Algorithms for Advanced Packet Classification with Ternary CAMs

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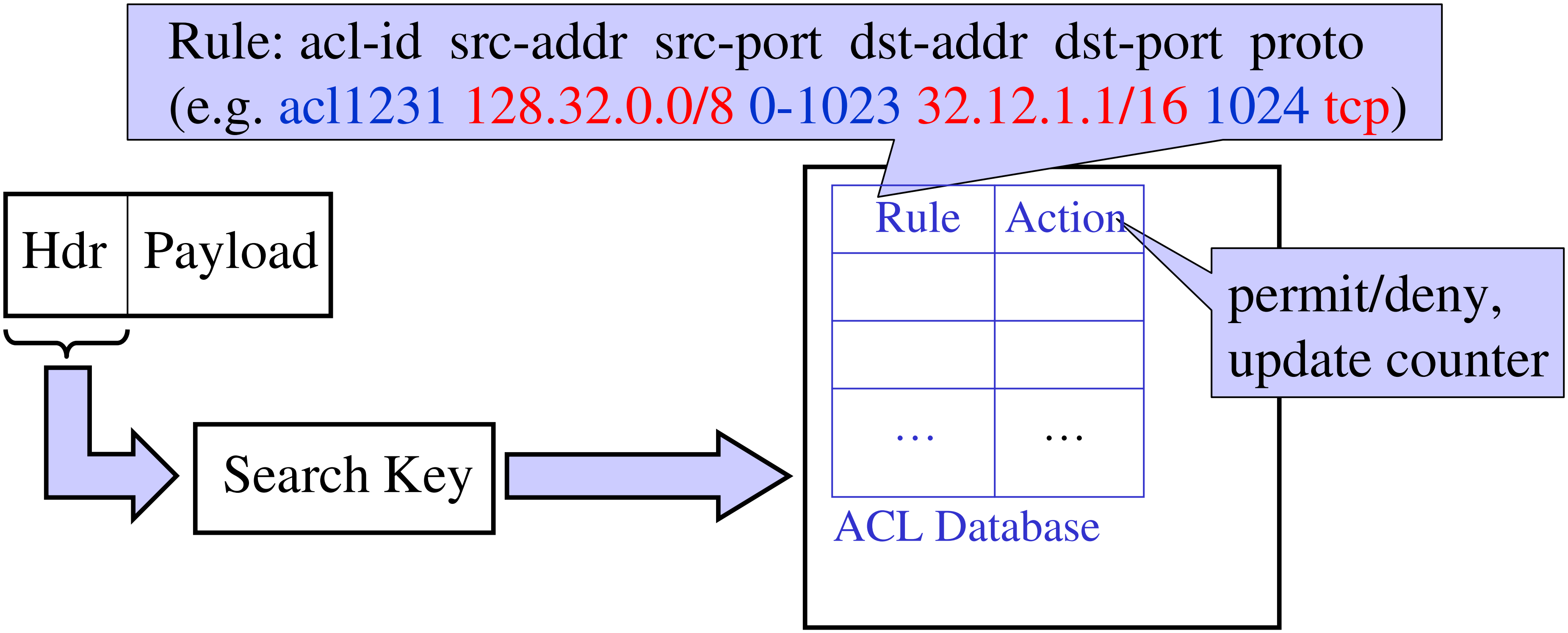
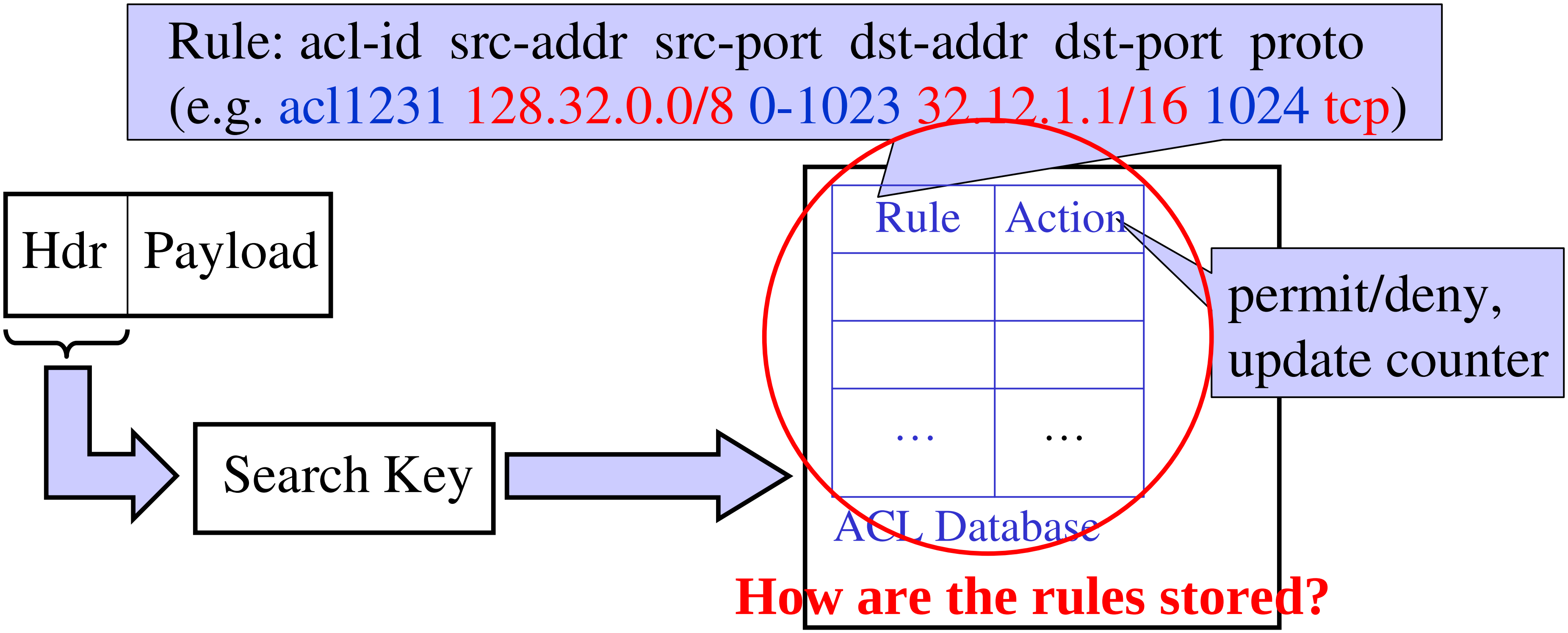
Packet Processing Environment



