Network Layer

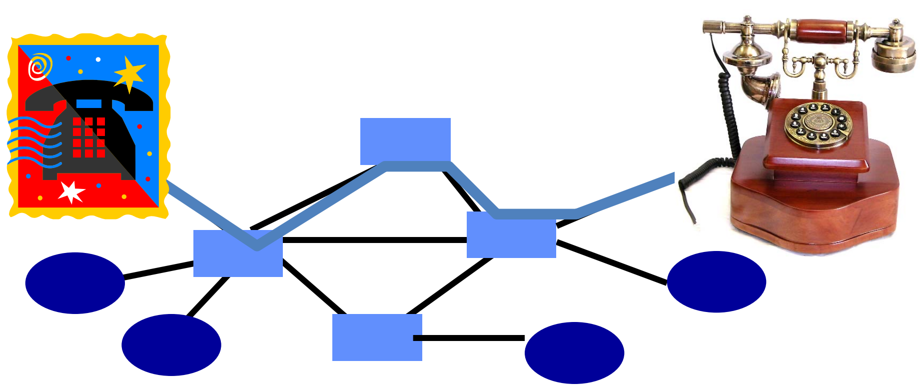
Note: The slides are adapted from the materials from Prof. Richard Han at CU Boulder and Profs. Jennifer Rexford and Mike Freedman at Princeton University, and the networking book (Computer Networking: A Top Down Approach) from Kurose and Ross.

IP Protocol Stack: Key Abstractions

Best-Effort Global Packet Delivery

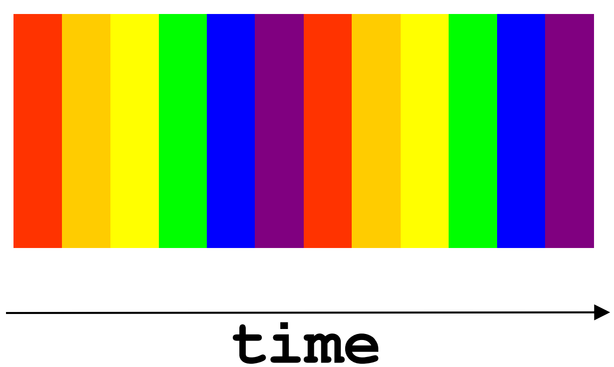
Circuit Switching (e.g., Phone Network)

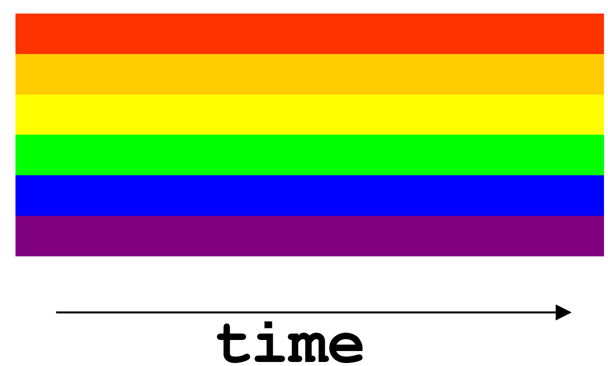
- Source establishes connection
  - Reserve resources along hops in the path
- Source sends data
  - Transmit data over the established connection
- Source tears down connection
  - Free the resources for future connections



