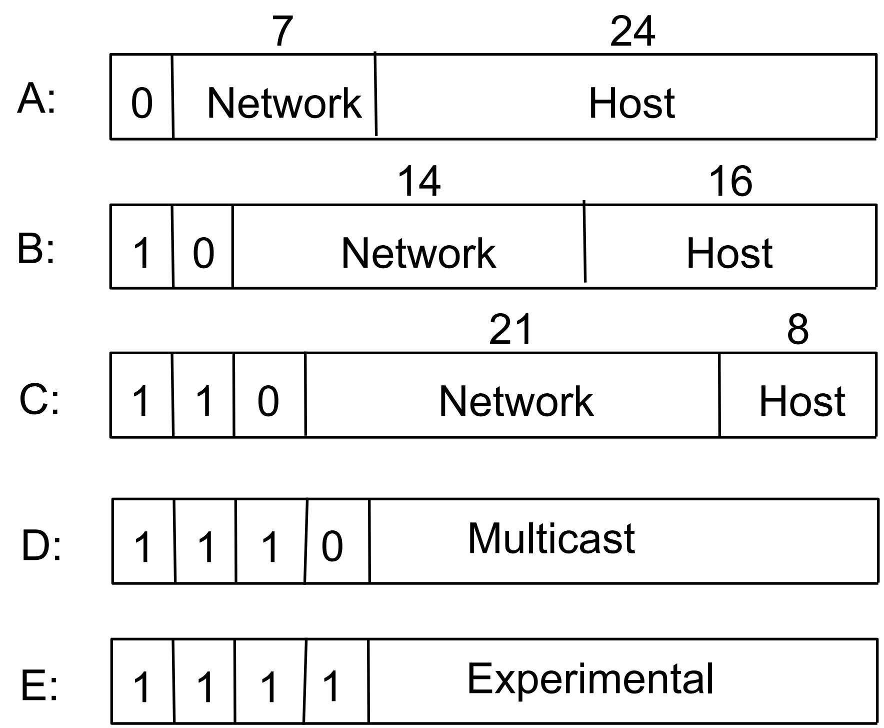
Efficient Addressing and Forwarding

Outline

- Addressing
- Subnetting
- Supernetting
- CIDR
- Longest Prefix Match

Global Addresses

- Properties
  - IPv4 uses 32 bit address space
  - globally unique
  - hierarchical: network + host
- Dot Notation
  - 10.3.2.4
  - 128.96.33.81
  - 192.12.69.77
- Assigning authority
  - Jon Postel ran IANA ‘til ‘98
  - Assigned by ICANN



How to Make Routing Scale

- Flat (Ethernet) versus Hierarchical (Internet) Addresses
  - All hosts attached to same network have same network address
- Problem: inefficient use of Hierarchical Address Space
  - class C with 2 hosts (2/255 = 0.78% efficient)
  - class B with 256 hosts (256/65535 = 0.39% efficient)
- Problem: still Too Many Networks
  - routing tables do not scale
    - Big tables make routers expensive
  - route propagation protocols do not scale

Today’s Internet

- Consists of ISP’s (Internet Service Providers) who run AS’s (Autonomous Systems)
- All you need to become an ISP is some address space, an AS number and a peer or two
  - Easier said than done
    - Getting addresses and AS number is the tricky part
    - There are public peering points (MAE East, Central and West)
      - NAP’s run by MCI where peering can take place
    - Most peering points are private
- Number of connections have been doubling for some time – how do we deal with this kind of scaling?

Subnetting - 1985

- Original intent was for network to identify one physical network
  - Lots of small networks are what we actually have – how do we handle this?
- Solution: add another level to address/routing hierarchy: *subnet*
  - Allocate addresses to several physical networks
  - Routers in other ASs route all traffic to network as if it is a single physical network
- *Subnet masks* define variable partition of host part
  - 1's identify subnet, 0's identify hosts within the subnet
  - Mechanism for sharing a single network number among multiple networks
- Subnets visible only within a site

