COS 461 *Computer Networks*

Lecture 3: Network Layer

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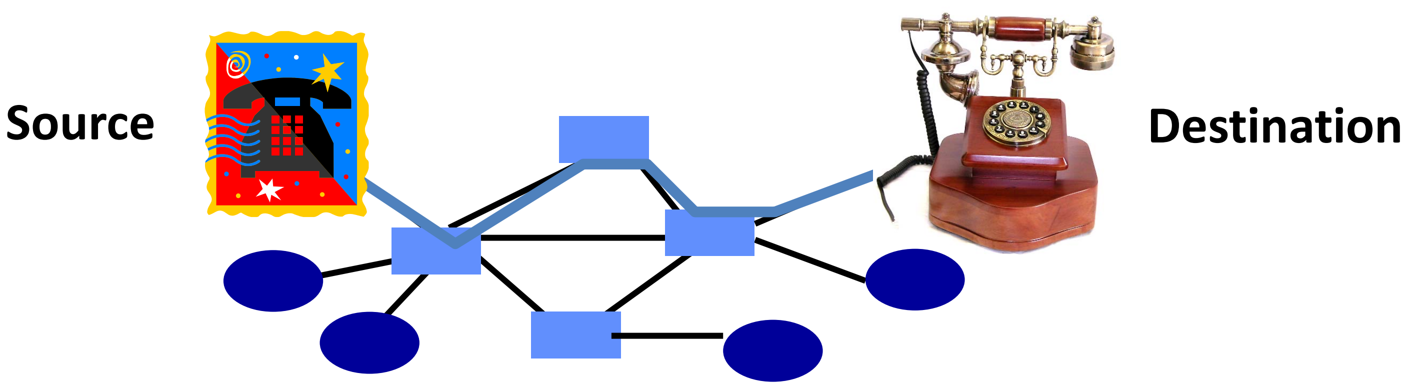
The Network Layer

- Local area networks have **limitations**:
  1. **Scaling** number of networks and users
  2. **Heterogeneity**: users of one network want to communicate with other

- How to interconnect **large, heterogeneous networks?**
  - ***What exactly should network layer's service contract be?***

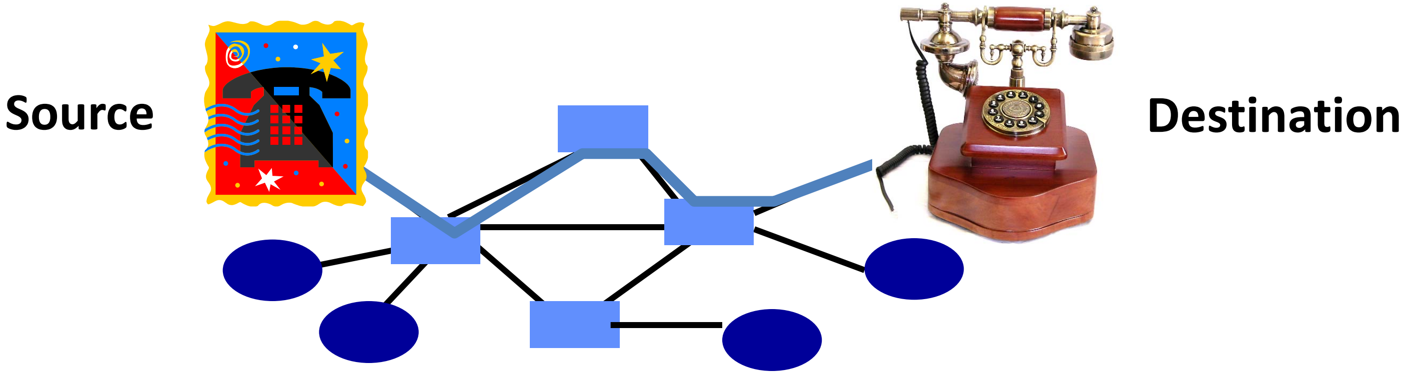
A Reliable Network: Circuit Switching
(*e.g.*, Phone Network)

Network	*Global* ***reliable voice call***
Link	Best-effort *local* packet delivery



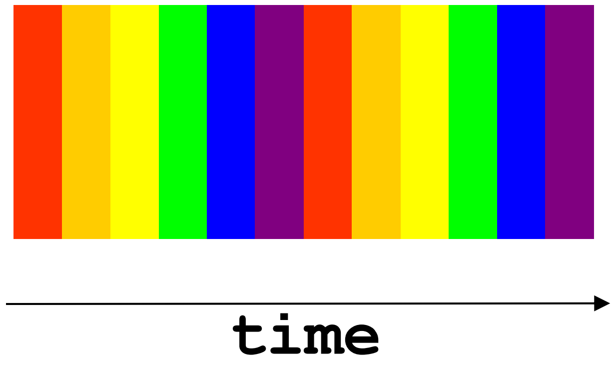
A Reliable Network: Circuit Switching
(*e.g.*, Phone Network)

- 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

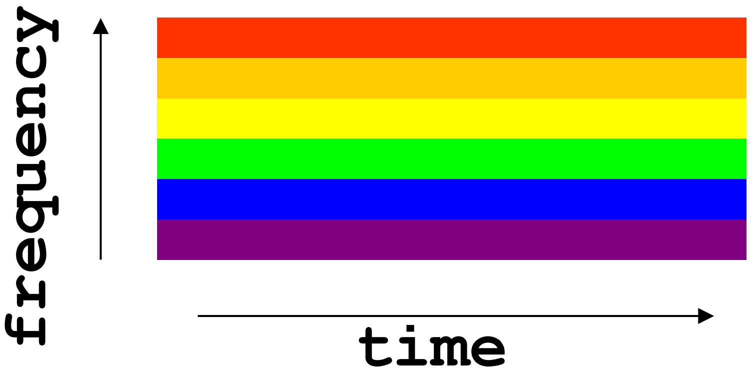


Circuit Switching: Static Allocation

- Time-division
  - Each circuit allocated certain time slots



- Frequency-division
  - Each circuit allocated certain frequencies

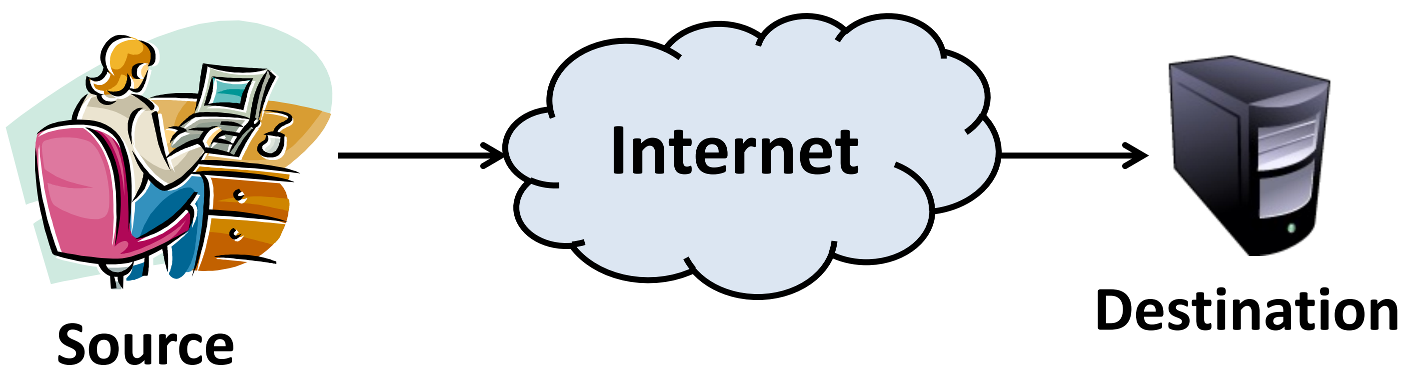


The Internet's Network Layer
service contract:

Best-Effort Global ***Datagram*** Delivery

What is “Best Effort?”