Circuit Switching: Static Allocation

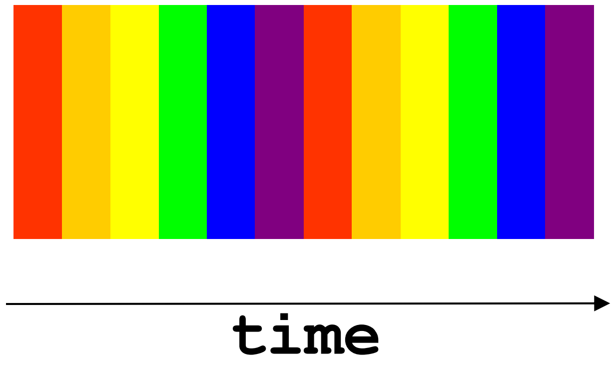
Q: Frequency-Division vs. Time-Division



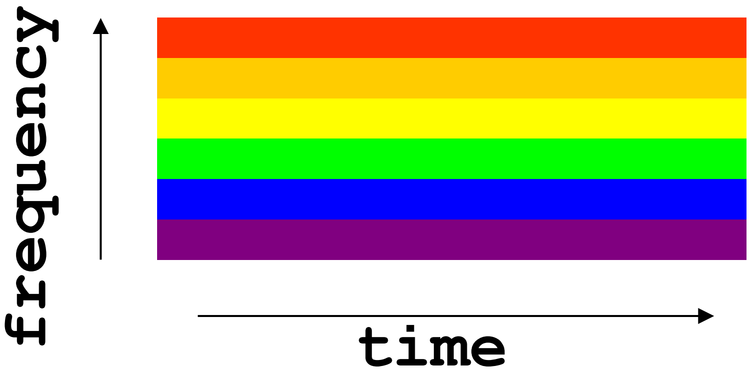


Circuit Switching: Static Allocation

- Time-division
  - Each circuit allocated certain time slots

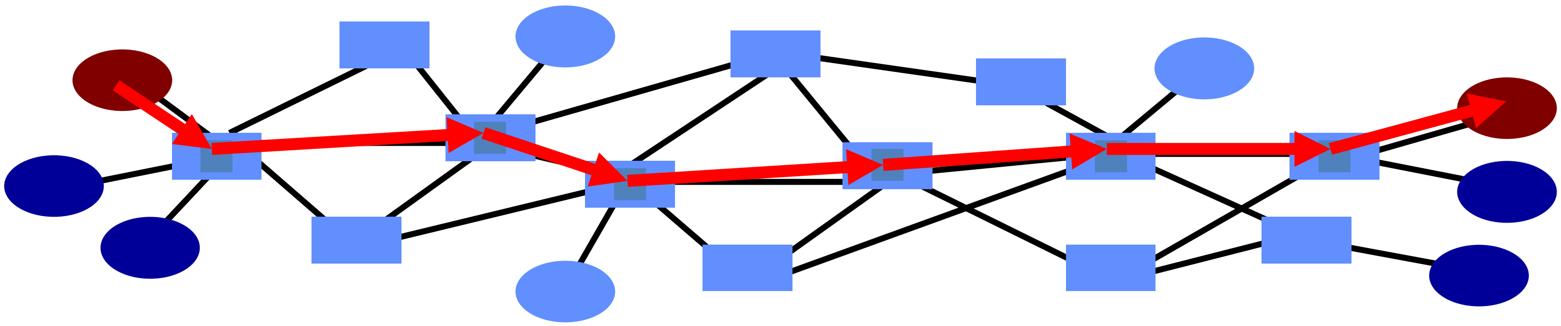


- Frequency-division
  - Each circuit allocated certain frequencies

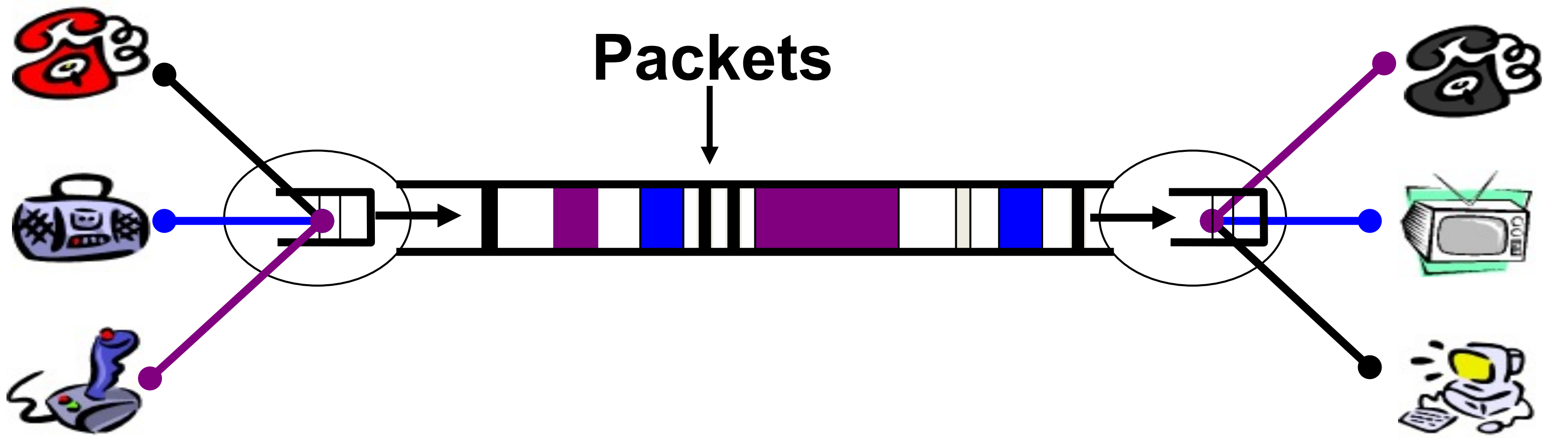


Packet Switching (e.g., Internet)

1. Data traffic divided into packets
   – Each packet contains header (with src and dst addr)
2. Packets travel separately through network
   – Packet forwarding based on the header
   – Network nodes may store packets temporarily
   – Best effort: Packets may be loss, corrupted, reordered
3. Destination reconstructs the message



Packet Switching: Statistical (Time Division) Multiplexing



- Intuition: Traffic by computer end-points is bursty!
  - Versus: Telephone traffic not bursty (e.g., constant 56 kbps)
  - One can use network while others idle

- Packet queuing in network: tradeoff space for time
  - Handle short periods when outgoing link demand > link speed

Best Effort: Celebrating Simplicity

- Packets may be lost, corrupted, reordered
- Never having to say you're sorry…
  - Don't reserve bandwidth and memory
  - Don't do error detection and correction
  - Don't remember from one packet to next
- Easier to survive failures
  - Transient disruptions are okay during failover
- Easier to support on many kinds of links
  - Important for *inter*connecting different networks

Is Best Effort Good Enough?

- Packet loss and delay
  - Sender can resend
- Packet corruption
  - Receiver can detect, and sender can resend
- Out-of-order delivery
  - Receiver can put the data back in order
- Packets follow different paths
  - Doesn't matter
- Network failure
  - Drop the packet
- Network congestion
  - Drop the packet

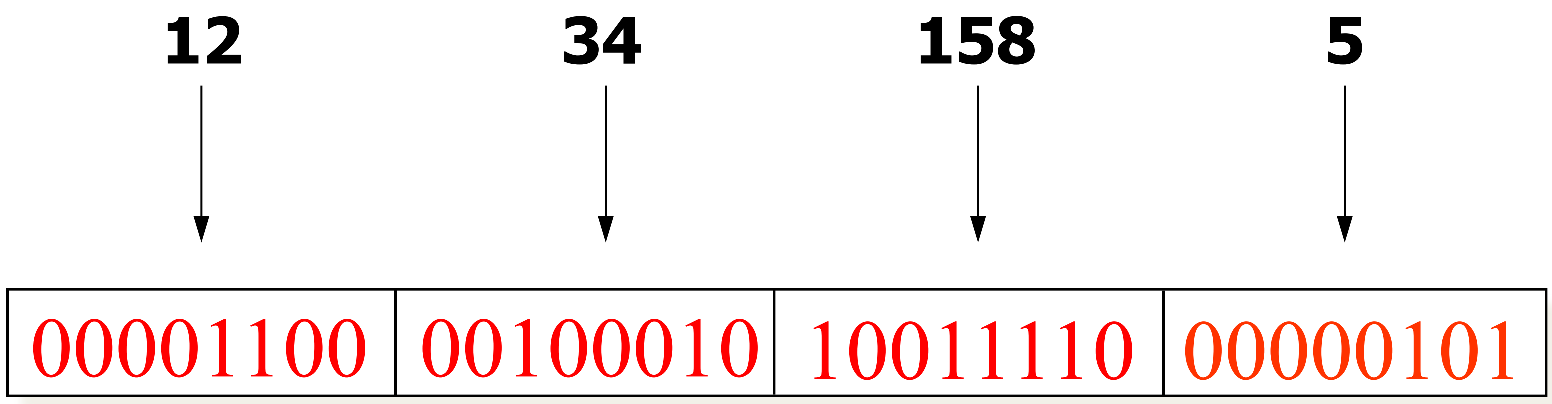
Packet vs. Circuit Switching?

• Predictable performance	Circuit
• Network never blocks senders	Packet
• Reliable, in-order delivery	Circuit
• Low delay to send data	Packet
• Simple forwarding	Circuit
• No overhead for packet headers	Circuit
• High utilization under most workloads	Packet
• No per-connection network state	Packet

Network Addresses

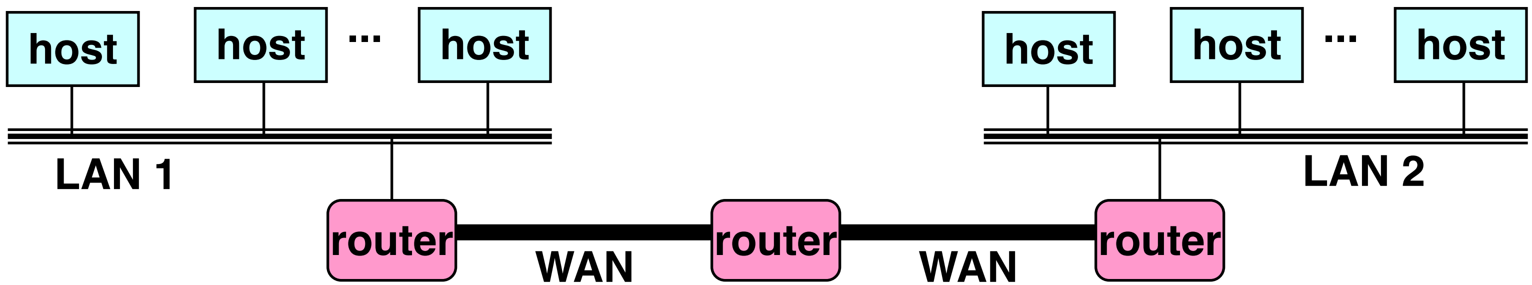
IP Address (IPv4)

- 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
  - Need to address a network (i.e., group of hosts)

