Network Layer

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COS 461: Computer Networks

http://www.cs.princeton.edu/courses/archive/spr20/cos461/

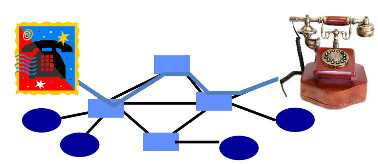
IP Protocol Stack: Key Abstractions

Application	Applications
Transport	Reliable streams / Messages
Network	Best-effort *global* packet delivery
Link	Best-effort *local* packet delivery

Best-Effort Global Packet Delivery

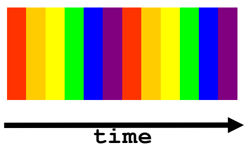
Circuit Switching (e.g., Phone Network)

- 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

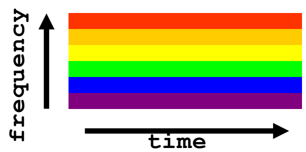


Circuit Switching: Static Allocation

- Time-division
  - Each circuit allocated certain time slots

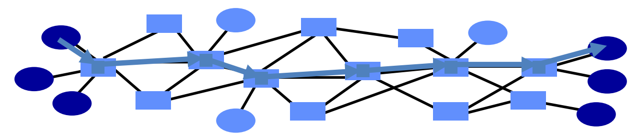


- Frequency-division
  - Each circuit allocated certain frequencies

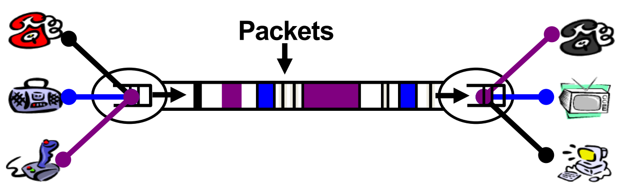


Packet Switching

- Message divided into packets
  - Header identifies the destination address
- Packets travel separately through the network
  - Forwarding based on the destination address
  - Packets may be buffered temporarily
- 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

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

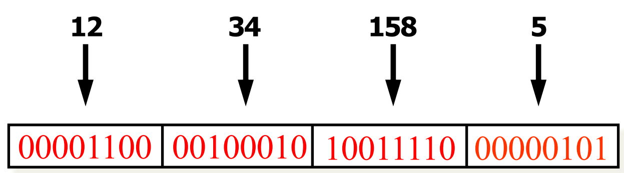
Packet (Y) vs. Circuit Switching (A)?

• 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

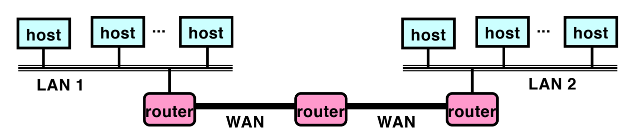
IP Address (IPv4)

- 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)