- Network makes no service guarantees
  - Just gives its ***Best Effort***
- The network has ***failure modes***:
  a) Packets may be lost
  b) Packets may be corrupted
  c) Packets may be delivered out of order
  d) Packet may be significantly delayed

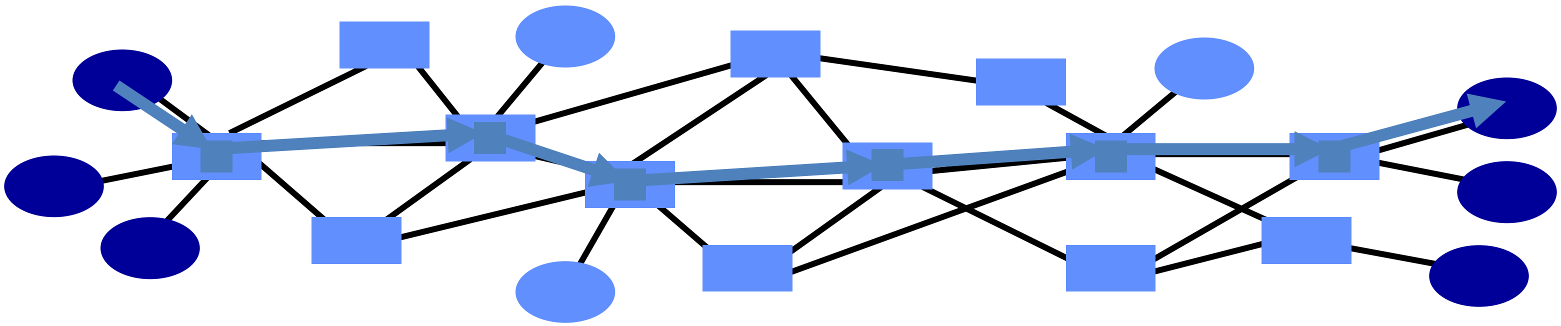


Why best effort?

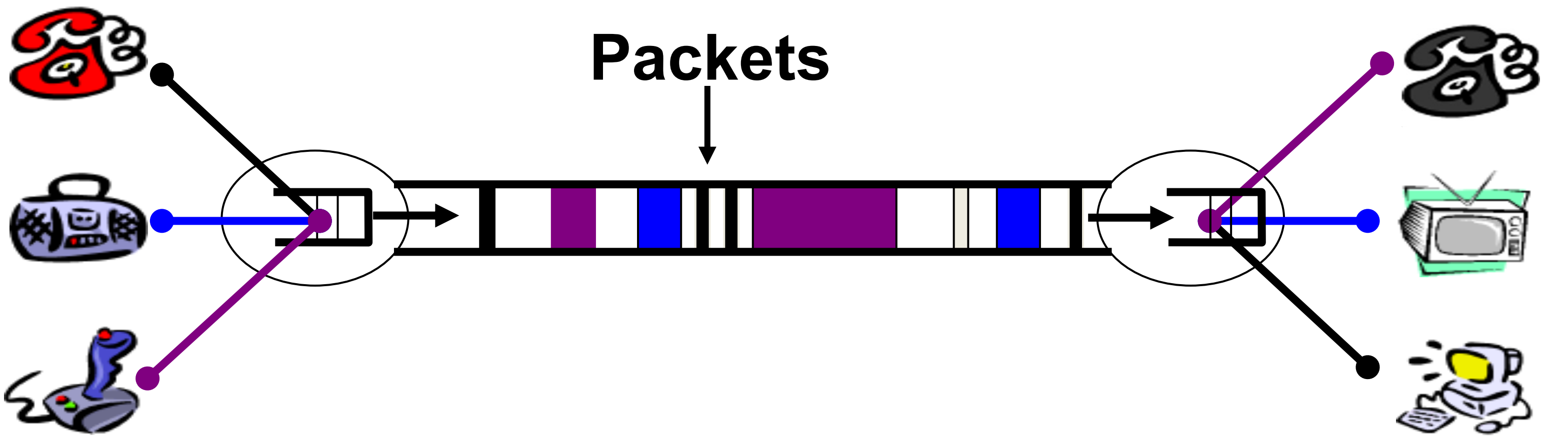
- Best effort means task of network is **simple**
  - No need to do error detection and correction
  - No need to remember from one packet to next
  - No need to manage congestion in the network
    - No need to reserve bandwidth and memory in the network
  - No need to make packets follow same path
- Easier to survive failures (transient disruptions ok)
- Simplifies interconnection between networks

Internet: Best Effort **Datagram Switching**

- Message divided into packets (***datagrams***)
  - Header identifies the destination address
- Datagrams travel **separately** through network
  - Forwarding based on the destination address
  - Packets may be buffered temporarily
- Destination reconstructs the message



Datagram Switching: Statistical (Time Division) Multiplexing



- Intuition: Traffic by computer end-points is bursty!
  - Versus: Telephone traffic not bursty (constant bit rate)
  - One can use network while others idle

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

Is The Internet's Design Good Enough?

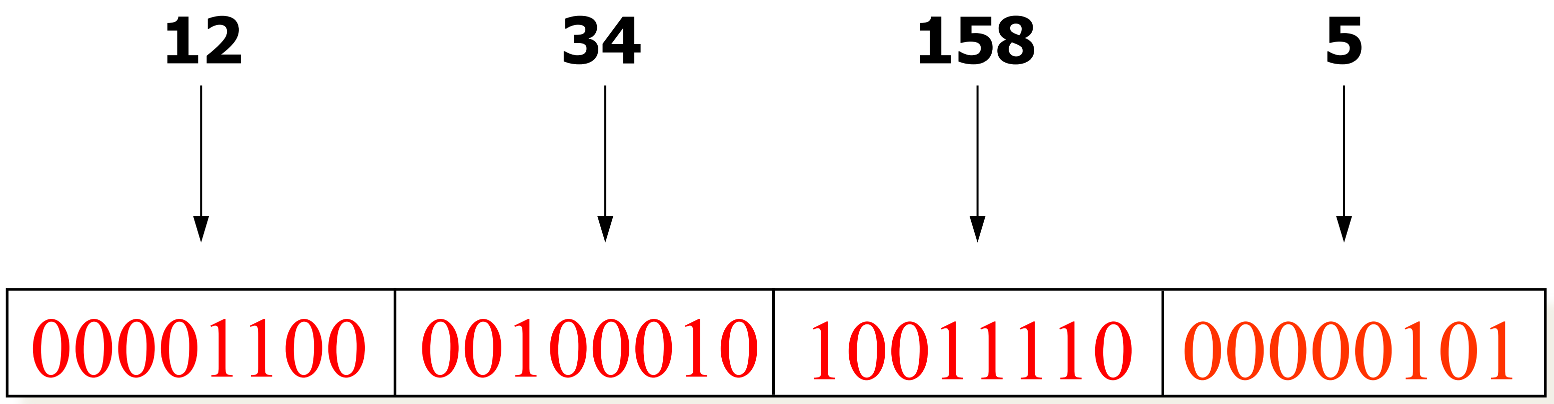
- Packet loss and delay
  - Sender can resend
- Packet corruption
  - Receiver can detect, and sender can resend
- Out-of-order delivery
  - Receiver can put the data back in order
- Packets follow different paths
  - Doesn't matter
- Network failure
  - Drop the packet
- Network congestion
  - Drop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