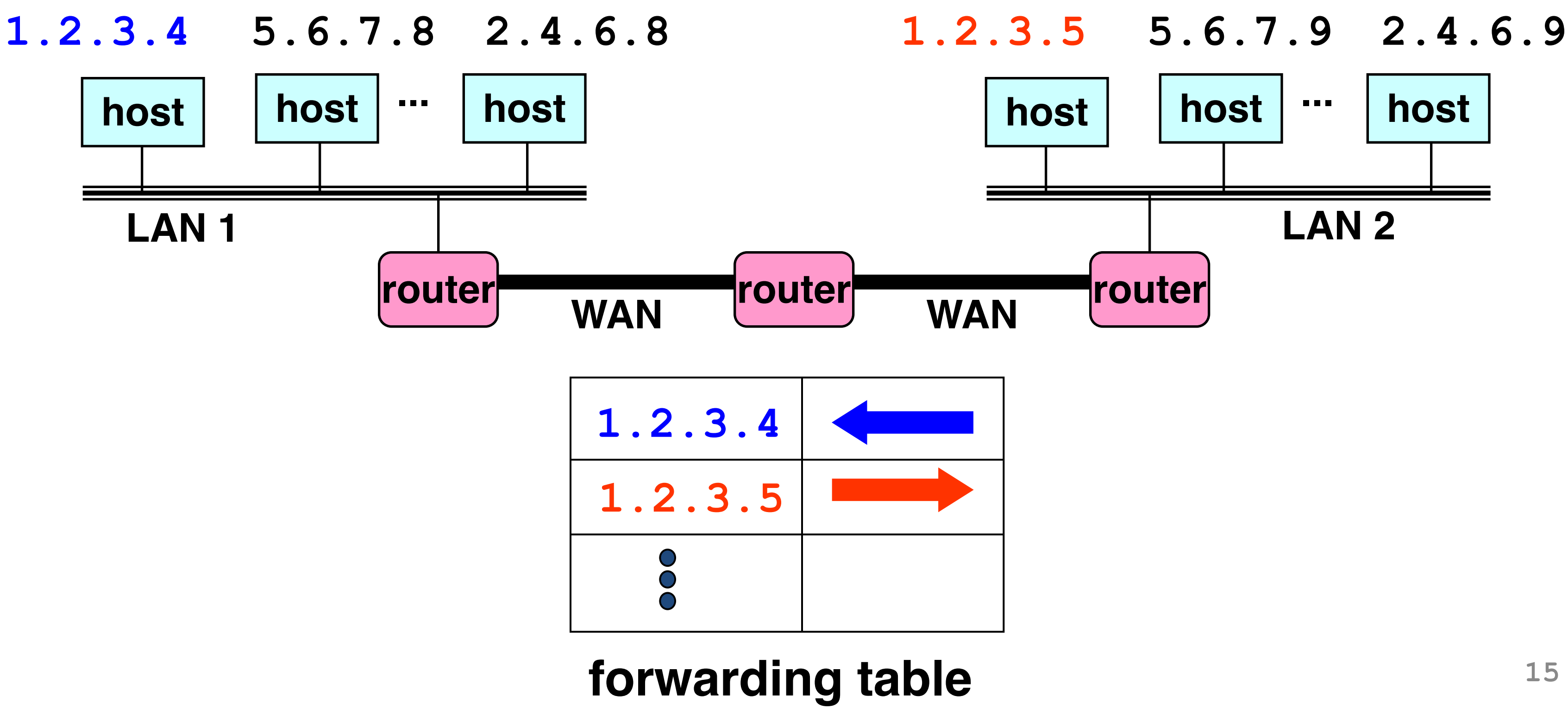


LAN = Local Area Network

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



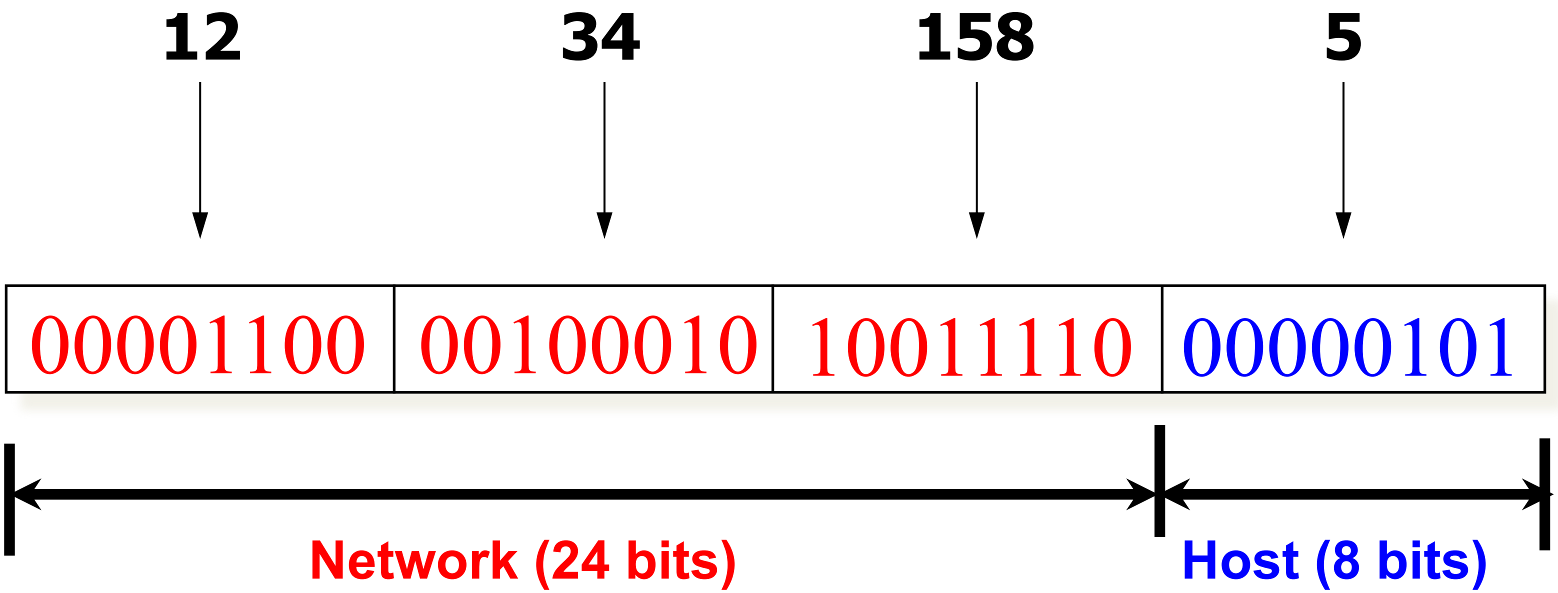
Hierarchical Addressing in U.S. Mail

- Addressing in the U.S. mail
  - Zip code: 80309
  - Building: 1045 Regent Drive
  - Room in building: ECCR 1B14
  - Name of occupant: Sangtae Ha

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

Hierarchical Addressing: IP Prefixes

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



IP Address and 24-bit Subnet Mask

Address	**12**	**34**	**158**	**5**
	00001100	00100010	10011110	00000101
	11111111	11111111	11111111	00000000
Mask	**255**	**255**	**255**	**0**

Network Address and Broadcast Address

- IP address: 10.10.1.97/23
- Network address – IP & Netmask

```
           IP: 00001010.00001010.00000001.01100001
    & Netmask: 11111111.11111111.11111110.000000000
-----------------------------------------------------
Network Addr: 00001010.00001010.00000000.00000000
```

Network address: 10.10.0.0

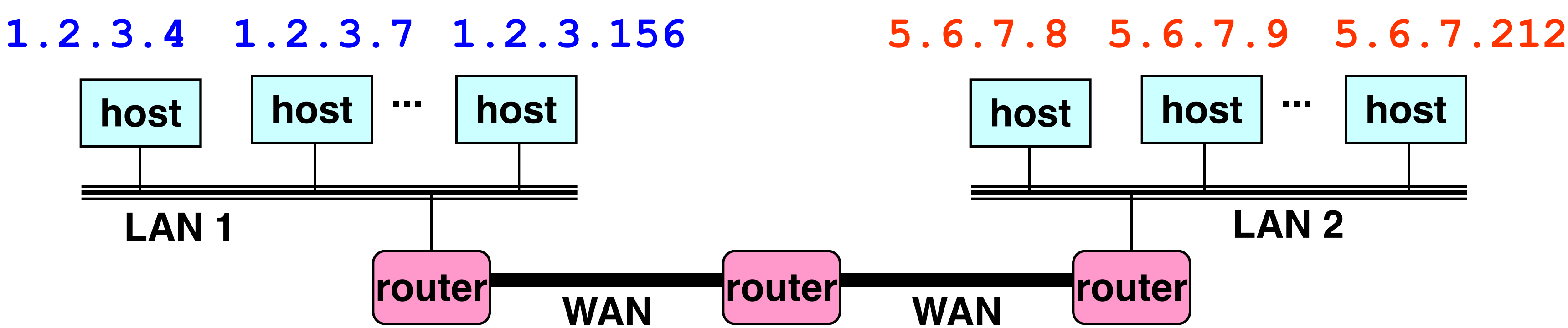
- Broadcast address – IP | ~Netmask

Broadcast address: 10.10.1.255

Please check the example at https://www.countryipblocks.net/identifying-the-network-and-broadcast-address-of-a-subnet

