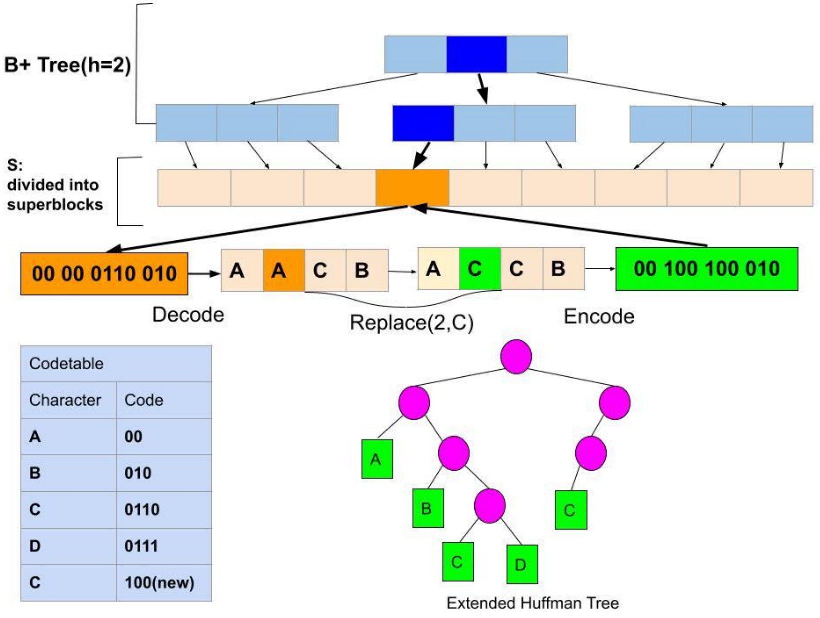
- After replace, if the class of c is changed (increased), we assign a new codeword according to the class of c.
- If there is no unused code for c, reconstruct the entire DS (this can be amortized in theory).
- In theory, $\Omega(n')$ replace operations can be performed before the reconstruction. Hence one can support replace in O(1) time.

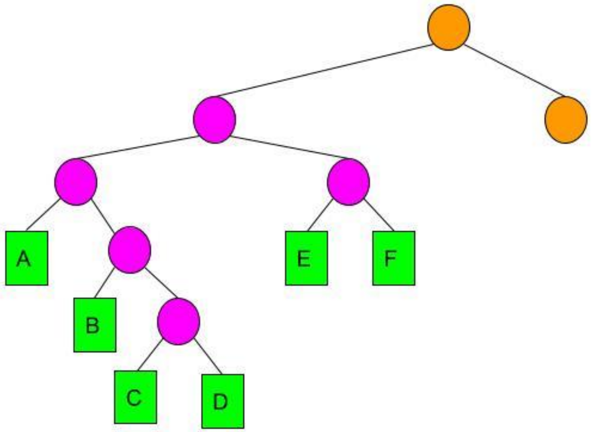
Practical Implementation of CRAM



- Each blocks of S is encoded using Huffman code. We do linear scan on the superblock.
- For managing superblocks, we use **B^+-tree with fixed height h** (i.e., root is not splitted. h is depending on the size of S) instead of darray.
- O(h log (r/ε) + r/ε) for time for both operations.
- For supporting sequential operations efficiently, we store the position of the superblock that recently used, and apply some SIMD operations.

