IP Addressing and Forwarding

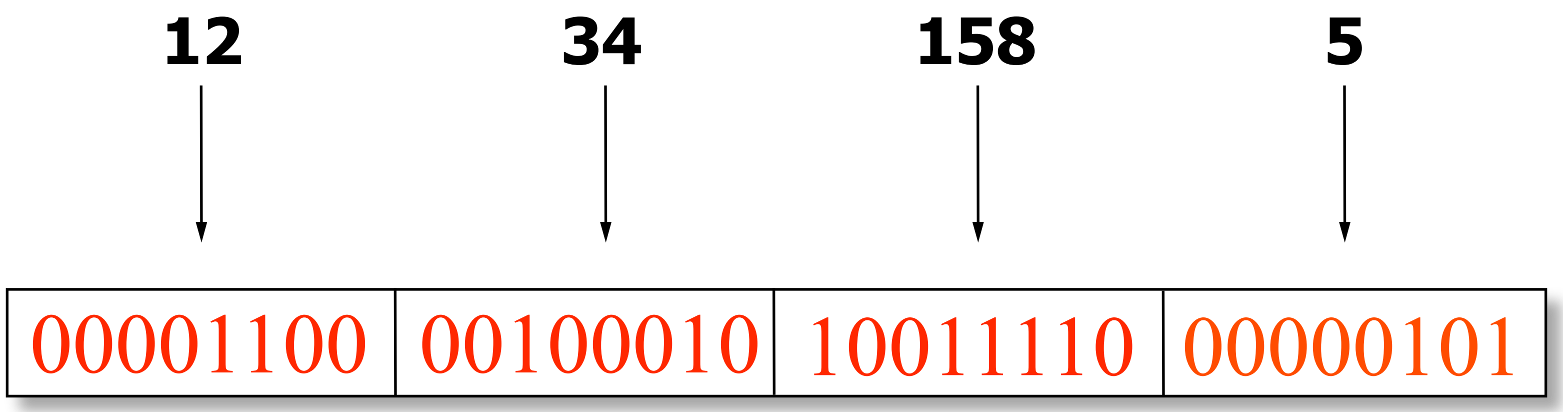
Acknowledgments: Lecture slides are from Computer networks course thought by Jennifer Rexford at Princeton University. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.

Goals of Today's Lecture

- IP addresses
  - Dotted-quad notation
  - IP prefixes for aggregation
- Address allocation
  - Classful addresses
  - Classless InterDomain Routing (CIDR)
  - Growth in the number of prefixes over time
- Packet forwarding
  - Forwarding tables
  - Longest-prefix match forwarding
  - Where forwarding tables come from

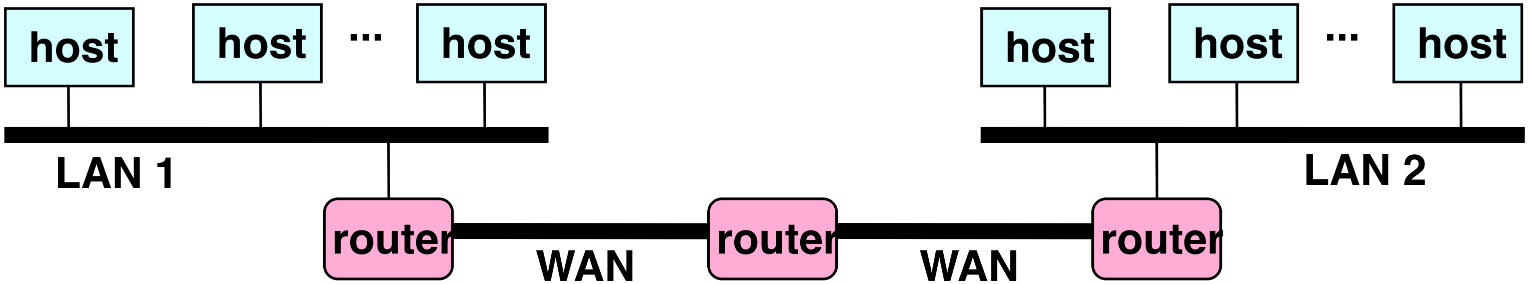
IP Address (IPv4)

- A unique 32-bit number
- Identifies an interface (on a host, on a router, …)
- Represented in dotted-quad notation



Grouping Related Hosts

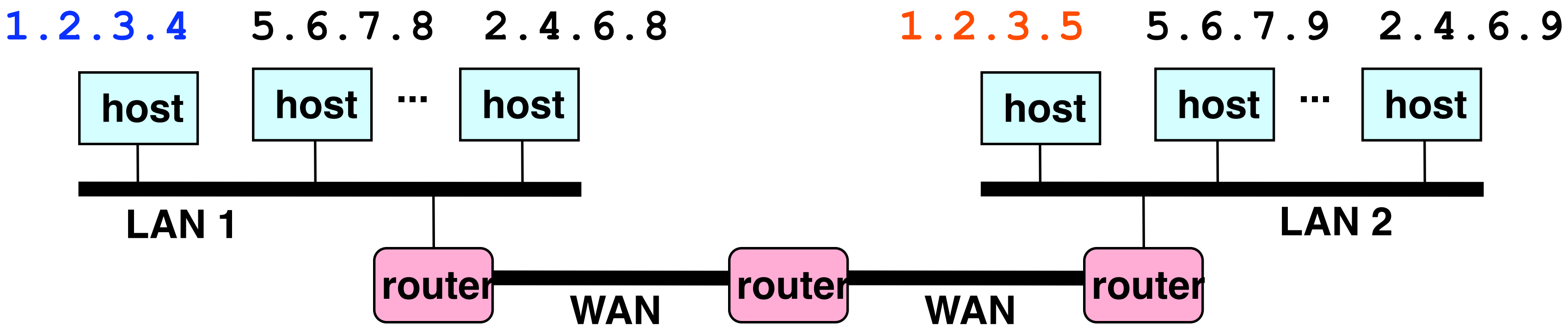
- The Internet is an “inter-network”
  - Used to connect *networks* together, not *hosts*
  - Needs a way to address a network (i.e., group of hosts)



LAN = Local Area Network
WAN = Wide Area Network

Scalability Challenge

- Suppose hosts had arbitrary addresses
  - Then every router would need a lot of information
  - …to know how to direct packets toward *every* host



1.2.3.4	←
1.2.3.5	→
⋮	

forwarding table

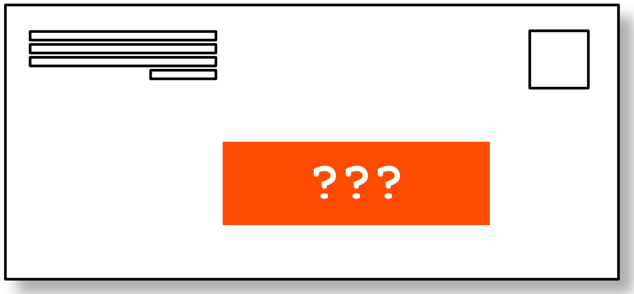
Standard CS Trick

Have a scalability problem?

