Compressing IP Forwarding Tables: Towards Entropy Bounds and Beyond

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SIGCOMM'13, August 12–16, 2013, Hong Kong, China

MŰEGYETEM 1782

Motto

IP forwarding table compression is boring. . .

but compressed data structures are beautiful!

Encoding Strings

- Suppose we want to encode the string `"labanana"`
- Just 4 symbols, so we can use 2 bits per symbol

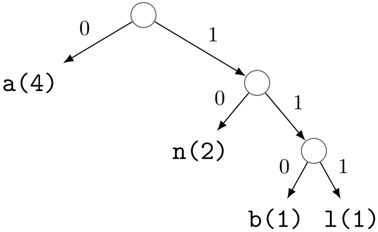
symbol	code
a	00
b	01
l	10
n	11

l	a	b	a	n	a	n	a
10	00	01	00	11	00	11	00

- Size is information-theoretic limit: 16 bits
- Fast access to symbol at any position, fast search, etc.
- But this format is not particularly memory efficient

Huffman Coding

- Compression by encoding popular symbols on fewer bits
- Huffman tree sorted by symbol frequencies



Huffman Coding

- Compression by encoding popular symbols on fewer bits
- Huffman tree sorted by symbol frequencies
- Use tree-prefix as symbol code

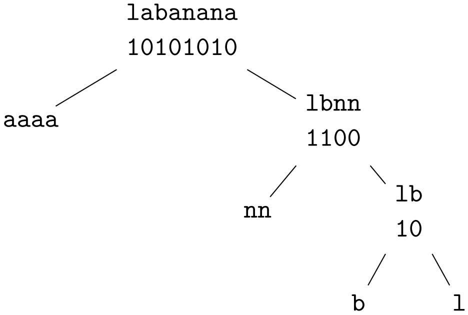
symbol	code
a	0
b	110
l	111
n	10

l	a	b	a	n	a	n	a
111	0	110	0	10	0	10	0

- Size is nH_0 bits, where n is length and H_0 is entropy
- Only 14 bits, minimal for a zero order source
- But **no fast access to symbols, no search!**

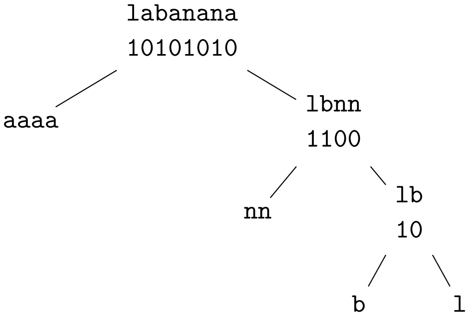
Wavelet Trees

- Indexing and Huffman coding simultaneously
- A bitmap at each node of the Huffman tree
- Tells whether symbol belongs to the left/right branch



Wavelet Trees: Access

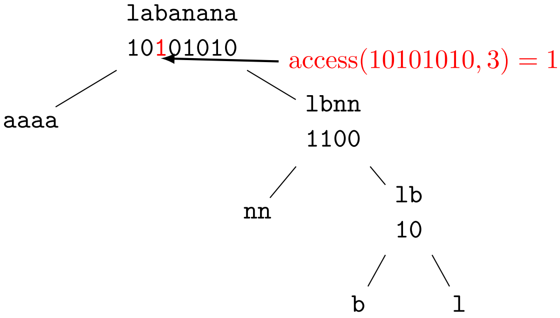
- Store bitmaps in **succinct bitstring indexes** (e.g., `RRR`)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$
- E.g., accessing the 3rd position



Wavelet Trees: Access

- Store bitmaps in **succinct bitstring indexes** (e.g., `RRR`)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$

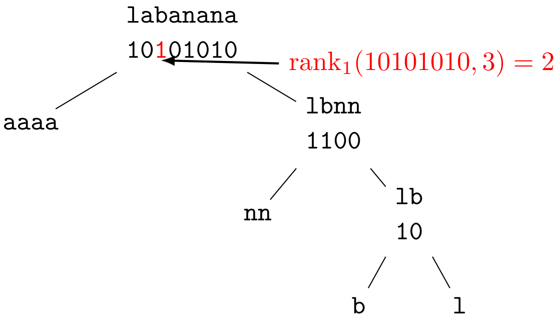
1. "Which branch the 3rd symbol belongs to?"



