CS 268: Lectures 13/14 (Route Lookup and Packet Classification)

Ion Stoica

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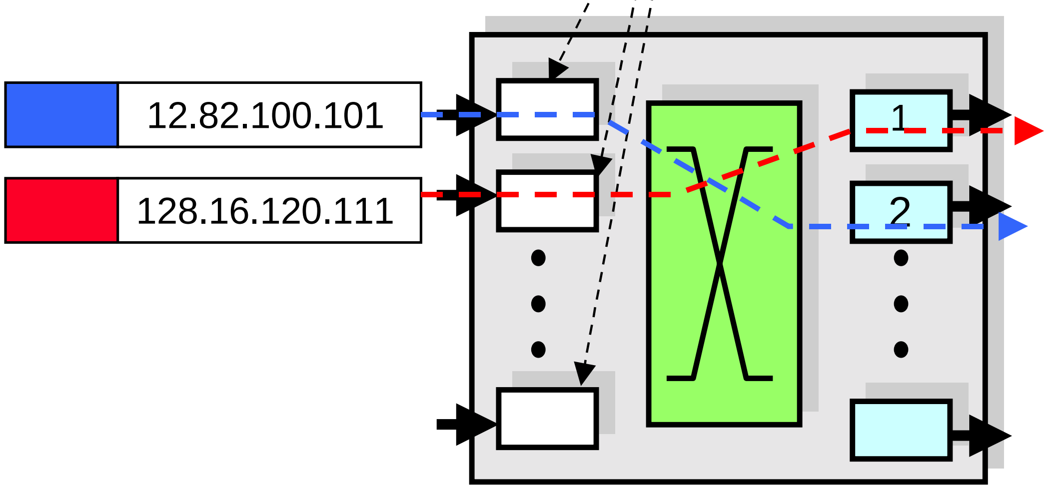
Lookup Problem

- Identify the output interface to forward an incoming packet based on its destination address
- Routing (forwarding) tables summarize information by maintaining prefixes
- Route lookup → find the longest prefix in the table that matches the packet destination address

Example

- Packet with destination address 12.82.100.101 is sent to interface 2, as 12.82.100.xxx is the longest prefix matching packet's destination address

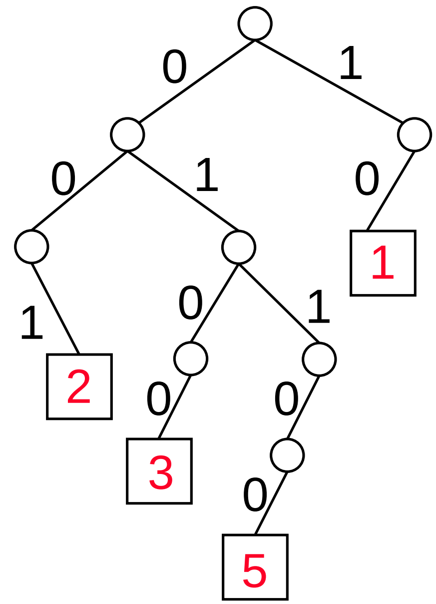
128.16.120.xxx	1
12.82.xxx.xxx	3
12.82.100.xxx	2
…	…



Patricia Tries

- Use binary tree paths to encode prefixes

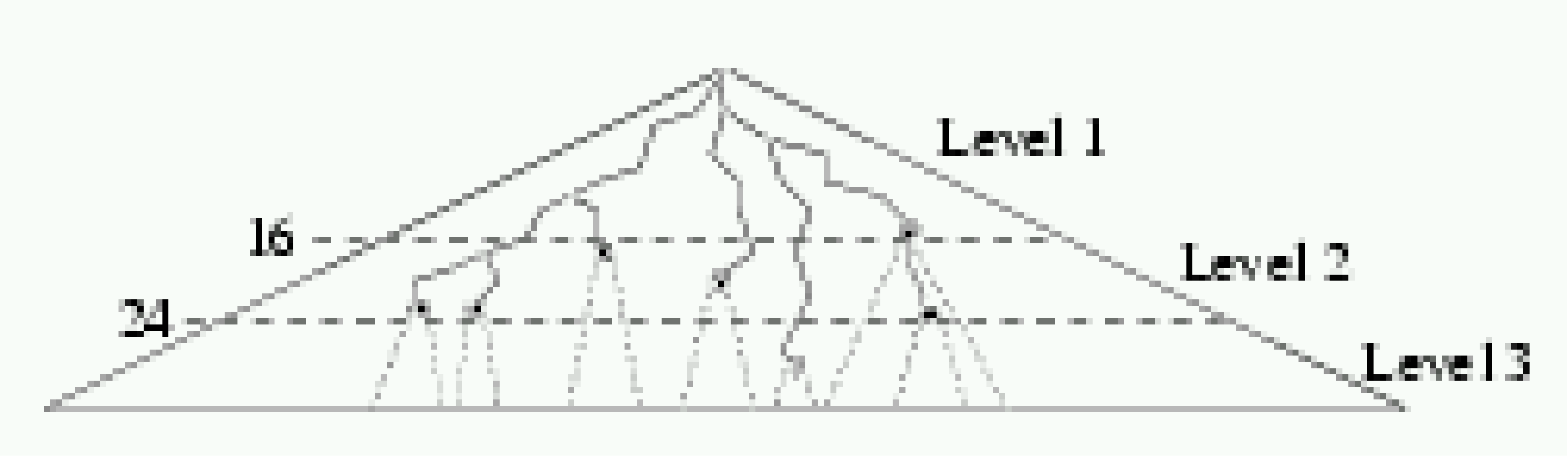
001xx	2
0100x	3
10xxx	1
01100	5



- Advantage: simple to implement
- Disadvantage: one lookup may take O(m), where m is number of bits (32 in the case of IPv4)