Introduce hierarchy…

Hierarchical Addressing in U.S. Mail

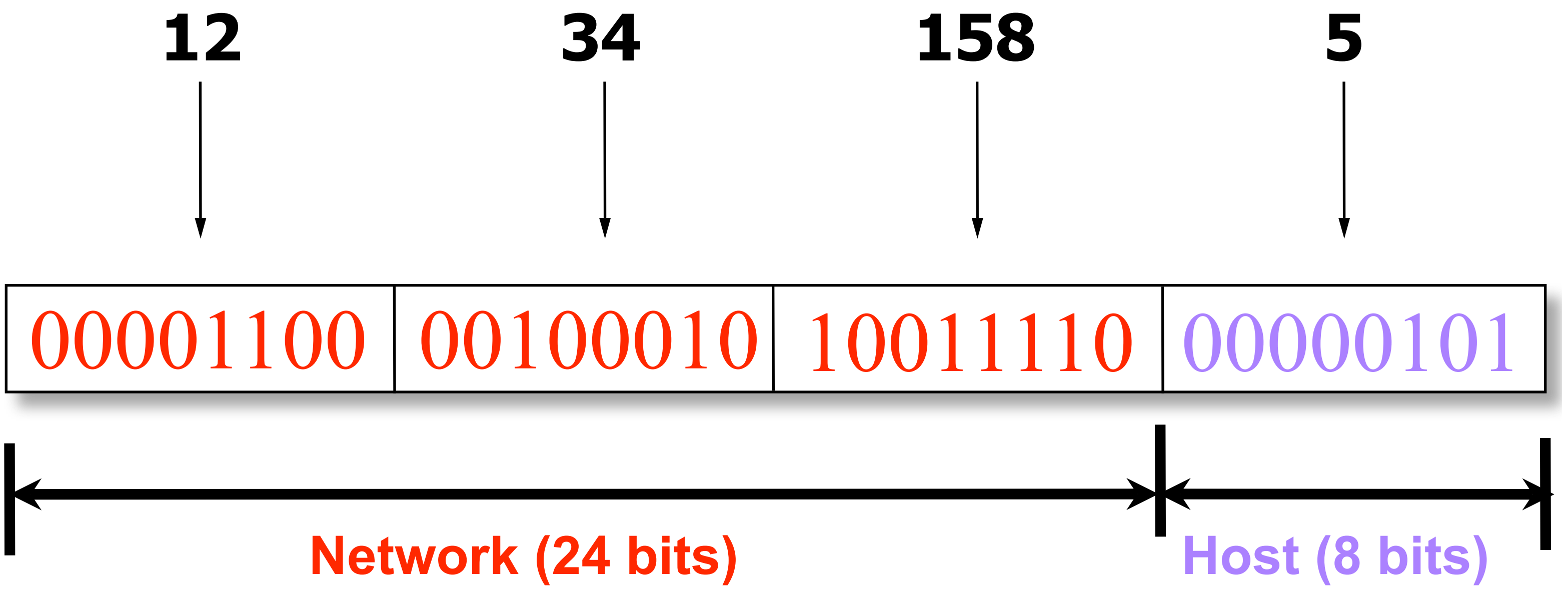
- Addressing in the U.S. mail
  - Zip code: 08540
  - Street: Olden Street
  - Building on street: 35
  - Room in building: 306
  - Name of occupant: Jennifer Rexford



- Forwarding the U.S. mail
  - Deliver letter to the post office in the zip code
  - Assign letter to mailman covering the street
  - Drop letter into mailbox for the building/room
  - Give letter to the appropriate person

Hierarchical Addressing: IP Prefixes

- Divided into network & host portions (left and right)
- 12.34.158.0/24 is a 24-bit **prefix** with 2^8 addresses



IP Address and a 24-bit Subnet Mask

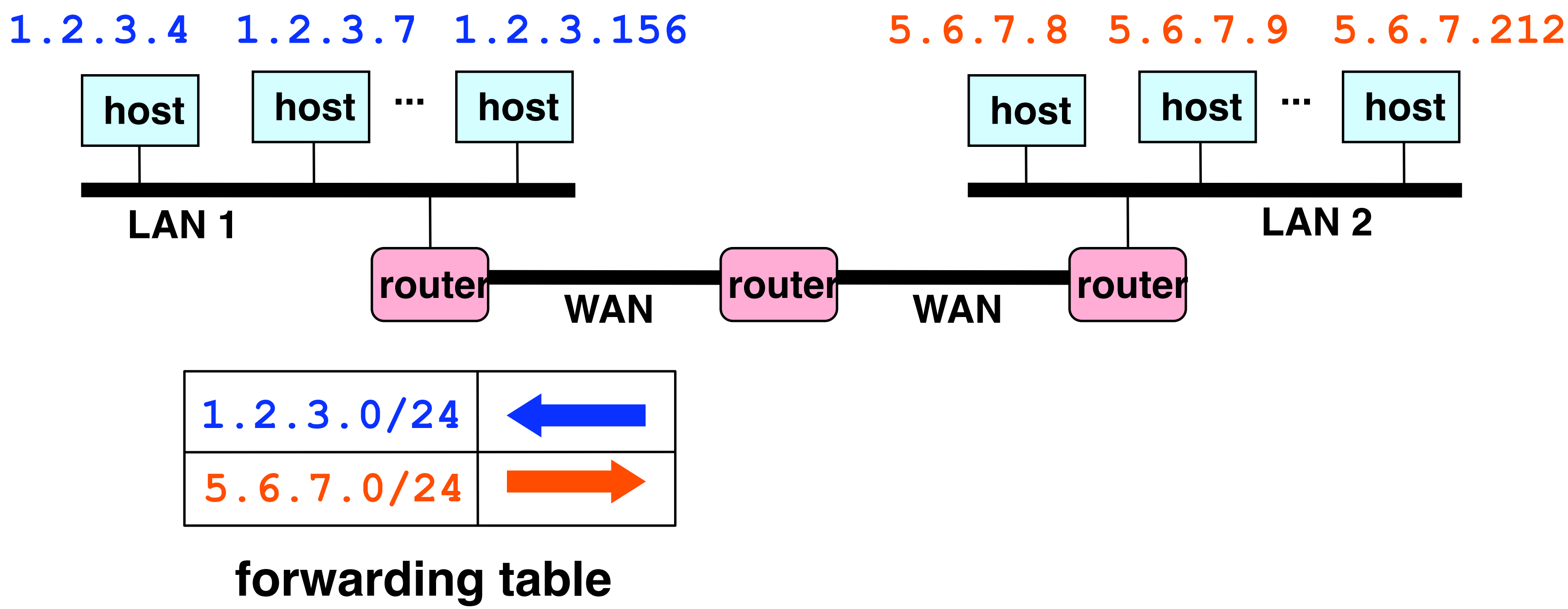
Address

Address (decimal)	12	34	158	5
Address (binary)	00001100	00100010	10011110	00000101
Mask (binary)	11111111	11111111	11111111	00000000
Mask (decimal)	255	255	255	0

Mask

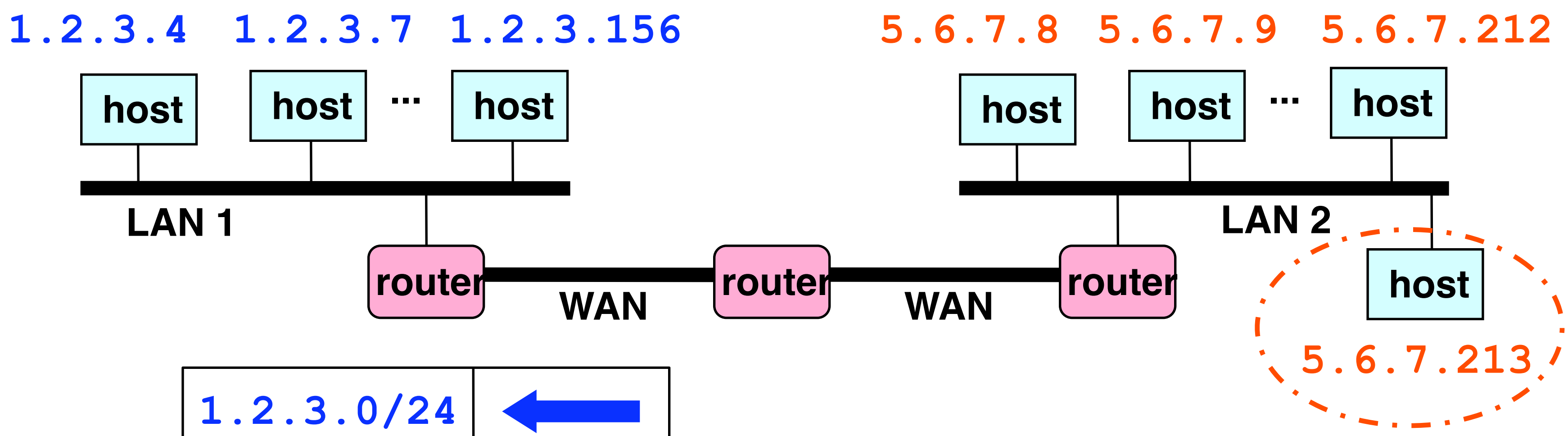
Scalability Improved

- Number related hosts from a common subnet
  - 1.2.3.0/24 on the left LAN
  - 5.6.7.0/24 on the right LAN