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

Packet Processing Environment



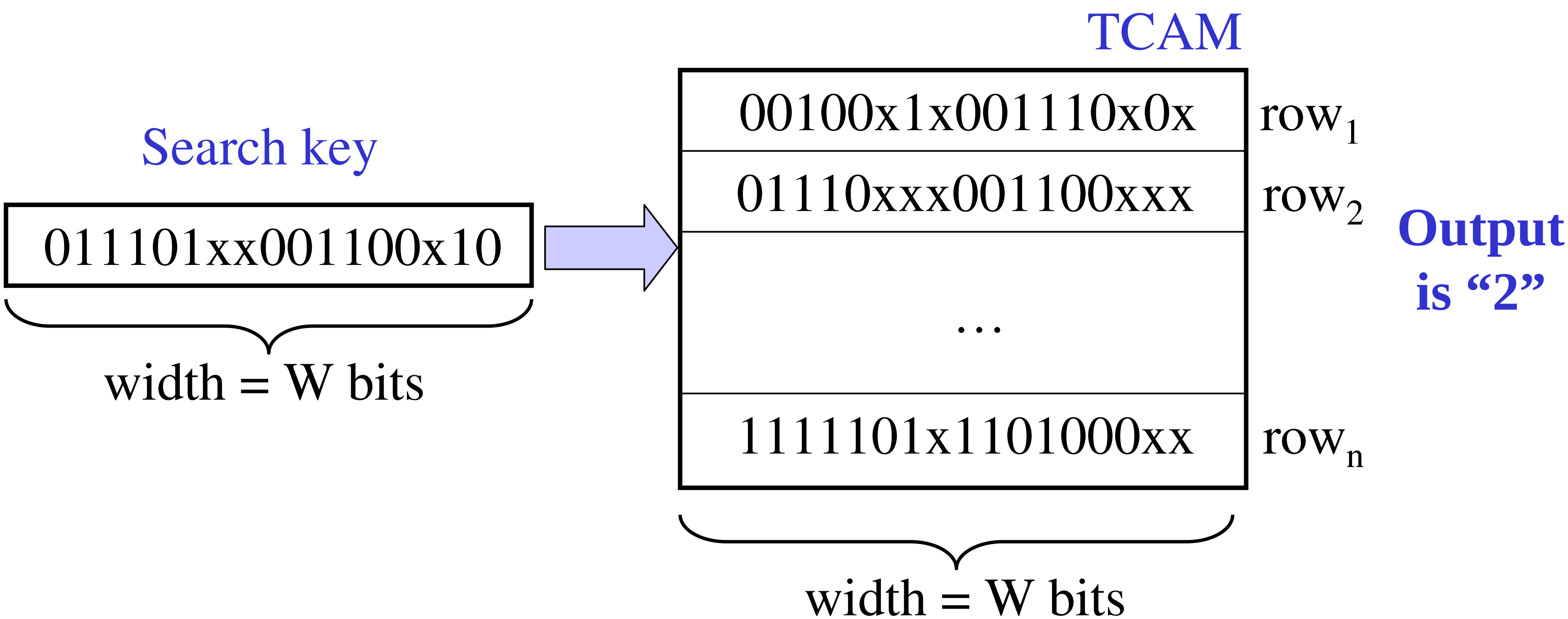
- TCAMs gaining widespread deployment
  - 6 million TCAM devices deployed
  - Used in multi-gigabit systems that have O(10,000) rules