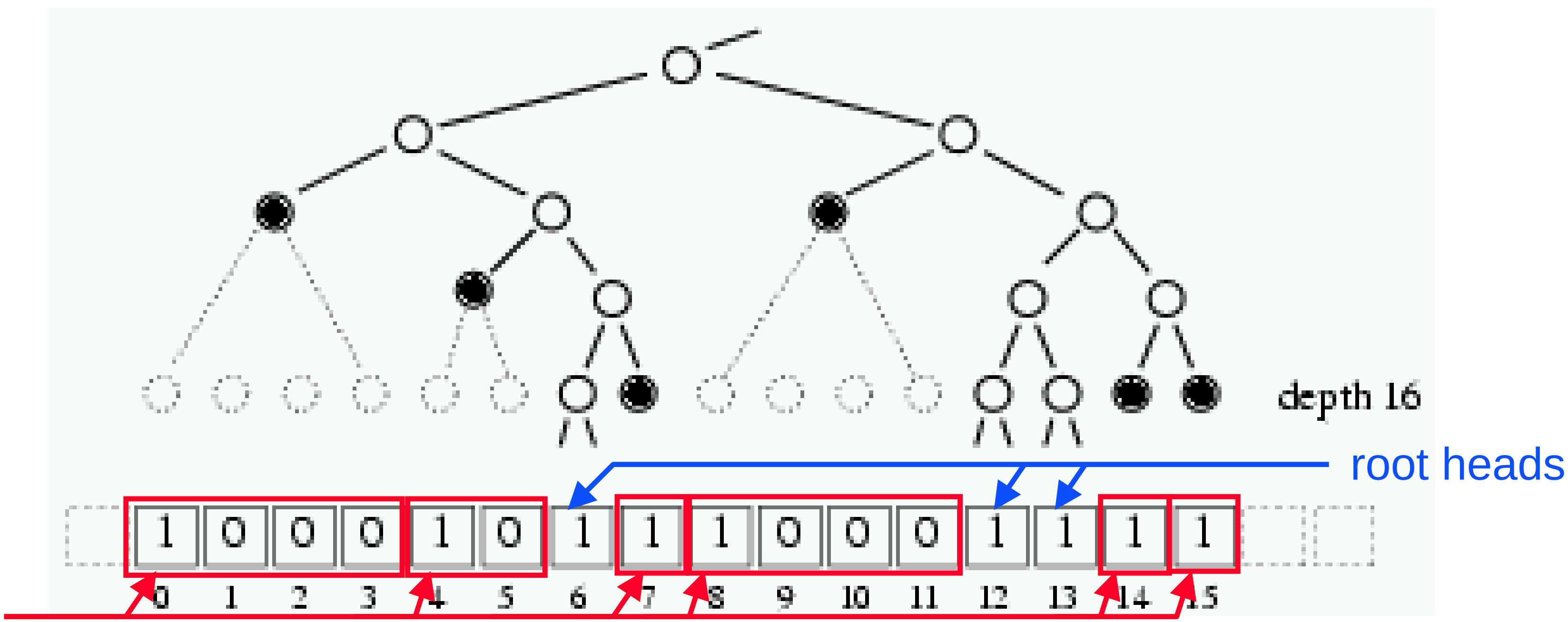
Lulea's Routing Lookup Algorithm

- Minimize number of memory accesses
- Minimize size of data structure
  - Small size allow to fit entire data structure in the cache (why do you care about size?)
- Solution: use a three level data structure



First Level: Bit-Vector

- Cover all prefixes down to depth 16
- Use one bit to encode each prefix
  - Memory requirements: 2^{16} = 64 Kb = 8 KB