Easy to Add New Hosts

- No need to update the routers
  - E.g., adding a new host 5.6.7.213 on the right
  - Doesn't require adding a new forwarding-table entry



1.2.3.0/24	←
5.6.7.0/24	→

forwarding table

Address Allocation

Classful Addressing

- In the olden days, only fixed allocation sizes
  - Class A: 0*
    - Very large /8 blocks (e.g., MIT has 18.0.0.0/8)
  - Class B: 10*
    - Large /16 blocks (e.g,. Princeton has 128.112.0.0/16)
  - Class C: 110*
    - Small /24 blocks (e.g., AT&T Labs has 192.20.225.0/24)
  - Class D: 1110*
    - Multicast groups
  - Class E: 11110*
    - Reserved for future use
- This is why folks use dotted-quad notation!

Classless Inter-Domain Routing (CIDR)

Use two 32-bit numbers to represent a network.
Network number = IP address + Mask

IP Address : 12.4.0.0 IP Mask: 255.254.0.0

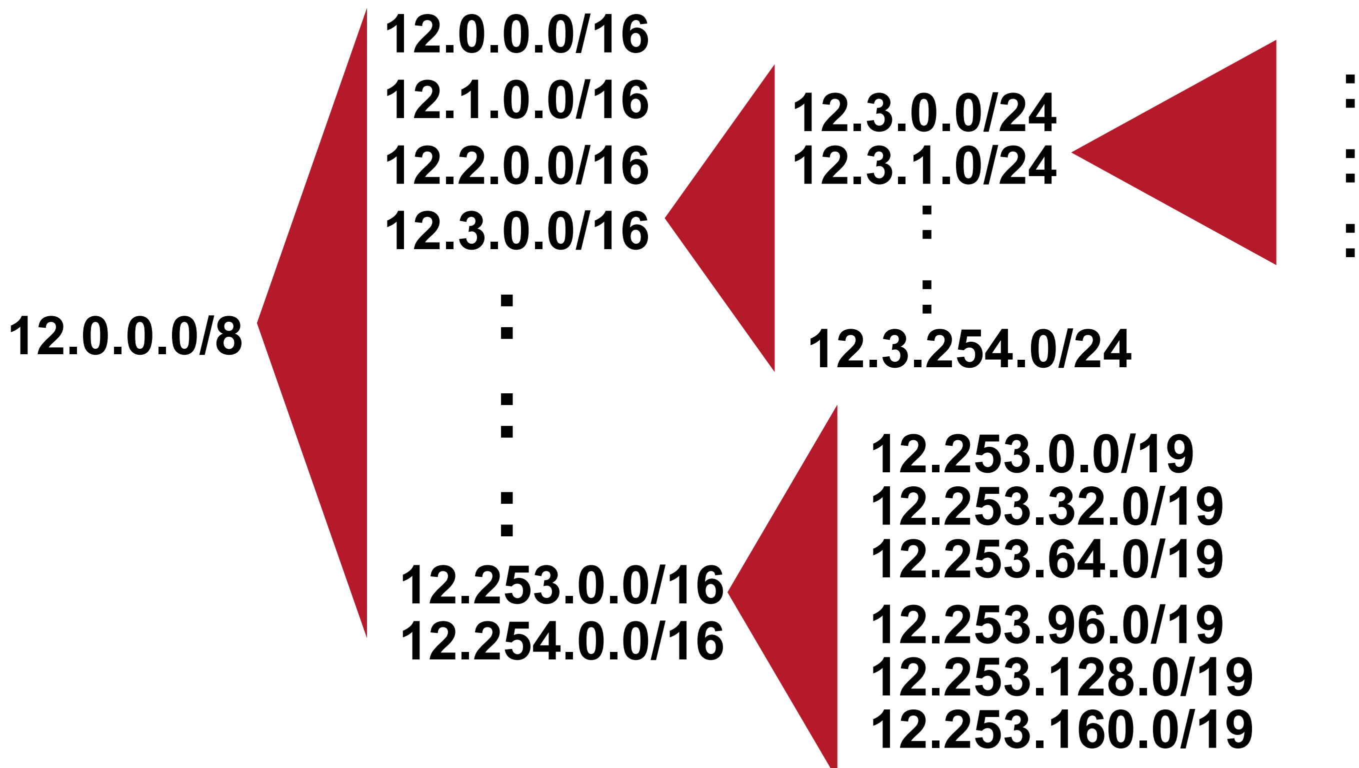
Address	00001100	00000100	00000000	00000000
Mask	11111111	11111110	00000000	00000000

← **Network Prefix** → ← **for hosts** →

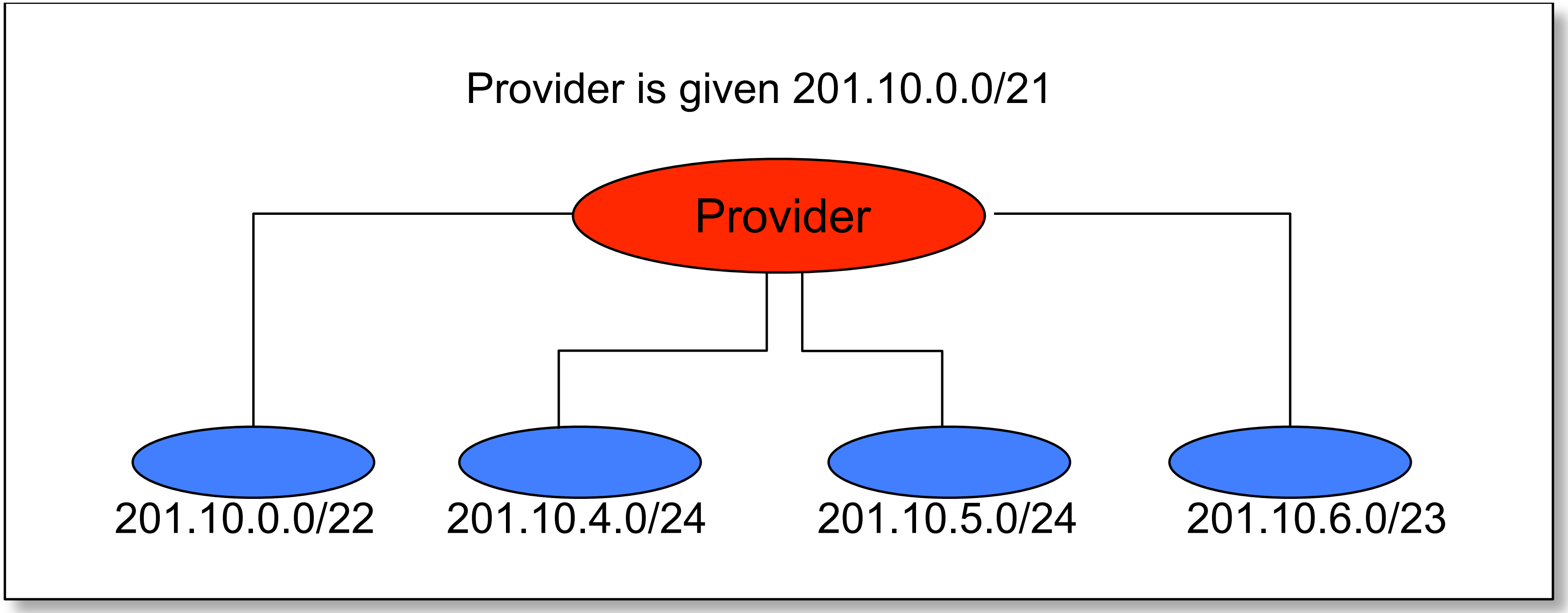
Written as 12.4.0.0/15

CIDR: Hierarchal Address Allocation

- Prefixes are key to Internet scalability
  - Address allocated in contiguous chunks (prefixes)
  - Routing protocols and packet forwarding based on prefixes
  - Today, routing tables contain ~200,000 prefixes