Network number	Host number

Class B address

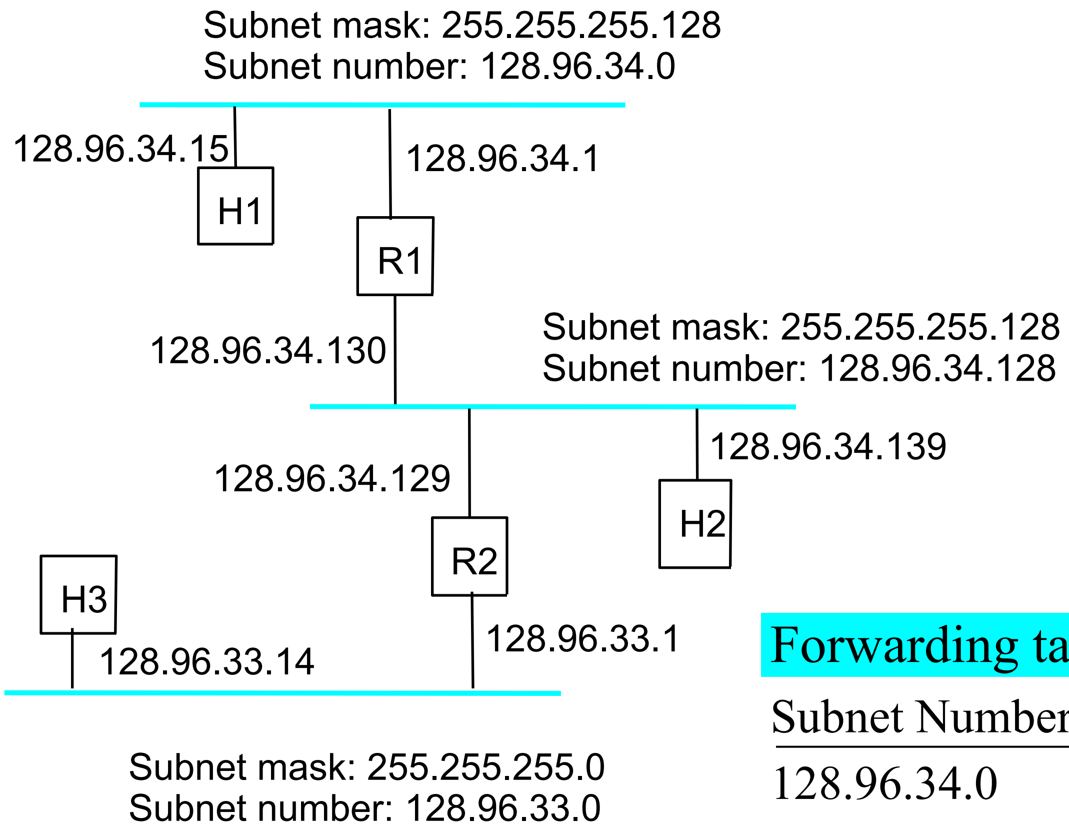
111111111111111111111111	00000000

Subnet mask (255.255.255.0)

Network number	Subnet ID	Host ID

Subnetted address

Subnet Example



Forwarding table at router R1

Subnet Number	Subnet Mask	Next Hop
128.96.34.0	255.255.255.128	interface 0
128.96.34.128	255.255.255.128	interface 1
128.96.33.0	255.255.255.0	R2

Forwarding Algorithm

```
D = destination IP address
for each entry (SubnetNum, SubnetMask, NextHop)
   D1 = SubnetMask & D
   if D1 = SubnetNum
      if NextHop is an interface
         deliver datagram directly to D
      else
         deliver datagram to NextHop
```

- Use a *default router* if nothing matches
- Not necessary for all 1s in subnet mask to be contiguous
- Can put multiple subnets on one physical network
- Subnets not visible from the rest of the Internet
- This is a simple, toy example!!

Subnets contd.

- Subnetting is not the only way to solve scalability problems
- Additional router support is necessary to include netmask and forwarding functionality
- Non-contiguous netmask numbers can be used
  - They make administration more difficult
- Multiple subnets can reside on a single network
  - Requires routers within the network
- Subnets help solve scalability problems
  - Do not require us to use class B or C address for each physical network
  - Help us to aggrigate information
- Chief advantage of IP addresses: routers could keep one entry per network instead of one per destination host

Continued Problems with IPv4 Addresses

- Problem:
  - Potential exhaustion of IPv4 address space (due to inefficiency)
    - Class B network numbers are highly prized
      - Not everyone needs one
    - Lots of class C addresses but no one wants them
  - Growth of back bone routing tables
    - We don't want lots of small networks since this causes large routing tables
    - Route calculation and management requires high computational overhead
- Solution:
  - Allow addresses assigned to a single entity to span multiple classed prefixes
  - Enhance route aggregation

Supernetting

- Assign block of contiguous network numbers to nearby networks
- Called CIDR: Classless Inter-Domain Routing
  - Breaks rigid boundries between address classes
  - If ISP needs 16 class C addresses, make them contiguous
    - Eg.192.4.16 to 192.4.31 enables a 20-bit network number
  - Idea is to enable network number to be any length
  - Collapse multiple addresses assigned to a single AS to one address
- Represent blocks (number of class C networks) with a single pair

  `(first_network_address, count)`
- Restrict block sizes to powers of 2
- Use a bit mask (CIDR mask) to identify block size
- All routers must understand CIDR addressing