IP Protocol Stack: Key Abstractions

Network Addresses

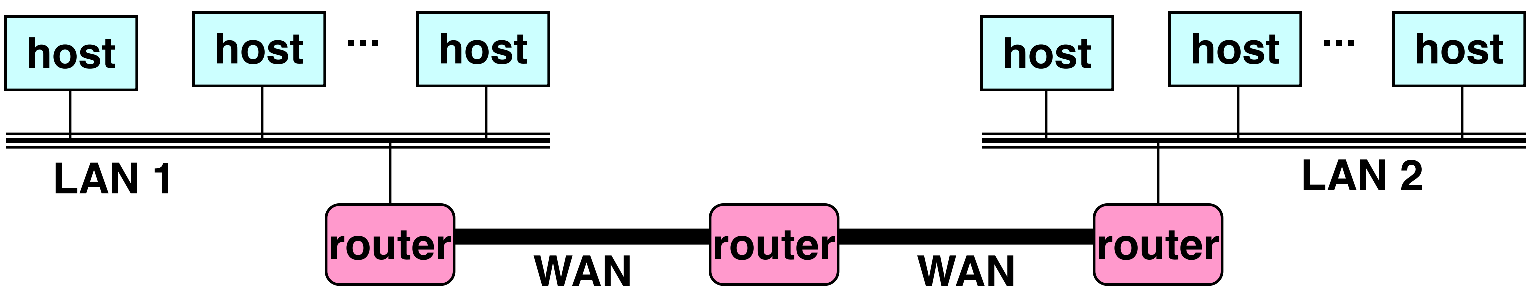
IP Address (IPv4)

- 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)

