Original Idea:
- Network is dumb
- Simple, robust service
- Shift complexity to endpoints
- Acts like postal system (packet-based) rather than traditional phone system (circuit-based)
Need protocol to actually communicate

A protocol is an agreement on how to communicate.

Includes syntax and semantics.

- **Syntax:** How communication is specified and structured.
  - Format, order messages are sent and received.
A protocol is an agreement on how to communicate.

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- **Syntax:** How communication is specified and structured.
  - Format, order messages are sent and received.
- **Semantics:** What a communication means
  - Actions taken when transmitting, receiving, or timer expires.
- **Example:** RFC 2616 (HTTP/1.1)
  - Section 5: Syntax of HTTP Requests
  - Section 9.3: Semantics of GET Requests
Protocols are layered

- Networks use a stack of layers
- Lower layers provide services to layers above
  - Don’t care what higher layers do
- Higher layers use services of layers below
  - Don’t care how lower layers implement services
- Layers define abstraction boundaries
  - At a given layer, all layers above and below are opaque
Basic Internet Architecture “Hourglass”
Narrow waist = interoperability
Packet encapsulation at each layer
Link layer: Connecting hosts to local network

Most common link layer protocol: **Ethernet**

- Messages organized into **frames**
- Every node has a globally unique 6-byte MAC address

Link layer: Connecting hosts to local network

- Originally a broadcast protocol: every node on network received every packet
- Now switched: switch learns the physical port for each MAC address and sends packets to correct port if known
- WiFi similar to Ethernet, but nodes can move
IP: Internet Protocol

- Connectionless delivery model
- “Best effort” = no guarantees about delivery
- No attempt to recover from failure
- Packets might be lost, delivered out of order, delivered multiple times
- Packets might be fragmented
- Provides hierarchical addressing scheme
IP: Internet Protocol

- **IPv4**
  - 32-bit host addresses
  - Written as 4 bytes in decimal,
  - e.g. 192.168.1.1

- **IPv6**
  - 128-bit host addresses
  - Written as 16 bytes in hex
  - :: implies zero bytes
  - e.g. 2620:0:e00:b::53 = 2620:0:e00:b:0:0:0:53
Example Internet Datagram Header

Note that each tick mark represents one bit position.
ARP: Address Resolution Protocol

- Problem: How does a host learn what MAC addresses to send packets to?
- ARP lets hosts build table mapping IP addresses to MAC addresses.
ARP: Address Resolution Protocol

• Problem: How does a host learn what MAC addresses to send packets to?

• ARP lets hosts build table mapping IP addresses to MAC addresses.

• ARP request: source MAC, dest MAC, “Who has IP address N?”

• ARP reply: source MAC, dest MAC, “IP address N is at MAC address M.”
Routing: BGP (Border Gateway Protocol)

- Internet organized into ASes (Autonomous Systems) with peer, provider, or customer relationships between them
- Rough tree shape, with a small number of backbone ASes in a clique at the root
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- Internet organized into ASes (Autonomous Systems) with peer, provider, or customer relationships between them
- Rough tree shape, with a small number of backbone ASes in a clique at the root
- BGP allows routers to exchange information about their routing tables
- Routers maintain global table of routes
- Each router announces what it can route to its neighbors
- Routes propagate through network
TCP (Transmission Control Protocol)

• Want abstraction of a stream of bytes delivered reliably and in-order between applications on different hosts

• TCP provides:
  • Reliable in-order byte stream
  • Connection-oriented protocol
  • Explicit setup/teardown
  • End hosts (processes) have multiple concurrent long-lived dialogs
  • Congestion control: adapt to network path capacity, receiver’s ability to receive packets
TCP Header Format

Note that one tick mark represents one bit position.
Ports

- Each application is identified by a port number.
- TCP connection established between port A on host address M to port B on host address N. Ports are 16 bits, 1–65535.
- Some destination ports are used for particular applications by convention:
  - 80 HTTP (web)
  - 443 HTTPS (web)
  - 25 SMTP (mail)
  - 67 DHCP (host configuration)
  - 22 SSH (secure shell)
  - 23 telnet
TCP Sequence Numbers

