Algorithms for Advanced Packet Classification with TCAMs

(sigcomm 2005)

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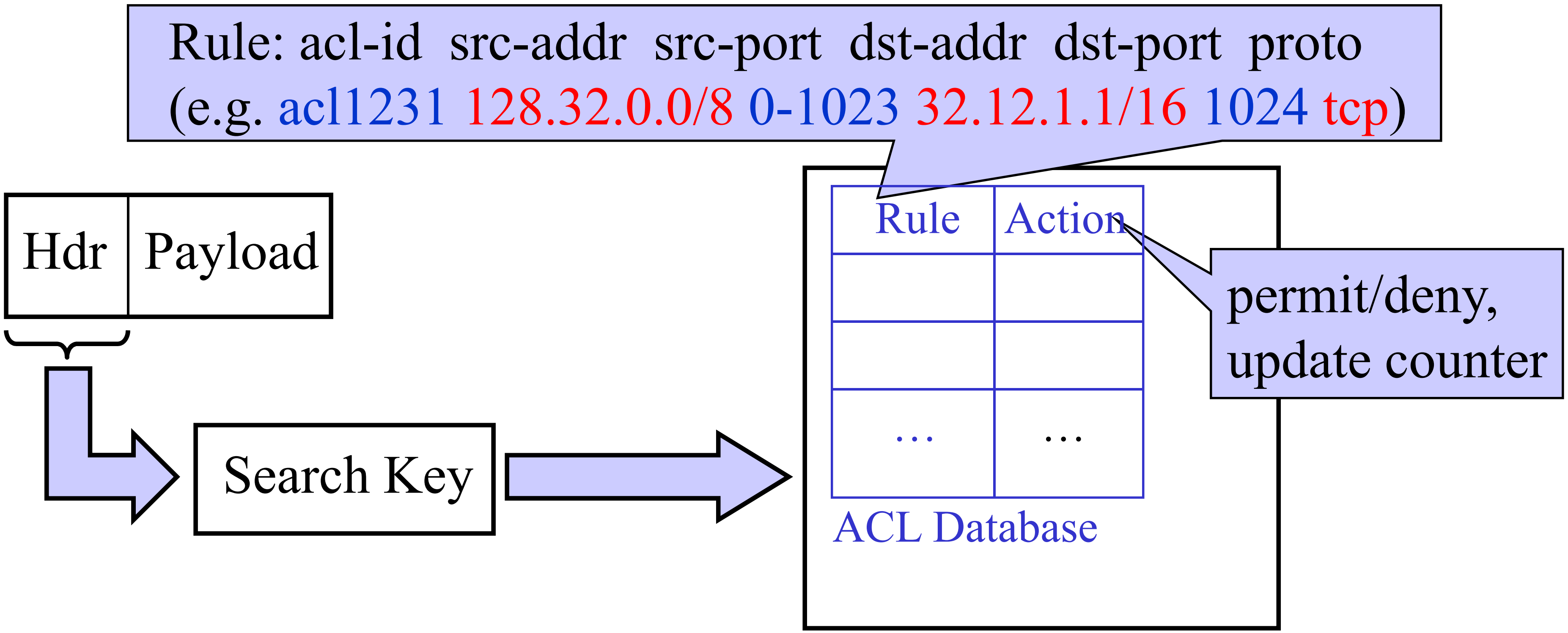
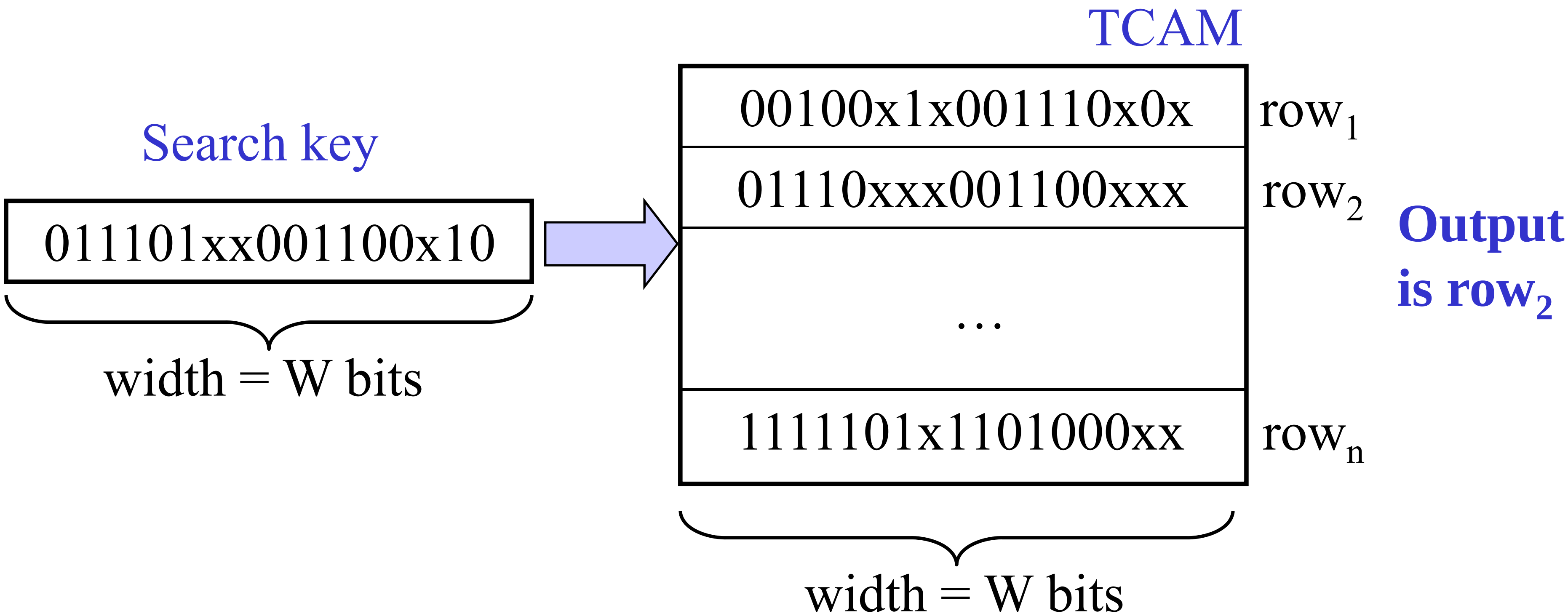
Packet Processing Environment