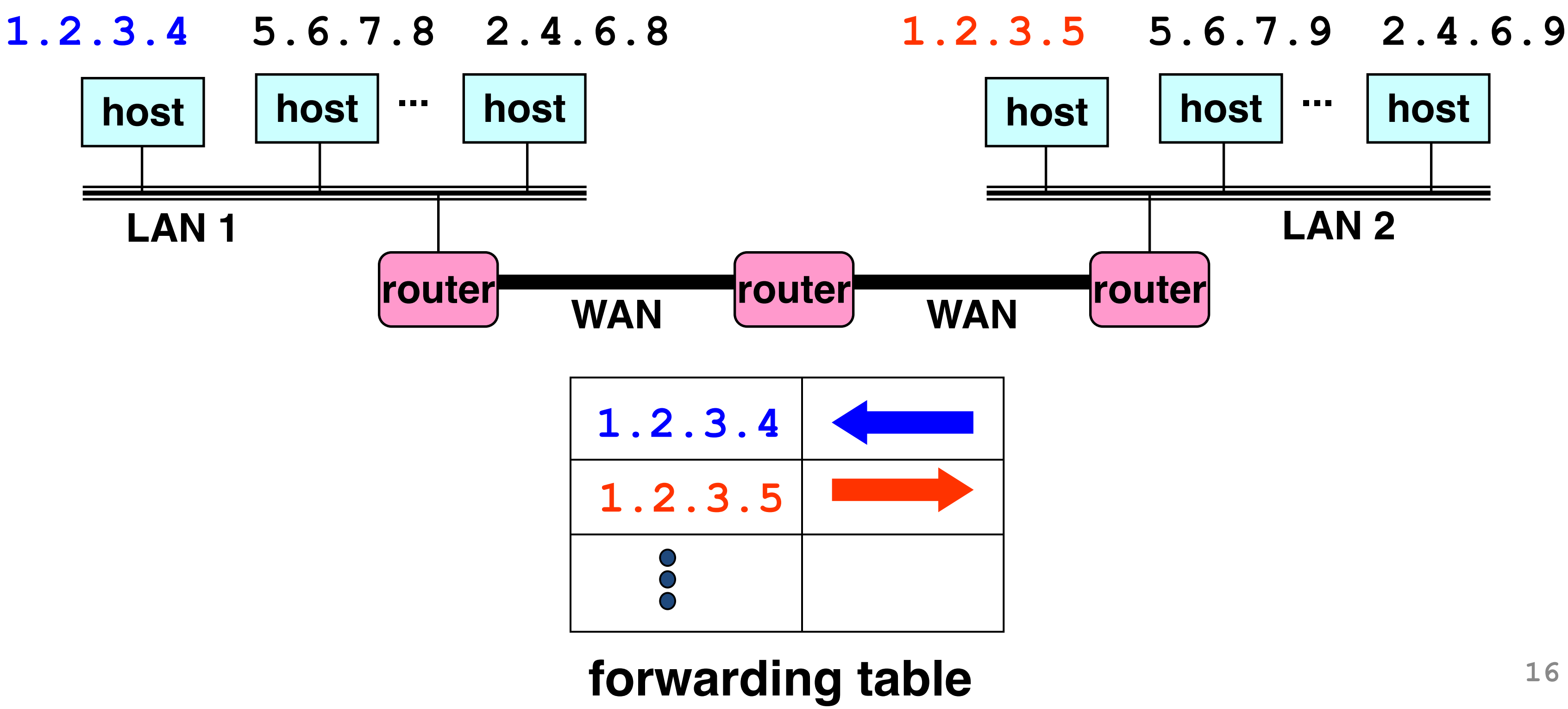


LAN = Local Area Network

WAN = Wide Area Network

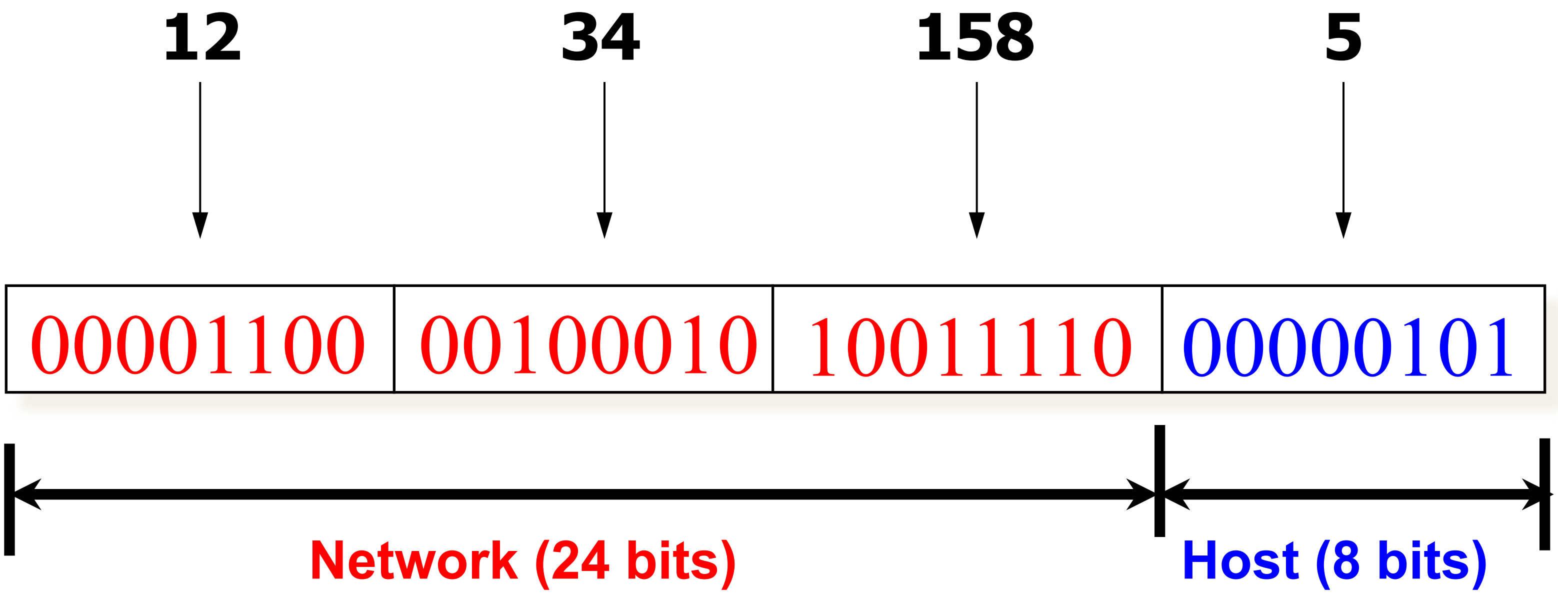
Scalability Challenge

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



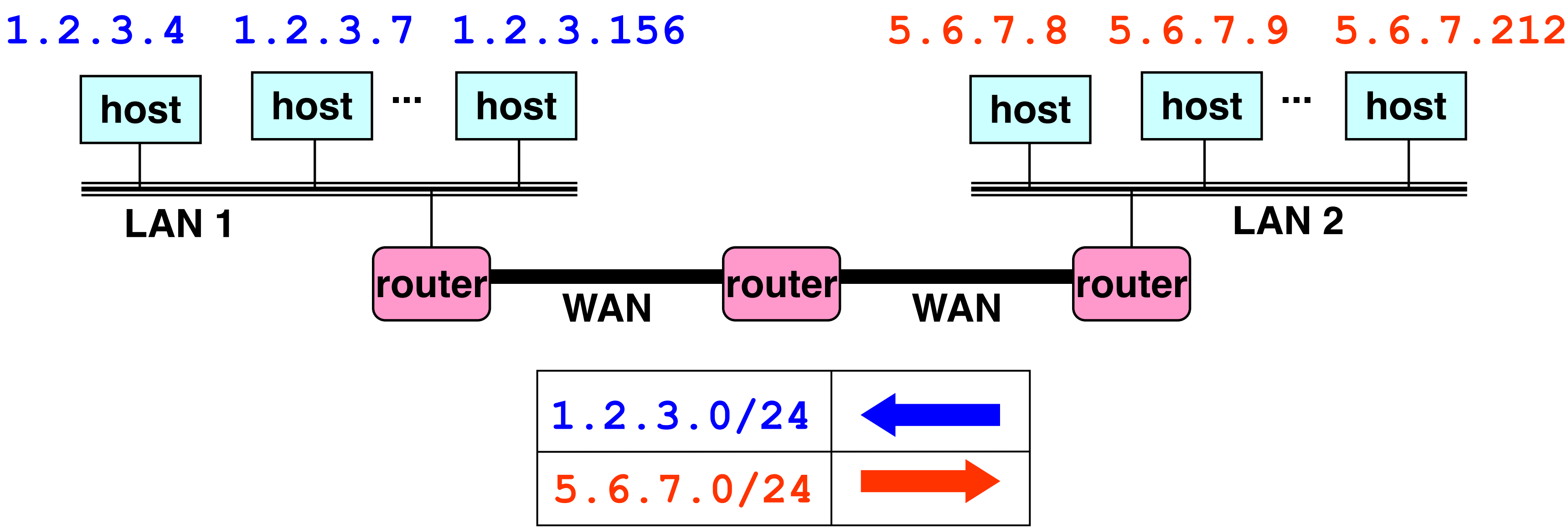
Hierarchical Addressing: IP Prefixes

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



Scalability Improved

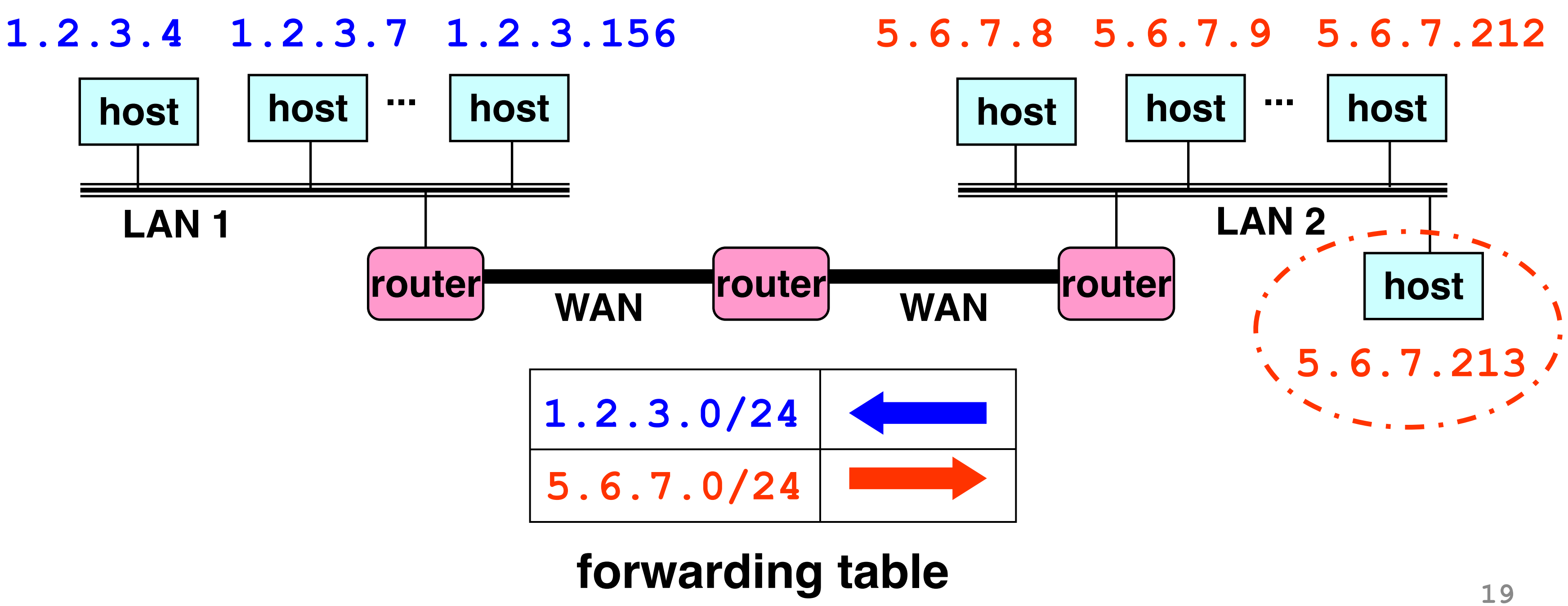
- Number related hosts from a common subnet
  - 1.2.3.0/24 on the left LAN
  - 5.6.7.0/24 on the right LAN