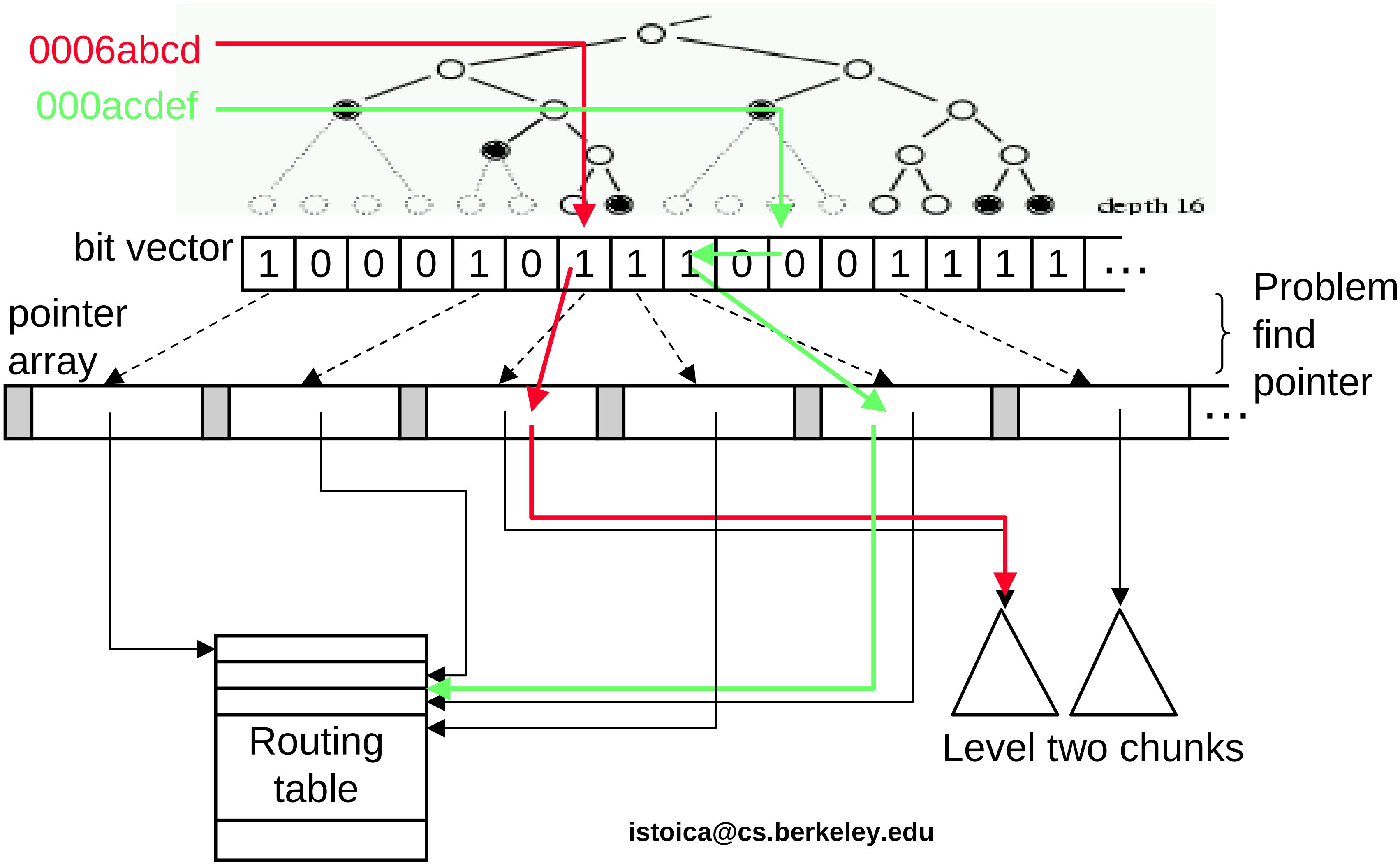


genuine heads

First Level: Pointers

- Maintain 16-bit pointers to (1) next-hop (routing) table or (2) to two level chuncks
  - 2 bits encode pointer type
  - 14 bits represent an index into routing table or into an array containing level two chuncks
- Pointers are stored at consecutive memory addresses
- Problem: find the pointer

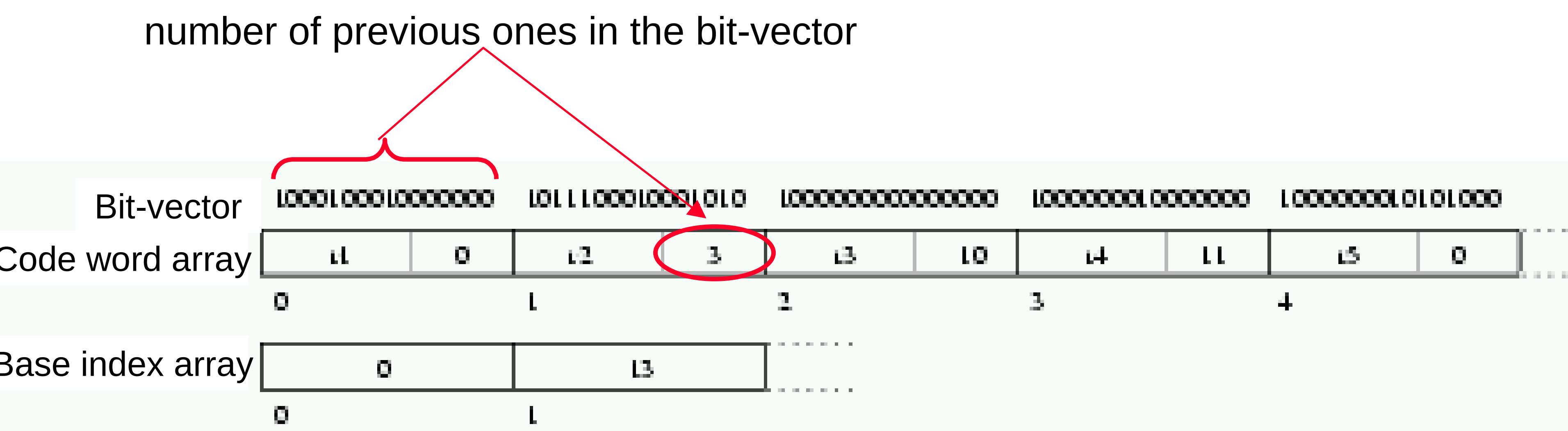
Example



0006abcd
000acdef
depth 16
bit vector
1 0 0 0 1 0 1 1 1 0 0 0 1 1 1 1 …
pointer array
…
Problem: find pointer
Routing table
Level two chunks

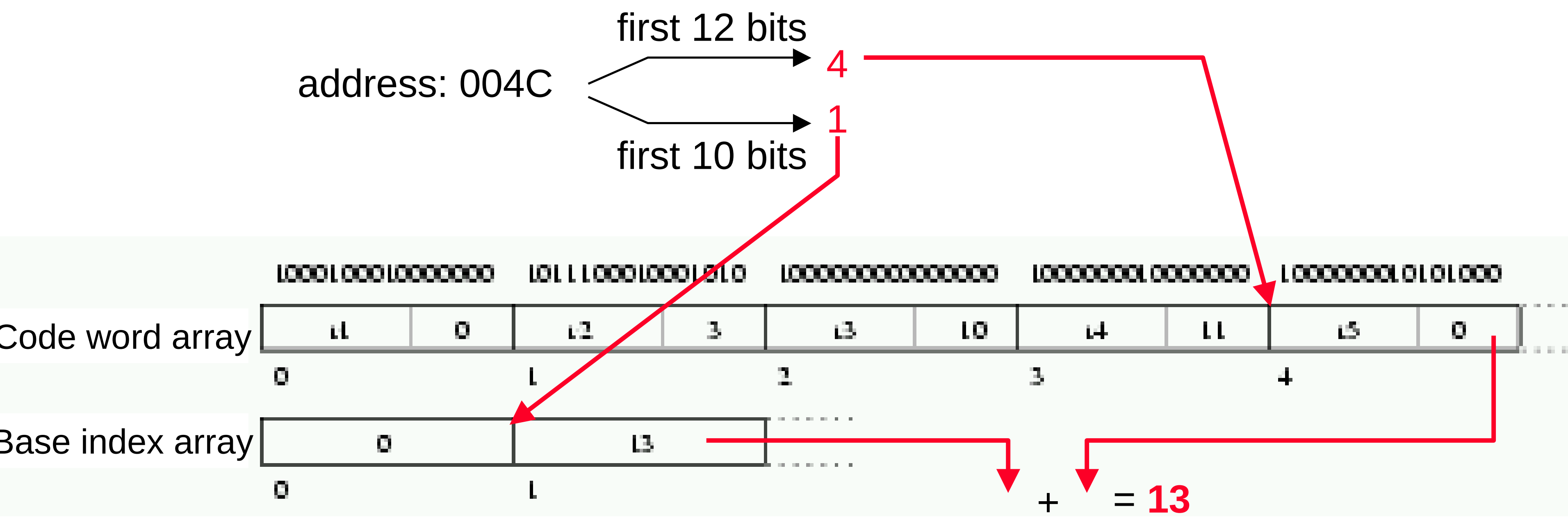
Code Word and Base Indexes Array

- Split the bit-vector in bit-masks (16 bits each)
- Find corresponding bin-mask
- How?
  - Maintain a16-bit code word for each bit-mask (10-bit value; 6-bit offset)
  - Maintain a base index array (one 16-bit entry for each 4 code words)