- Packet matches a set of rules based on the header
- Examples: routers, intrusion detection systems

Ternary Content Addressable Memory

- Memory device with fixed width arrays
- Each bit is 0, 1 or x (don't care)
- Search is performed against all entries in *parallel* and the *first result* is returned



TCAM: Benefits and Disadvantages

- Benefits:
  - Deterministic Search Throughput—O(1) search
- Disadvantages:
  - Cost
  - Power consumption
- Current TCAM usage:
  - 6 million TCAM devices deployed (by 2005)
  - Used in multi-gigabit systems that have O(10,000) rules
  - TCAMs can support a table of size 128K (18Mbits/144bits) ternary entries and 133 million (133M/15M=88Gbps 64B packets) searches per second for 144-bit keys

Range Representation Problem

- Representing prefixes in ternary is trivial
  - IP address prefixes present in rules
- Representing arbitrary ranges is not easy though
  - port fields might contain ranges
    - e.g. sPort [1024, 65536], dPort [6110, 6112]
  - intrusion detection may check packet length field
    - e.g. packet size [1, 254]
- Problem Statement
  - given a range R, find the minimum number of ternary entries to represent R

Why is efficient range representation an important problem?

Statistic	1998 database	2004 database
Total number of rules	41190	215183
With single range field	4236 (10.3%)	54352 (25.3%)
With single non-"$\geq$ 1024" range field	553 (1.3%)	25311 (11.8%)
With two range fields	0 (0%)	3225 (1.5%)
Unique ranges in first field	62	270
Unique ranges in second field	0	37

Number of unique ranges have increased over time

Earlier Approaches – I

Prefix expansion of ranges:

- express ranges as a union of prefixes
- have a separate TCAM entry for each prefix
- expansion: the number of entries a rules expands to

- Example: the range [3,12] over a 4-bit field would expand to:
  - 0011 (3), 01xx (4-7), 10xx (8-11) and 1100 (12)
- Worst-case expansion for a single W-bit field is 2W-2
  - example: [1,14] would expand to 0001, 001x, 01xx, 10xx, 110x, 1110
  - 16-bit port field expands to 30 entries
  - F W-bit fields is thus $(2W\text{-}2)^F$

Earlier Approaches – II

Database-dependent encoding:

– observation: TCAM array has some unused bits

– use these additional bits to encode commonly occurring ranges in the database

- TCAMs with IP ACLs have ~ 36 extra bits
  - 144-bit wide TCAMs
  - 104-bits + 4-bits for IP ACL rules

Earlier Approaches – II

Database-dependent encoding:

– observation: TCAM array has some unused bits

– use these additional bits to encode commonly occurring ranges in the database

- Example:

Address	Port	…		
12.123.0.0/16	20-24	…	⟶	**Set extra bit to 1**
32.12.13.0/24	1024-	…	⟶	**Set extra bit to x**
128.0.0.0/8	20-24	…	⟶	**Set extra bit to 1**

If search key falls in 20-24, set extra bit to 1, else set it to 0

Earlier Approaches – II

Database-dependent encoding:

- observation: TCAM array has some unused bits
- use these additional bits to encode commonly occurring ranges in the database

- Disadvantages:
  - extra bits is limited
  - number of unique ranges is increasing
  - incremental update is hard
  - …
  - all due to: database dependency

Database-Independent Range Pre-Encoding

- Key insight: use additional bits in a database independent way
  - wider representation of ranges
  - reduce expansion in the worst-case

Database-Independent Range Pre-Encoding

- Fence encoding (W bits):
  - total of 2^W-1 bits
  - encoding of *i* has *i* ones preceded by 2^W-*i*-1 zeros
  - e.g. W=3, f(0) = 0000000, f([1, 3]) = 0000xx1
- With 2^W-1 bits, fence encoding achieves an expansion of 1

Range	Encoding
$= i$	$0^{2^k-i-1}1^i$
$\geq i$	$x^{2^k-i-1}1^i$
$< i$	$0^{2^k-i}x^{i-1}$
$[i, j]$	$0^{2^k-1-j}x^{j-i}1^i$

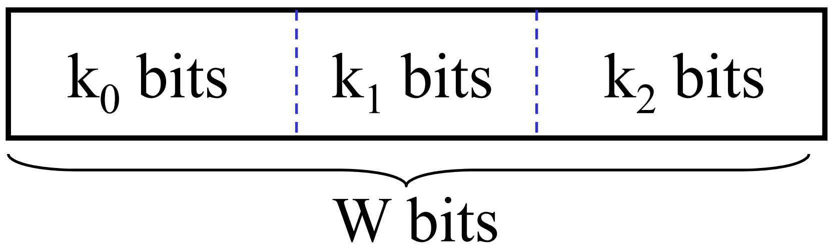
Theorem: For achieving a worst-case row expansion of 1 for a W-bit range, 2^W-1 bits are necessary

DIRPE: Using the Available Extra Bits

- Two extremes:
  - no extra bits → worst case expansion is $2W-2$
  - 2^W-W-1 extra bits → worst case expansion is 1
- Is there something in between?
  - appropriate worst-case based on number of extra bits available

Database-Independent Range Pre-Encoding

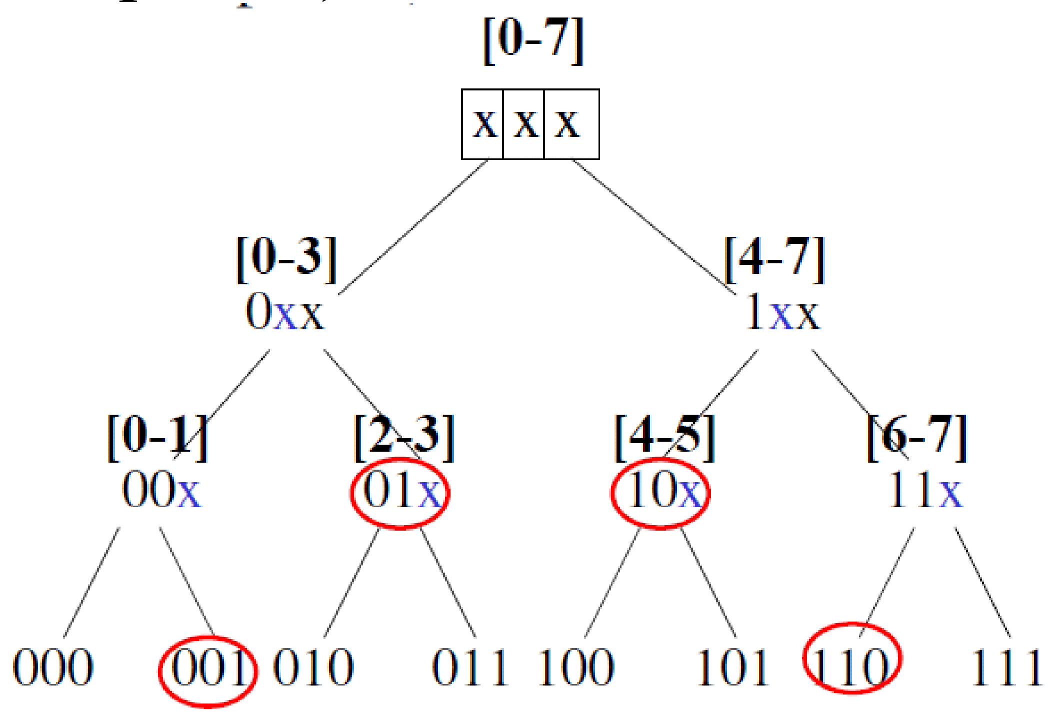
- Procedure:
  - split W-bit field into multiple *chunks*
  - encode each chunk using fence encoding
  - “combine” the chunks to form ternary entries



