CSCI-1680
Network Layer:
IP & Forwarding

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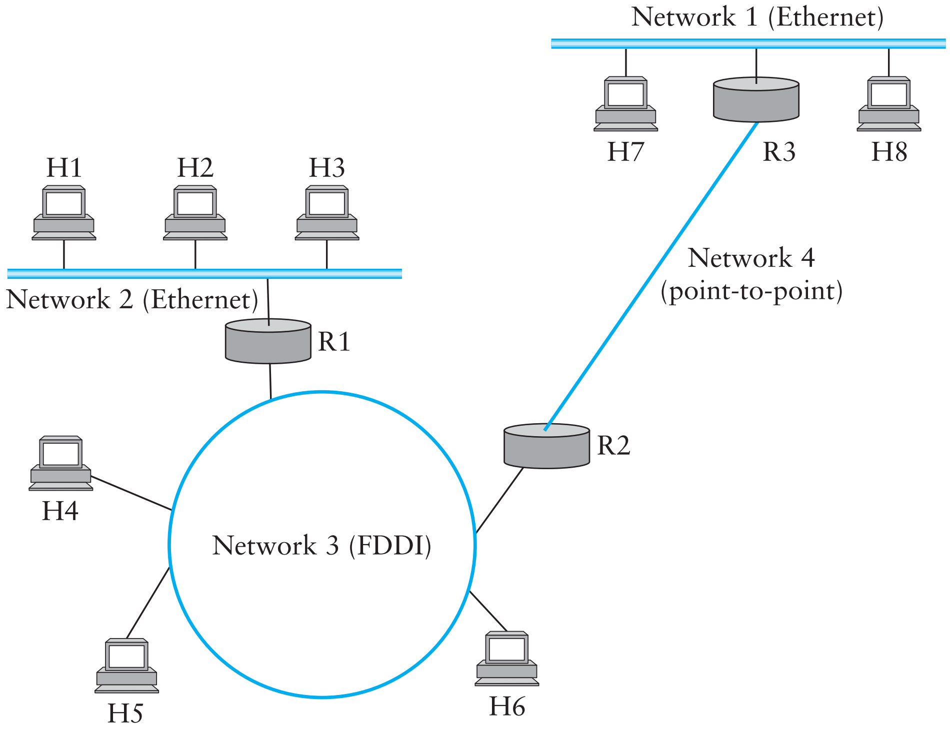
Based partly on lecture notes by David Mazières, Phil Levis, John Jannotti

Today

- Network layer: Internet Protocol (v4)
- Forwarding
- Next 2 classes: Routing

Internet Protocol Goal

- **How to connect everybody?**
  - New global network or connect existing networks?
- **Glue lower-level networks together:**
  - allow packets to be sent between any pair or hosts
- **Wasn't this the goal of switching?**



Inter-networking Challenges

- **Heterogeneity**
  - Different addresses
  - Different service models
  - Different allowable packet sizes
- **Scaling**
- **Congestion control**

How would you design such a protocol?