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



History of IP Address Allocation

Classful Addressing

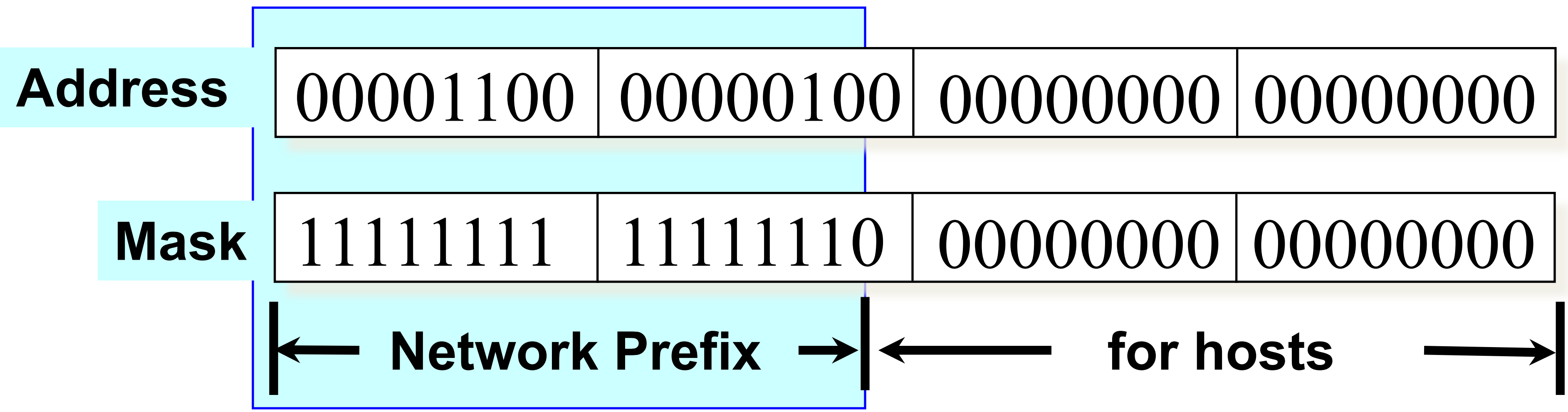
- In the olden days, only fixed allocation sizes
  - Class A: 0*
    - Very large /8 blocks (e.g., MIT has 18.0.0.0/8)
  - Class B: 10*
    - Large /16 blocks (e.g,. Princeton has 128.112.0.0/16)
  - Class C: 110*
    - Small /24 blocks (e.g., AT&T Labs has 192.20.225.0/24)
  - Class D: 1110* for multicast 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

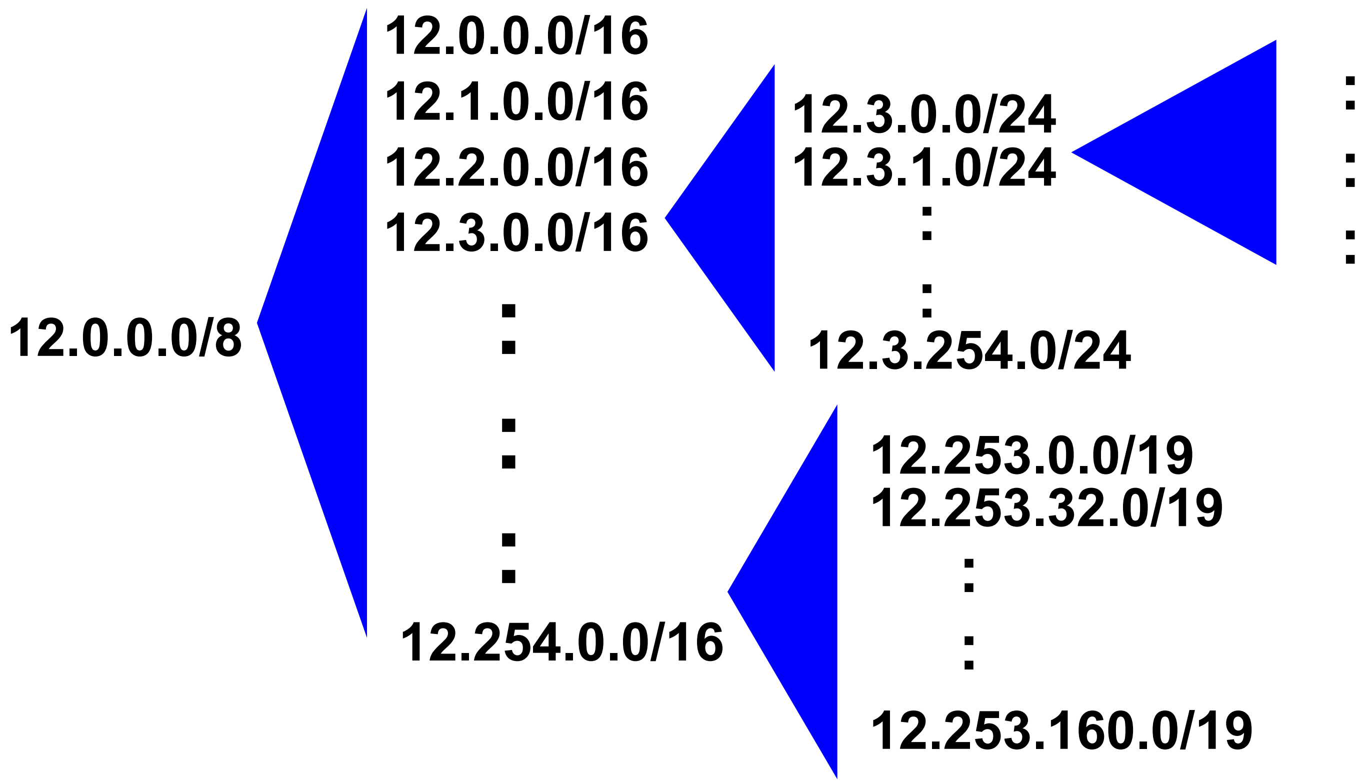
IP Address : 12.4.0.0   IP Mask: 255.254.0.0