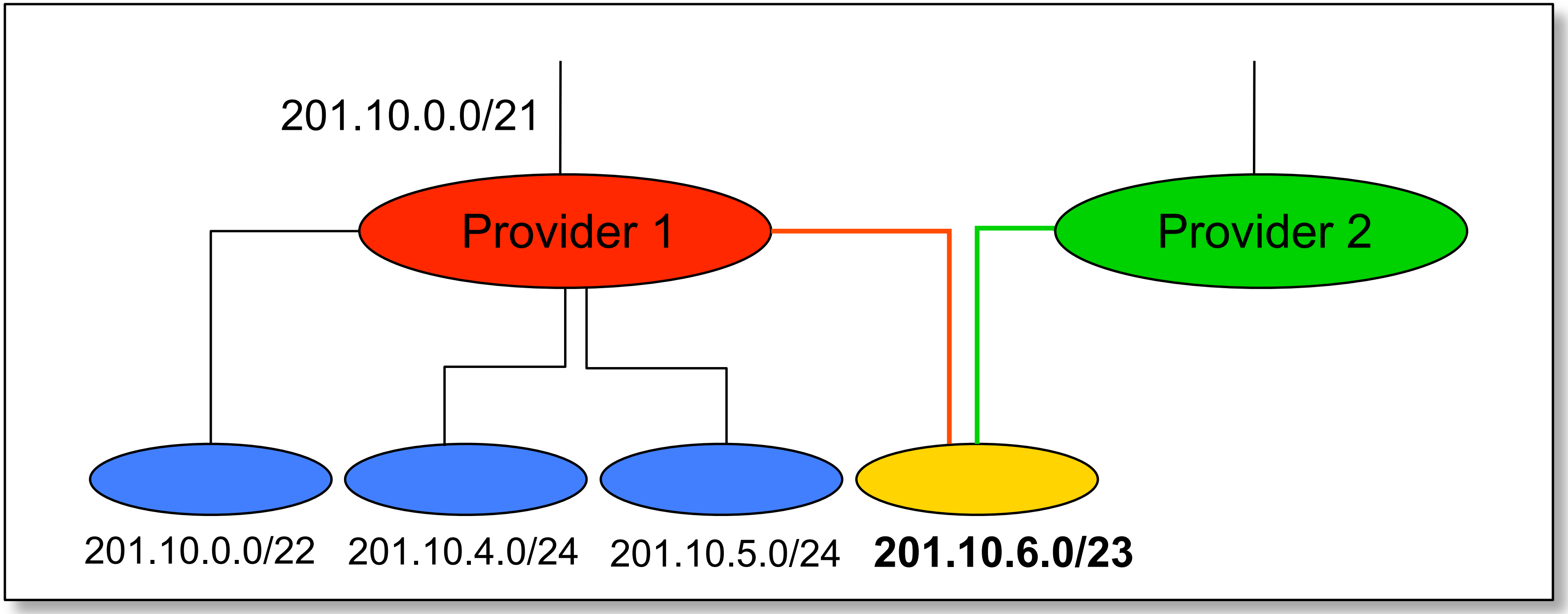


Scalability: Address Aggregation



Routers in the rest of the Internet just need to know how to reach 201.10.0.0/21. The provider can direct the IP packets to the appropriate customer.

But, Aggregation Not Always Possible

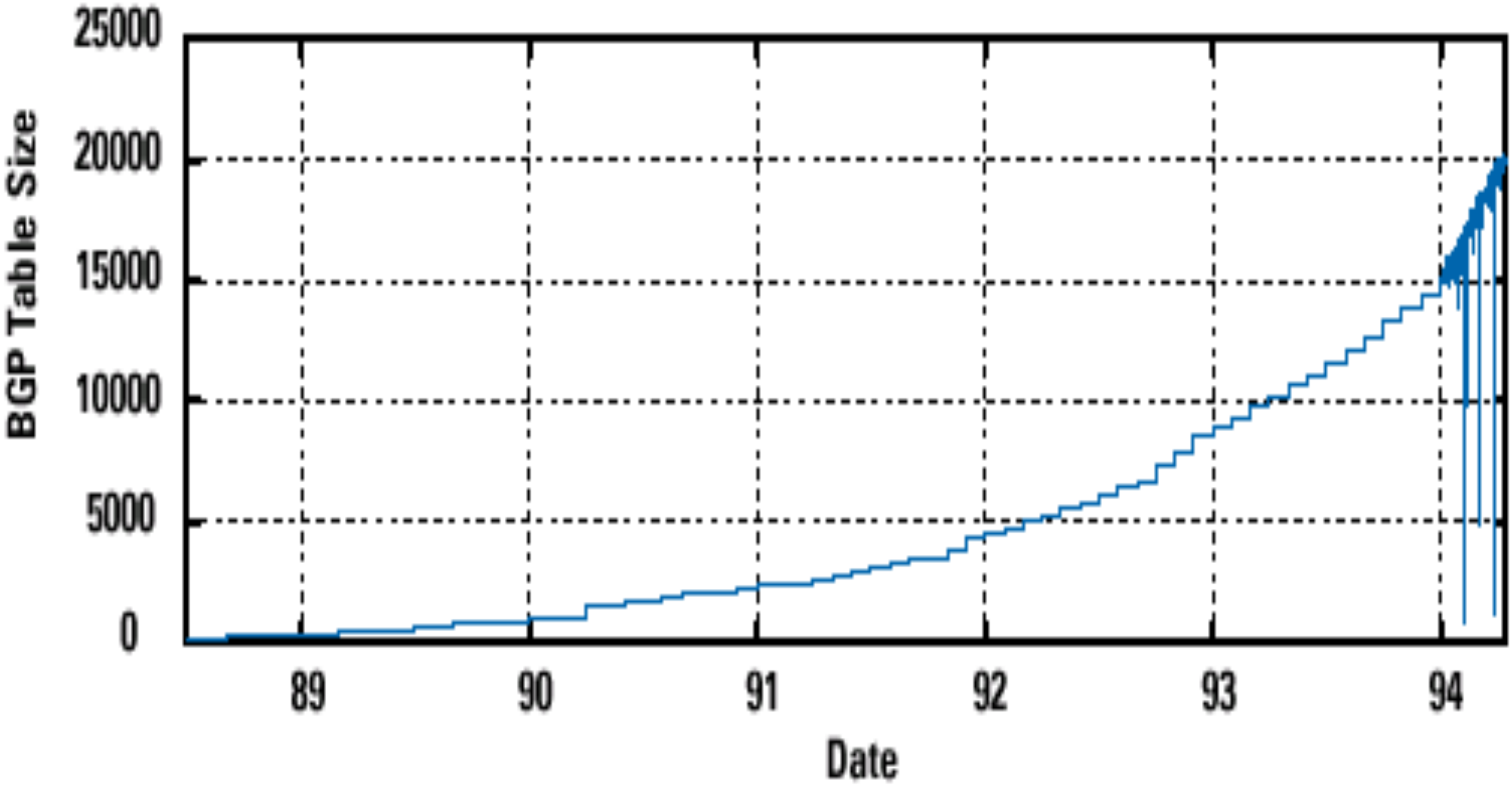


Multi-homed **customer with 201.10.6.0/23 has two providers. Other parts of the Internet need to know how to reach these destinations through *both* providers.**