First Level: Finding Pointer Group

- Use first 12 bits to index into code word array
- Use first 10 bits to index into base index array

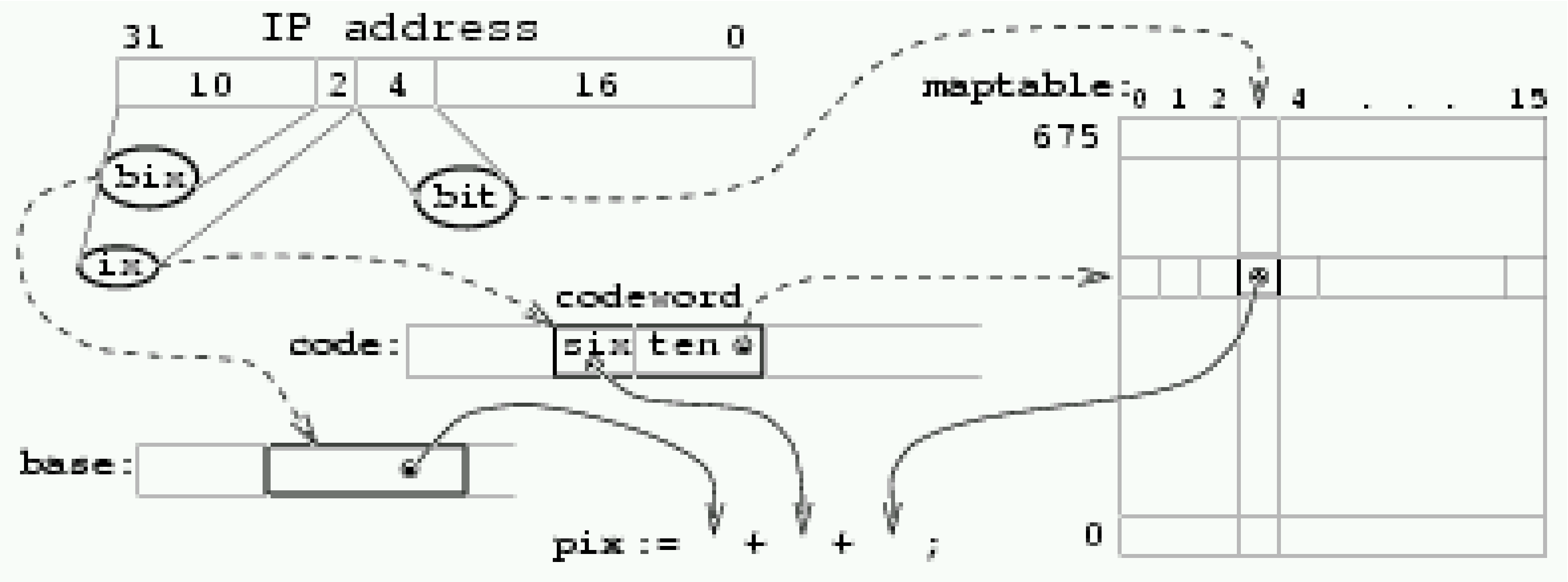


First Level: Encoding Bit-masks

- Observation: not all 16-bit values are possible
  - Example: bit-mask 1001… is not possible (why?)
- Let a(n) be number of bit-masks of length 2^n
- Compute a(n) using recurrence:
  - $a(0) = 1$
  - $a(n) = 1 + a(n-1)^2$
- For length 16, we get only 677 possible values for bit-masks
- This can be encoded in 10 bits
  - Values r_i in code words
- Store all possible bit-masks in a table, called maptable

First Level: Finding Pointer Index

- Each entry in Maptable is an offset of 4 bits:
  - Offset of pointer in the group
- Number of memory accesses: 3 (7 bytes accessed)



First Level: Memory Requirements

- Code word array: one code word per bit-mask
  - 64 Kb
- Based index array: one base index per four bit-mask
  - 16 Kb
- Maptable: 677x16 entries, 4 bits each
  - ~ 43.3 Kb
- Total: 123.3 Kb = 15.4 KB

First Level: Optimizations

- Reduce number of entries in Maptable by two:
  - Don’t store bit-masks 0 and 1; instead encode pointers directly into code word
  - If r value in code word larger than 676 → direct encoding
  - For direct encoding use r value + 6-bit offset

Levels 2 and 3

- Levels 2 and 3 consists of chunks
- A chunck covers a sub-tree of height 8 → at most 256 heads
- Three types of chunks
  - Sparse: 1-8 heads
    - 8-bit indices, eight pointers (24 B)
  - Dense: 9-64 heads
    - Like level 1, but only one base index (< 162 B)
  - Very dense: 65-256 heads
    - Like level 1 (< 552 B)
- Only 7 bytes are accessed to search each of levels 2 and 3

Limitations

- Only 2^{14} chuncks of each kind
  - Can accommodate a growth factor of 16
- Only 16-bit base indices
  - Can accommodate a growth factor of 3-5
- Number of next hops <= 2^{14}

Notes

- This data structure trades the table construction time for lookup time (build time < 100 ms)
  - Good trade-off because routes are not supposed to change often
- Lookup performance:
  - Worst-case: 101 cycles
    - A 200 MHz Pentium Pro can do at least 2 millions lookups per second
  - On average: ~ 50 cycles
- Open question: how effective is this data structure in the case of IPv6 ?