Ternary Content Addressable Memory

- **RAM: input = address, output = value**
- **CAM: input = value, output = address**

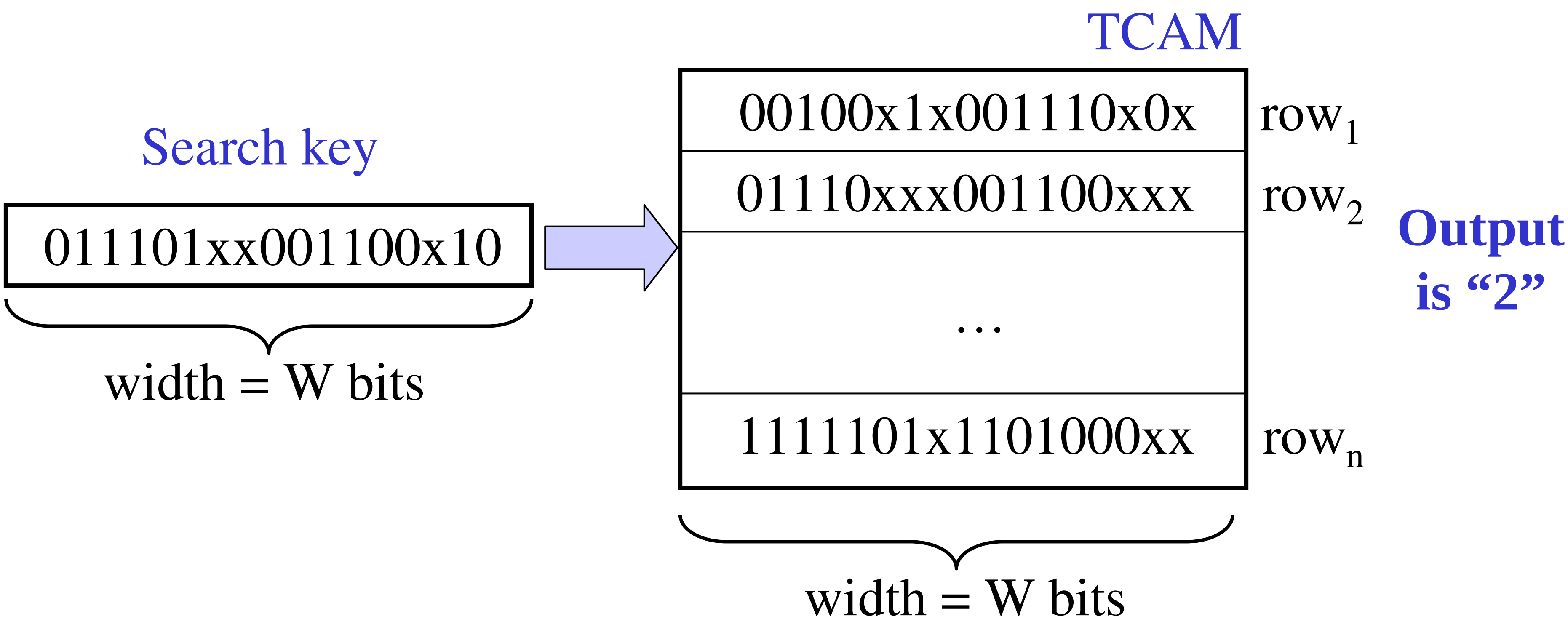
Ternary Content Addressable Memory

- 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



Ternary Content Addressable Memory

- Benefits: Deterministic Search Throughput
  - single cycle search irrespective of search key