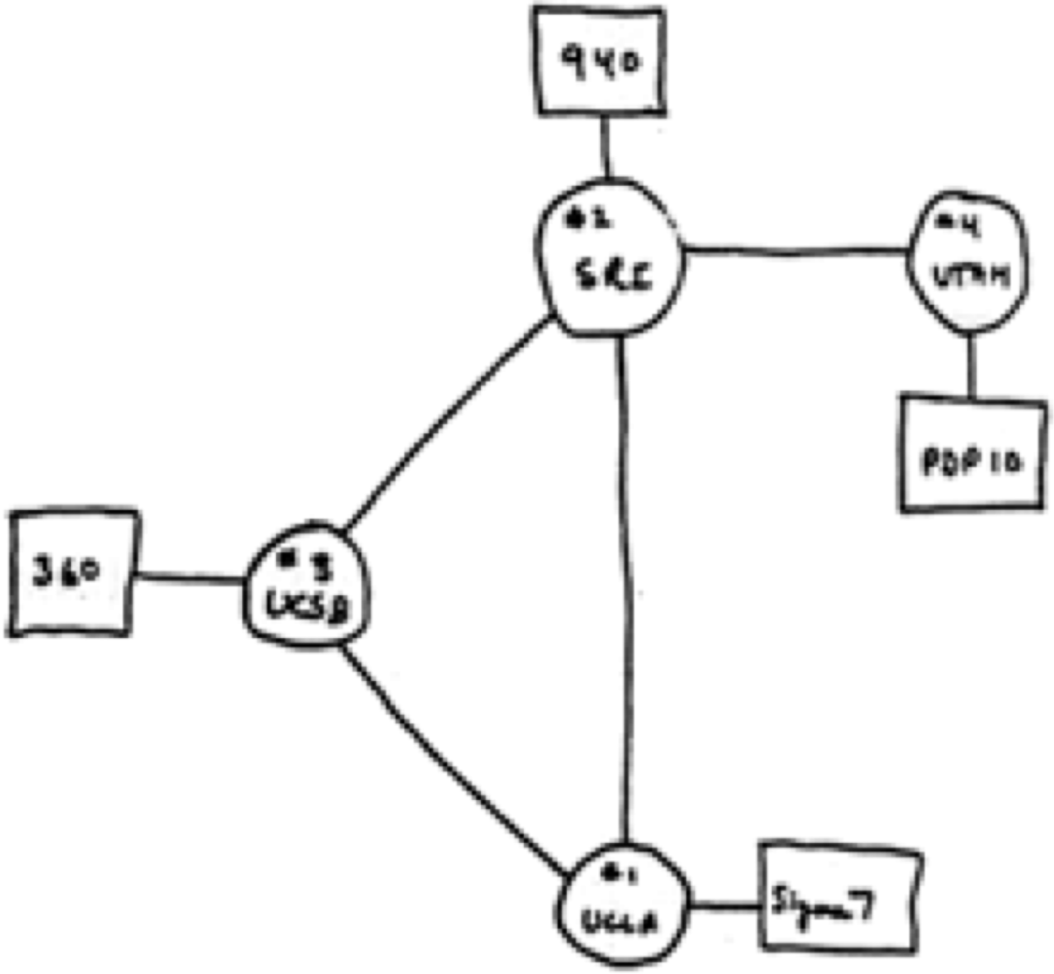
- **Circuits or packets?**
  - Predictability
- **Service model**
  - Reliability, timing, bandwidth guarantees
- **Any-to-any**
  - Finding nodes: naming, routing
  - Maintenance (join, leave, add/remove links,…)
  - Forwarding: message formats

IP's Decisions

- **Packet switched**
  - Unpredictability, statistical multiplexing
- **Service model**
  - Lowest common denominator: best effort, connectionless datagram
- **Any-to-any**
  - Common message format
  - Separated routing from forwarding
  - Naming: uniform addresses, hierarchical organization
  - Routing: hierarchical, prefix-based (longest prefix matching)
  - Maintenance: delegated, hierarchical

A Bit of History

- **Packet switched networks: Arpanet's IMPs**
  - Late 1960's
  - RFC 1, 1969!
  - Segmentation, framing, routing, reliability, reassembly, primitive flow control
- **Network Control Program (NCP)**
  - Provided connections, flow control
  - Assumed reliable network: IMPs
  - Used by programs like telnet, mail, file transfer
- **Wanted to connect multiple networks**
  - Not all reliable, different formats, etc…