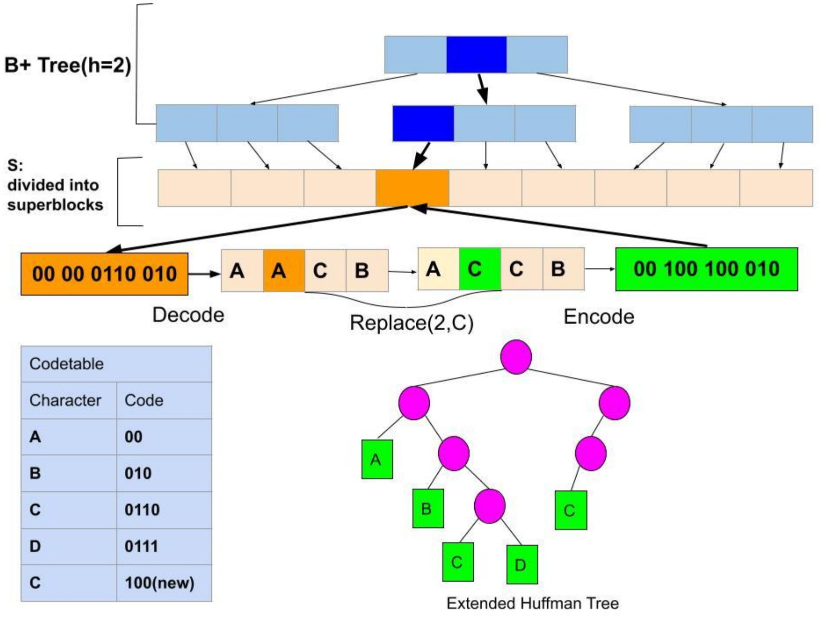
Practical Implementation of DCRAM

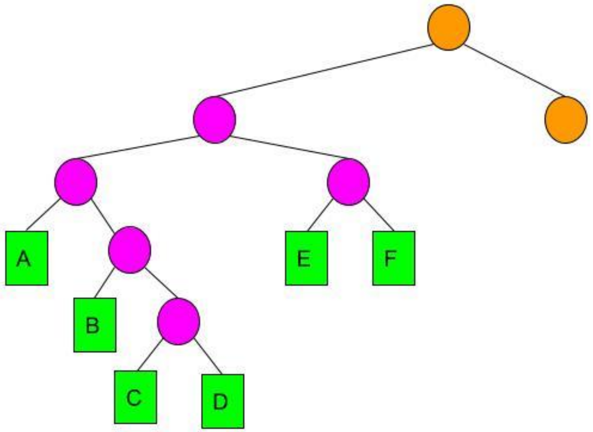




- We need some unused codes for DCAM.
- We make a space for unused codes using **Extended Huffman tree**. For implementation we consider (i) Type-1: codes starting with 1 is initially unused, and (ii) Type-2: codes starting with 11 is initially unused.
- For both Type-1 and -2 trees, at least Ω(n′) update operations are necessary before reconstructing the tree.

Practical Implementation of DCRAM





- In addition to Extended Huffman tree, we use **lazy update** on DCRAM, which combines the update algorithms of CRAM and DCRAM.
- In lazy update, we reconstruct the tree when (i) every superblock is re-encoded, and (ii) there is no unused code.

Experimental Results

Equipment specifications

AMD Ryzen 5 1600 Six-Core Processor (576KB L1, 3MB L2, and 16MB L3 cache) with 32GB RAM.

Datasets from Pizza&Chilli Corpus (http://pizzachili.dcc.uchile.cl/texts.html)

File Name	σ	H_0	H_1
DNA	16	0.247	0.245
ENGLISH	225	0.565	0.509
PROTEINS	25	0.525	0.524
XML	96	0.657	0.547

All files sizes are 200MB

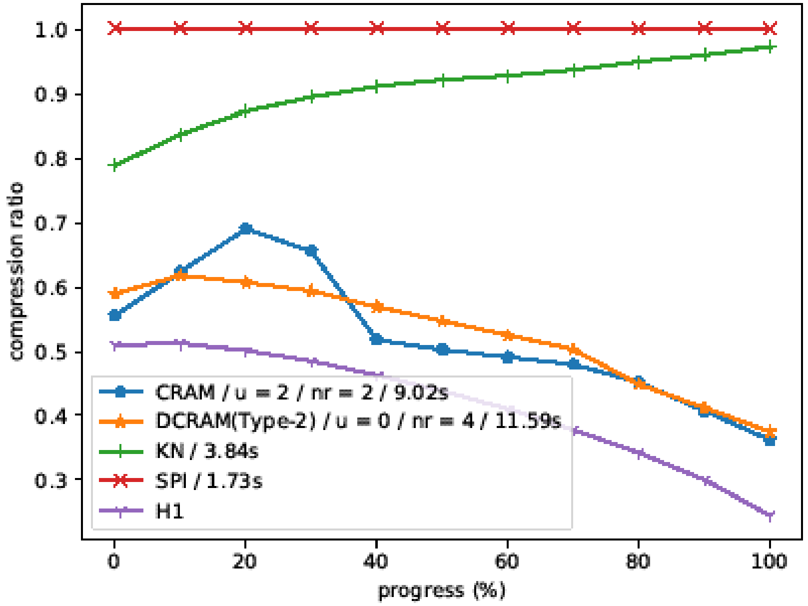
Experimental Results

Some parameters for experiments

- r (block size): 2
- $1/\varepsilon$ (#blocks in each superblock for CRAM): 512 initially
- h (height of fixed B^+-tree): 2, each node contains the information of ~200 consecutive superblocks.
- u (for CRAM and DCAM with lazy update): decides how many superblocks are additionally re-encoded for each updated.
- For CRAM, u = 1 means no reconstruction, and u (>1) reconstructions during n′ updates.