Problems

- Range Representation Problem

- Multimatch Classification Problem

No modifications to TCAMs and simple
→ Easy to deploy

Problems

- Range Representation Problem
- Multimatch Classification Problem

Range Representation Problem

- (Recall that rules contain prefixes and ranges)
- Representing prefixes in ternary is trivial
  - IP address prefixes present in rules
  - e.g. 128.32.136.0/24 would contain 8 ‘x’s at the end
- Representing arbitrary ranges is not easy though
  - port fields might contain ranges
  - e.g. some security applications may allow ports 1024-65535 only

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 range rules has increased over time

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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

- Example: the range [3,12] over a 4-bit field would expand to:
  - 0011 (3), 01xx (4-7), 10xx (8-11) and 1100 (12)
  - expansion: the number of entries a rule expands to
- Worst-case expansion for a 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

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Two range fields – multiplicative effect

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 typically used 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

- Improved version: Region-based Range Encoding
- Disadvantages:
  - database dependent → incremental update is hard

Database-Independent Range Pre-Encoding (DIRPE)

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

DIRPE: Fence Encoding

- Fence encoding (W-bit field)
  - total of 2^W-1 bits
  - Encoding(0) = **0000000**
  - Encoding(2) = **0000011**
  - Encoding(4) = **0001111**
  - Encoding[2,4] = **000xx11**

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

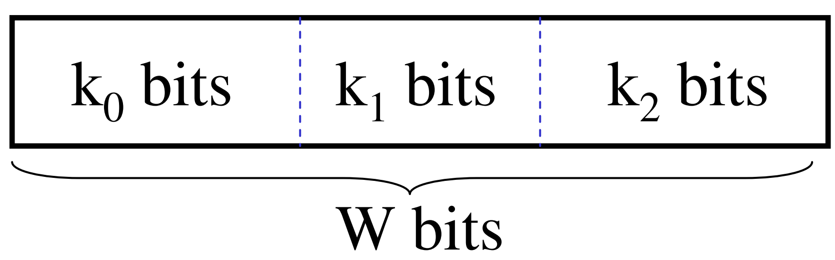
- Using 2^W-1 bits, fence encoding achieves an expansion of 1
- Theorem: For achieving a worst-case row expansion of 1 for a W-bit range, 2^W-1 bits are necessary

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

DIRPE: Splitting the Range Field

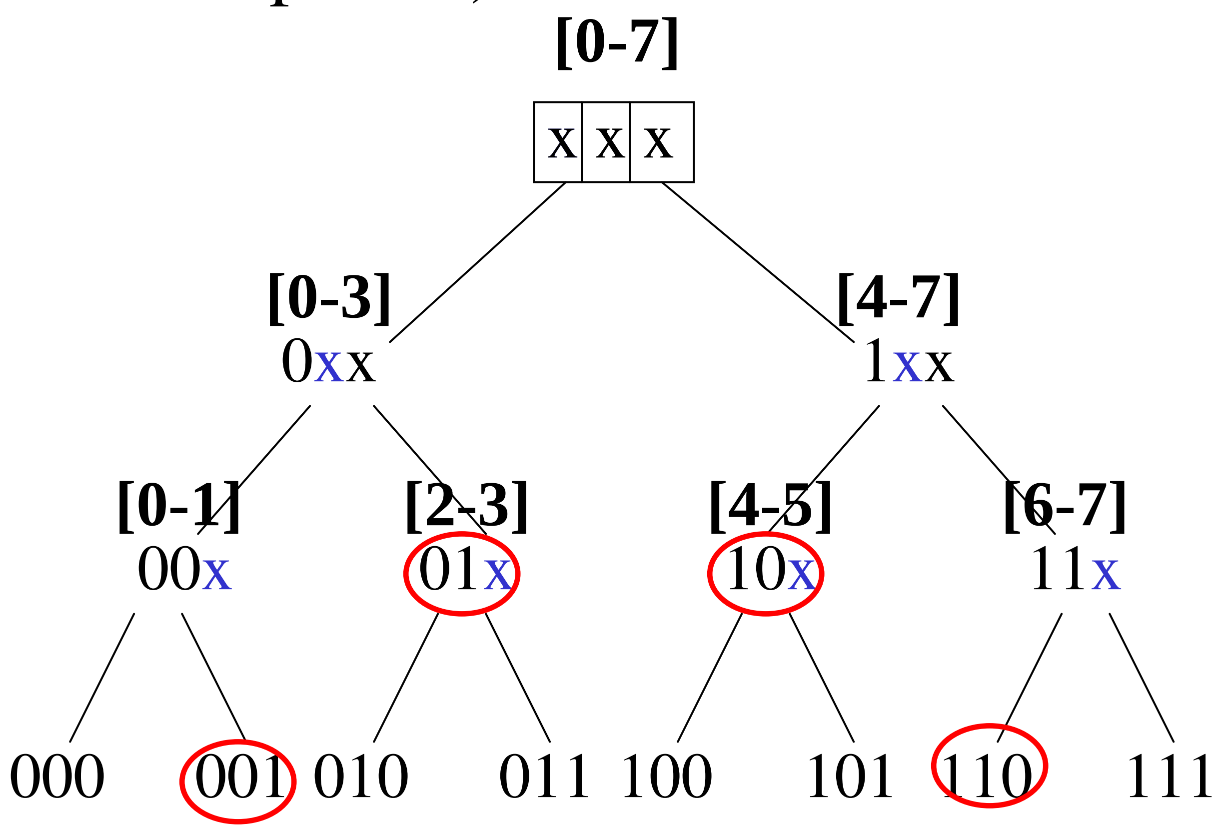
- Procedure:
  - split W-bit field into multiple *chunks*
  - encode each chunk using fence encoding
  - “combine” the chunks to form ternary entries