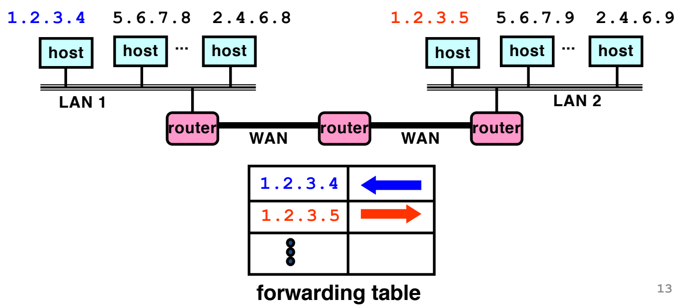


LAN = Local Area Network

WAN = Wide Area Network

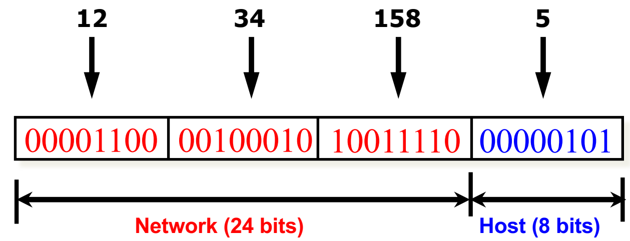
Scalability Challenge

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



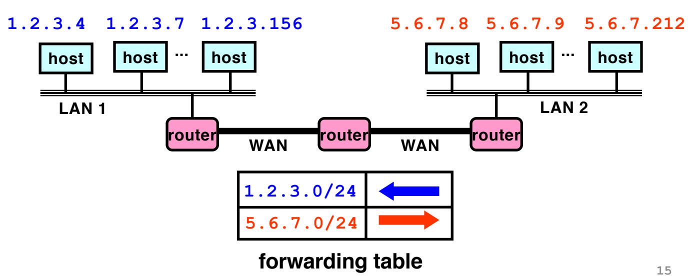
Hierarchical Addressing: IP Prefixes

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



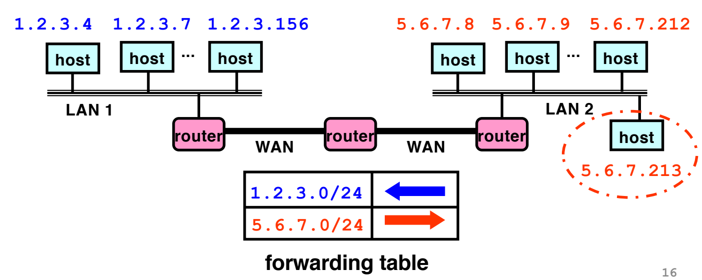
Scalability Improved

- 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



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

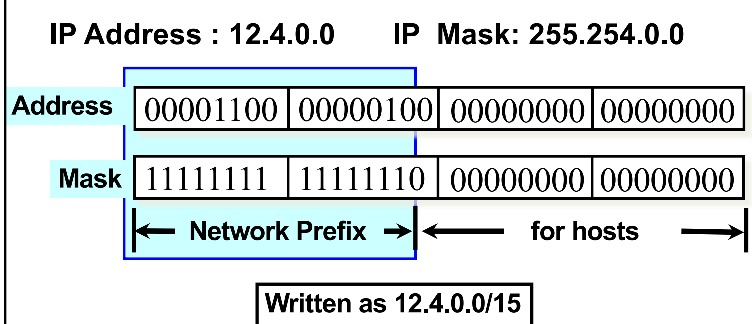
Classful Addressing

- 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)

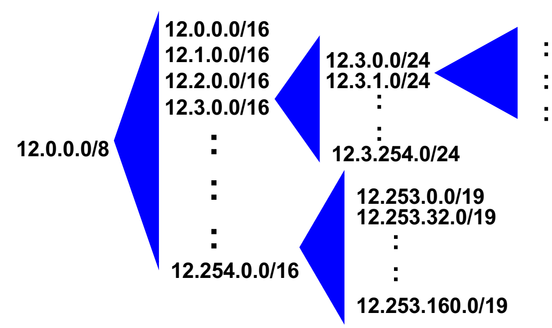
- Use two 32-bit numbers to represent network:

  Network number = IP address + Mask



Hierarchical Address Allocation

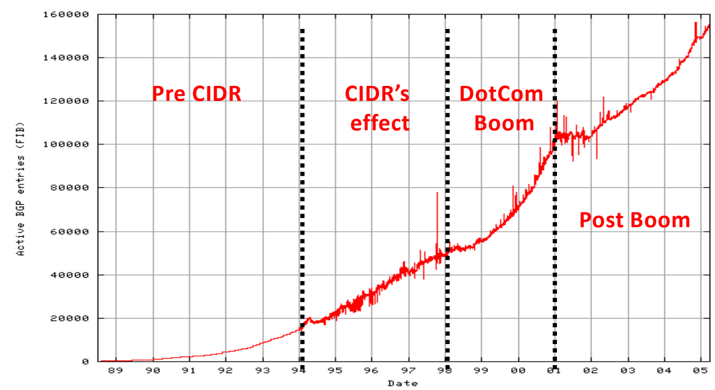
- Hierarchy is key to scalability
  - Address allocated in contiguous chunks (prefixes)
  - Today, the Internet has about 600-800,000 prefixes



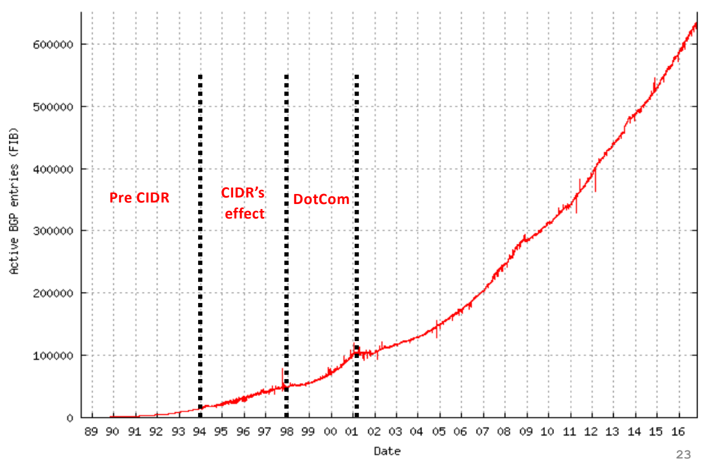
Obtaining a Block of Addresses

- 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 (1989-2005)



Long Term Growth (1989-2017)



Packet Forwarding

Hop-by-Hop Packet Forwarding

- Each router has a forwarding table
  - Maps destination 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