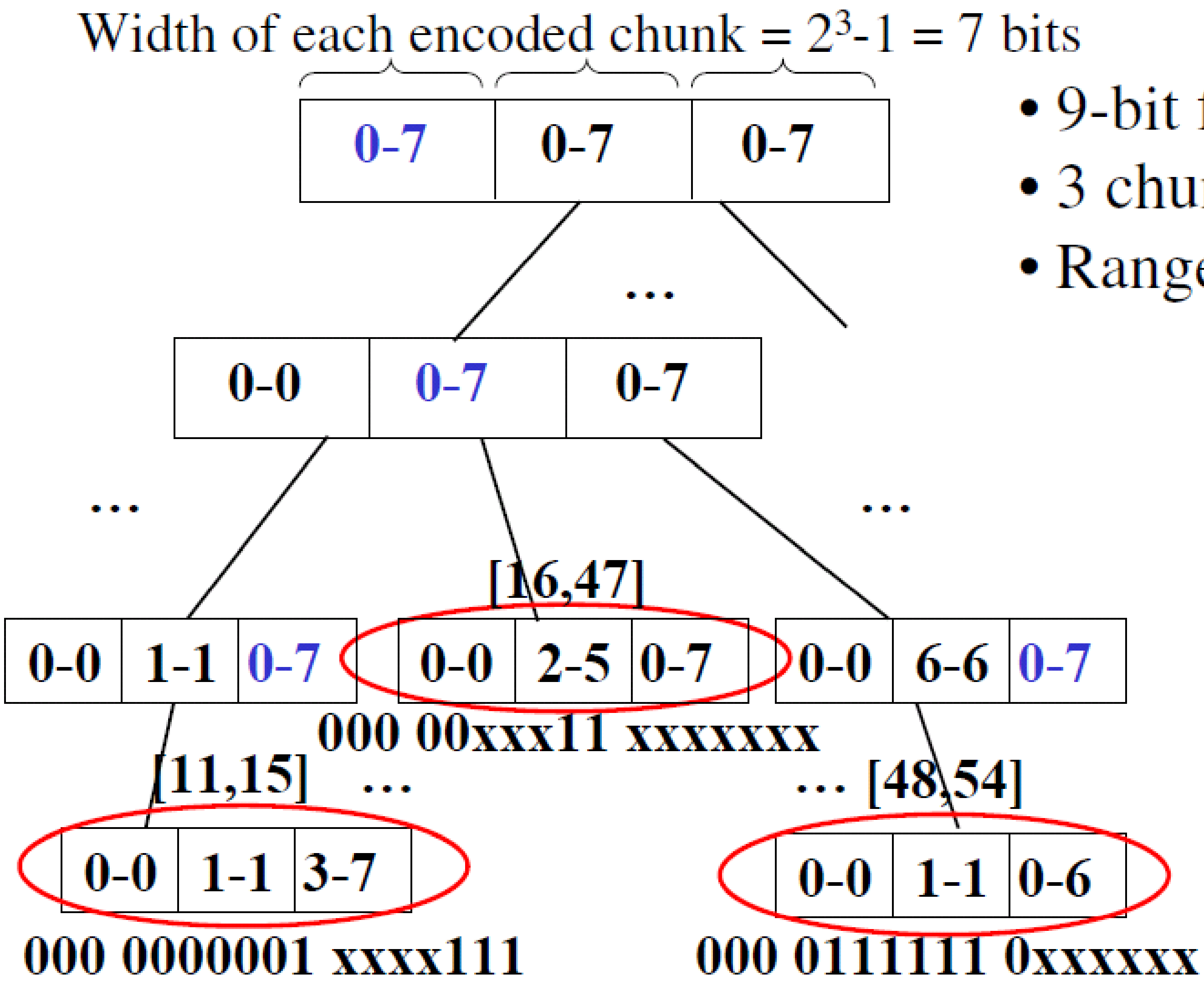
Combining chunks: analogous to multi-bit tries

Unibit view of DIRPE (Prefix expansion)

- W=3 divided into 3 one-bit chunks
- R=[1,6]—prefixes = {001,01x,10x,110}
- Each level can contribute to at most 2 prefixes (but the top level)