Written as 12.4.0.0/15

Hierarchical Address Allocation

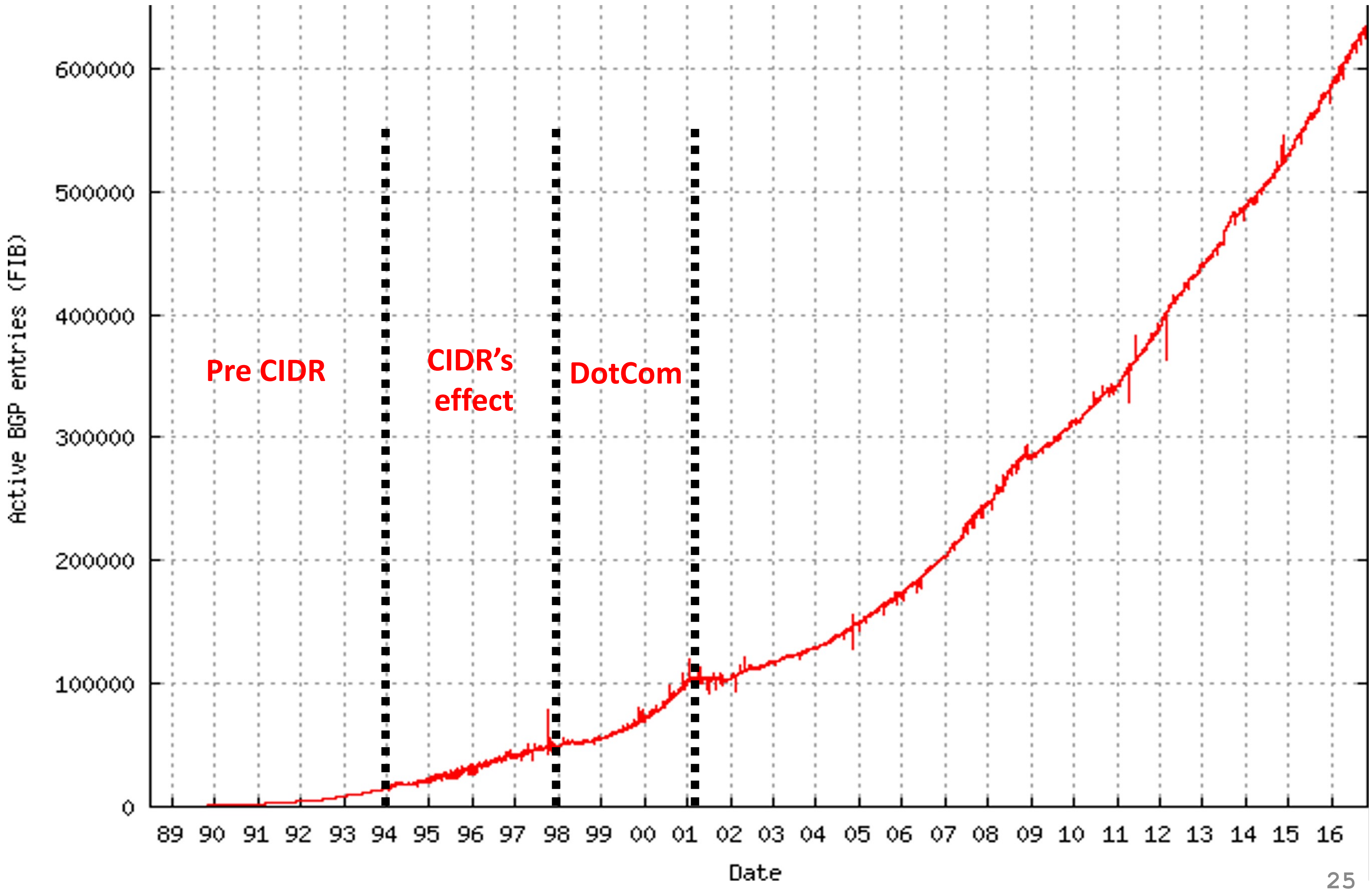
- Hierarchy is key to scalability
  - Address allocated in contiguous chunks (prefixes)
  - Today, the Internet has about 600-800,000 prefixes



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…

Long Term Growth (1989-2017)



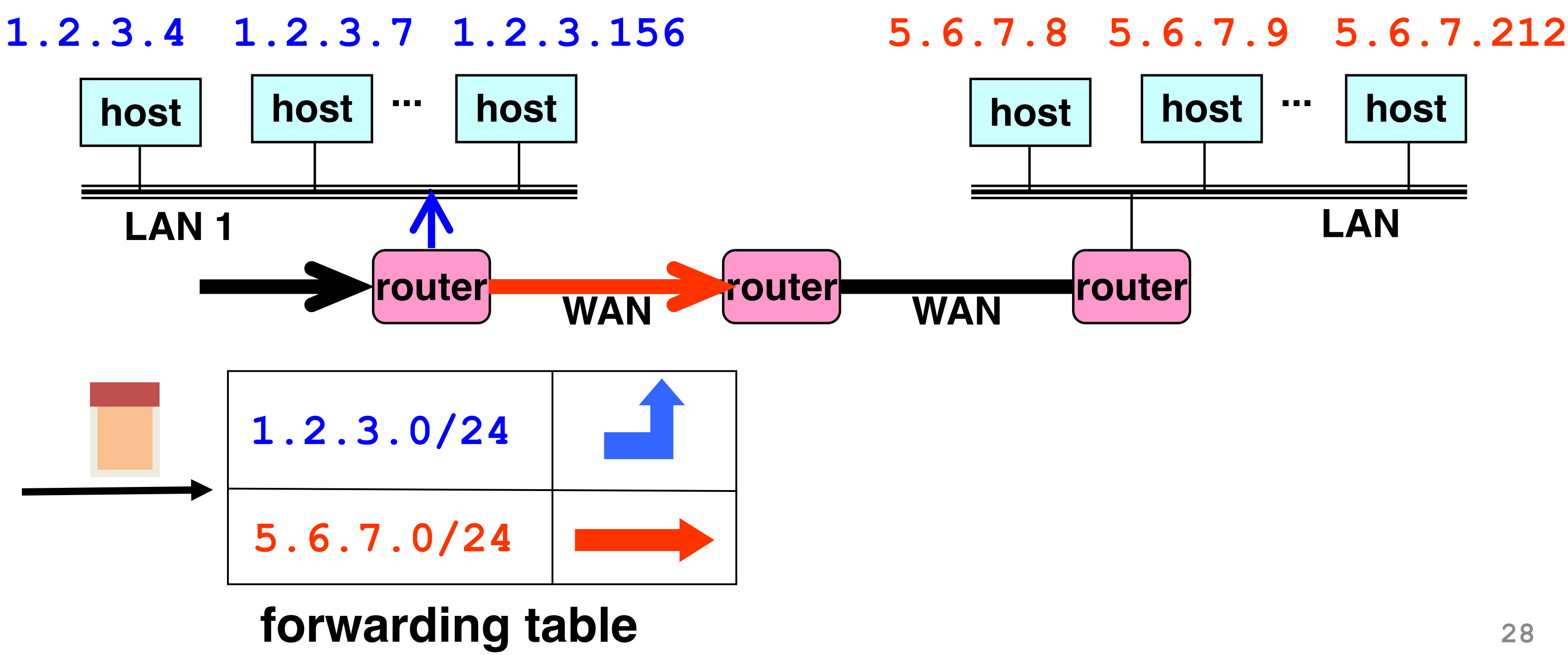
Packet Forwarding

Hop-by-Hop Packet Forwarding

- Each router has a ***forwarding table***
  - **Maps** destination IP address to outgoing interface
- Upon receiving a packet
  - Inspect the destination 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