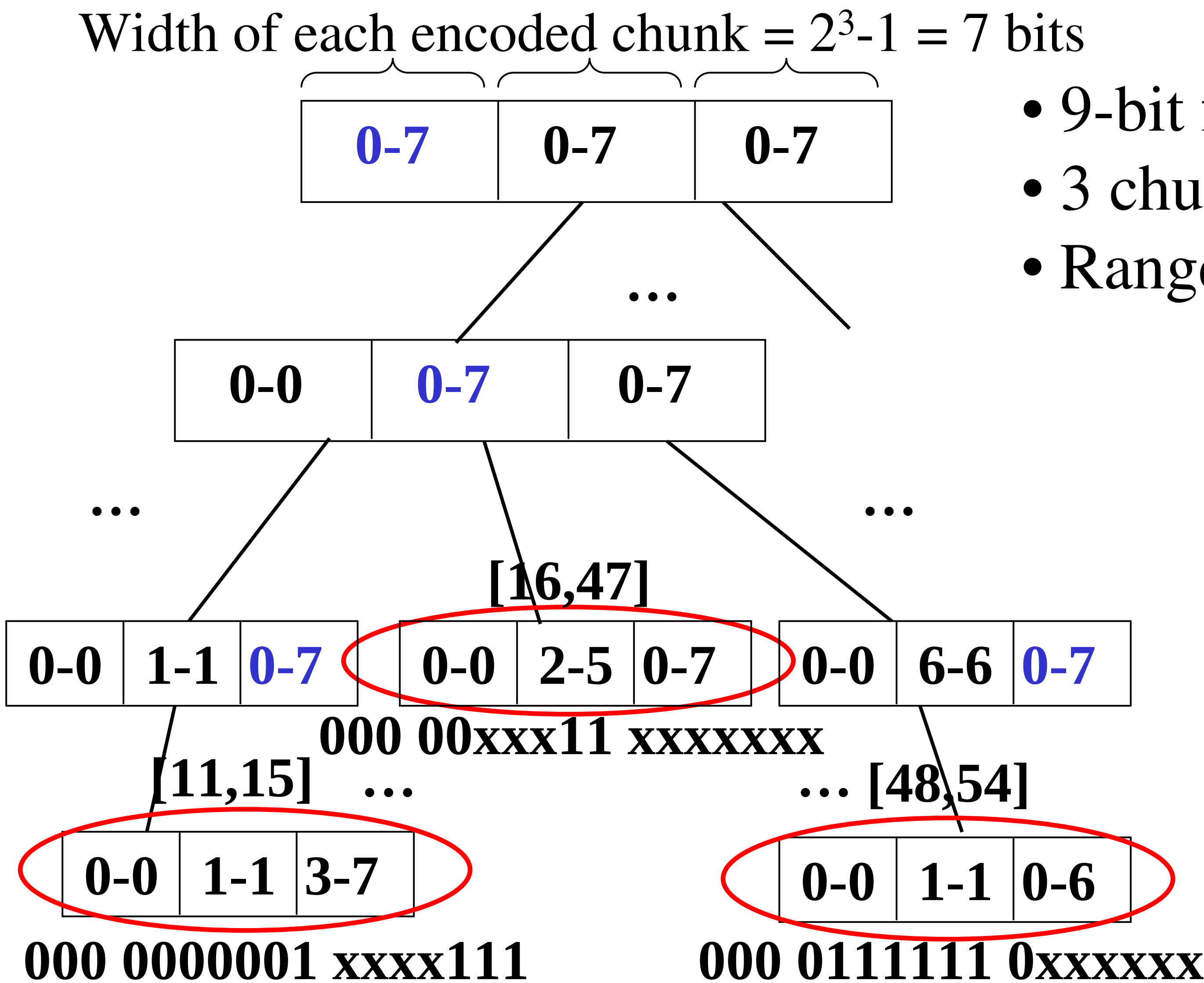
Combining chunks: analogous to multi-bit tries