CIDR Addresses

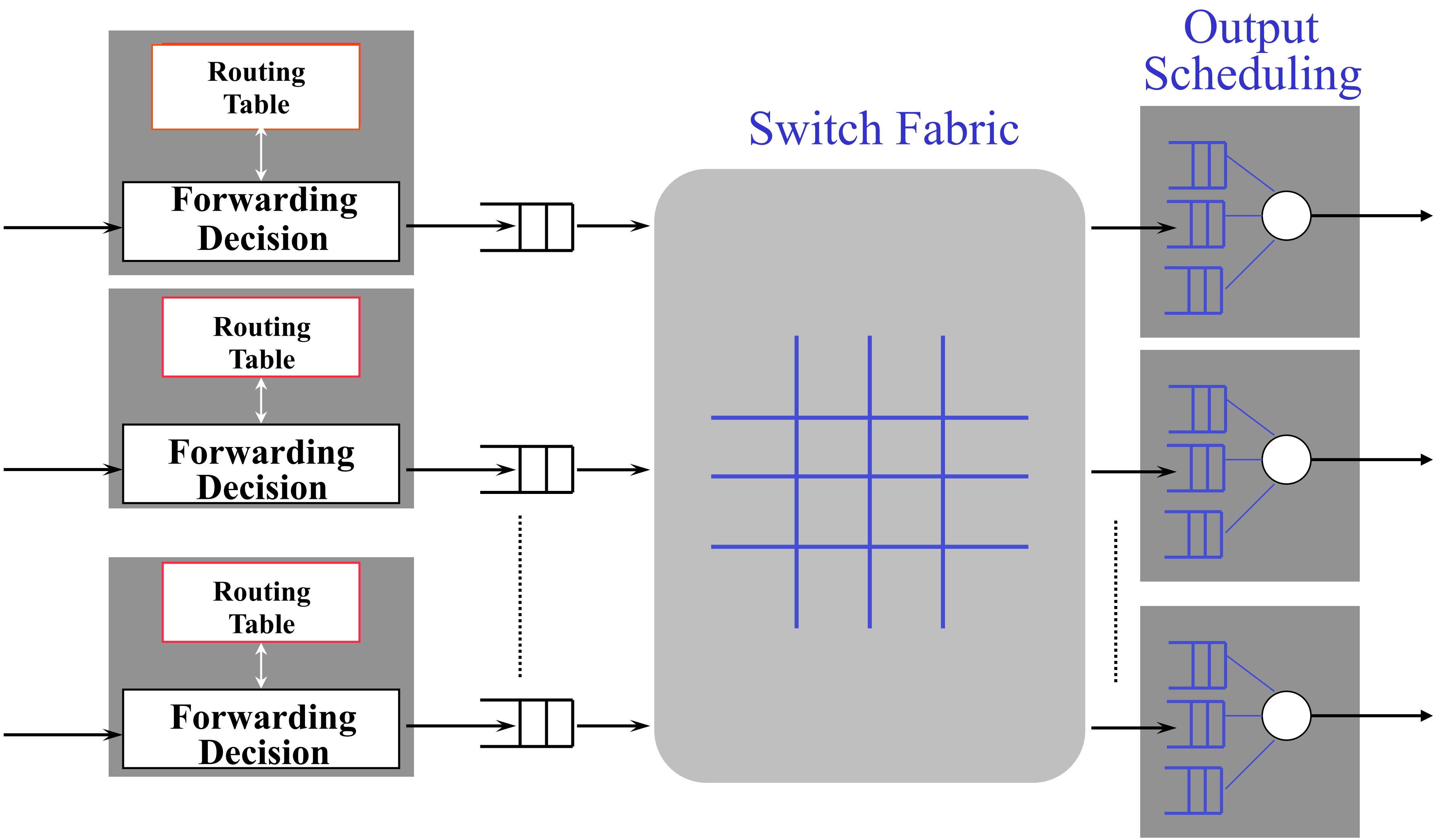
- Identifying a CIDR block requires both an address and a mask
  - Slash notation
  - 128.211.168.0/21 for addresses 128.211.168.0 – 128.211.175.255
    - Here the /21 indicates a 21 bit mask
  - All possible CIDR masks can easily be generated
    - /8, /16, /24 correspond to traditional class A, B, C categories
- IP addresses are now arbitrary integers, not classes
- Raises interesting questions about lookups
  - Routers cannot determine the division between prefix and suffix just by looking at the address
    - Hashing does not work well
    - Interesting lookup algorithms have been developed and analyzed

CIDR – A Couple Details

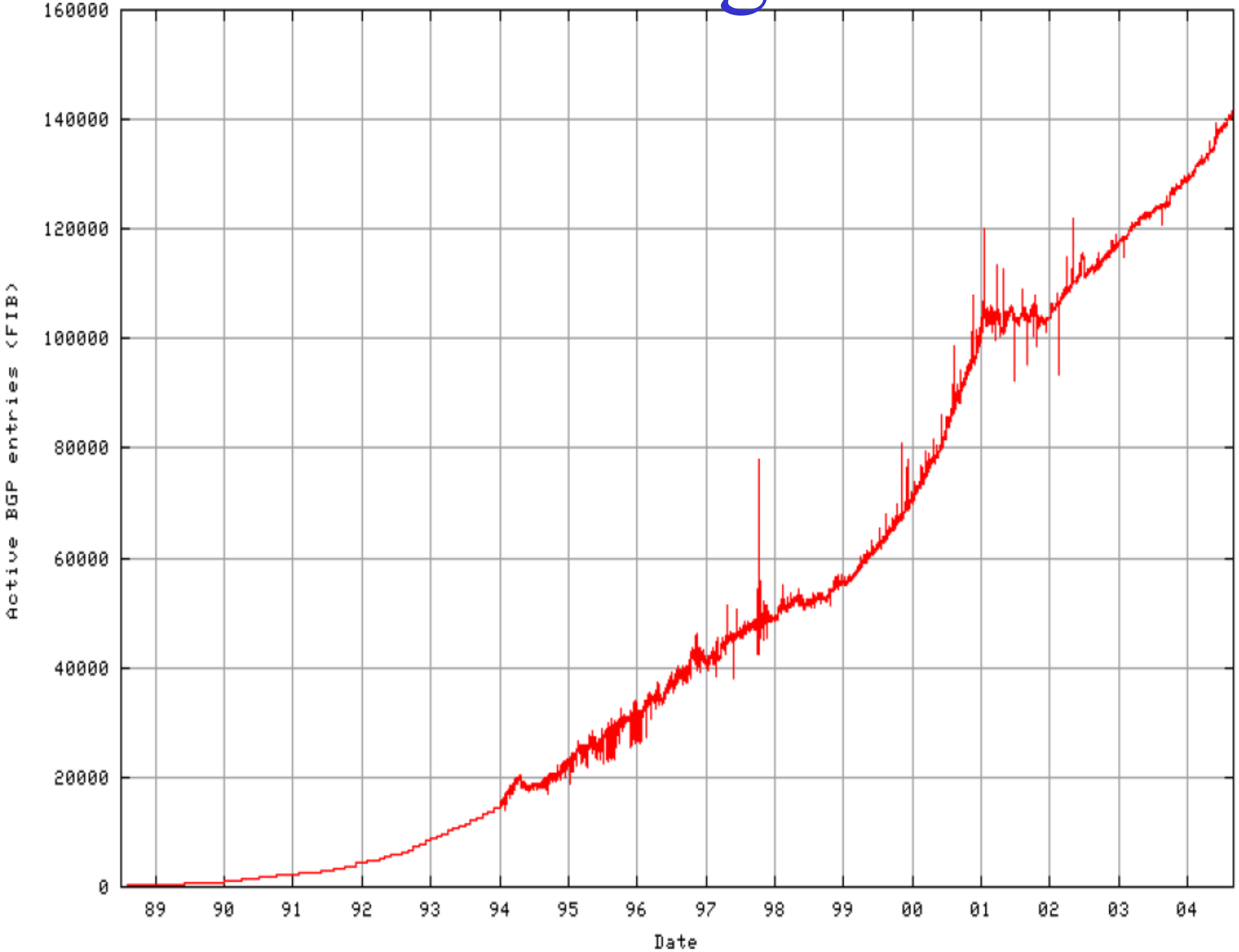
- ISP's can further subdivide their blocks of addresses using CIDR
- Some prefixes are reserved for private addresses
  - 10/8, 172.16/12, 192.168/16, 169.254/16
  - These are not routable in the Internet