THE ARPA NETWORK

DEC 1969

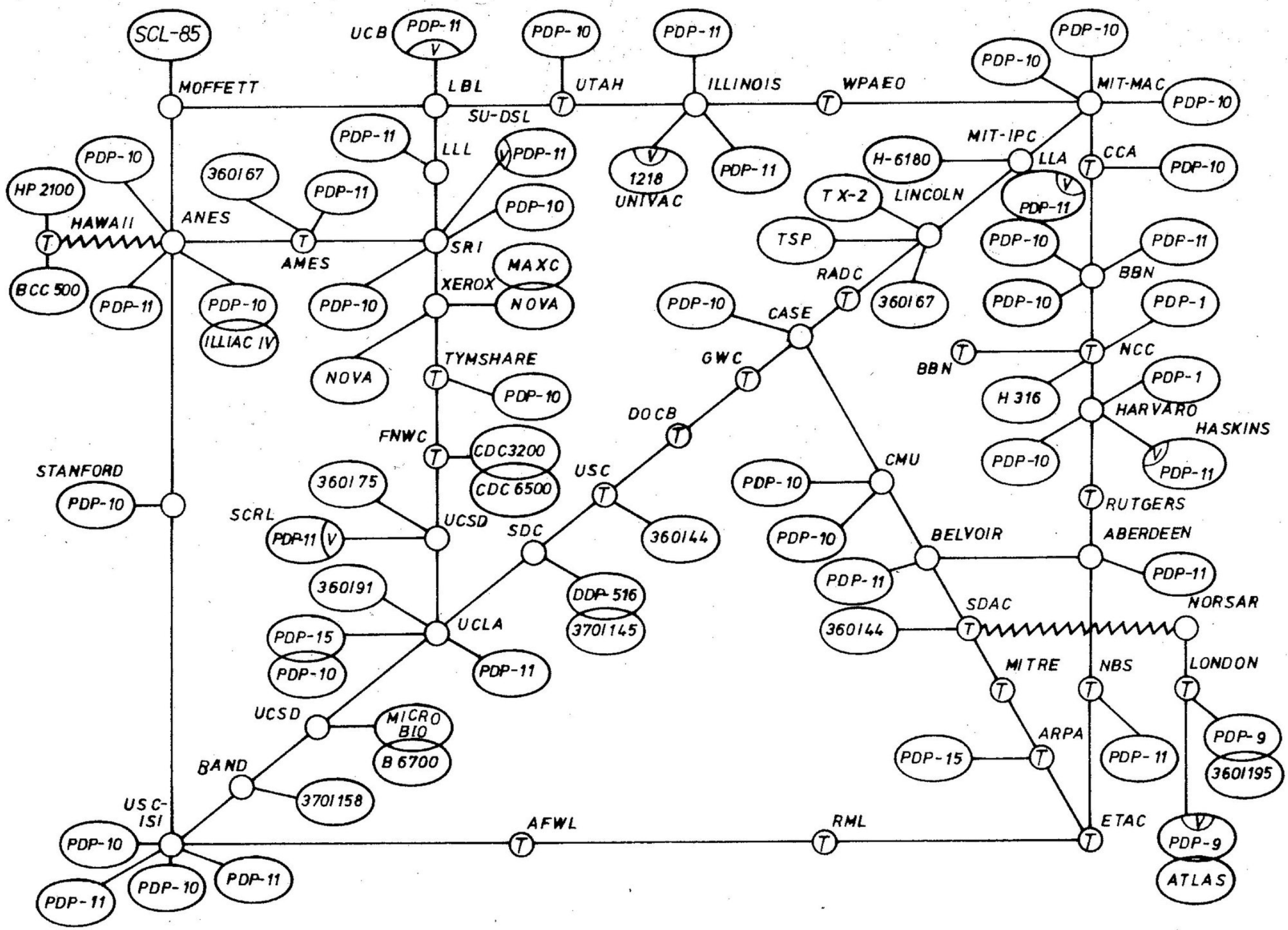


Abb. 4 ARPA NETwork, topologische Karte. Stand Juni 1974.