Scalability Through Hierarchy

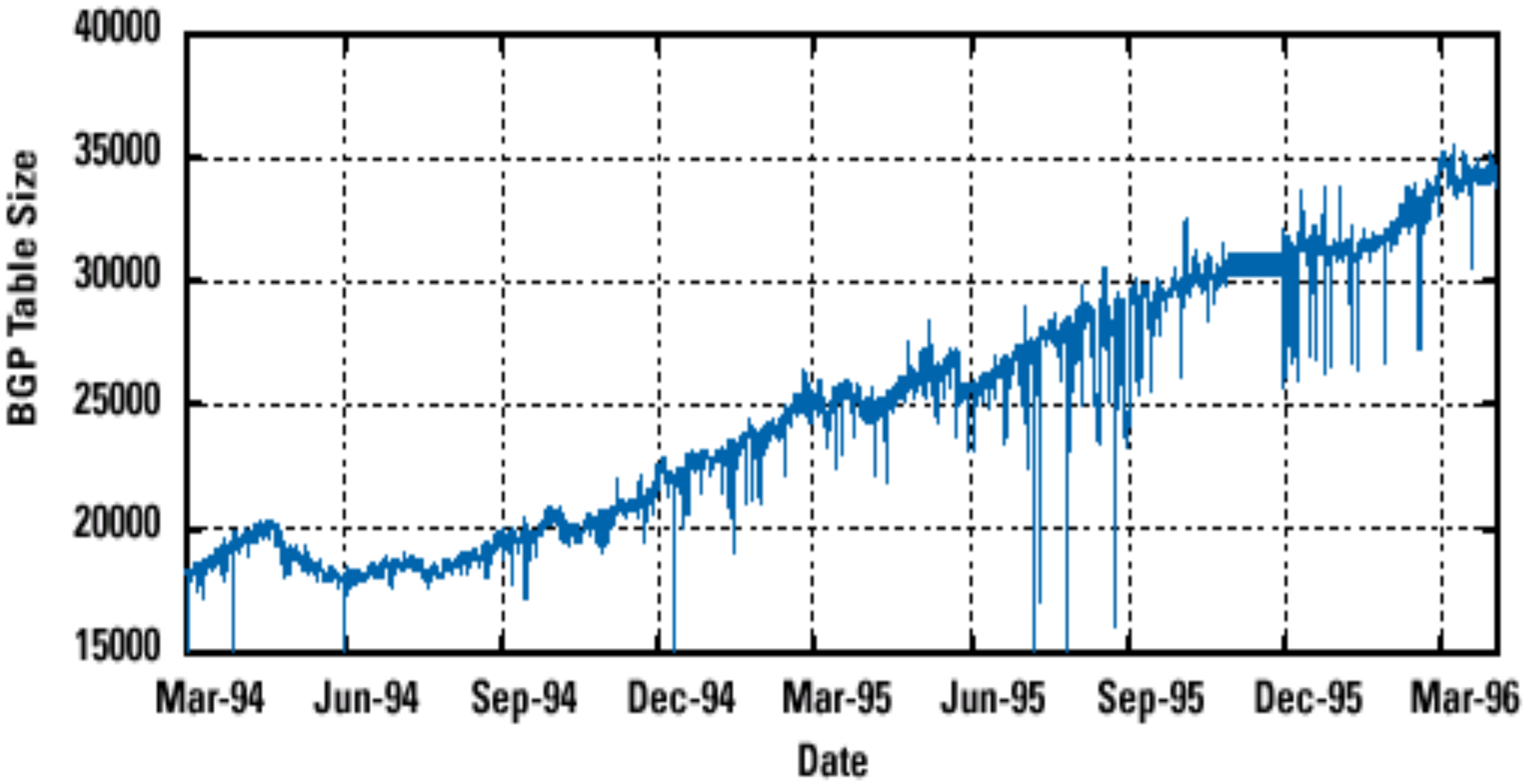
- Hierarchical addressing
  - Critical for scalable system
  - Don't require everyone to know everyone else
  - Reduces amount of updating when something changes
- Non-uniform hierarchy
  - Useful for heterogeneous networks of different sizes
  - Initial class-based addressing was far too coarse
  - Classless InterDomain Routing (CIDR) helps
- Next few slides
  - History of the number of globally-visible prefixes
  - Plots of # of prefixes vs. time

Pre-CIDR (1988-1994): Steep Growth



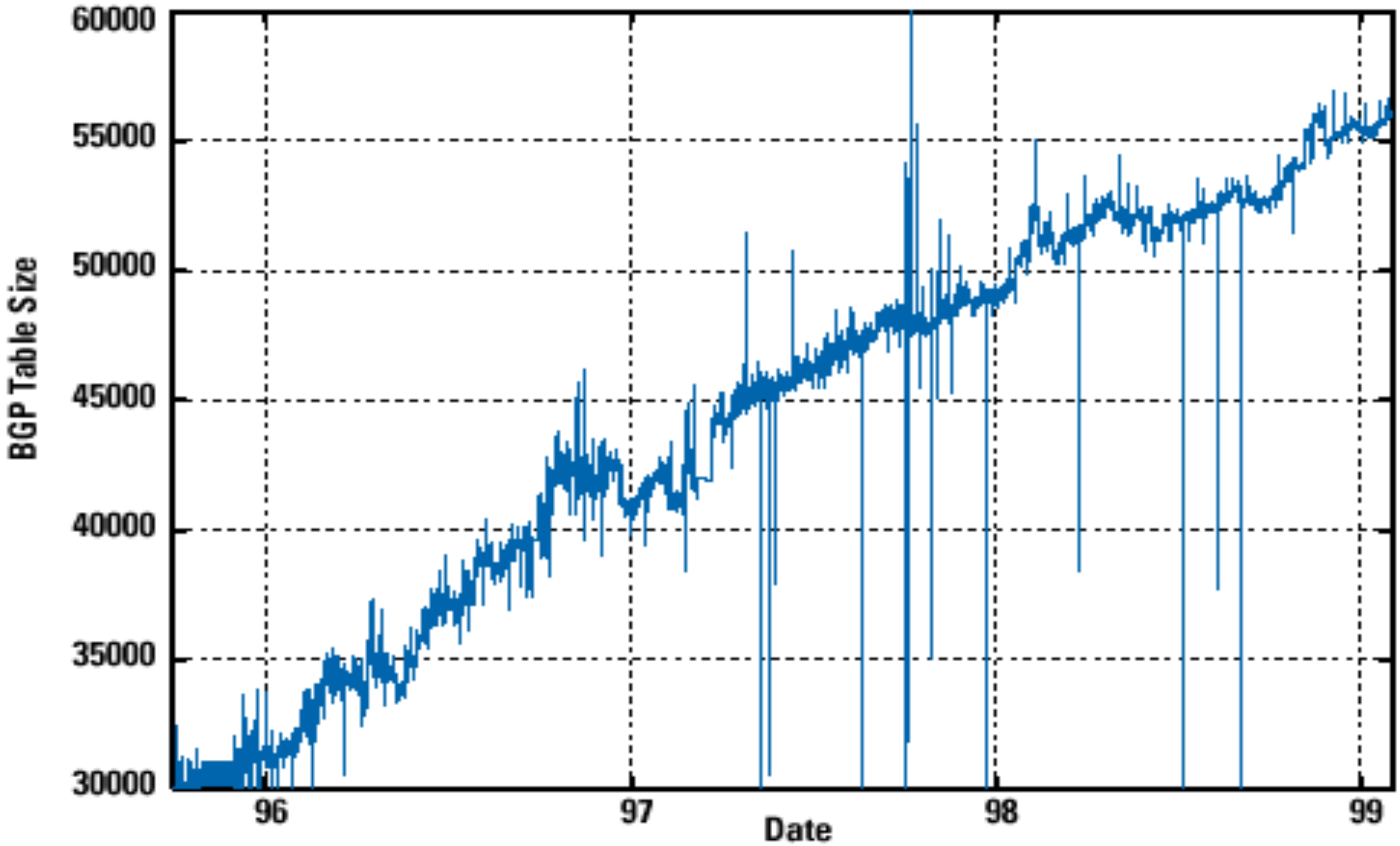
Growth faster than improvements in equipment capability