Address Lookup in IP Routers

Routing Table Lookup

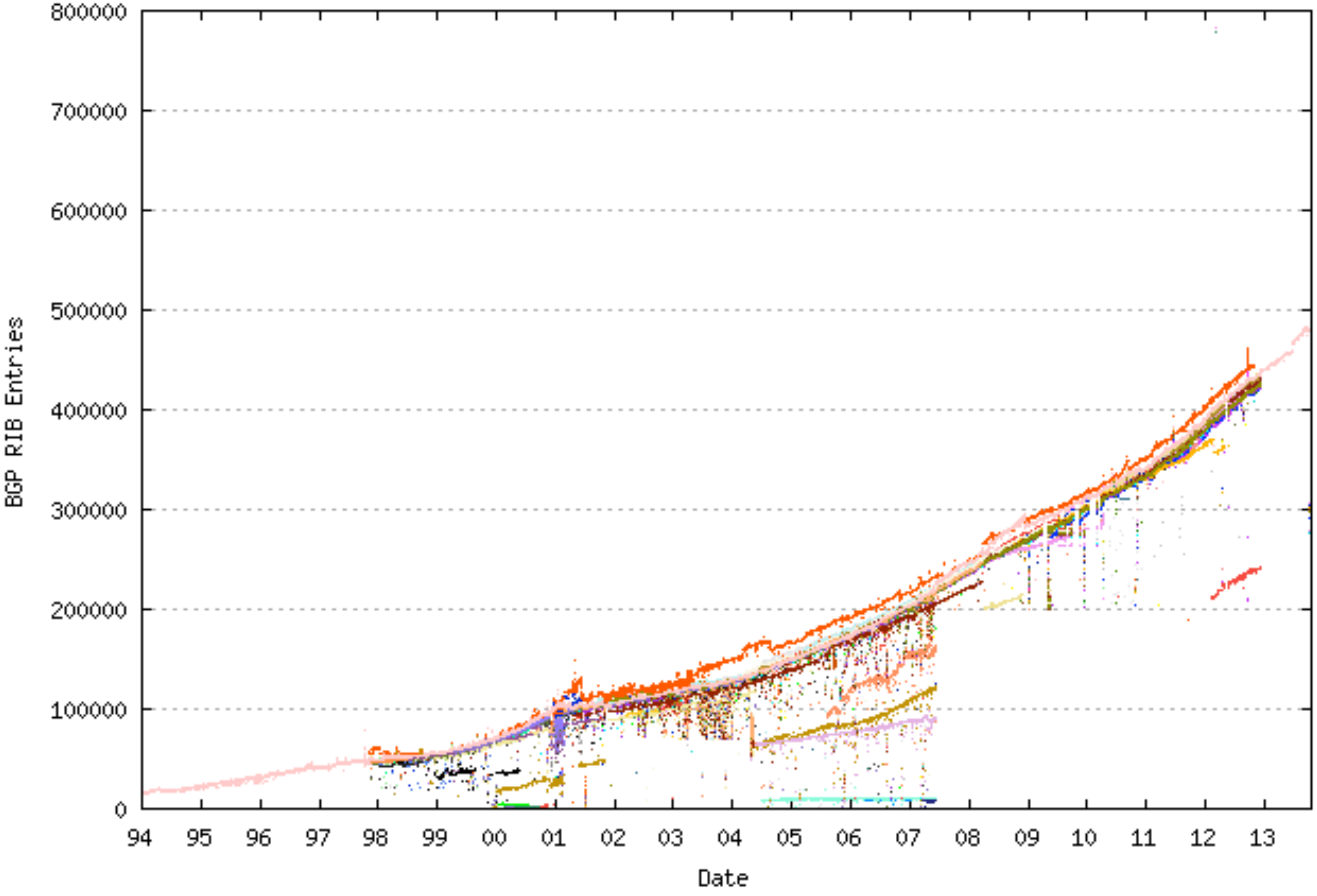


IPv4 Routing Table Size



Source: Geoff Huston, APNIC

IPv4 Routing Table Size



Source: bgp.potaroo.net, 2013

Routing table lookup: Longest Prefix Match

With CIDR, there can be multiple matches for a destination address in the routing table