TCP/IP Introduced

- **Vint Cerf, Robert Kahn**
- **Replace NCP**
- **Initial design: single protocol providing a unified reliable pipe**
  - Could support any application
- **Different requirements soon emerged, and the two were separated**
  - IP: basic datagram service among hosts
  - TCP: reliable transport
  - UDP: unreliable *multiplexed* datagram service

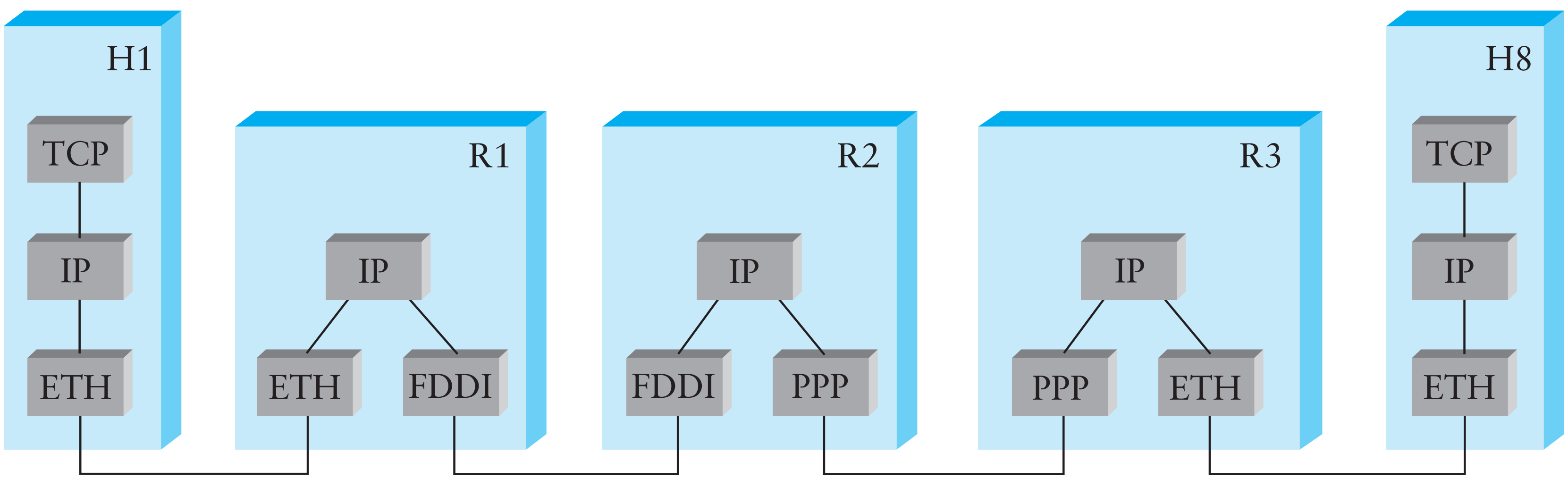
An excellent read

David D. Clark, "The design Philosophy of the DARPA Internet Protocols", 1988

- Primary goal: multiplexed utilization of existing interconnected networks
- Other goals:
  - Communication continues despite loss of networks or gateways
  - Support a variety of communication services
  - Accommodate a variety of networks
  - Permit distributed management of its resources
  - Be cost effective
  - Low effort for host attachment
  - Resources must be accountable