CIDR Deployed (1994-1996): Much Flatter



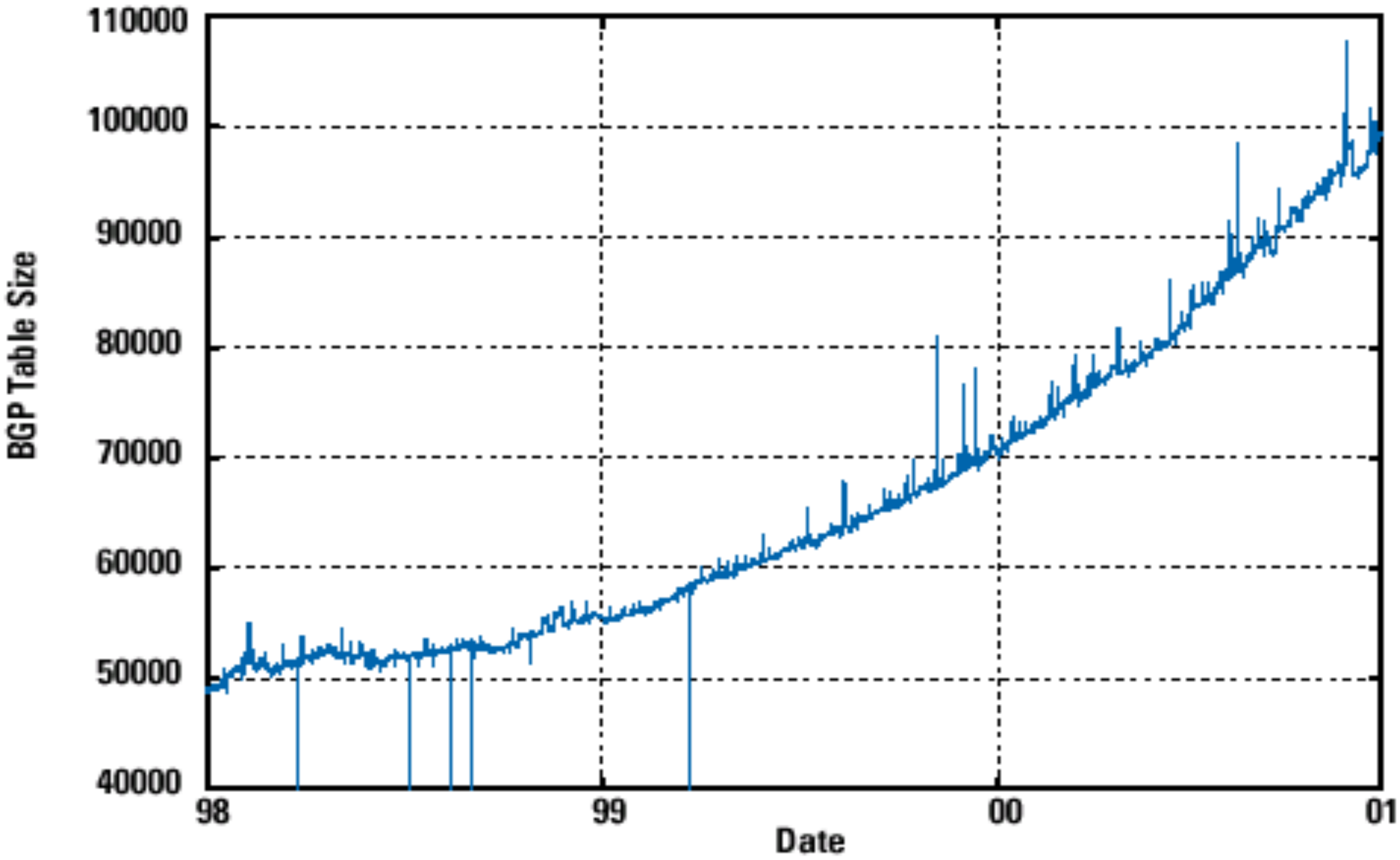
Efforts to aggregate (even decreases after IETF meetings!)

CIDR Growth (1996-1998): Roughly Linear



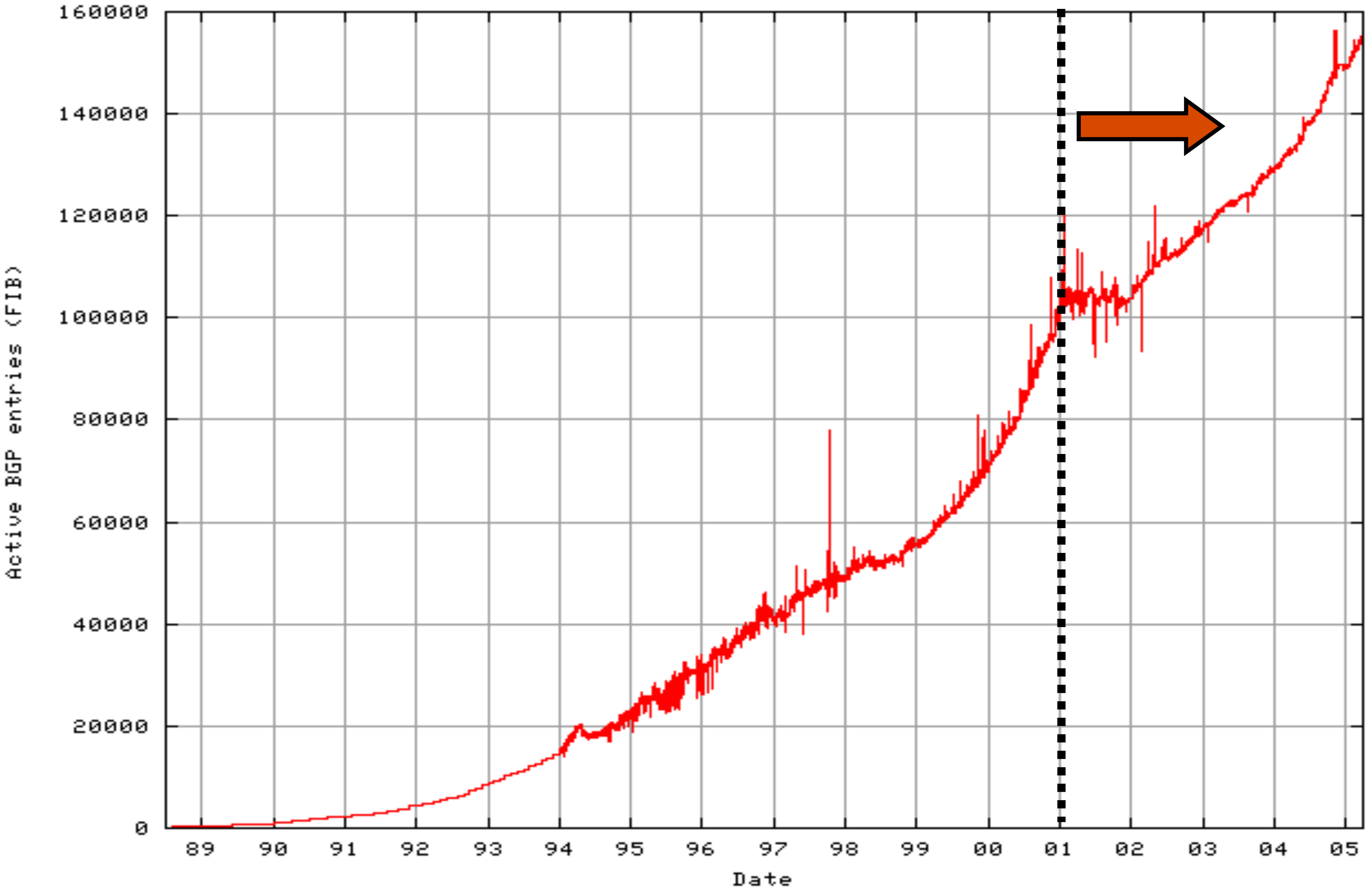
Good use of aggregation, and peer pressure in CIDR report