Longest Prefix Match: Search for the routing table entry that has the longest match with the prefix of the destination IP address (=Most Specific Router):

1. *Search for a match on all 32 bits*
2. *Search for a match for 31 bits*

   .....

32. *Search for a mach on 0 bits*

Needed: Data structures that support a fast longest prefix match lookup!

128.143.71.21

Destination address	Next hop
10.0.0.0/8	R1
128.143.0.0/16	R2
128.143.64.0/20	R3
128.143.192.0/20	R3
128.143.71.0/24	R4
128.143.71.55/32	R3
default	R5

The longest prefix match for 128.143.71.21 is for 24 bits with entry 128.143.71.0/24

Datagram will be sent to R4

IP Address Lookup Algorithms

- The following algorithms are suitable for Longest Prefix Match routing table lookups

  - Tries
  - Path-Compressed Tries
  - Disjoint-prefix binary Tries
  - Multibit Tries
  - Binary Search on Prefix
  - Prefix Range Search

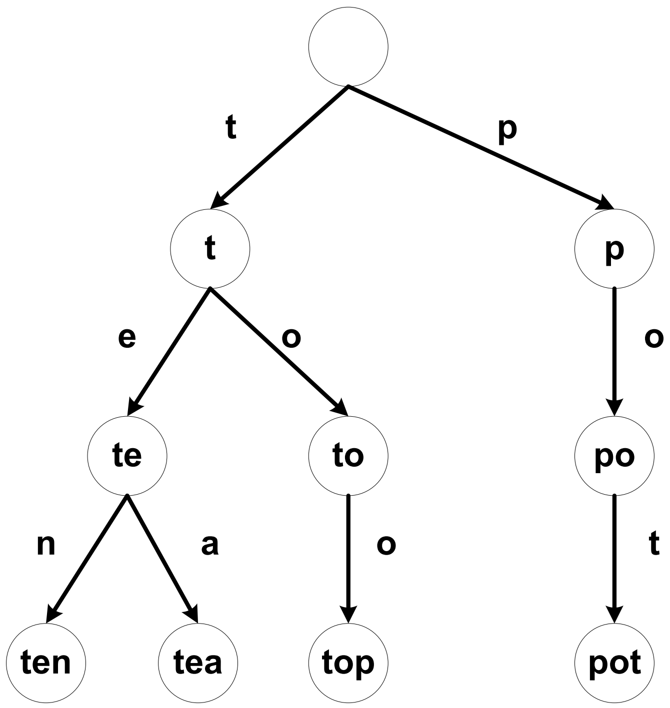
IP Address Lookup Algorithms

- The following algorithms are suitable for Longest Prefix Match routing table lookups

  - Tries
  - Path-Compressed Tries
  - Disjoint-prefix binary Tries
  - Multibit Tries
  - Binary Search on Prefix
  - Prefix Range Search

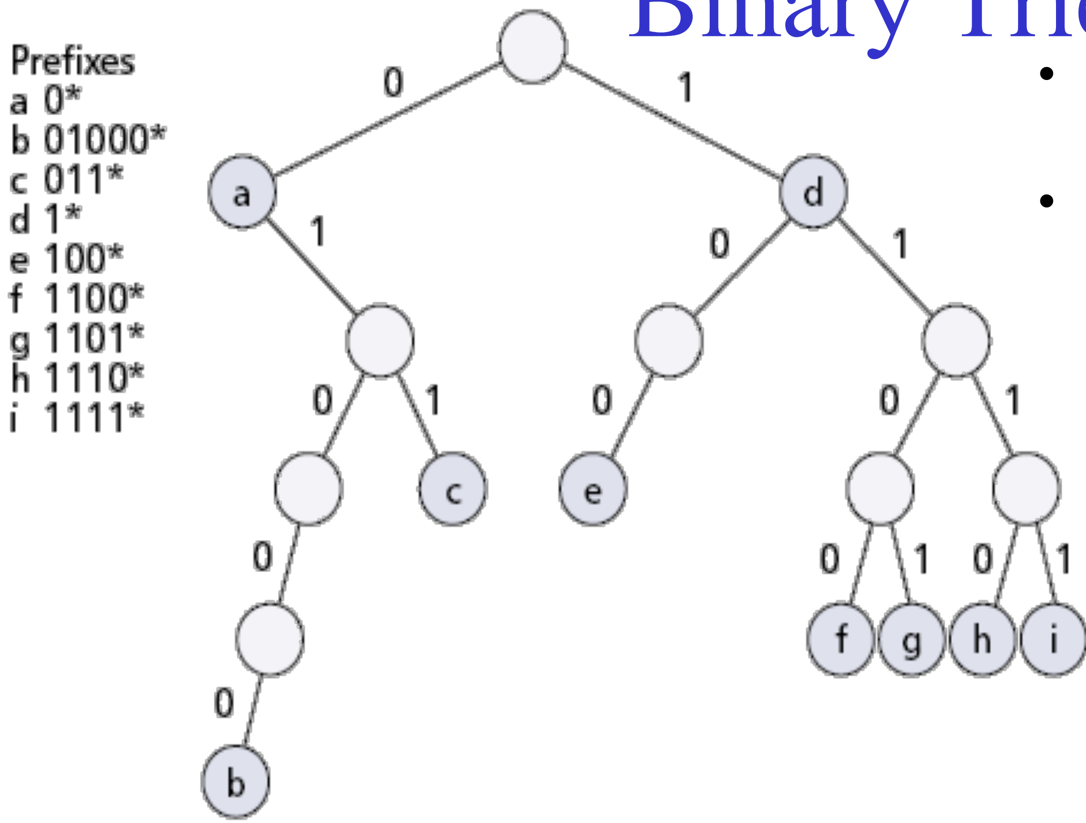
What is a Trie?