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

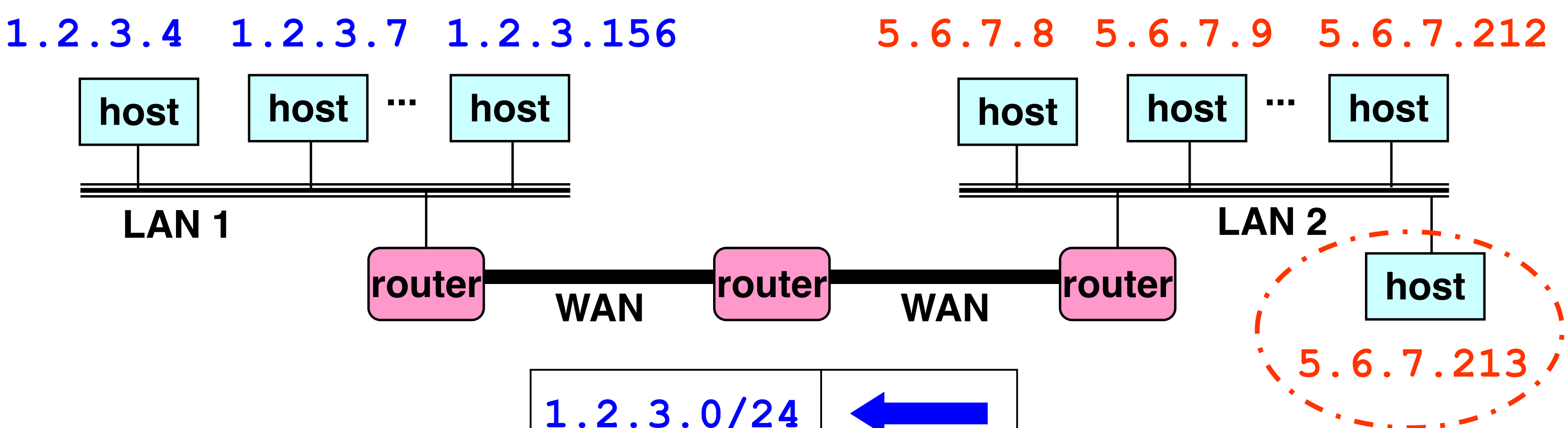


1.2.3.0/24	←
5.6.7.0/24	→

forwarding table

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

History of IP Address Allocation

Classful Addressing

- In the olden days, only fixed allocation sizes
  - Class A: 0*
    - Very large /8 blocks
  - Class B: 10*
    - Large /16 blocks
  - Class C: 110*
    - Small /24 blocks (e.g., AT&T Labs has 192.20.225.0/24)
  - Class D: 1110* for 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 network:

  Network number = IP address + Mask

IP Address : 12.4.0.0   IP Mask: 255.254.0.0

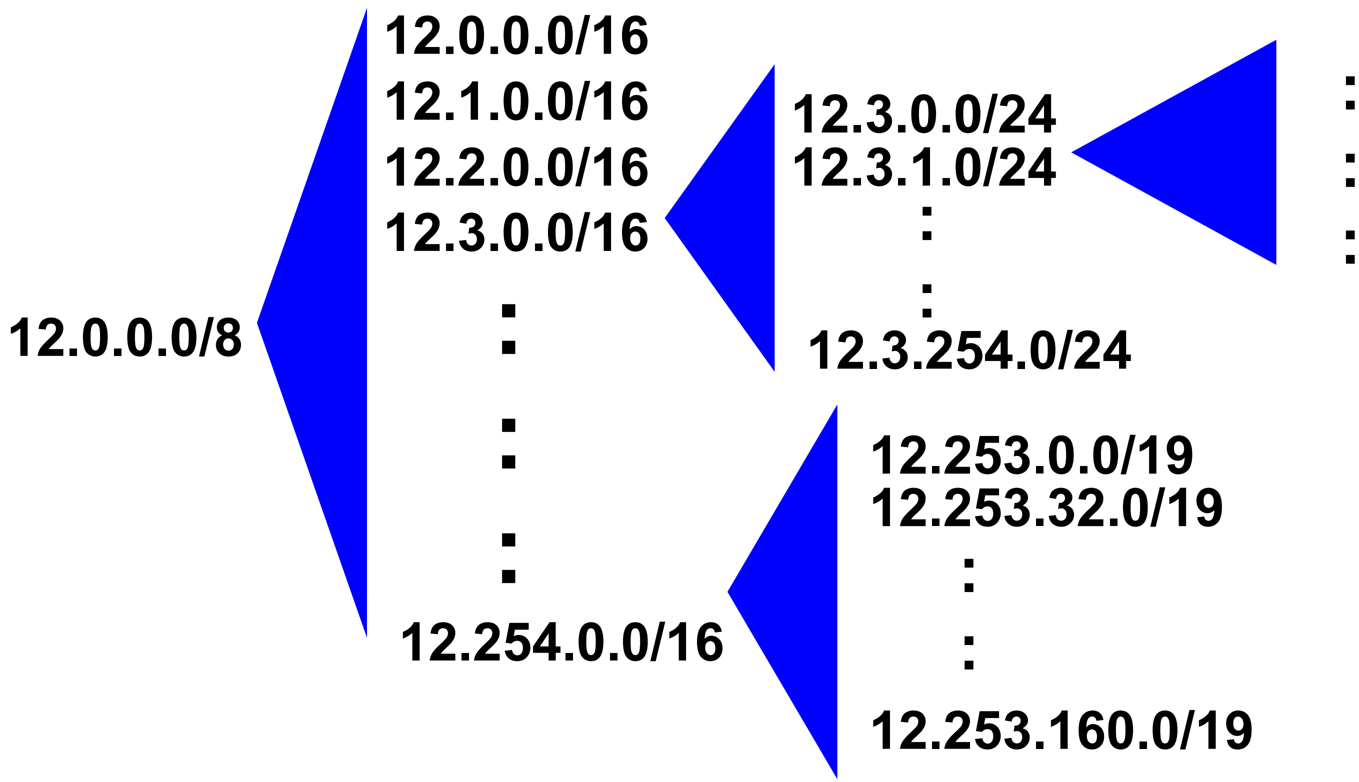
Address	00001100	00000100	00000000	00000000
Mask	11111111	11111110	00000000	00000000