Experimental Results

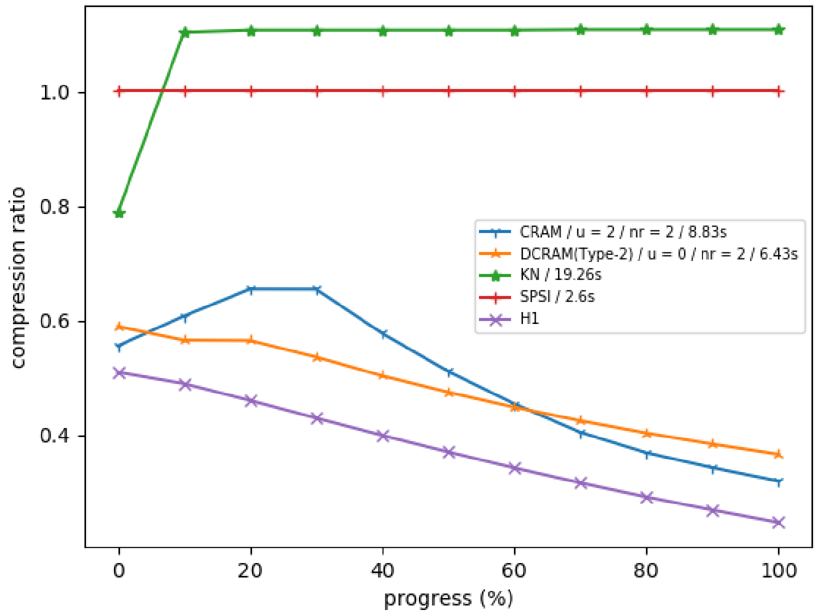
(i) Replace-seq: Overwrites from ENGLISH to DNA sequentially.



- SPSI is ~7 times faster than ours (does not compress the input).
- KN is 2~3 times faster than ours (highly optimized for sequential updates)
- Only our implementations reduce the space usage based on the input's entropy.

Experimental Results

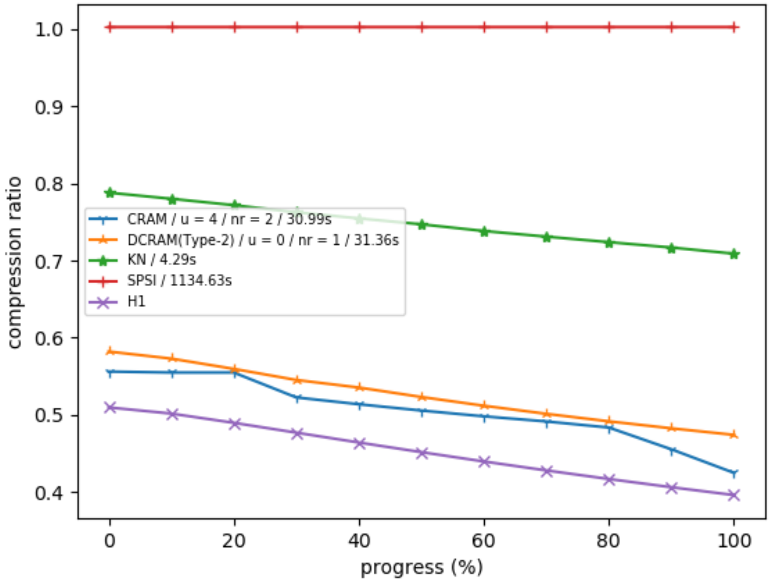
(ii) Replace-random2 (ENGLISH): Perform n′ε replace operations with the same character



- DCRAM with lazy update works faster than KN while using less space during the progress.

Experimental Results

(iii) Insert-seq (ENGLISH): Insert n/2 same characters consecutively.



- KN is ~7 times faster than ours (highly optimized for sequential updates) while our implementations take less space.
- SPSI is worse in both time and space.

Conclusion

- New implementation of compressed RAM, which changes the space adaptively for the input's entropy.
- Supporting decent operations times in both sequential and random tests.

Future work

- More optimization for sequential operations.
- Implementation based on the work of [Munro and Nekrich 15].

Thank You