- A **trie** is a tree-based data structure for storing strings:
  - There is one *node* for every common *prefix*
  - The strings are stored in extra *leaf* nodes



- Tries can be used to store network prefixes
  - **Note:** Prefixes are not only stored at leaf nodes but also at internal nodes

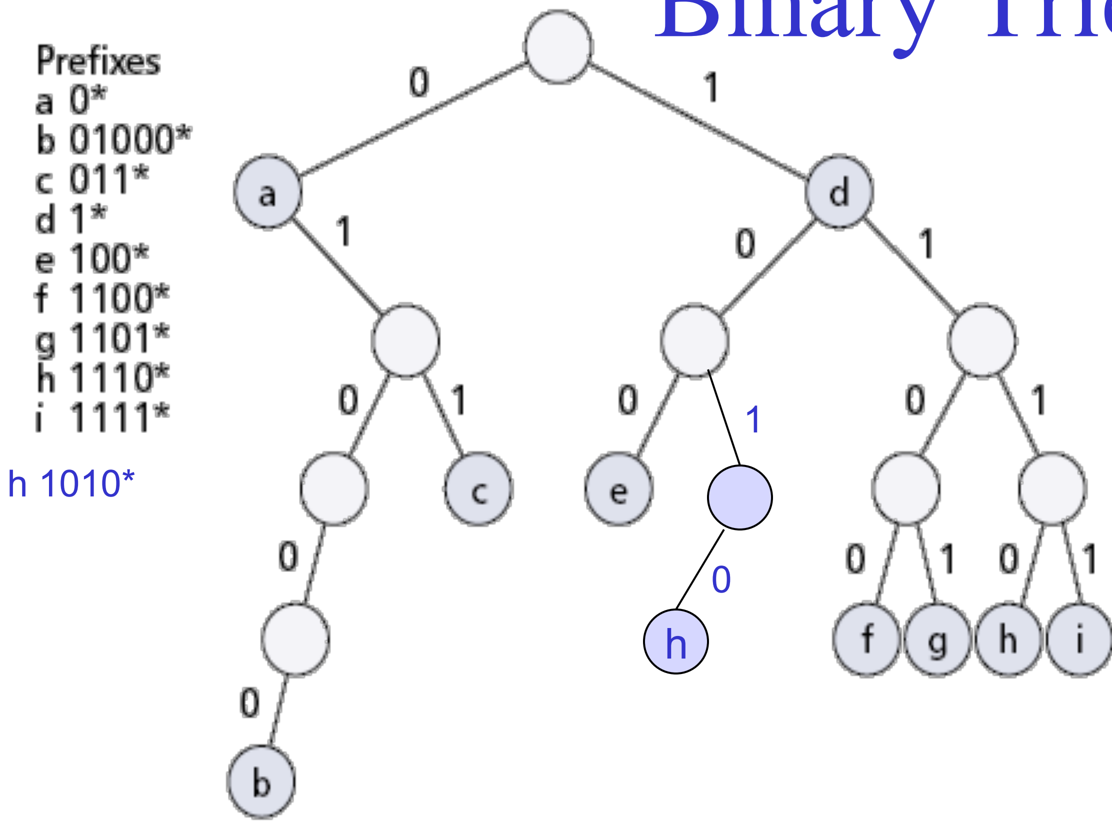
Binary Trie



- Each leaf contains a possible address
- Prefixes in the table are marked (dark)

- **Search:**
  - Traverse the tree according to destination address
  - Most recent marked node is the current longest prefix
  - Search ends when a leaf node is reached