Classification Problem

- Classify an IP packet based on a number of fields in the packet header, e.g.,
  - source/destination IP address (32 bits)
  - source/destination port number (16 bits)
  - TOS byte (8 bits)
  - Type of protocol (8 bits)
- In general fields are specified by range

Example of Classification Rules

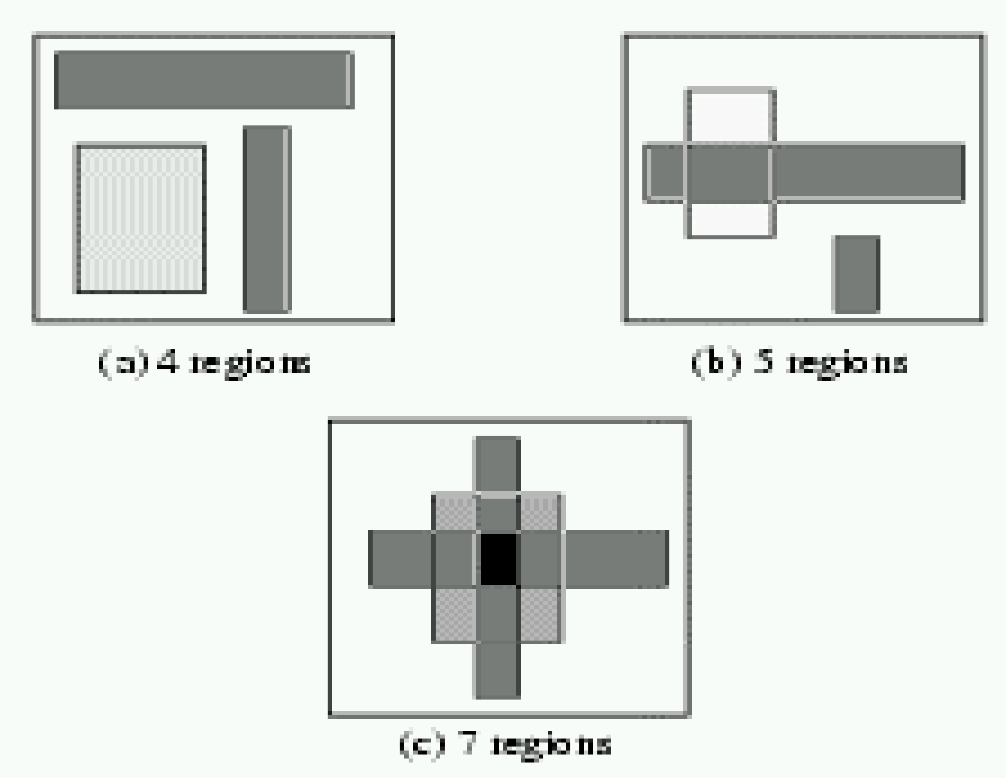
- Access-control in firewalls
  - Deny all e-mail traffic from ISP-X to Y
- Policy-based routing
  - Route IP telephony traffic from X to Y via ATM
- Differentiate quality of service
  - Ensure that no more than 50 Mbps are injected from ISP-X

Characteristics of Real Classifiers

- Results are collected over 793 packet classifiers from 101 ISPs, with a total of 41,505 rules
  - Classifiers do not contain many rules: mean = 50 rules, max = 1734 rules, only 0.7% contain over 1000 rules
  - Many fields are specified by range, e.g., greater than 1023, or 20-24
  - 14% of classifiers had a rule with a non-contiguous mask !
  - Rules in the same classifier tend to share the same fields
  - 8% of the rules are redundant, i.e., they can be eliminated without changing classifier’s behavior

Example

- Two-dimension space (i.e., classification based on two fields)
- Complexity depends of the layout (i.e., how many distinct regions are created)



(a) 4 regions (b) 5 regions (c) 7 regions

Hard Problem

- Even if regions don't overlap, with n rules and F fields we have the following lower-bounds
  - O(log n) time and $O(n^F)$ space
  - $O(\log^{F-1} n)$ time and O(n) space

Simplifying Assumptions

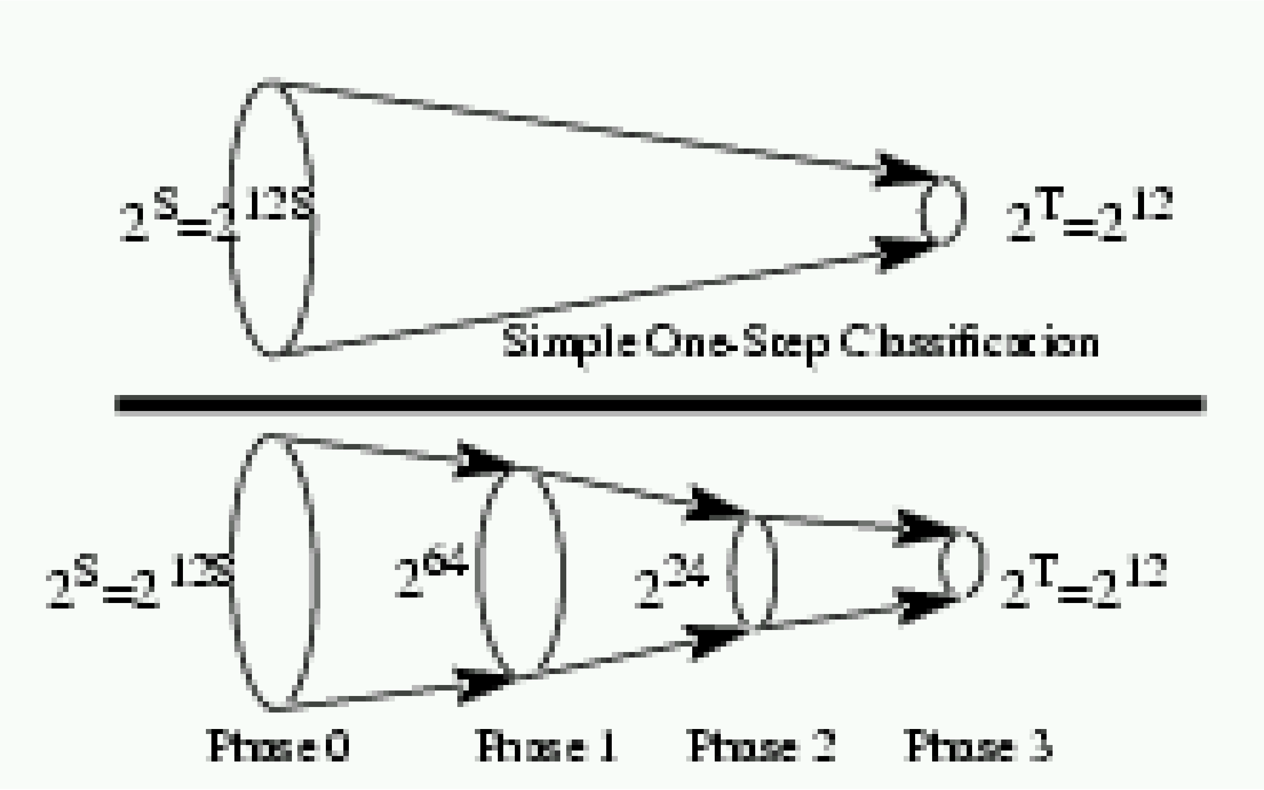
- In practice, you get the average not the worst-case, e.g., number of overlapping regions for the largest classifier 4316 vs. theoretical worst case 10^{13}
- The number of rules is reasonable small, i.e., at most several thousands
- The rules do not change often