Network Prefix   **for hosts**

Written as 12.4.0.0/15

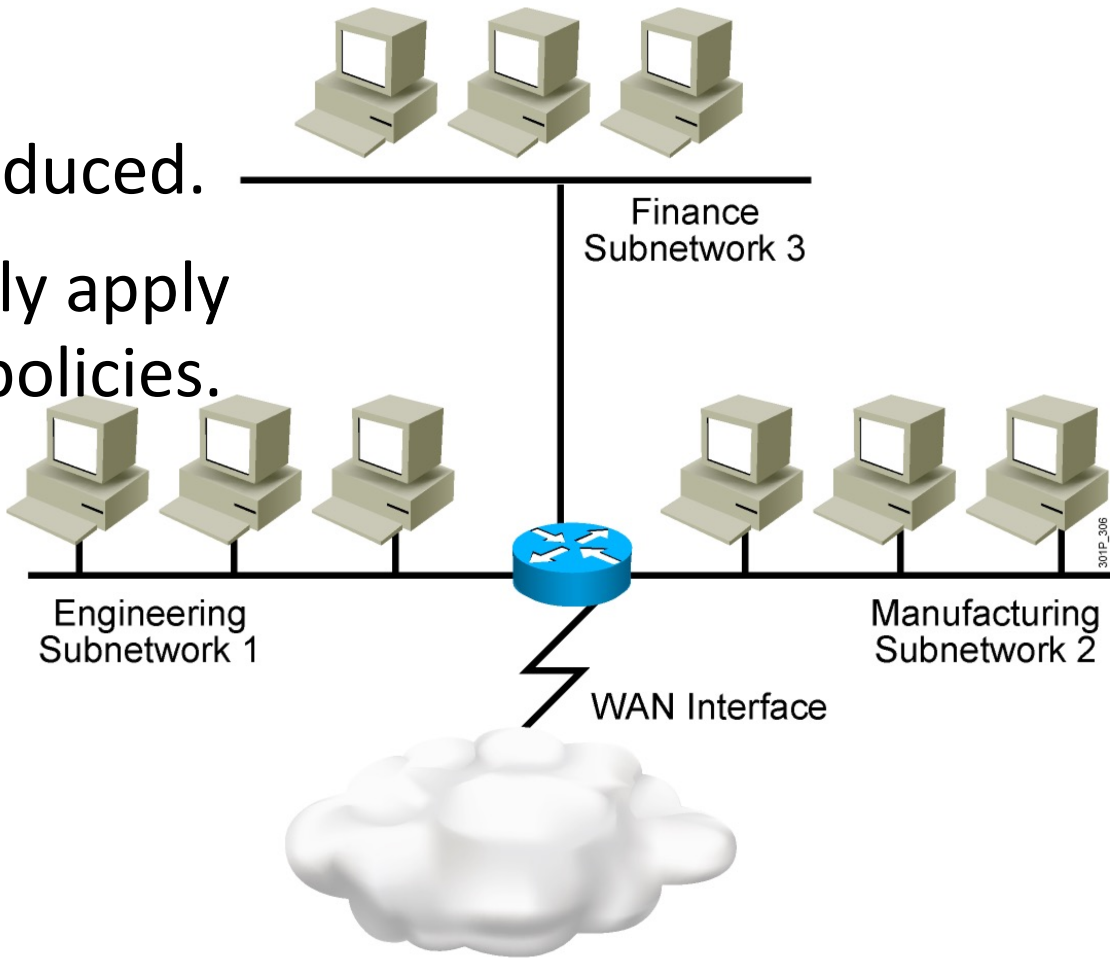
Hierarchical Address Allocation

- Hierarchy is key to scalability
  - Address allocated in contiguous chunks (prefixes)
  - Today, the Internet has about 400,000 prefixes

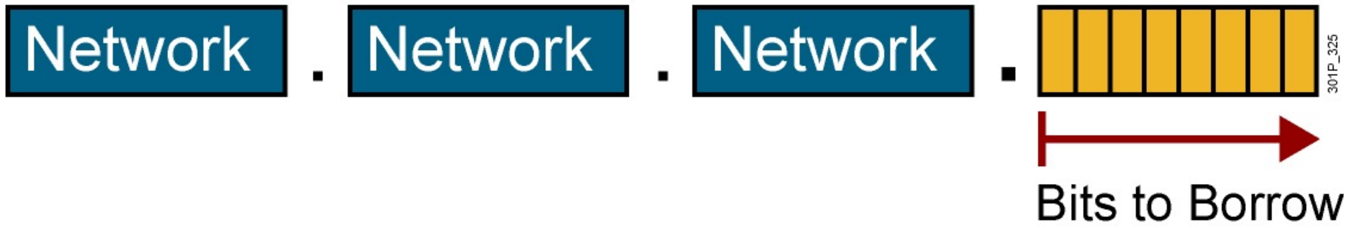


Subnetworks (subnets)

- Smaller networks are easier to manage.
- Overall traffic is reduced.
- You can more easily apply network security policies.