Wavelet Trees: Access

- Store bitmaps in **succinct bitstring indexes** (e.g., `RRR`)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$

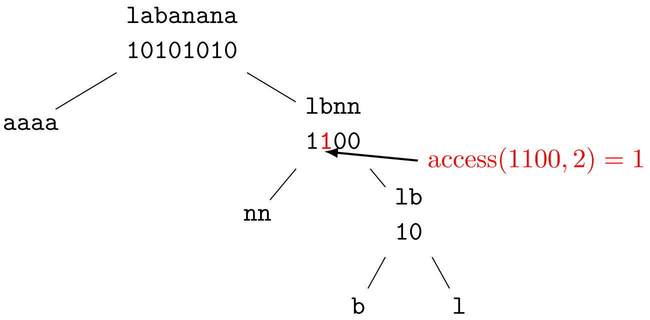
2. "How many symbols from this branch occurred this far?"



Wavelet Trees: Access

- Store bitmaps in **succinct bitstring indexes** (e.g., RRR)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$

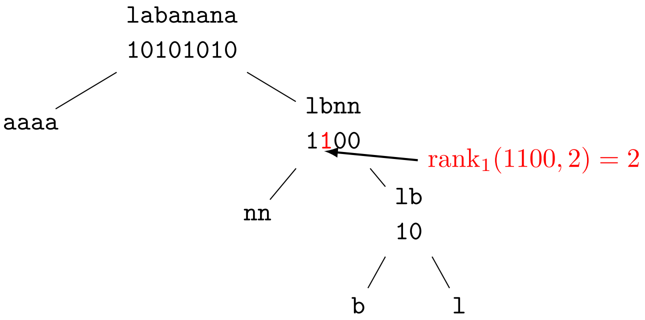
3. "Which branch this symbol belongs to?"



Wavelet Trees: Access

- Store bitmaps in **succinct bitstring indexes** (e.g., `RRR`)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$

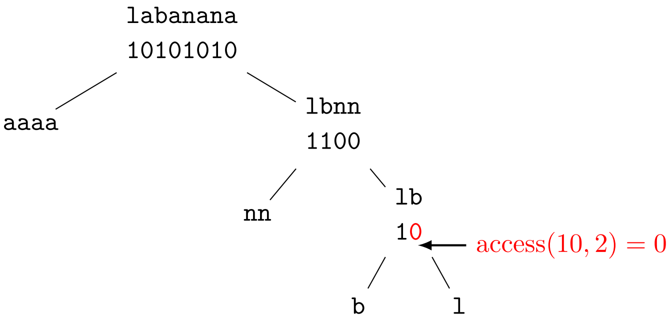
4. "How many symbols from this branch occurred this far?"



Wavelet Trees: Access

- Store bitmaps in **succinct bitstring indexes** (e.g., `RRR`)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$

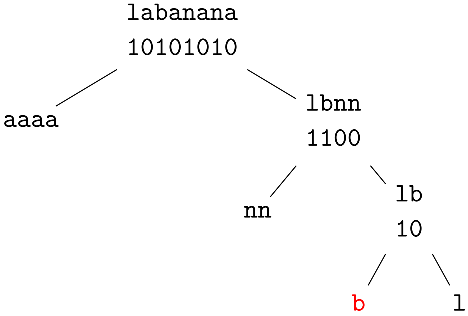
5. "Which of the remaining two symbols is the result?"



Wavelet Trees: Access

- Store bitmaps in **succinct bitstring indexes** (e.g., `RRR`)
  - encode an n bit long bitmap on roughly n bits
  - support access/rank queries in $O(1)$

6. The 3rd symbol is `b`



Wavelet Trees: Size

- We only store the bitmaps at each level

```
labanana
10101010
        lbnn
        1100
            lb
            10
```

```
 l   a   b   a  n  a  n  a
111  0  110  0  10 0 10  0
```

- Every symbol appears with its Huffman code
- Size is nH_0 bits (plus negligible overhead)
- But we still have efficient access

Compressed Data Structures

- **Compression not necessarily sacrifices fast access!**
- Store information in entropy-bounded space **and** provide fast in-place access to it
  - take advantage of regularity, if any, to compress
  - data drifts closer to the CPU in the cache hierarchy
  - operations are even faster than on the original uncompressed form
- No space-time trade-off!
- **This paper: advocate compressed data structures to the networking community**
- IP forwarding table compression as a use case

IP Forwarding Information Base

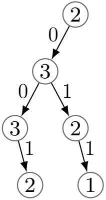
- The fundamental data structure used by IP routers to make forwarding decisions
- Stores more than 440K IP-prefix-to-nexthop mappings as of January, 2013
    - consulted on a packet-by-packet basis at line speed
    - queries are complex: longest prefix match
    - updated couple of hundred times per second
    - takes several MBytes of fast line card memory and counting
- May or may not become an Internet scalability barrier