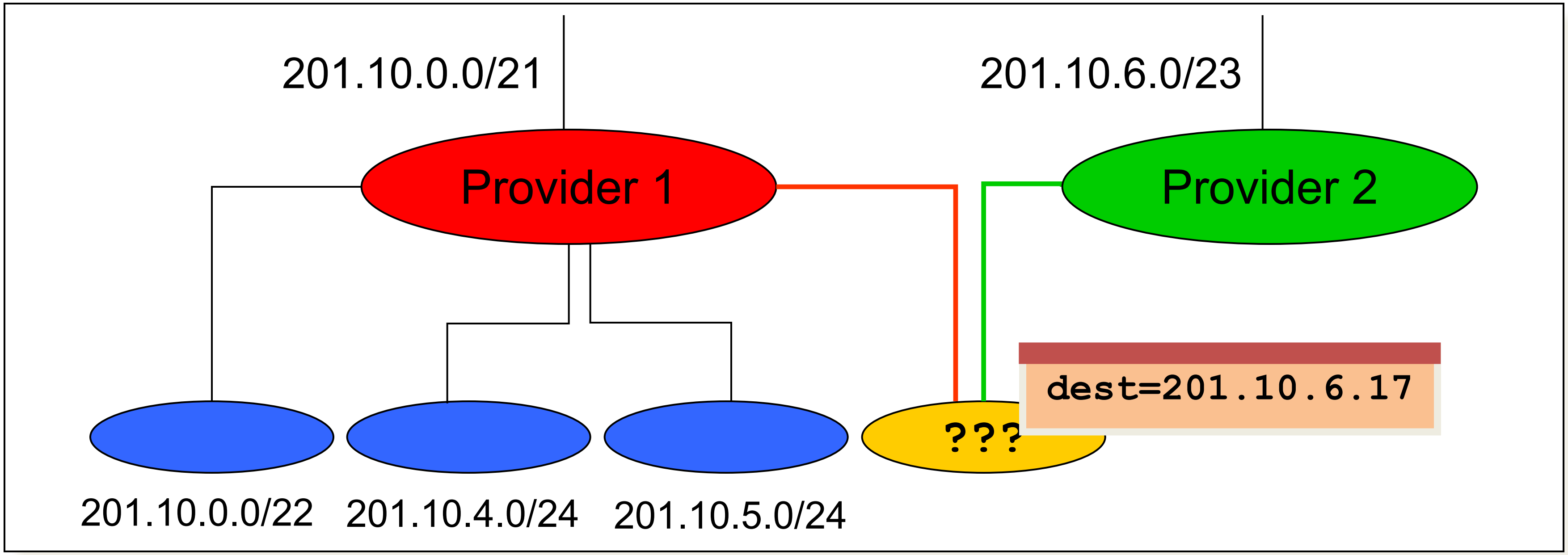
Separate Forwarding Entry Per Prefix

- Prefix-based forwarding
  - Map the destination address to matching prefix
  - Forward to the outgoing interface



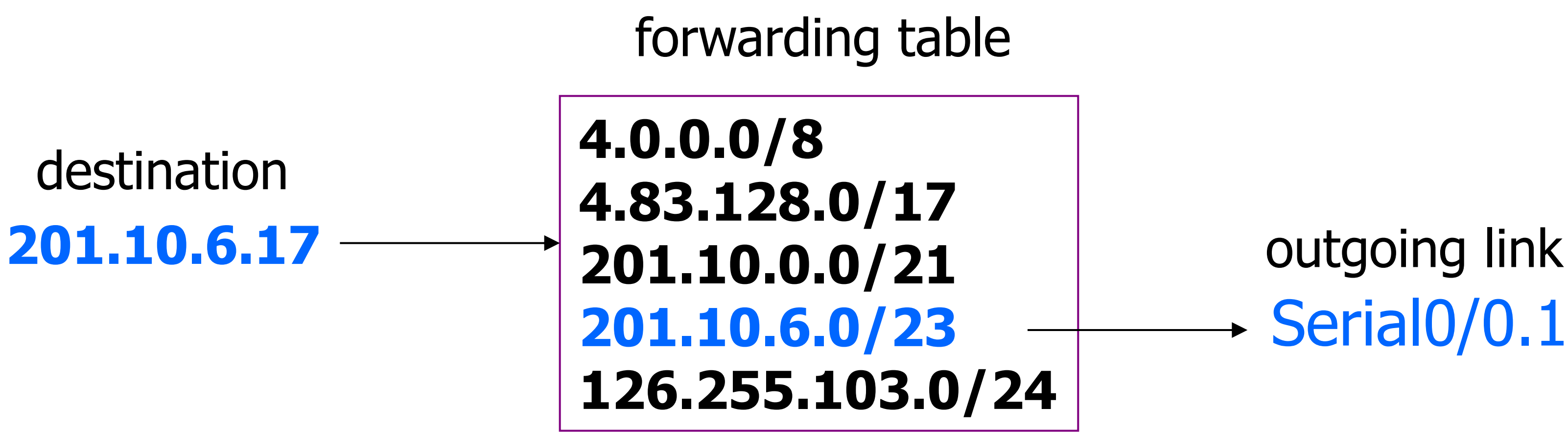
CIDR Makes Packet Forwarding Harder

- Forwarding table may have many matches
  - E.g., entries for 201.10.0.0/21 and 201.10.6.0/23
  - Packet's destination IP matches both networks!



Longest Prefix Match Forwarding

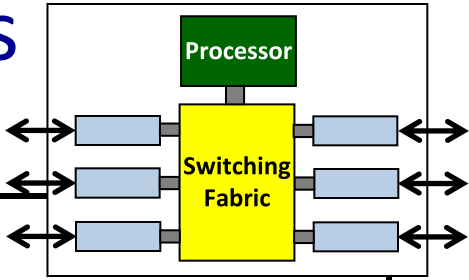
- Destination-based forwarding
  - Packet has a destination address
  - Router identifies longest-matching prefix
    - i.e., the **most specific** match to the destination address



Creating a Forwarding Table

- 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 the *control plane* comes in
  - Routing protocols