- Bytes in application data stream numbered with 32-bit sequence number
- Data sent in segments: sequences of contiguous bytes sent in a single IP datagram
- Sequence number indicates where data belongs in byte sequence
- Sequence number in packet header is the sequence number of the first byte in the payload
TCP Sequence Numbers and Acknowledgement

- Two logical data streams in a TCP connection: one in each direction
- Receiver acknowledges received data: acknowledgement number is sequence number of next expected byte of stream in opposite direction
- ACK flag set to acknowledge data
- Sender retransmits lost data
- Congestion control: sender adapts retransmission according to timeouts
TCP 3-Way Handshake
Starting a TCP connection
TCP 3-Way Handshake

Starting a TCP connection

Client

State changes to SYN-SENT

SYN-ACK
seq: 200
ack: 101

State changes to ESTABLISHED

Server

SYN
seq: 100

State changes to SYN-RECEIVED

ACK
seq: 101
ack: 201

State changes to ESTABLISHED
FIN/RST: Closing TCP connections

- FIN initiates a clean close of a TCP connection, waits for ACK from receiver
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• FIN initiates a clean close of a TCP connection, waits for ACK from receiver

• If a host receives a TCP packet with RST flag, it tears down the connection

• Designed to handle spurious TCP packets from previous connections
UDP (User Datagram Protocol)

• UDP offers no service quality guarantee
• Essentially a transport layer protocol that is a wrapper around IP
• Adds ports to let applications demultiplex traffic
• Useful for applications that only need best-effort guarantee
• e.g. DNS, NTP
User Datagram Protocol

User Datagram Header Format
DNS (Domain Name Service)

- Handle mapping between host names (e.g. ucsd.edu) and IP addresses (e.g. 132.239.180.101)
- DNS is a delegatable, hierarchical name space

```
root
  org   net   edu   com   cn
  stanford   ucsd   princeton
  cse   ece   music
```
DNS Records

$ dig cseweb.ucsd.edu

; <<>> DiG 9.10.6 <<>> cseweb.ucsd.edu
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 3727
;; flags: qr rd ra; QUERY: 1, ANSWER: 2, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 4096
;; QUESTION SECTION:
cseweb.ucsd.edu. IN A

;; ANSWER SECTION:
cseweb.ucsd.edu. 3140 IN CNAME roweb.eng.ucsd.edu.
roweb.eng.ucsd.edu. 2855 IN A 132.239.8.30

;; Query time: 57 msec
;; SERVER: 192.168.1.254#53(192.168.1.254)
;; WHEN: Sun Nov 03 20:49:08 PST 2019
;; MSG SIZE  rcvd: 84
DNS Details

• 13 main DNS root servers
• DNS responses are cached for quicker responses
• DNS authorities queried progressively according to domain name hierarchy
$ dig cseweb.ucsd.edu +trace

; <<>> DiG 9.10.6 <<>> cseweb.ucsd.edu +trace
;; global options: +cmd
. 105604 IN NS d.root-servers.net.
. 105604 IN NS h.root-servers.net.
. 105604 IN NS c.root-servers.net.
. 105604 IN NS j.root-servers.net.
. 105604 IN NS l.root-servers.net.
. 105604 IN NS i.root-servers.net.
. 105604 IN RRSIG NS 8 0 518400 20191115050000 20191102040000 22545 . Z14B+vD/MKz0X1UBwu04kzwQNajhg1Af1K7j5Jvd9NZ2

;; Received 525 bytes from 192.168.1.254#53(192.168.1.254) in 44 ms

edu. 172800 IN NS b.edu-servers.net.
edu. 172800 IN NS f.edu-servers.net.
edu. 172800 IN NS i.edu-servers.net.