Multi-bit view of DIRPE



- 9-bit field (W=9)
- 3 chunks, 3 bits wide
- Range = [11,54]
  = [013, 066]

Worst case expansion = 2W/k – 1

Number of extra bits needed = $(2^k-1)W/k - W$

Comparison of Expansion

Extra bits	DIRPE	Region-based Range Encoding
0	30	30
8	15	30
18	11	16
27	9	14
44	7	12

Worst-case expansion

Extra bits	DIRPE	Region-based Range Encoding
0	2.69	2.69
8	2.08	2.33
18	1.79	2.17
36	1.57	1.58

Real-life expansion

DIRPE + DB-dependent → Net expansion was 1.12

Metric	Prefix Expansion	Region-based Encoding (with *r* regions)	DIRPE (with *k*-bit chunks)	DIRPE + Region-based
Extra bits	0	$F(\log_2 r + \frac{2n-1}{r})$	$F(\frac{W(2^k-1)}{k} - W)$	$F(\frac{(2^k-1)\log_2 r}{k} + \frac{2n-1}{r})$
Worst-case capacity degradation	$(2W-2)^F$	$(2\log_2 r)^F$	$(\frac{2W}{k} - 1)^F$	$(\frac{2\log_2 r}{k})^F$
Cost of an incremental update	$O(W^F)$	$O(N)$	$O((\frac{W}{k})^F)$	$O(N)$
Overhead on the packet processor	None	Pre-computed table of size: $O((\log_2 r + \frac{2n-1}{r}) F.2^W)$ (*or*) $O(nF)$ comparators of width W bits	$O(\frac{W.2^k}{k})$ logic gates	Both pieces of logic from previous two columns

DIRPE: Summary

↑ Database independent

↑ Scales well for large databases

↑ Good incremental update properties

↓ Additional bits needed

↓ Small logic needed for modifying search key

Related Work I

- Range-to-prefix conversion
  - Represent a range by a set of prefixes, each of which can be stored by a single TCAM entry. *(V. Srinivasan, G. Varghese, S. Suri, and M. Waldvogel, "Fast and scalable layer four switching," in ACM SIGCOMM, Sep. 1998, pp. 191–202.)*
  - The worst-case expansion ratio is 2W−2, in a single dimension.
  - A single rule can generate up to 900 prefixes (only for the two port fields).
  - prefix expansion may increase the number of required TCAM entries by a factor of more than 6.
- Direct hardware solution
  - Extended TCAMs, implements range matching directly in hardware. *(E. Spitznagel, D. Taylor, and J. Turner, "Packet classification using extended TCAMs," in ICNP, 2003.)*
  - Reducing power consumption by over 90% relative to standard TCAM
  - Will not be accomplished in the near future

Related Work II

- Database-dependent range encoding algorithms
  - Encoding is a function of the distribution of ranges in the database
  - Basic idea: a single extra bit is assigned to each selected range *r* in order to avoid the need to represent *r* by prefix expansion
    - the number of unique ranges in today' s databases is ~300
    - we have ~30 extra bits…
  - Region Partition: split a range into multiple sub-ranges. Each such sub-range is encoded by two numbers: the region number into which it falls, and the sub-range number within that region. *(H. Liu, "Efficient mapping of range classifier into ternary-cam," in Hot Interconnects, 2002.)*
  - Dynamic Range Encoding (DRES): a greedy algorithm that assigns extra bits to the ranges with highest prefix expansion. *(H. Che, Z. Wang, K. Zheng, and B. Liu, "Dres: Dynamic range encoding scheme for tcam coprocessors," IEEE Transaction on Computers, vol. 57, no. 6, 2008.)*
  - Layered Interval Coding (LIC): a more efficient representations based on the observation that, sets of disjoint ranges may be encoded much more efficiently than sets of overlapping ranges. *(Anat Bremler-Barr, David Hay, Danny Hendler, Beer-Sheva and Boris Farber, " Layered interval codes for tcam-based classification, INFOCOM 2009.)*

Related Work III

- Database-independent range encoding algorithms
  - Encoding of a specific range does not change across different databases.
  - Fence coding: just presented. *(K. Lakshminarayanan, A. Rangarajan, and S. Venkatachary, "Algorithms for advanced packet classification with ternary CAMs," in ACM SIGCOMM, 2005.)*
  - Grey coding: based on the observation that small ranges, which occur frequently in real-world databases, are encoded more efficiently. *(A. Bremler-Barr and D. Hendler, "Space-efficient tcam-based classification using gray coding," in IEEE INFOCOM, 2007, pp. 1388–1396.)*

Thanks!

Q & A