Recursive Flow Classification (RFC) Algorithm

- Problem formulation:
  - Map S bits (i.e., the bits of all the F fields) to T bits (i.e., the class identifier)
- Main idea:
  - Create a 2^S table with pre-computed values; each entry would contain the class identifier
    - Only one memory access needed
  - …but this is impractical → require huge memory

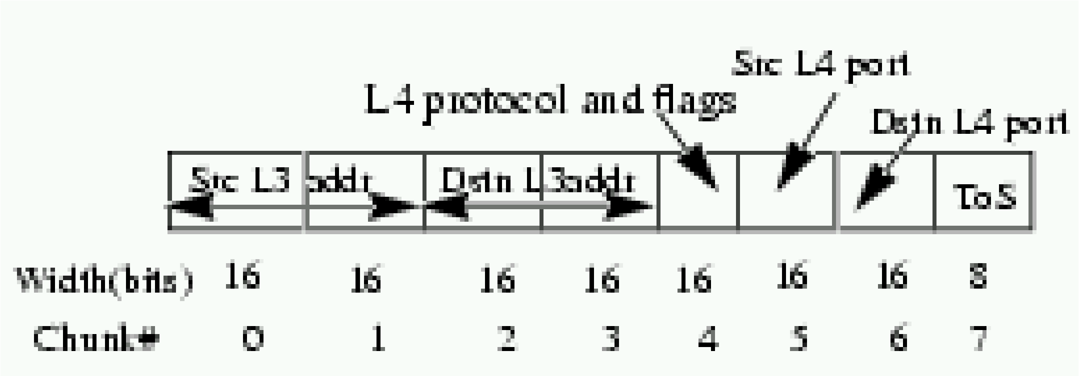
RFC Algorithm

- Use recursion: trade speed (number of memory accesses) for memory footprint



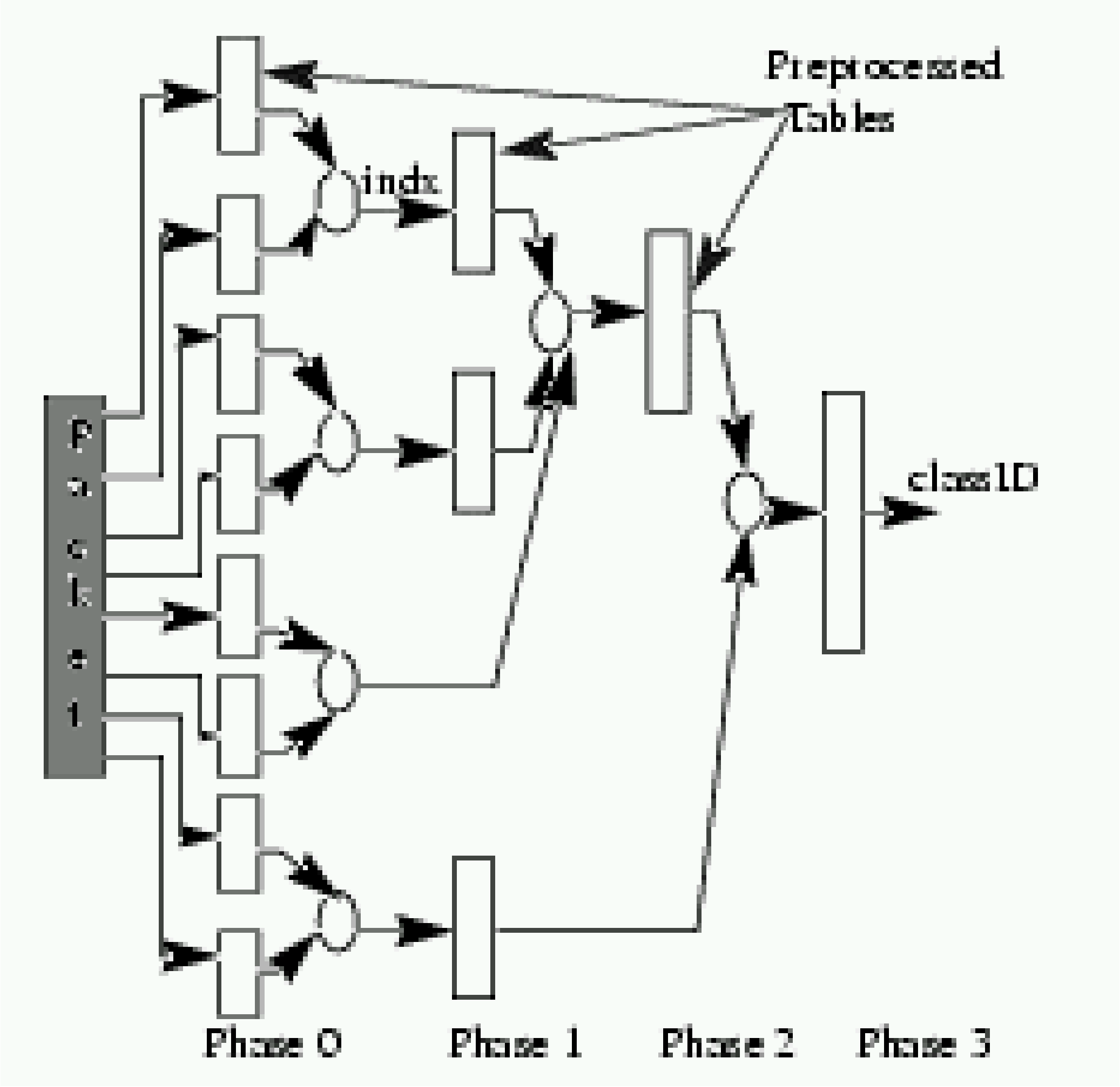
The RFC Algorithm

- Split the F fields in chuncks



- Use the value of each chunck to index into a table
  - Indexing is done in parallel
- Combine results from previous phase, and repeat
- In the final phase we obtain only one value