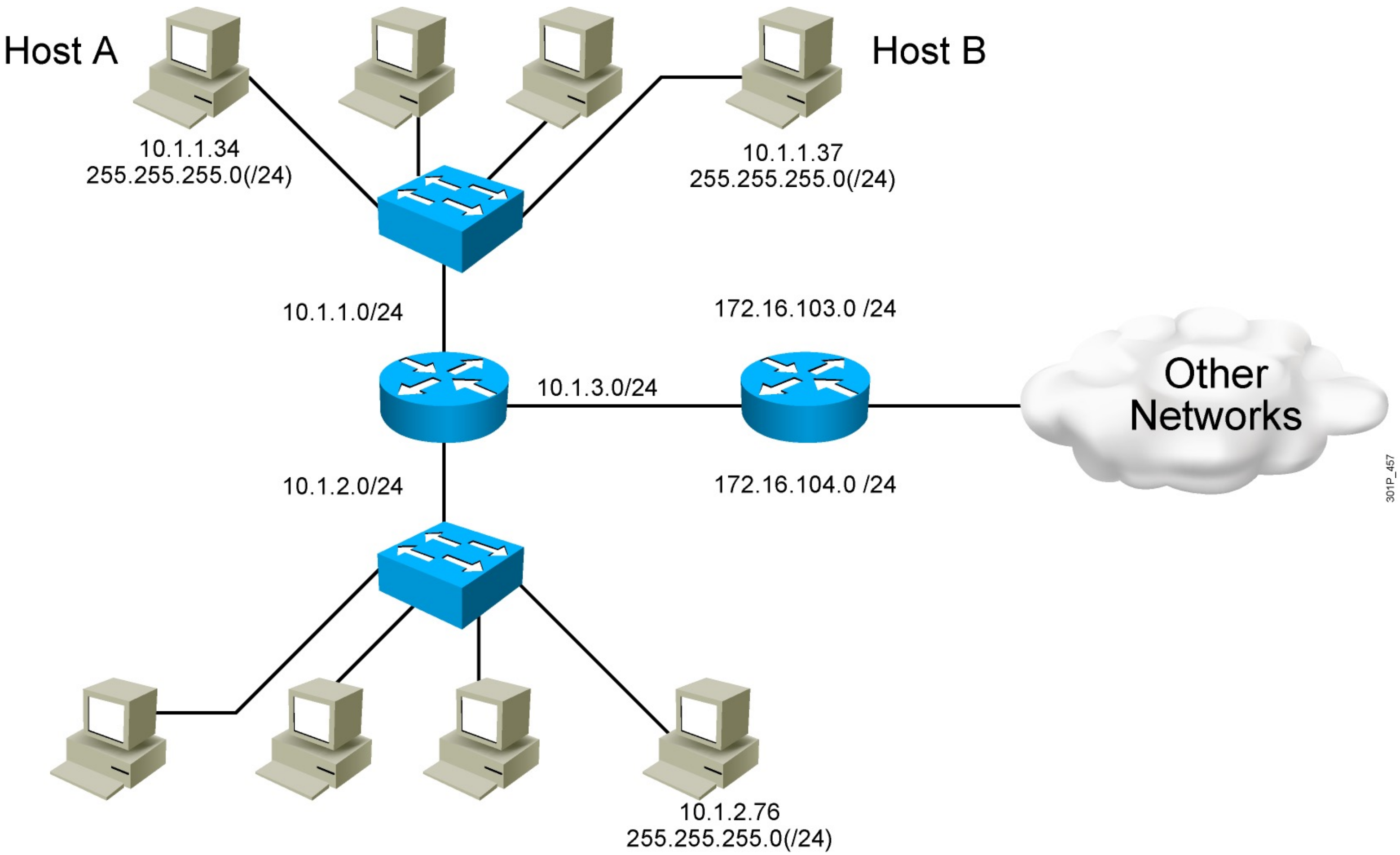


Possible Subnets for a Class C Network

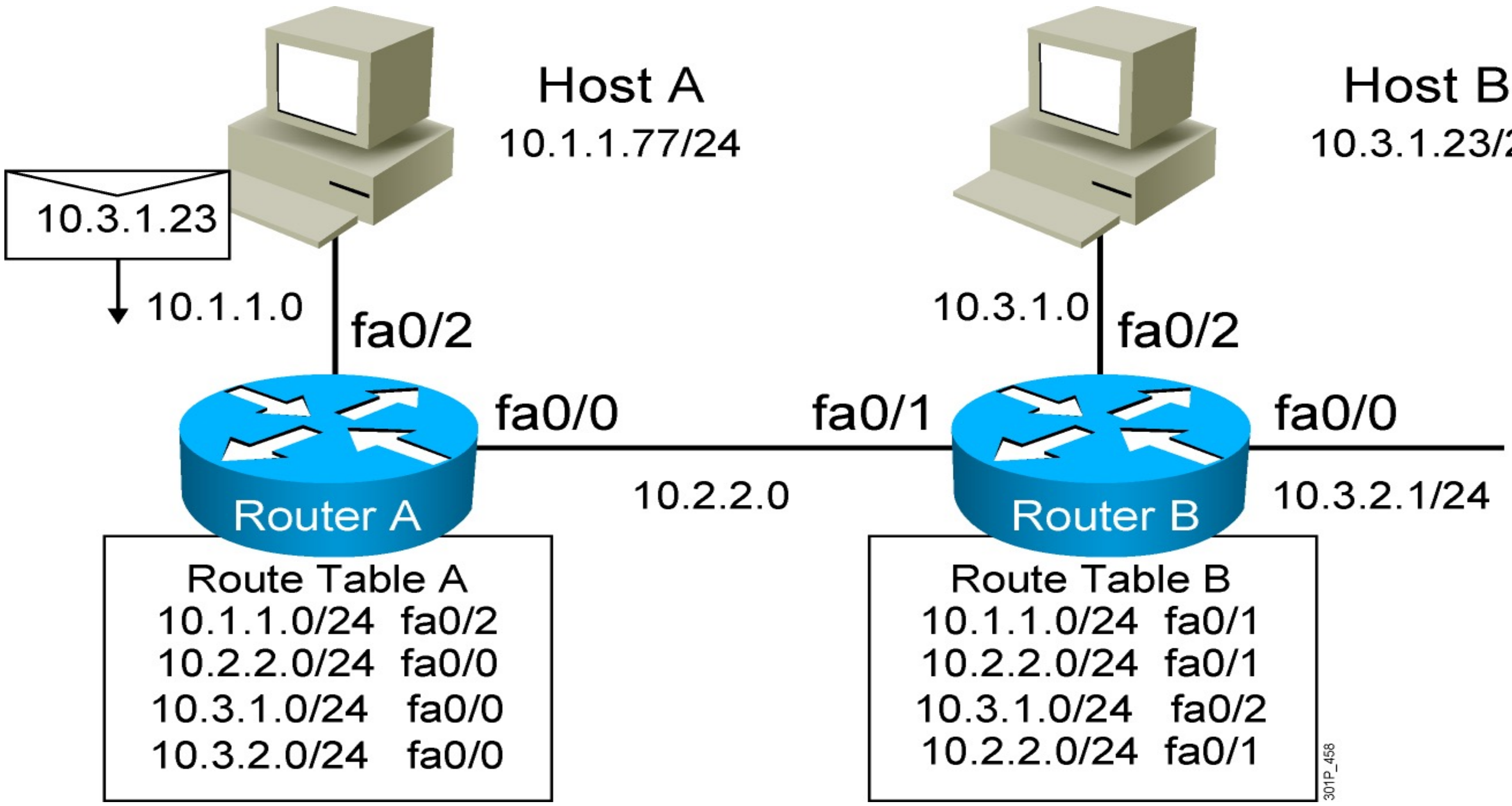


Number of Bits Borrowed (s)	Number of Subnets Possible (2^s)	Number of Bits Remaining in Host ID ($8 - s = h$)	Number of Hosts Possible Per Subnet ($2^h - 2$)
1	2	7	126
2	4	6	62
3	8	5	30
4	16	4	14
5	32	3	6
6	64	2	2
7	128	1	2