edu. 172800 IN NS c.edu-servers.net.
edu. 172800 IN NS e.edu-servers.net.
edu. 172800 IN NS d.edu-servers.net.
edu. 86400 IN DS 28065 8 2 4172496CDE85534E51129040355BD04B1FCFEBAE996DFDDE652006F6 F8B2CE76
edu. 86400 IN RRSIG DS 8 1 86400 20191116170000 20191103160000 22545 . BsoO9Wl4UphaCN5rL0B4f3bCzVPptbmTCKHwcMgbe

;; Received 1174 bytes from 192.58.128.30#53(j.root-servers.net) in 20 ms

cseweb.ucsd.edu. 172800 IN NS ns-auth2.ucsd.edu.
cseweb.ucsd.edu. 172800 IN NS ns-auth3.ucsd.edu.
9DHS4EP5G85PF9NUFK06HEK0048QGK77.edu. 86400 IN NSEC3 1 1 0 - 9V5L4LUB1VN9EQLIEQCBREACL2500 NS SOA RRSIG DNSKEY
9DHS4EP5G85PF9NUFK06HEK0048QGK77.edu. 86400 IN RRSIG NSEC3 8 2 86400 20191111043435 20191104032435 47252 edu. M5W
3FTB9RSLR0QJUO<6nljje2I3u25M4MG.edu. 86400 IN NSEC3 1 1 0 - 4586u2HHMPEAQLHJD6R9INNA38POF8KL NS DS RRSIG
3FTB9RSLR0QJUO<6nljje2I3u25M4MG.edu. 86400 IN RRSIG NSEC3 8 2 86400 20191111041950 20191104030950 47252 edu. BKv

;; Received 671 bytes from 192.41.162.30#53(l.edu-servers.net) in 9 ms

cseweb.ucsd.edu. 3600 IN CNAME roweb.eng.ucsd.edu.
roweb.eng.ucsd.edu. 3600 IN A 132.239.8.30

;; Received 84 bytes from 132.239.252.186#53(ns-auth3.ucsd.edu) in 14 ms
You connect your laptop to a cafe wifi network and type ucsd.edu into your browser’s URL bar. What happens?
Using the internet: A worked example

1. Your laptop uses DHCP (Dynamic Host Configuration Protocol) to bootstrap itself on the local network.
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   - New host has no IP address, doesn’t know who to ask
   - Broadcasts DHCPDISCOVER to 255.255.255.255 with its MAC address
   - DHCP server responds with config: lease on host IP address, gateway IP address, DNS server information
2. Your laptop makes an ARP request to learn the MAC address of the local router.

- Every connection outside the local network will be encapsulated in a link-layer frame with the local router’s MAC address as the destination.
Using the internet: A worked example

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- Your laptop encapsulates each IP packet in a WiFi Ethernet frame addressed to the local router.

- The local router decapsulates these Ethernet frames and re-encodes them to forward them on its fiber connection to its upstream ISP, or to another part of the network.

- Each hop re-encodes the link layer for its own network.
Using the internet: A worked example

3. Your laptop does a DNS lookup on ucsd.edu.
   - It learned the IP address of a local DNS server from DHCP, or had a server (like 9.9.9.9) already hard-coded.
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   • Each response tells the laptop what authority to query, until it learns the final IP address (75.2.44.127) for ucsd.edu.
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- Each response tells the laptop what authority to query, until it learns the final IP address (75.2.44.127) for ucsd.edu.
- This address is cached, along with the authorities for the hierarchy in the hostname.
Using the internet: A worked example

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Using the internet: A worked example

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   • From cafe network (ATT), go through sbcglobal.net → att.net → level3.net → cenic.net → ucsd.edu.
Using the internet: A worked example

5. Your laptop sends a HTTP GET request inside the TCP connection.

6. Based on the HTTP response, the laptop performs a new DNS lookup, TCP handshake, and HTTP GET requests for every resource in the HTML as it renders.