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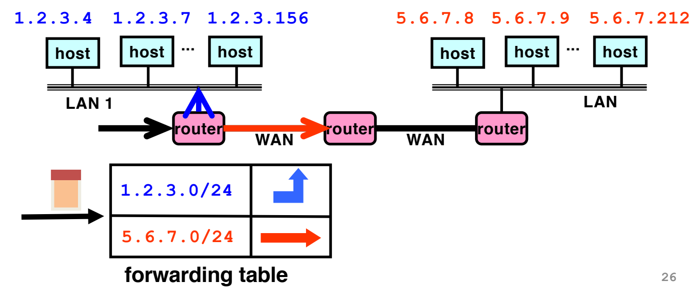
Separate Forwarding Entry Per Prefix

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



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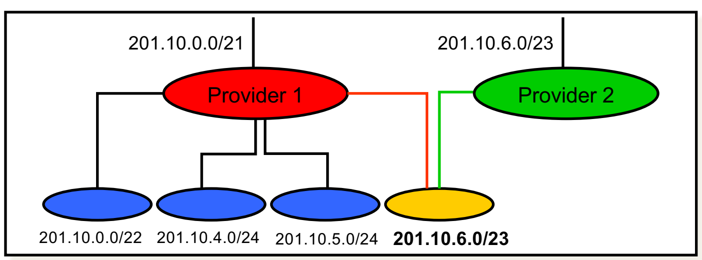
CIDR Makes Packet Forwarding Harder

- Forwarding table may have many matches
  - E.g., entries for 201.10.0.0/21 and 201.10.6.0/23
  - The IP address 201.10.6.17 would match both!



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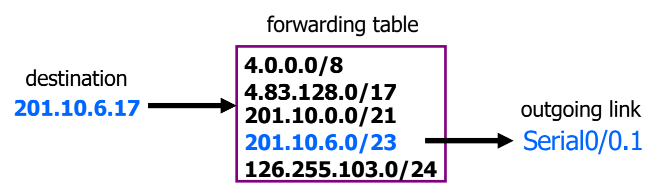
Longest Prefix Match Forwarding

- Destination-based forwarding
  - Packet has a destination address
  - Router identifies longest-matching prefix
  - Cute algorithmic problem: very fast lookups



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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

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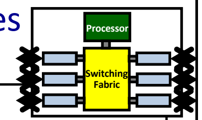
Data, Control, & Management Planes



	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

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Q's: MAC vs. IP Addressing

- Hierarchically allocated
  Y) MAC M) IP C) Both A) Neither
- Organized topologically
  Y) MAC M) IP C) Both A) Neither
- Forwarding via exact match on address
  Y) MAC M) IP C) Both A) Neither
- Automatically calculate forwarding by observing data
  Y) Ethernet switches M) IP routers C) Both A) Neither
- Per connection state in the network
  Y) MAC M) IP C) Both A) Neither
- Per host state in the network
  Y) MAC M) IP C) Both A) Neither

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  Y) MAC M) IP C) Both **A) Neither**
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  Y) MAC M) IP C) Both A) Neither

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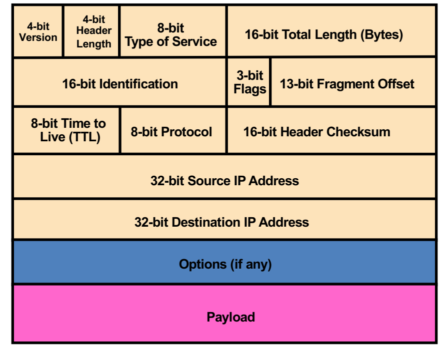
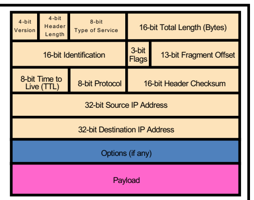
IP Packet Format

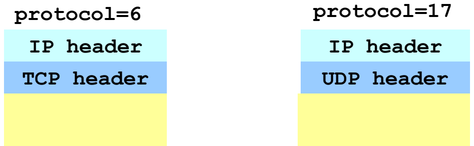
IP Packet Structure



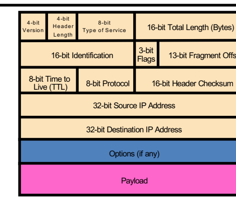
IP Header: Transport Protocol



- 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

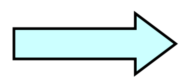


IP Header: Header Checksum



- 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

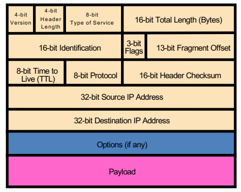
```
  134
+ 212
-----
= 346
```



Mismatch!

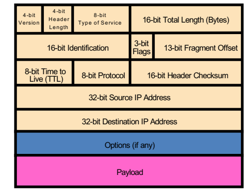
```
  134
+ 216
-----
= 350
```

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