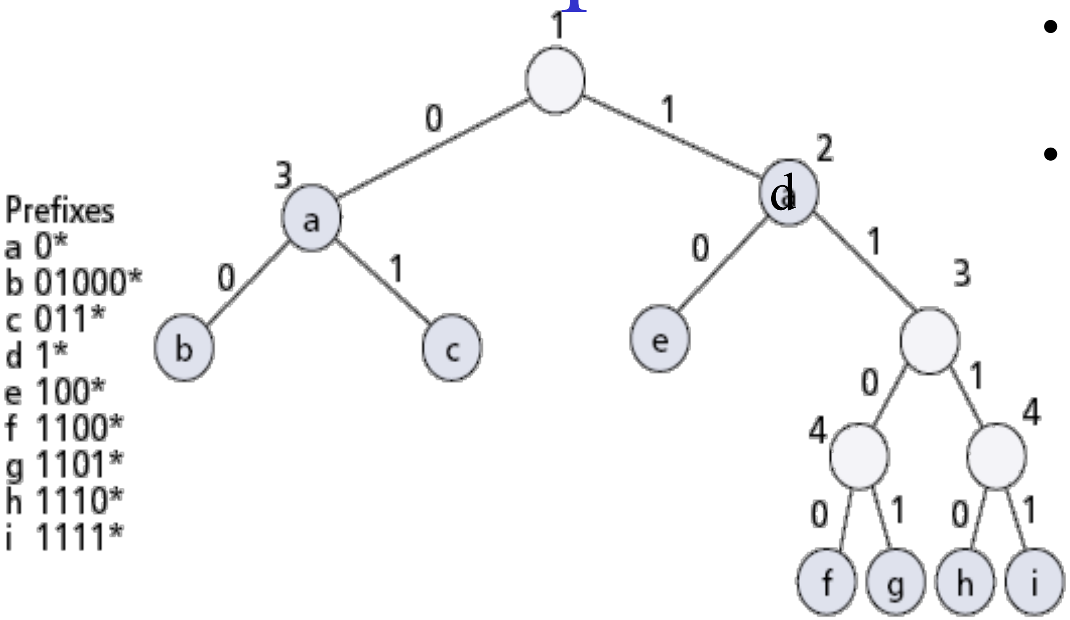
Binary Trie



- **Update:**
  - Search for the new entry
  - Search ends when a leaf node is reached
  - If there is no branch to take, insert new node(s)

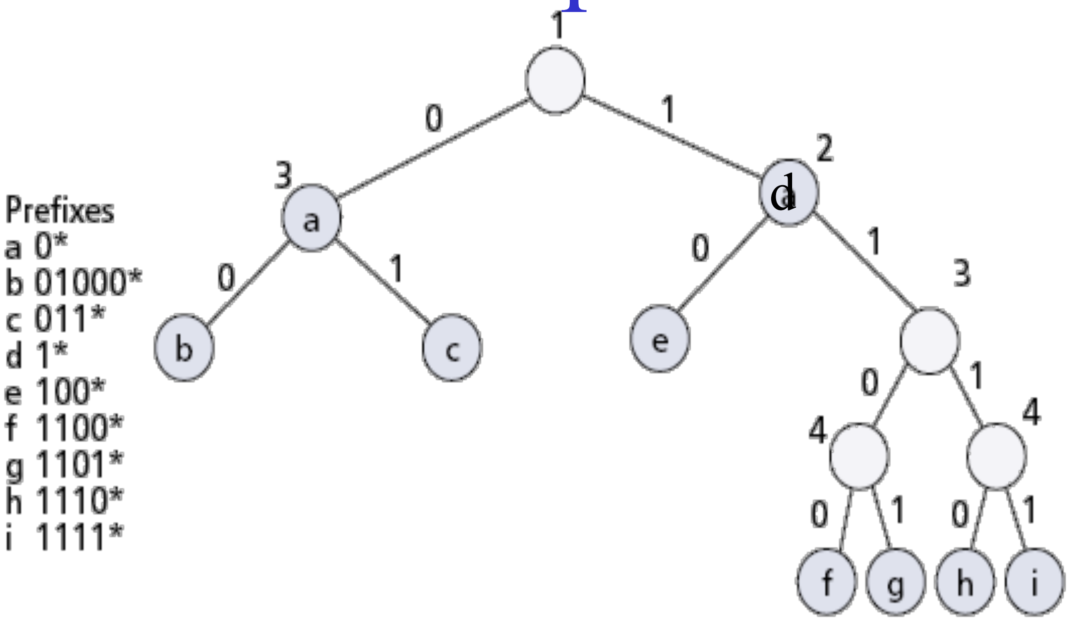
Compressed Binary Trie

- **Goal:** Eliminate long sequences of 1-child nodes
- Path compression → collapses 1-child branches



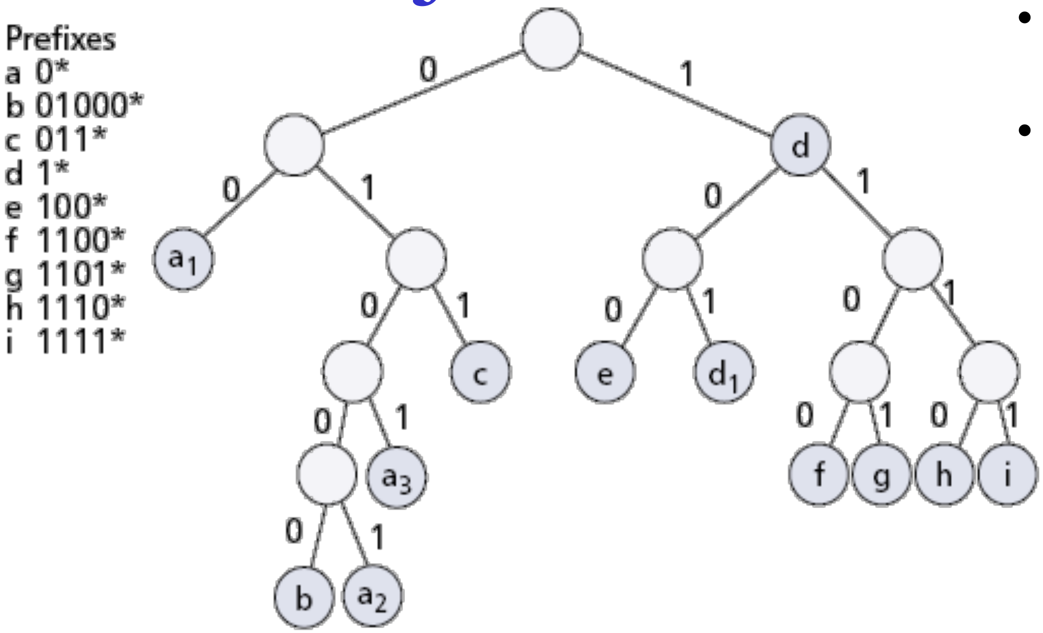
- **Path Compression:**
  - Requires to store additional information with nodes→ Bit number field is added to node
  - Bit string of prefixes must be explicitly stored at nodes
    - Need to make comparison when searching the tree