Example of Packet Flow in RFC

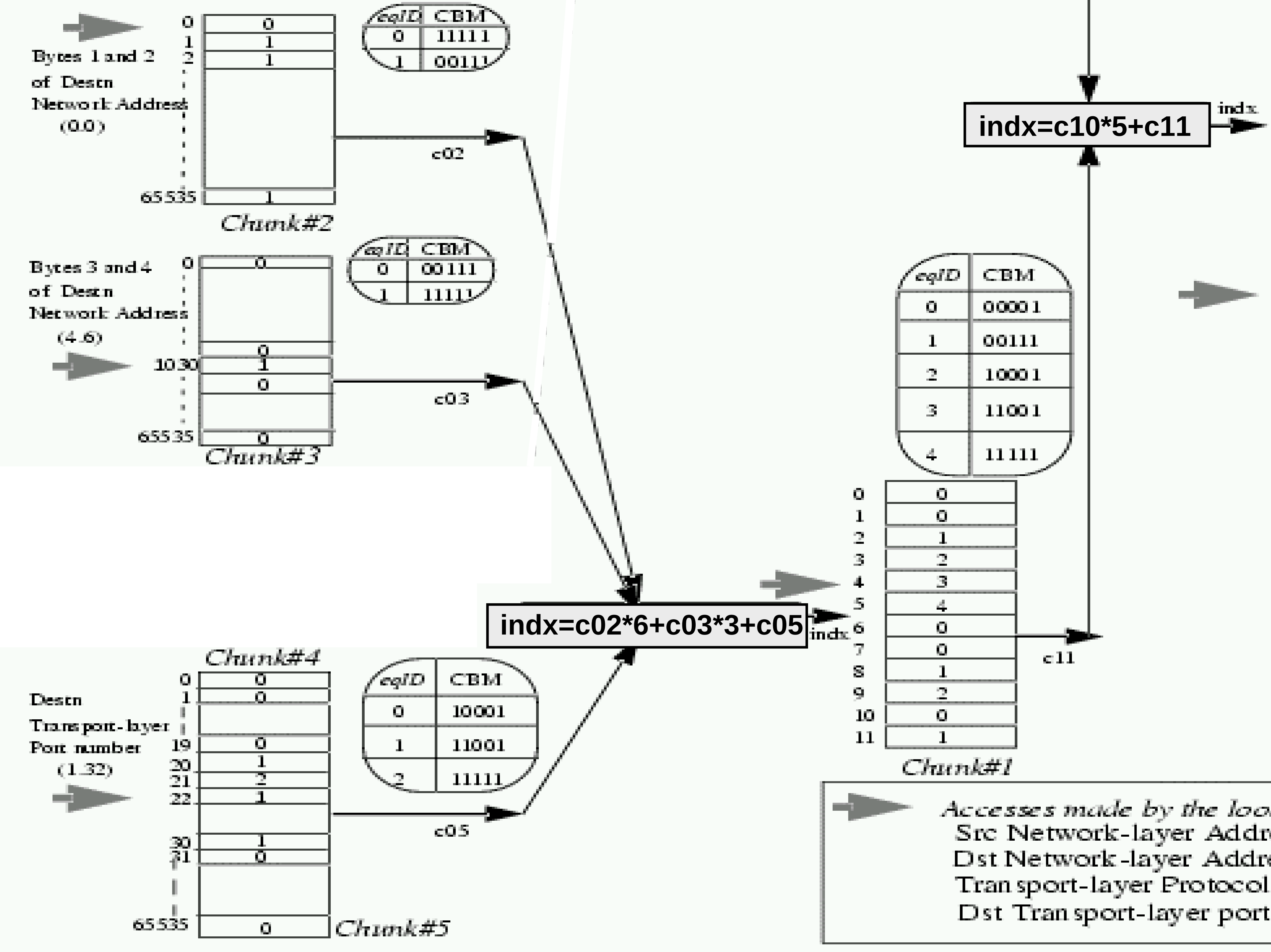


Complete Example

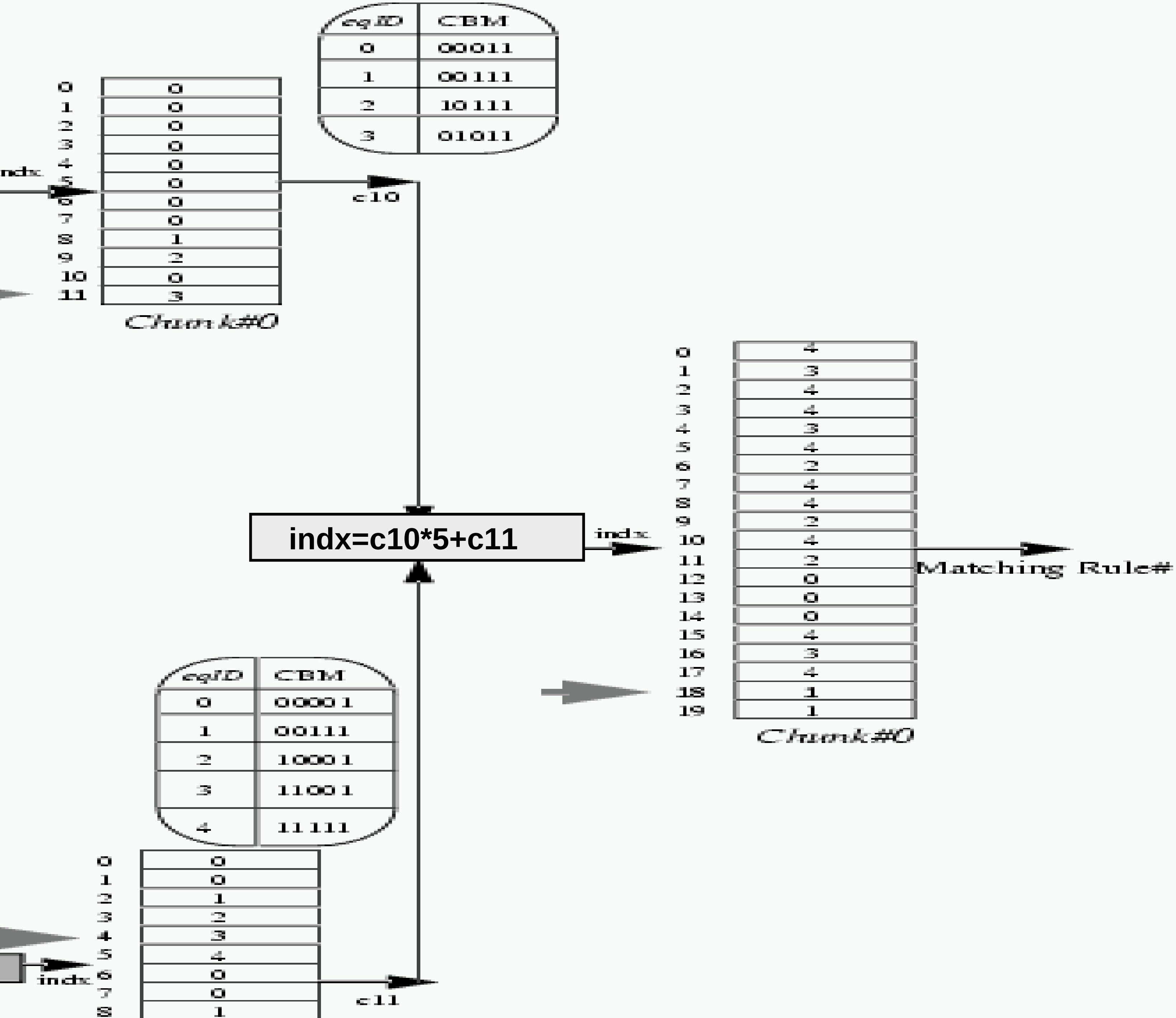
- Four fields → six chunks
  - Source and destination IP addresses → two chuncks each
  - Protocol number → one chunck
  - Destination port number → one chunck

Table 6:

Rule#	Chunk#0 (Src L3 bits 31..16)	Chunk#1 (Src L3 bits 15..0)	Chunk#2 (Dst L3 bits 31..16)	Chunk#3 (Dst L3 bits 15..0)	Chunk#4 (L4 protocol) [8 bits]	Chunk#5 (Dstn L4) [16 bits]	Action
(0)	0.83/0.0	0.77/0.0	0.0/0.0	4.6/0.0	udp (17)	*	permit
(1)	0.83/0.0	1.0/0.255	0.0/0.0	4.6/0.0	udp	range 20 30	permit
(2)	0.83/0.0	0.77/0.0	0.0/255.255	0.0/255.255	*	21	permit
(3)	0.0/255.255	0.0/255.255	0.0/255.255	0.0/255.255	*	21	deny
(4)	0.0/255.255	0.0/255.255	0.0/255.255	0.0/255.255	*	*	permit



Bytes 1 and 2 of Destn Network Address (0.0)
Chunk#2
eqID CBM
0 11111
1 00111
c02
Bytes 3 and 4 of Destn Network Address (4.6)
Chunk#3
eqID CBM
0 00111
1 11111
c03
Chunk#4
Destn Transport-layer Port number (1.32)
Chunk#5
eqID CBM
0 10001
1 11001
2 11111
c05
indx=c02*6+c03*3+c05
indx
Chunk#1
eqID CBM
0 00001
1 00111
2 10001
3 11001
4 11111
c11
indx=c10*5+c11
indx


eqID CBM
0 00011
1 00111
2 10111
3 01011
indx
c10
Chunk#0
indx=c10*5+c11
indx
Matching Rule#
Chunk#0
eqID CBM
0 00001
1 00111
2 10001
3 11001
4 11111
indx
c11

RFC Lookup Performance

- Dataset: classifiers used in practice
- Hardware: 31.25 millions pps using three stage pipeline, and 4-bank 64 Mb SRAMs at 125 MHz
- Software: > 1million pps on a 333 MHz Pentium

RFC Scalling

- RFC does not handle well large (general) classifiers