Boom Period (1998-2001): Steep Growth



Internet boom and increased multi-homing

Long-Term View (1989-2005): Post-Boom



Obtaining a Block of Addresses

- Separation of control
  - Prefix: assigned *to* an institution
  - Addresses: assigned *by* the institution to their nodes
- Who assigns prefixes?
  - Internet Corporation for Assigned Names and Numbers
    - Allocates large address blocks to Regional Internet Registries
  - Regional Internet Registries (RIRs)
    - E.g., ARIN (American Registry for Internet Numbers)
    - Allocates address blocks within their regions
    - Allocated to Internet Service Providers and large institutions
  - Internet Service Providers (ISPs)
    - Allocate address blocks to their customers
    - Who may, in turn, allocate to their customers…

Figuring Out Who Owns an Address

- Address registries
  - Public record of address allocations
  - Internet Service Providers (ISPs) should update when giving addresses to customers
  - However, records are notoriously out-of-date
- Ways to query
  - UNIX: "whois –h whois.arin.net 128.112.136.35"
  - http://www.arin.net/whois/
  - http://www.geektools.com/whois.php
  - …

Example Output for 213.233.168.1

inetnum:	213.233.168.0 - 213.233.175.255
netname:	SCHOOLNET-TEH-IR
descr:	Sharif University Of Technology
country:	IR
person:	Yahya Tabesh
address:	Computer Center, Sharif University of Technology
address:	Azadi Ave., Tehran, Iran.
phone:	+98 21 6005319
fax-no:	+98 21 6019568
e-mail:	tabesh@sharif.ac.ir
mnt-by:	SHARIF-EDU-MNT

Are 32-bit Addresses Enough?

- Not all that many unique addresses
  - 2^{32} = 4,294,967,296 (just over four billion)
  - Plus, some are reserved for special purposes
  - And, addresses are allocated in larger blocks
- And, many devices need IP addresses
  - Computers, PDAs, routers, tanks, toasters, …
- Long-term solution: a larger address space
  - IPv6 has 128-bit addresses ($2^{128} = 3.403 \times 10^{38}$)
- Short-term solutions: limping along with IPv4
  - Private addresses
  - Network address translation (NAT)
  - Dynamically-assigned addresses (DHCP)

Hard Policy Questions

- How much address space per geographic region?
  - Equal amount per country?
  - Proportional to the population?
  - What about addresses already allocated?
- Address space portability?
  - Keep your address block when you change providers?
  - Pro: avoid having to renumber your equipment
  - Con: reduces the effectiveness of address aggregation
- Keeping the address registries up to date?
  - What about mergers and acquisitions?
  - Delegation of address blocks to customers?
  - As a result, the registries are horribly out of date

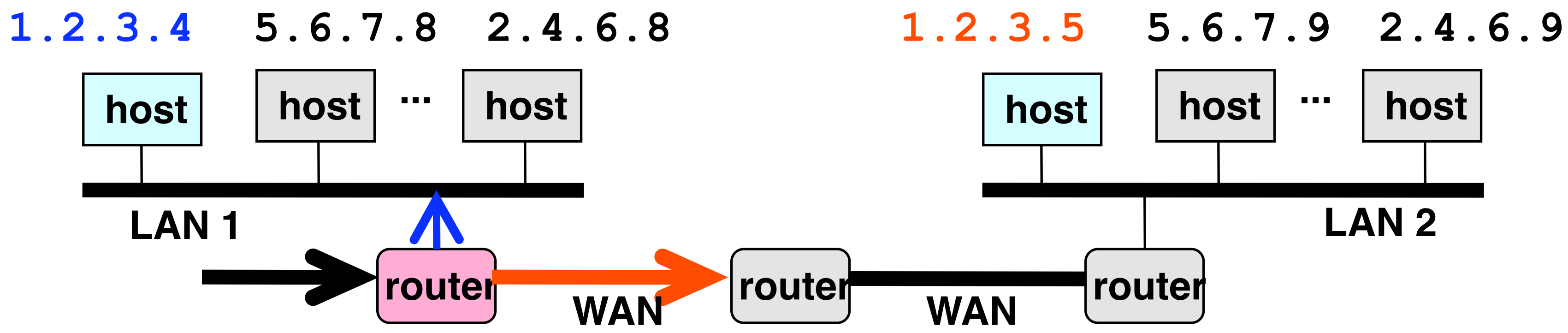
Packet Forwarding

Hop-by-Hop Packet Forwarding

- Each router has a forwarding table
  - Maps destination addresses…
  - … to outgoing interfaces
- Upon receiving a packet
  - Inspect the destination IP address in the header
  - Index into the table
  - Determine the outgoing interface
  - Forward the packet out that interface
- Then, the next router in the path repeats
  - And the packet travels along the path to the destination

Separate Table Entries Per Address

- If a router had a forwarding entry per IP address
  - Match *destination address* of incoming packet
  - … to the *forwarding-table entry*
  - … to determine the *outgoing interface*

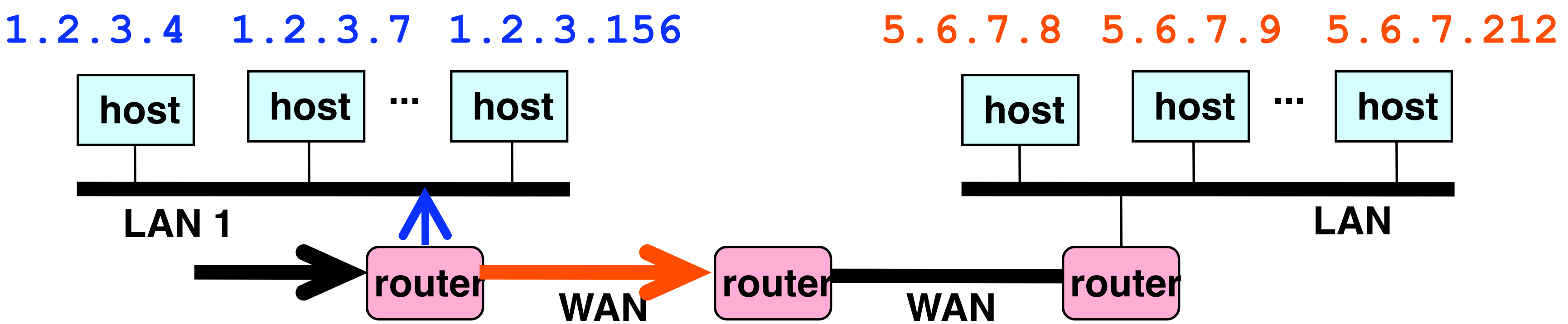


1.2.3.4	↑
1.2.3.5	→

forwarding table

Separate Entry Per 24-bit Prefix

- If the router had an entry per 24-bit prefix
  - Look only at the top 24 bits of the destination address
  - Index into the table to determine the next-hop interface