End System Subnet Mask Operation



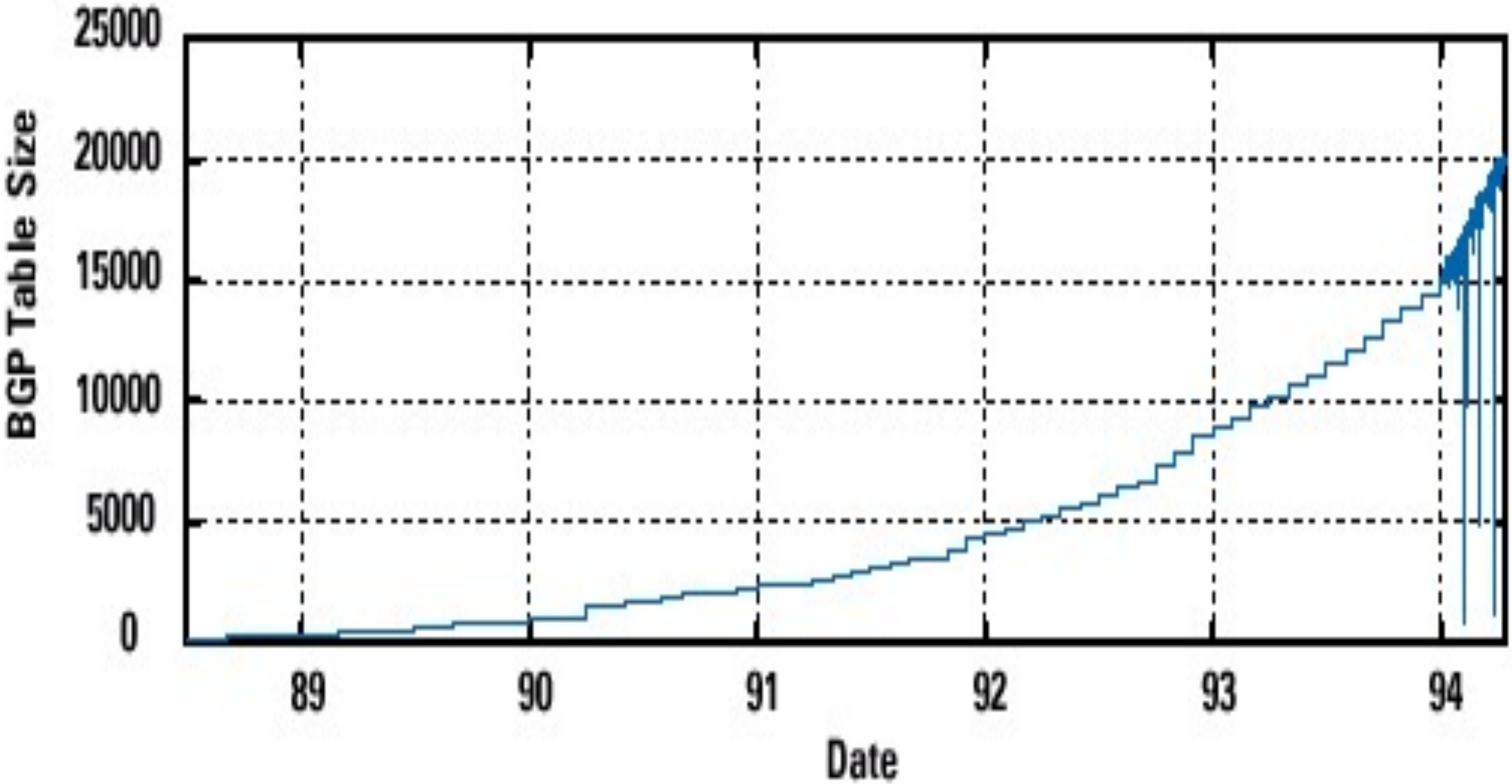
How Routers Use Subnet Masks



Obtaining a Block of Addresses

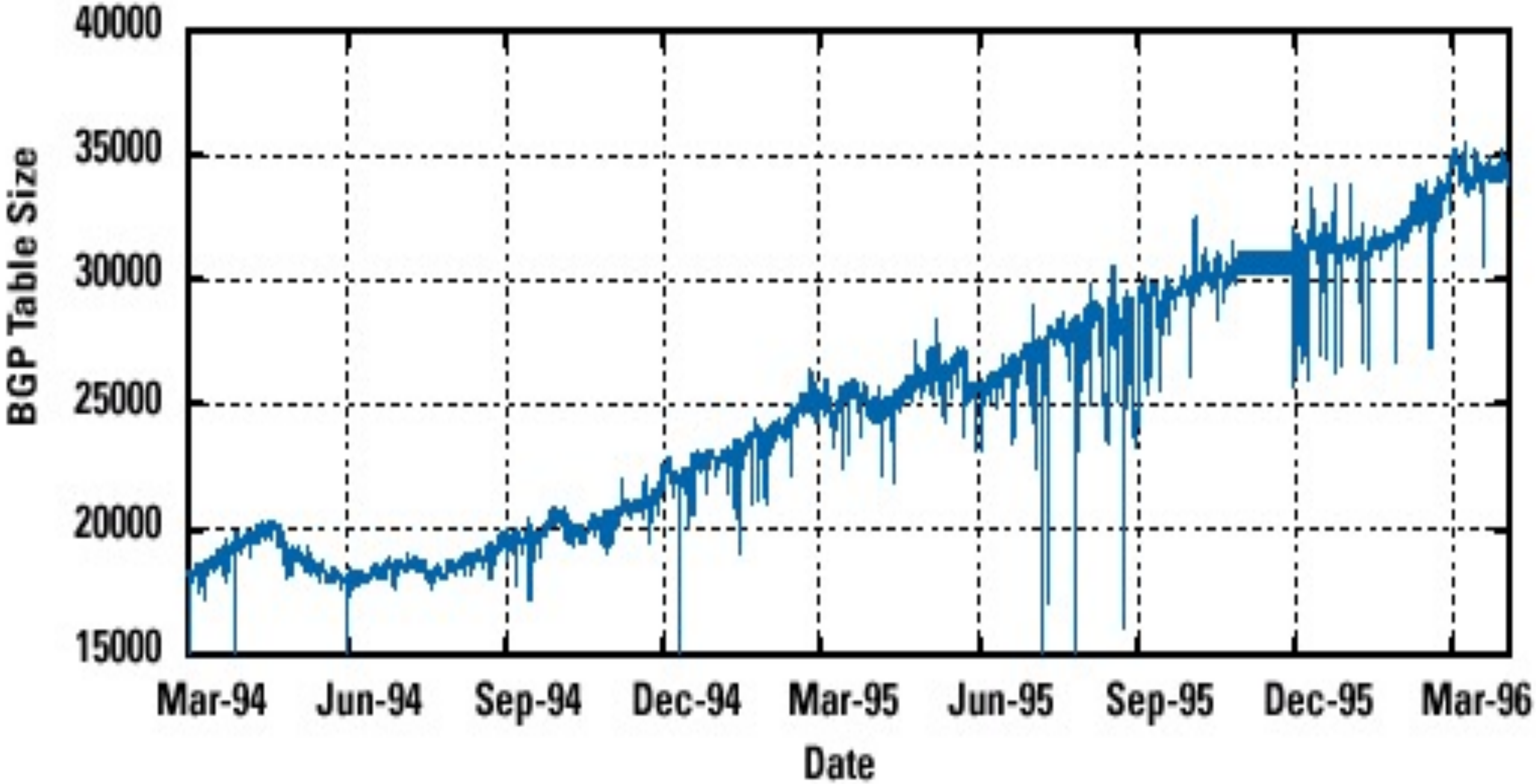
- Internet Corporation for Assigned Names and Numbers (ICANN)
  - Allocates large blocks to Regional Internet Registries
- Regional Internet Registries (RIRs)
  - E.g., ARIN (American Registry for Internet Numbers)
  - Allocates to ISPs and large institutions
- Internet Service Providers (ISPs)
  - Allocate address blocks to their customers
  - Who may, in turn, allocate to their customers…

Pre-CIDR (1988-1994): Steep Growth



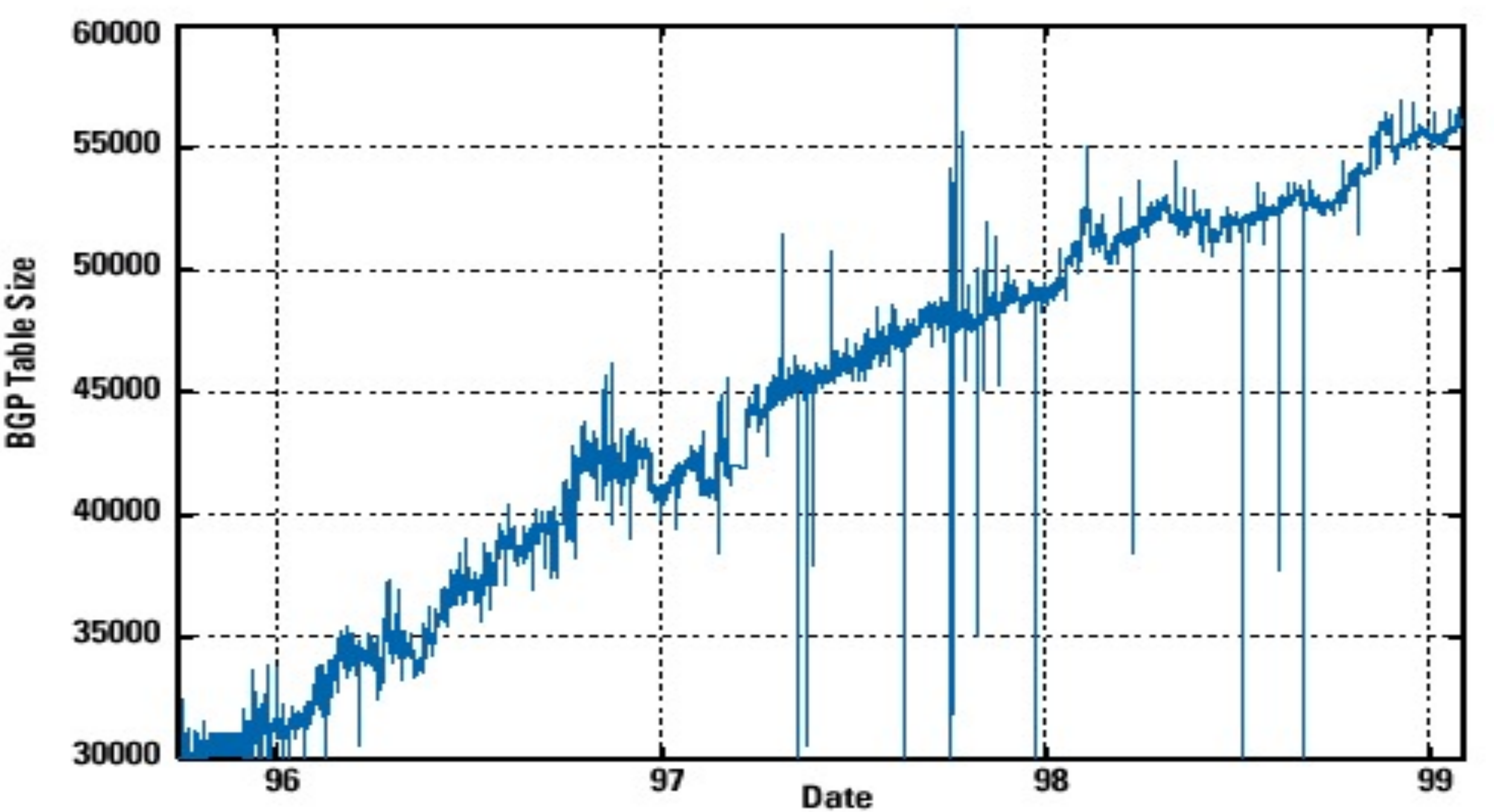
Growth faster than improvements in equipment capability