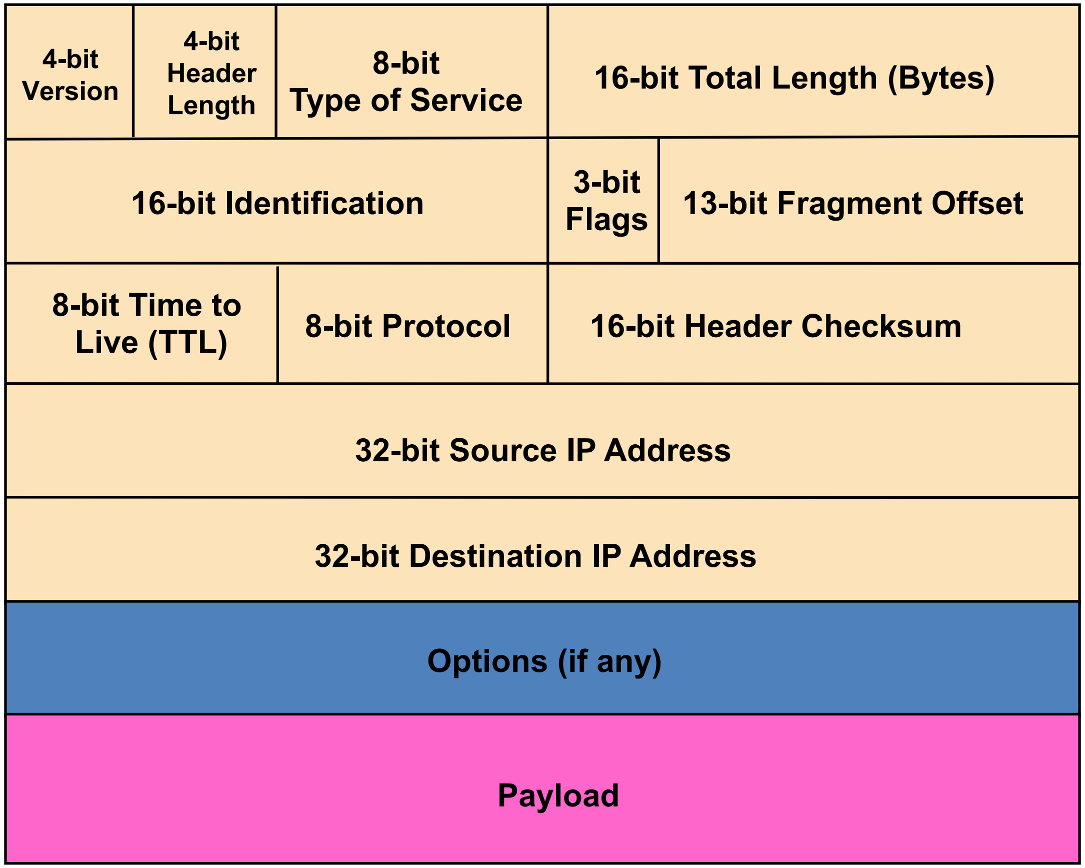
Data, Control, & Management Planes



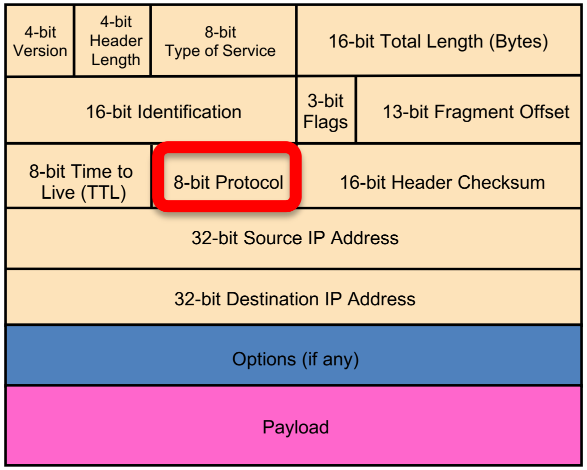
	Data	Control	Management
Time-scale	Packet (ns)	Event (10 ms to sec)	Human (min to hours)
Tasks	Forwarding, buffering, filtering, scheduling	Routing, signaling	Analysis, configuration
Location	Line-card hardware	Router software	Humans or scripts

IP Packet Format

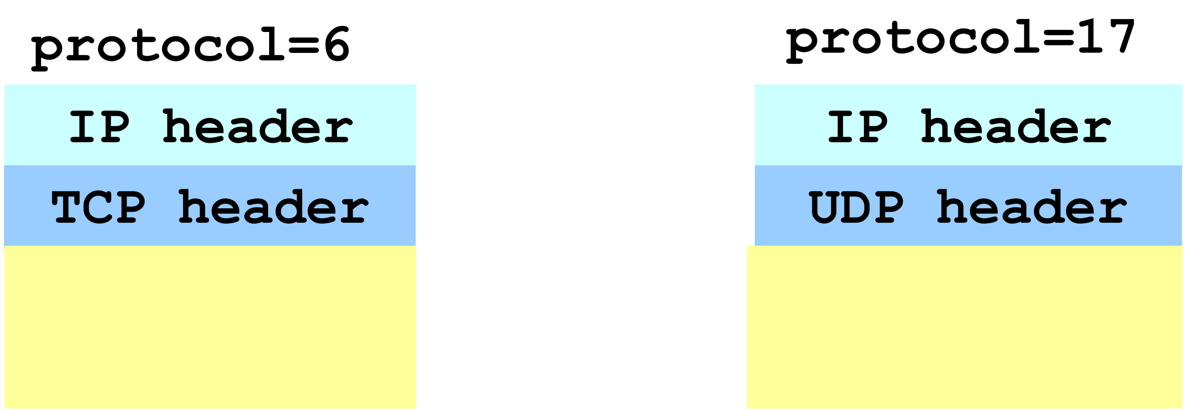
IP Packet Structure



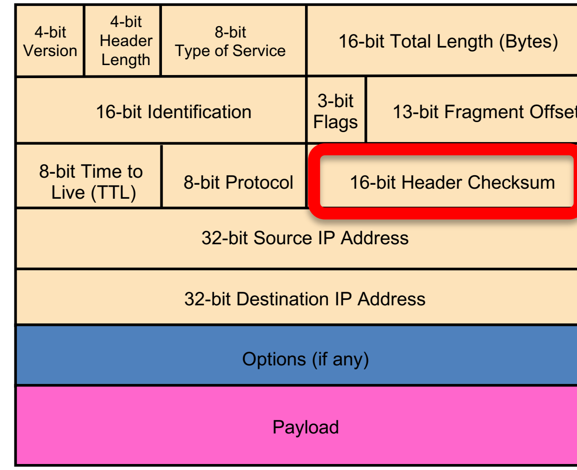
IP Header: Transport Protocol



- Protocol (8 bits)
  - Identifies the higher-level protocol
    - E.g., “6” for the Transmission Control Protocol (TCP)
    - E.g., “17” for the User Datagram Protocol (UDP)
  - Important for demultiplexing at receiving host
    - Indicates what kind of header to expect next



IP Header:
Header Checksum



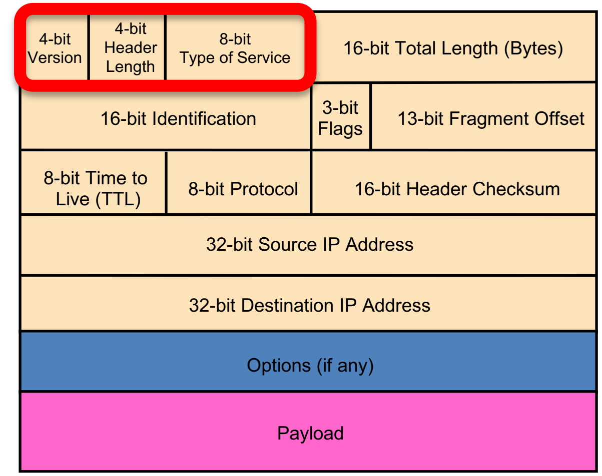
- Checksum (16 bits)
  - Sum of all 16-bit words in the header
  - If header bits are corrupted, checksum won't match
  - Receiving discards corrupted packets

```
  134
+ 212
-----
= 346
```

Mismatch!

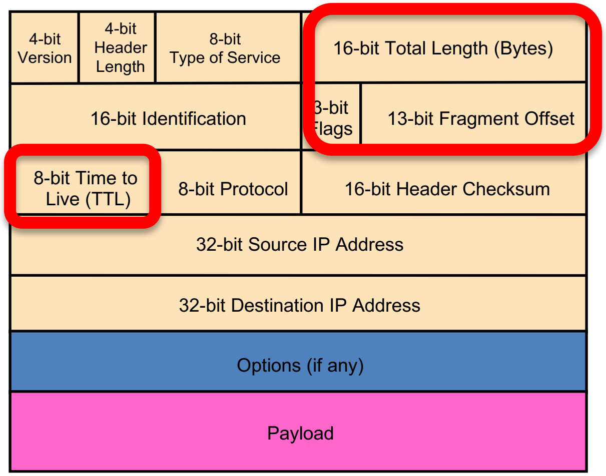
```
  134
+ 216
-----
= 350
```

IP Header: Version, Length, ToS



- Version number (4 bits)
  - Necessary to know what other fields to expect
  - Typically "4" (for IPv4), and sometimes "6" (for IPv6)
- Header length (4 bits)
  - Number of 32-bit words in the header
  - Typically "5" (for a 20-byte IPv4 header)
  - Can be more when "IP options" are used
- Type-of-Service (8 bits)
  - Allow different packets to be treated differently
  - Low delay for audio, high bandwidth for bulk transfer

IP Header: Length, Fragments, TTL



- Total length (16 bits)
  - Number of bytes in the packet
  - Max size is 63,535 bytes (2^{16} -1)
  - … though most links impose smaller limits
- Time-To-Live (8 bits)
  - Used to identify packets stuck in forwarding loops
  - … and eventually discard them from the network
- Fragmentation information (32 bits)
  - Supports dividing a large IP packet into fragments
  - … in case a link cannot handle a large IP packet

Conclusion

- Best-effort global packet delivery
  - Simple end-to-end abstraction
  - Enables higher-level abstractions on top
  - Doesn’t rely on much from the links below
- IP addressing and forwarding
  - Hierarchy for scalability and decentralized control
  - Allocation of IP prefixes
  - Longest prefix match forwarding
- Next time: switches & routers