Unibit view of DIRPE (Prefix expansion)

- W=3, split into three 1-bit chunks; Range=[1,6]
- Each level can contribute to at most 2 prefixes (but for 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

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

  ↑ Does not affect throughput

Problems

- Range Expansion Problem
- Multimatch Classification Problem

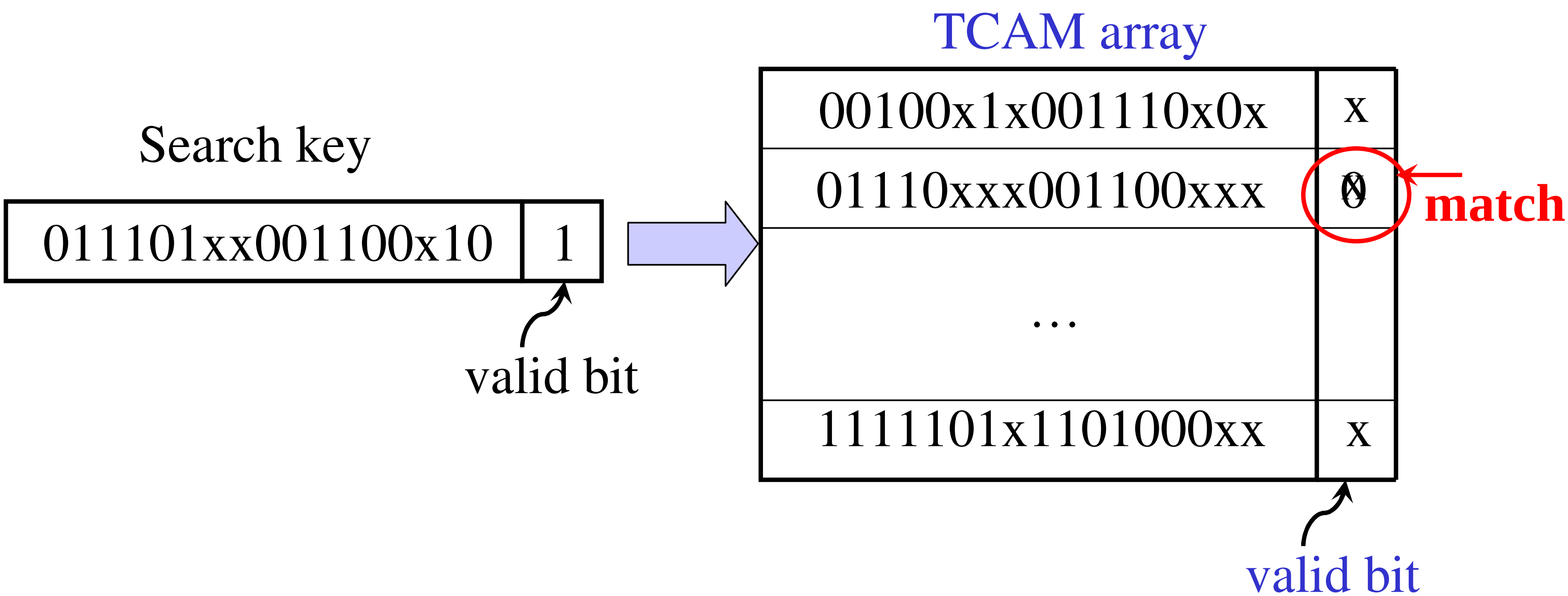
Multimatch Classification Problem

- TCAM search primitive: return first matching entry for a key
- Multimatch requirement: return *k* matches (or all matches) for a key
  - security applications where all signatures that match this packet need to be found
  - accounting applications where counters have to be updated for all matching entries