  - As the number of rules increases, the memory requirements increase dramatically, e.g., for 1500 rules you may need over 4.5 MB with a three stage classifier
- Proposed solution: adjacency groups
  - Idea: group rules that generate the same actions and use same fields
  - Problems: can't tell which rule was matched

Summary

- Routing lookup and packet classification → two of the most important challenges in designing high speed routers
- Very efficient algorithms for routing lookup → possible to do lookup at the line speed
- Packet classification still an area of active research
- Key difficulties in designing packet classification:
  - Requires multi-field classification which is an inherently hard problem
  - If we want per flow QoS insertion/deletion need also to be fast
    - Harder to make update-lookup tradeoffs like Lulea's algorithm

RFC Algorithm: Example

- Phase 0:
  - Possible values for destination port number: 80, 20-21, >1023, *
    - Use two bits to encode
    - Reduction: 16→2
  - Possible values for protocol: udp, tcp, *
    - Use two bits to encode
    - Reduction: 8→2
- Phase 1:
  - Concatenate from phase 1, five possible values: {80,udp}, {20-21,udp}, {80,tcp}, {>1023,tcp}, everything else
    - Use three bits to encode
    - Reduction 4→3

Network-layer Destination (addr/mask)	Network-layer Source (addr/mask)	Transport-layer Destination	Transport-layer Protocol
152.163.190.69/0.0.0.0	152.163.80.11/0.0.0.0	*	*
152.168.3.0/0.0.0.255	152.163.200.157/0.0.0.0	eq www	udp
152.168.3.0/0.0.0.255	152.163.200.157/0.0.0.0	range 20-21	udp
152.168.3.0/0.0.0.255	152.163.200.157/0.0.0.0	eq www	tcp
152.163.198.4/0.0.0.0	152.163.160.0/0.0.3.255	gt 1023	tcp
152.163.198.4/0.0.0.0	152.163.36.0/0.0.0.255	gt 1023	tcp