Compressed Binary Trie



- **Search: “010110”**
  - Root node: Inspect 1st bit and move left
  - “a” node:
    - Check with prefix of *a (“0*”)* and find a match
    - Inspect 3rd bit and move left
  - “b” node:
    - Check with prefix of *b (“01000*”)* and determine that there is no match
    - Search stops. Longest prefix match is with *a*

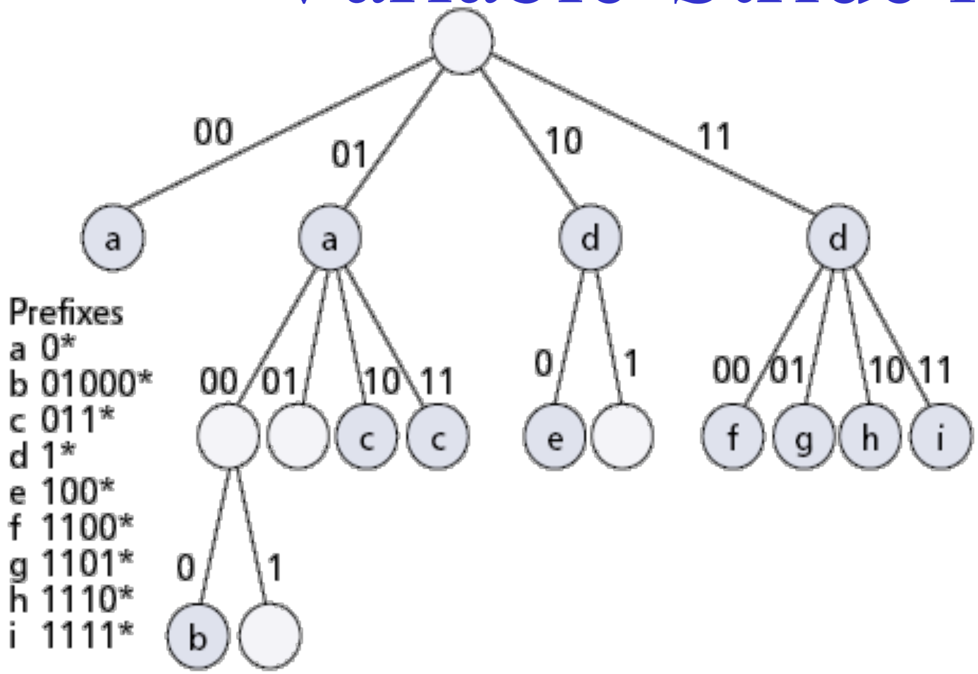
Disjoint-Prefix Binary Trie



- Multiple matches in longest prefix rule require backtracking of search
- **Goal:** Transform tree as to avoid multiple matches

- **Disjoint prefix:**
  - Nodes are split so that there is only one match for each prefix **("Leaf pushing")**
  - Consequence: Internal nodes do not match with prefixes
  - Results:
    - *a (0*)* is split into*:* a_1 *(00*)*, a_3 *(010*)*, a_2 *(01001*)*
    - *d (1*)* is represented as d_1 *(101*)*

Variable-Stride Multibit Trie



- **Goal:** Accelerate lookup by inspecting more than one bit at a time
- "Stride": number of bits inspected at one time
- With k-bit stride, node has up to 2^k child nodes

- ***2-bit stride:***
  - *1-bit prefix for a (0*) is split into 00* and 01**
  - *1-bit prefix for d (1*) is split into 10* and 11**
  - 3-bit prefix for *c* has been expanded to two nodes
  - Why are the prefixes for *b* and *e* not expanded?

Complexity of the Lookup

- Complexity is expressed with O(.) ("big – O") notation:
  - describes an **asymptotic upper bound** for the magnitude of a function in terms of another, usually simpler, function.

- W: length of the address (32 bits)
- N: number of prefix in the routing table

$O(N)$: growth is linear with N

$O(N^2)$: growth is quadratic with N

Complexity of the Lookup

- Bounds are expressed for
  - Look-up time: What is the longest lookup time?
  - Update time: How long does it take to change an entry?
  - Memory: How much memory is required to store the data structure?

Scheme	Lookup	Update	Memory
Binary trie	O(W)	O(W)	O(NW)
Path-compressed trie	O(W)	O(W)	O(NW)
k-stride multibit trie	O(W/k)	$O(W/k+2^k)$	$O(2^k NW/k)$