Earlier Approaches

Entry Invalidation scheme:

- maintain state of multimatch using an additional bit in TCAM called “valid” bit



Earlier Approaches

Entry Invalidation scheme:

– maintain state of multimatch using an additional bit in TCAM called “valid” bit

- Disadvantage:
  – ill-suited for multi-threaded environments

Earlier Approaches

Geometric intersection scheme:

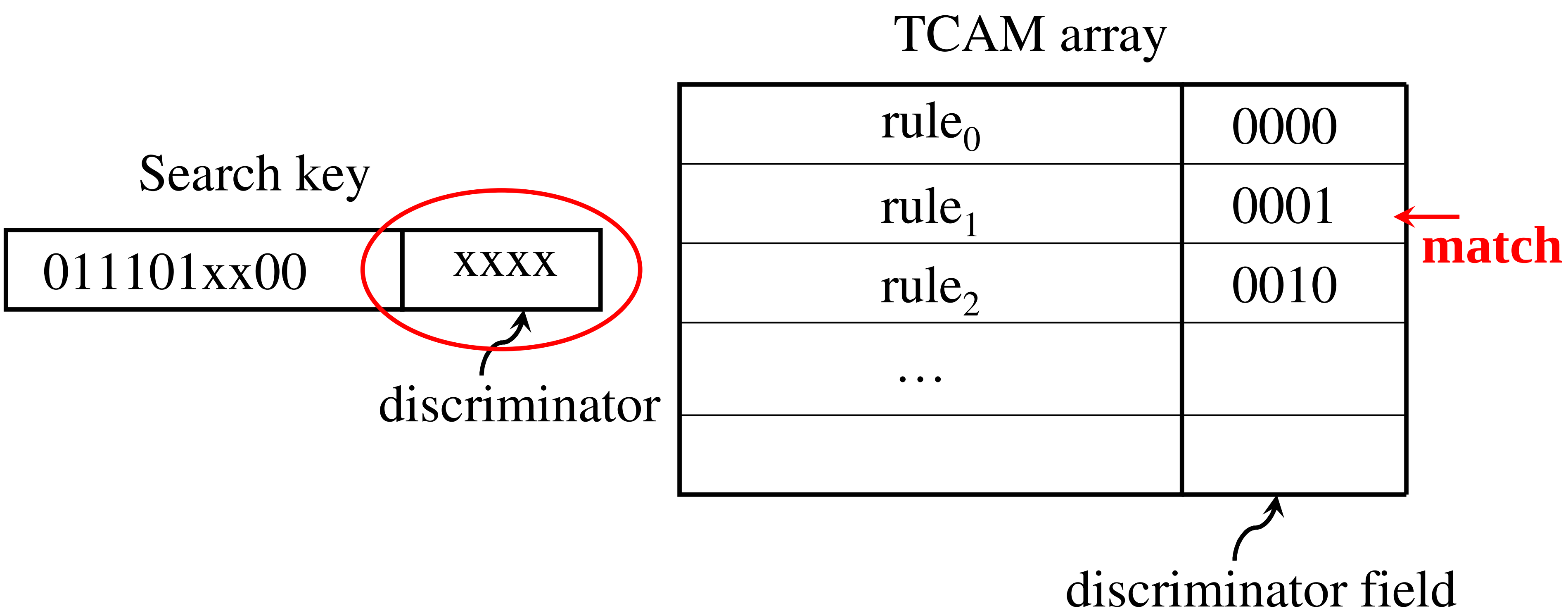
- construct geometric intersection (cross-products) of the fields and place in TCAM
- pre-processing step is expensive
- search is fast

- Disadvantage:
  - does not scale well in capacity
  - for router dataset: expansion of 25—100

Multimatch Using Discriminators (MUD)