Prefix Trees

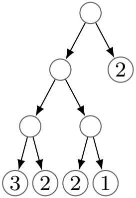
- Tries are the most convenient way to store IP FIBs

prefix	label
-/0	2
0/1	3
00/2	3
001/3	2
01/2	2
011/3	1

FIB



Prefix tree



Prefix-free trie

FIB Space Bounds

- A FIB can be uniquely represented by a binary prefix-free trie T
- Let T have n leaves labeled from an alphabet of size δ with Shannon-entropy H_0
- The **information-theoretic lower bound** to encode T is

$$4n + n \log_2 \delta \text{ bits}$$

- The **zero-order entropy** of T is

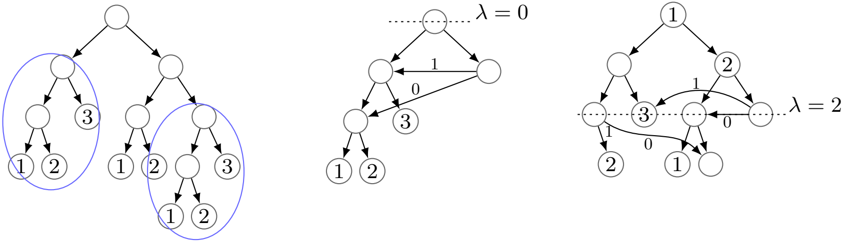
$$4n + nH_0 \text{ bits}$$

Static Compressed FIBs: `XBW-l`

- Apply the state-of-the-art in compressed data structures
  - convert FIB to prefix-free form
  - serialize the prefix tree into a set of strings
  - compress using wavelet trees and `RRR`
- We call the resultant data structure `XBW-l`
  - \+ realizes the zero-order entropy bound
  - \+ in fact, also attains higher-order entropy
  - \+ lookup goes in $O(\log n)$ time
  - – but update is linear
  - – lookup is too slow for practical applications
- Problem turns out that `XBW-l` is **pointerless**

Dynamic FIBs: Trie-folding

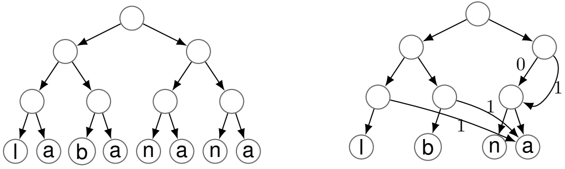
- Practical FIB compression, a good old **pointer machine**
- Fold the trie into a **prefix DAG** (DAFSA, DAWG, BDD)



- For good compression, we need the tree to be in a prefix-free form
- But prefix-free forms are expensive to update
- Balance by a parameter λ, called the leaf-push barrier

Prefix DAG Size

- View the problem as string compression: encode a string S into a prefix DAG $D(S)$



S $D(S)$

- **Theorem 1:** $D(S)$ needs $5n\log_2 \delta$ bits at most
- **Theorem 2:** $D(S)$ can be squeezed into $\sim 7nH_0$ bits in expectation
- **Theorem 3:** update goes in $O((1 + {}^1/_{H_0})\log n)$ steps

Evaluation

FIB	N	δ	H_0	I	E	XBW-l	pDAG	μ
taz	410K	4	1.00	112KB	93KB	105KB	178KB	1.90
access(d)	444K	28	1.06	235KB	149KB	167KB	369KB	2.47

- Entropy bound (E) is way smaller than information-theoretic limit (I): IP FIBs contain high regularity!
- XBW-l attains entropy bounds very closely, with prefix DAGs (pDAG) off by only a factor μ of 1.5–3
- FIBs can be encoded on roughly 2–6 bits per prefix (!)
  - that's roughly 100–400 KBytes of memory
- Several million lookups per sec both in HW and SW
  - faster than the uncompressed form
- pDAG tolerates more than $100,000$ updates per sec

Conclusions

- Compressed data structures are essential in information retrieval, computational biology, geometry, etc.
  - allow to sidestep notorious space-time trade-offs
  - as such, compressing comes essentially for free
- FIB compression is a poster child of why the networking field is in a sore need of good compression methods
  - permits to reason about size, lookup, and update performance (analyzability)
  - allows to state theoretical storage size bounds (predictability)
  - faster operations than on the uncompressed form (efficiency)

Thank you for the attention

Plese, share your FIBs with us at
`http://lendulet.tmit.bme.hu/fib_comp`

By the way, I am looking for a guest researcher/professor position...
feel free to contact me!