CIDR (1994-1996): Much Flatter



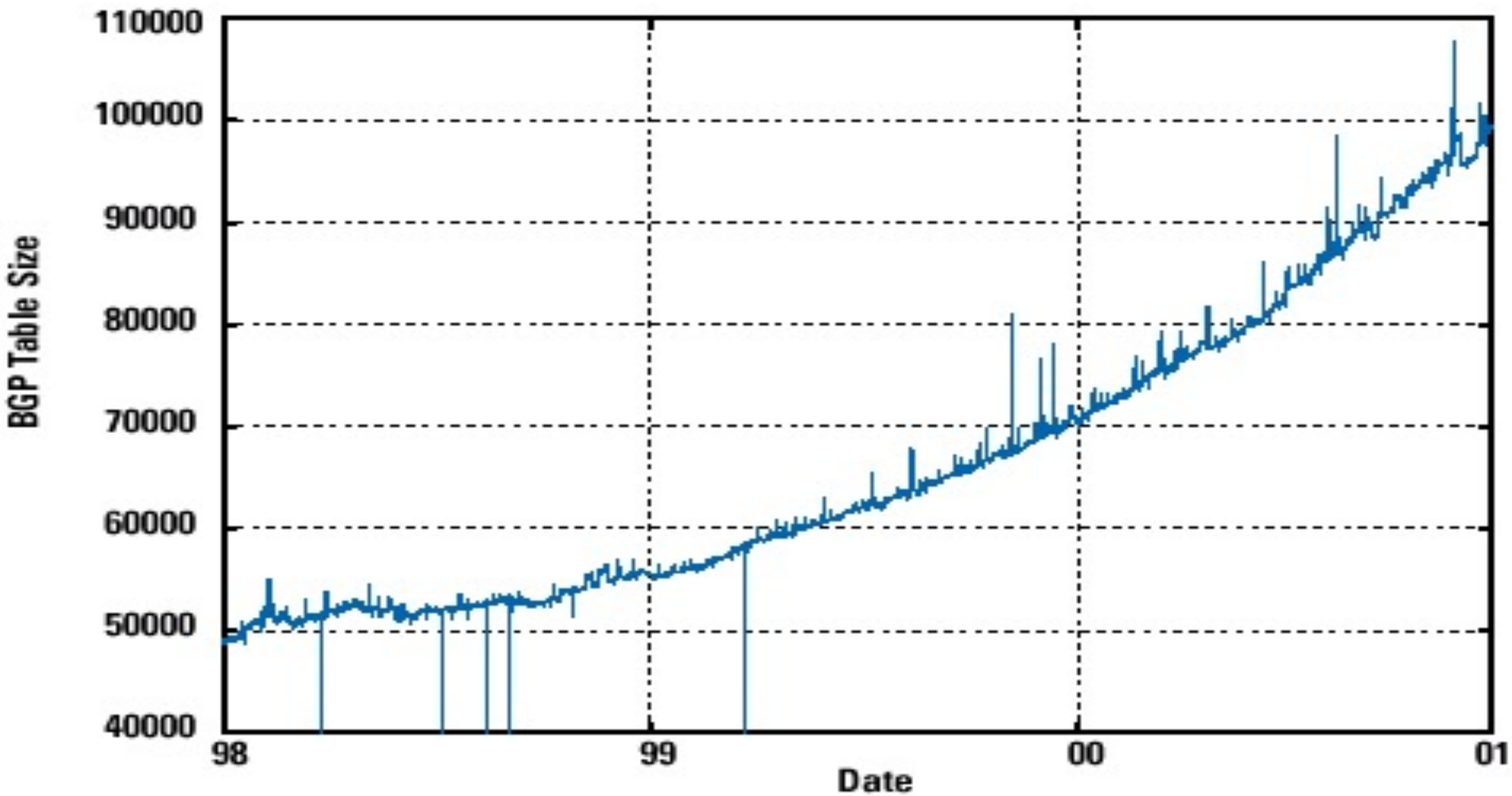
Efforts to aggregate

CIDR Growth (1996-1998): Roughly Linear



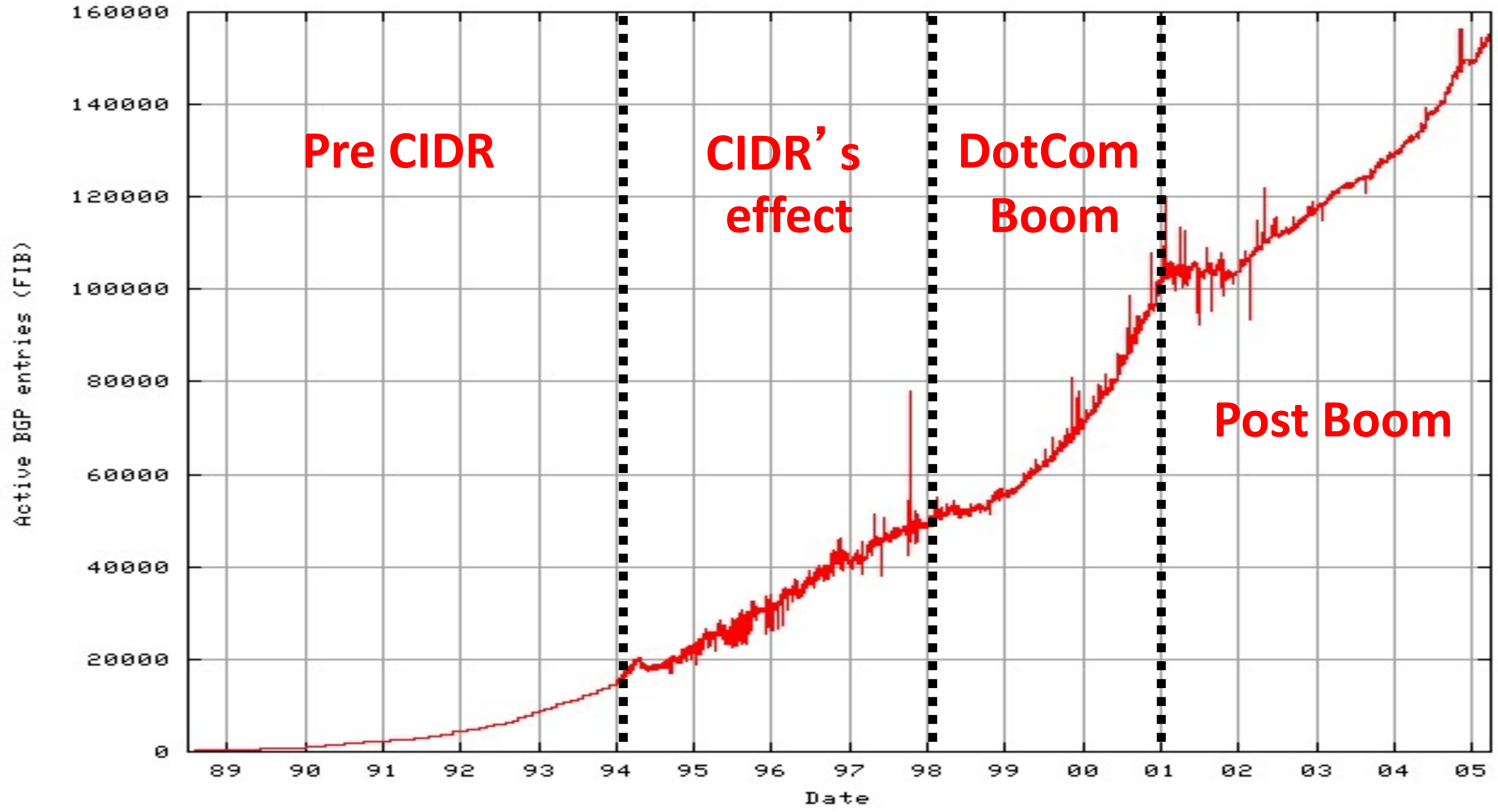
Good use of aggregation, and peer pressure!

DotCom Boom (1998-2001): Steep Growth



Internet boom and increased multi-homing

Long Term Growth (1989-2005)



Today we are up to ~400,000 prefixes