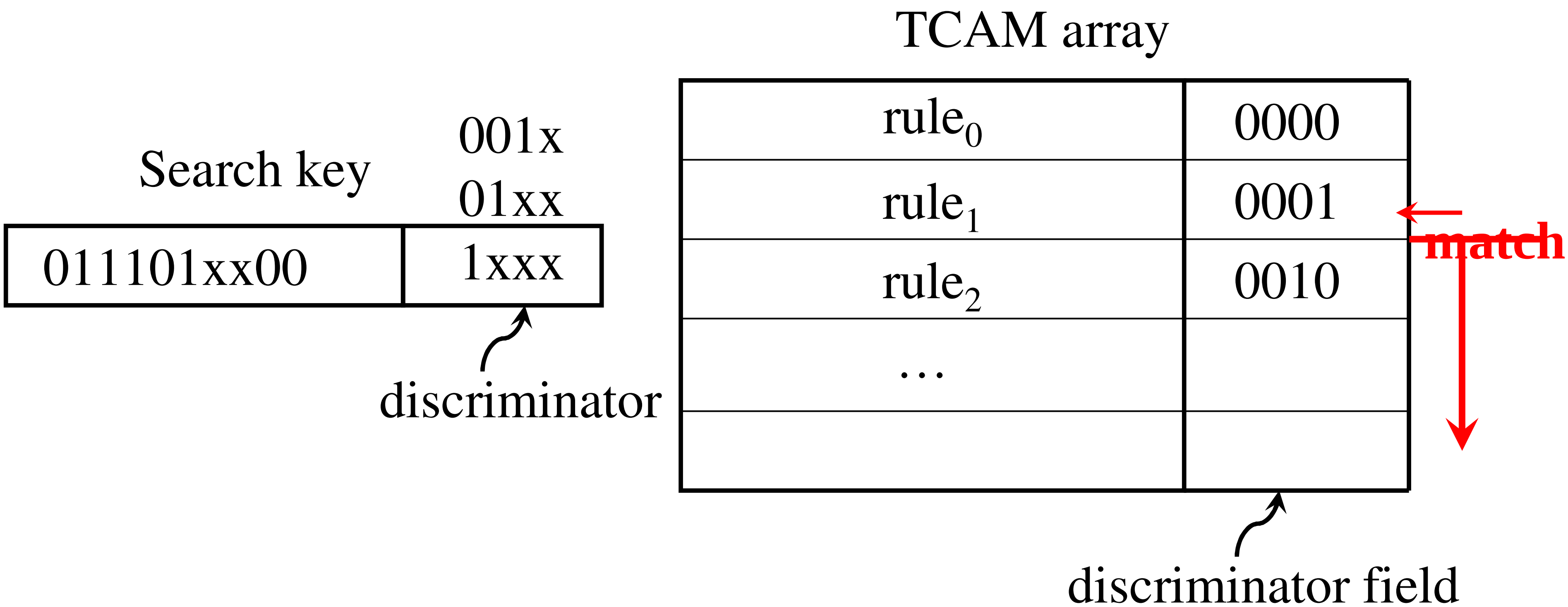
- Observation: after index *j* is matched, the ACL has to be searched for all indices >*j*
- Basic idea:
  - store a discriminator field with each row that encodes the index of the row
  - to search rows with index >*j*, the search key is expanded to prefixes that correspond to >*j*
  - multiple searches are then issued

MUD: Example



TCAM array
Search key
011101xx00
xxxx
discriminator
rule0
rule1
rule2
…
0000
0001
0010
match
discriminator field

MUD: Example


TCAM array
Search key
001x
01xx
011101xx00
1xxx
discriminator
rule0
0000
rule1
0001
rule2
0010
…
match
discriminator field

Metric	Entry Invalidation	Geometric Intersection-based	MUD
Multi-threading support	No	Yes	Yes
Worst-case TCAM entries for N rules	N	$O(N^F)$	N
Update cost	O(N)	$O(N^F)$	O(N)
Cycles for k multi-matches	7k	k	1 + d + (d-1)(k-2) with DIRPE: $1 + \frac{d(k-1)}{r}$
Extra bits	0	0	without DIRPE: d with DIRPE: $\log_2(d/r) + (d-r) + (2^r-1)$
Overhead on the packet processor	Small state machine logic; can be implemented using a few hundred gates or a few microcode instructions	None	Small state machine logic; can be implemented using a few hundred gates or a few microcode instructions

MUD: Summary

- ↑ No per-search state in TCAM — suitable for multi-threaded environments
- ↑ Incremental updates fast
- ↑ Scales well to large databases

- ↓ Additional bits needed
- ↓ Extra search cycles
  - ↑ Can still support Gbps speeds

Conclusion

- Range expansion problem: DIRPE, a database independent range encoding
  - scales to large number of ranges
  - good incremental update properties
- Multimatch classification problem: MUD
  - suitable for multithreaded environments
  - scales to large databases
- No change to TCAM hardware and simple

  → easy to deploy