1.2.3.0/24	↑
5.6.7.0/24	→

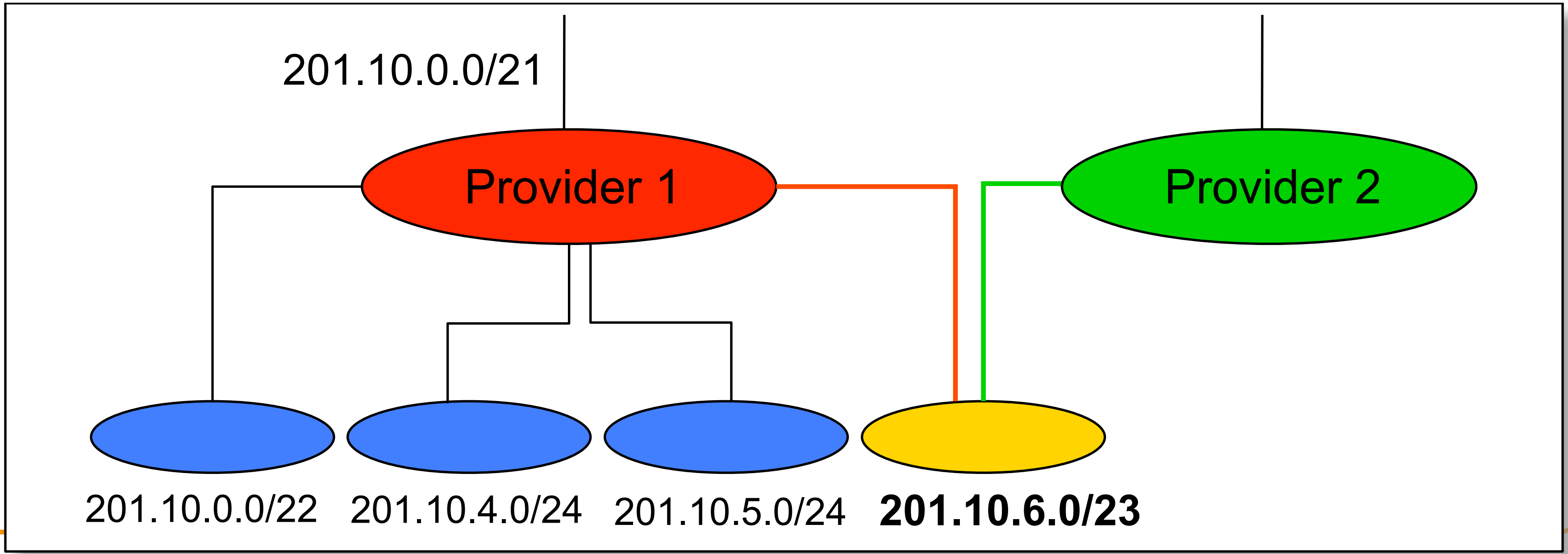
forwarding table

Separate Entry Classful Address

- If the router had an entry per classful prefix
  - Mixture of Class A, B, and C addresses
  - Depends on the first couple of bits of the destination
- Identify the mask automatically from the address
  - First bit of 0: class A address (/8)
  - First two bits of 10: class B address (/16)
  - First three bits of 110: class C address (/24)
- Then, look in the forwarding table for the match
  - E.g., 129.2.3.4 maps to 129.2.3.0/24
  - Then, look up the entry for 129.2.3.0/24
  - … to identify the outgoing interface

CIDR Makes Packet Forwarding Harder

- There's no such thing as a free lunch
  - CIDR allows efficient use of the limited address space
  - But, CIDR makes packet forwarding much harder
- Forwarding table may have many matches
  - E.g., table entries for 201.10.0.0/21 and 201.10.6.0/23
  - The IP address 201.10.6.17 would match *both*!



Longest Prefix Match Forwarding

- Forwarding tables in IP routers
  - Maps each IP prefix to next-hop link(s)
- Destination-based forwarding
  - Packet has a destination address
  - Router identifies longest-matching prefix
  - Cute algorithmic problem: very fast lookups

forwarding table

destination

201.10.6.17 →

4.0.0.0/8
4.83.128.0/17
201.10.0.0/21
201.10.6.0/23 →
126.255.103.0/24

outgoing link

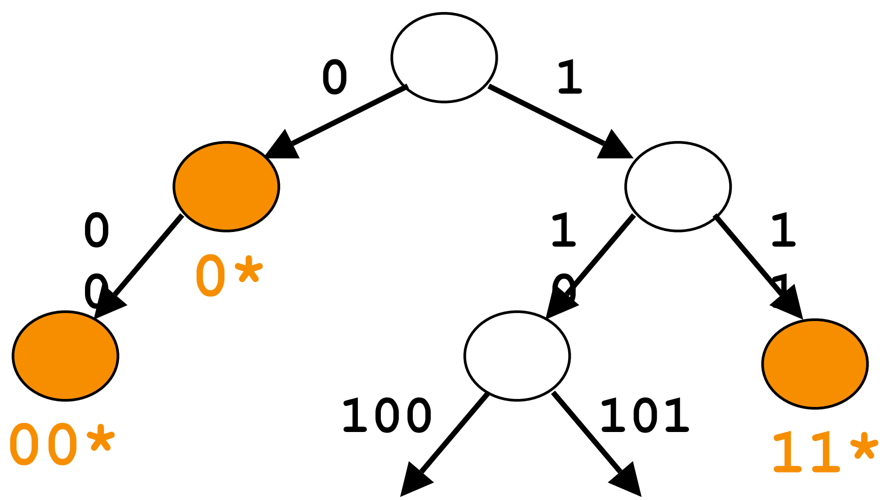
Serial0/0.1

Simplest Algorithm is Too Slow

- Scan the forwarding table one entry at a time
  - See if the destination matches the entry
  - If so, check the size of the mask for the prefix
  - Keep track of the entry with longest-matching prefix
- Overhead is linear in size of the forwarding table
  - Today, that means 200,000 entries!
  - And, the router may have just a few nanoseconds
  - … before the next packet is arriving
- Need greater efficiency to keep up with *line rate*
  - Better algorithms
  - Hardware implementations

Patricia Tree

- Store the prefixes as a tree
  - One bit for each level of the tree
  - Some nodes correspond to valid prefixes
  - ... which have next-hop interfaces in a table
- When a packet arrives
  - Traverse the tree based on the destination address
  - Stop upon reaching the longest matching prefix



Even Faster Lookups

- Patricia tree is faster than linear scan
  - Proportional to number of bits in the address
- Patricia tree can be made faster
  - Can make a k-ary tree
    - E.g., 4-ary tree with four children (00, 01, 10, and 11)
  - Faster lookup, though requires more space
- Can use special hardware
- Huge innovations in the mid-to-late 1990s
  - After CIDR was introduced (in 1994)
  - … and longest-prefix match was a major bottleneck

Where do Forwarding Tables Come From?

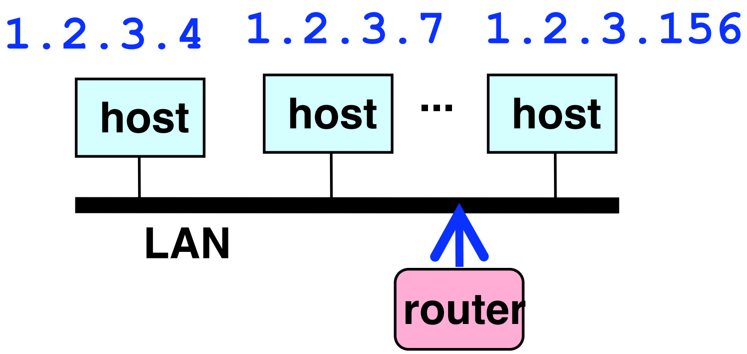
- Routers have forwarding tables
  - Map prefix to outgoing link(s)
- Entries can be statically configured
  - E.g., "map 12.34.158.0/24 to Serial0/0.1"
- But, this doesn't adapt
  - To failures
  - To new equipment
  - To the need to balance load
  - …
- That is where other technologies come in…
  - Routing protocols, DHCP, and ARP (later in course)

How Do End Hosts Forward Packets?

- End host with single network interface
  - PC with an Ethernet link
  - Laptop with a wireless link
- Don’t need to run a routing protocol
  - Packets to the host itself (e.g., 1.2.3.4/32)
    - Delivered locally
  - Packets to other hosts on the LAN (e.g., 1.2.3.0/24)
    - Sent out the interface
  - Packets to external hosts (e.g., 0.0.0.0/0)
    - Sent out interface to local gateway
- How this information is learned
  - Static setting of address, subnet mask, and gateway
  - Dynamic Host Configuration Protocol (DHCP)

What About Reaching the End Hosts?

- How does the last router reach the destination?



- Each interface has a persistent, global identifier
  - MAC (Media Access Control) address
  - Burned in to the adaptors Read-Only Memory (ROM)
  - Flat address structure (i.e., no hierarchy)
- Constructing an address resolution table
  - Mapping MAC address to/from IP address
  - Address Resolution Protocol (ARP)

Conclusions

- IP address
  - A 32-bit number
  - Allocated in prefixes
  - Non-uniform hierarchy for scalability and flexibility
- Packet forwarding
  - Based on IP prefixes
  - Longest-prefix-match forwarding
- Next lecture
  - Transmission Control Protocol (TCP)
- We’ll cover some topics later
  - Routing protocols, DHCP, and ARP