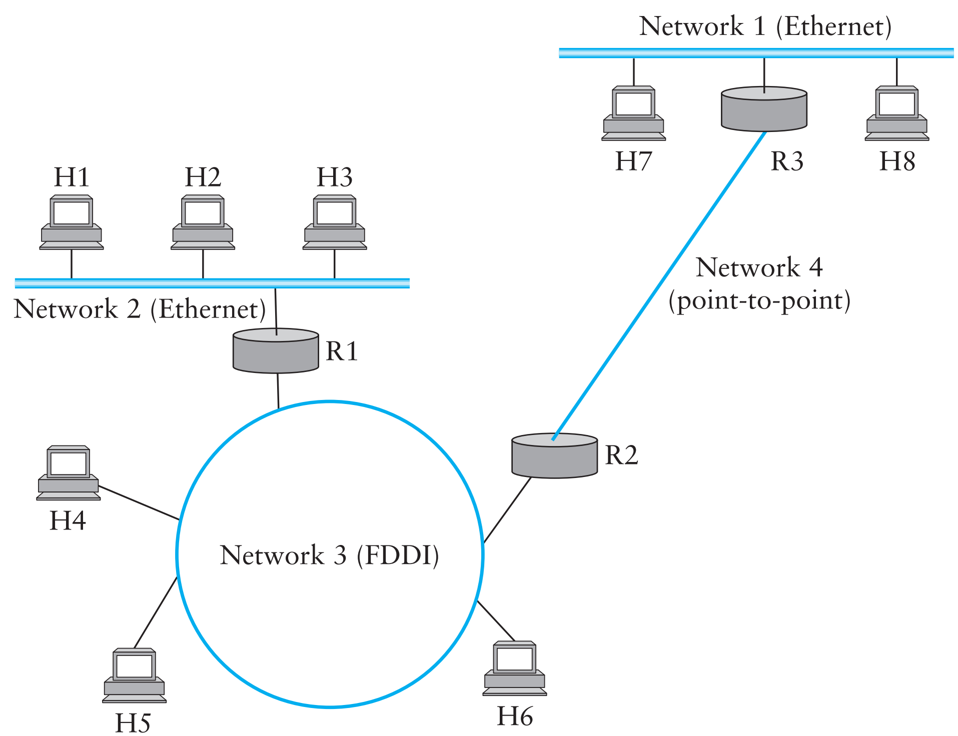
Internet Protocol

- **IP Protocol running on all hosts *and routers***
- **Routers are *present in all networks they join***
- **Uniform addressing**
- **Forwarding/Fragmentation**
- **Complementary:**
  - Routing, Error Reporting, Address Translation



How does this work?

- **Routers are *present in all networks they join***
  - Nodes only know how to talk on the networks they are in
- **What about addresses?**
  - IP addresses mean nothing for the L2 networks!
  - Need a mapping
- **Forwarding**
  - Decide whether to deliver locally, or to another router in the same network
  - Addresses are allocated in a way to make this work



IP Protocol

- **Provides addressing and *forwarding***
  - Addressing is a set of conventions for naming nodes in an IP network
  - Forwarding is a local action by a router: passing a packet from input to output port
- **IP forwarding finds output port based on destination address**
  - Also defines certain conventions on how to handle packets (e.g., fragmentation, time to live)
- **Contrast with *routing***
  - Routing is the process of determining how to map packets to output ports (topic of next two lectures)

Service Model

- **Connectionless (datagram-based)**
- **Best-effort delivery (unreliable service)**
  - packets may be lost
  - packets may be delivered out of order
  - duplicate copies of packets may be delivered
  - packets may be delayed for a long time
- **It's the lowest common denominator**
  - A network that delivers no packets fits the bill!
  - All these can be dealt with above IP (if probability of delivery is non-zero…)

Format of IP addresses

- **Globally unique (or made seem that way)**
  - 32-bit integers, read in groups of 8-bits: 128.148.32.110
- **Hierarchical organization:**
  - Assign blocks of contiguous addresses to the same parts of the network
  - All hosts in the same *network* share the same *prefix*
  - Networks can have different sizes (different prefix sizes)
  - Addresses have network and host parts

Prefix Notation

- **Significant bits + mask**
- **E.g. all nodes which share prefix 128.148.0.0:**
  - 16 MSB matter
  - Mask is: 11111111 11111111 00000000 00000000
  - Or 255.255.0.0
  - Or /16
- **Could say**
  - 128.148
  - 128.148/16
  - 128.148.0.0/16
  - 128.148.0.0 netmask 255.255.0.0

Forwarding Tables

- Exploit hierarchical structure of addresses: need to know how to reach *networks*, not hosts

Network	Next Address
212.31.32.*	0.0.0.0
18.*.*.*	212.31.32.5
128.148.*.*	212.31.32.4
Default	212.31.32.1

- Keyed by network portion, not entire address
- Next address should be local: router knows how to reach it directly* (we'll see how soon)

IP Forwarding Table

Network	Next Address
212.31.32/24	0.0.0.0
18/8	212.31.32.5
128.148/16	212.31.32.4
128.148.128/17	212.31.32.8
0/0	212.31.32.1

- **Forwarding is done by *longest prefix matching***
  - More on this later

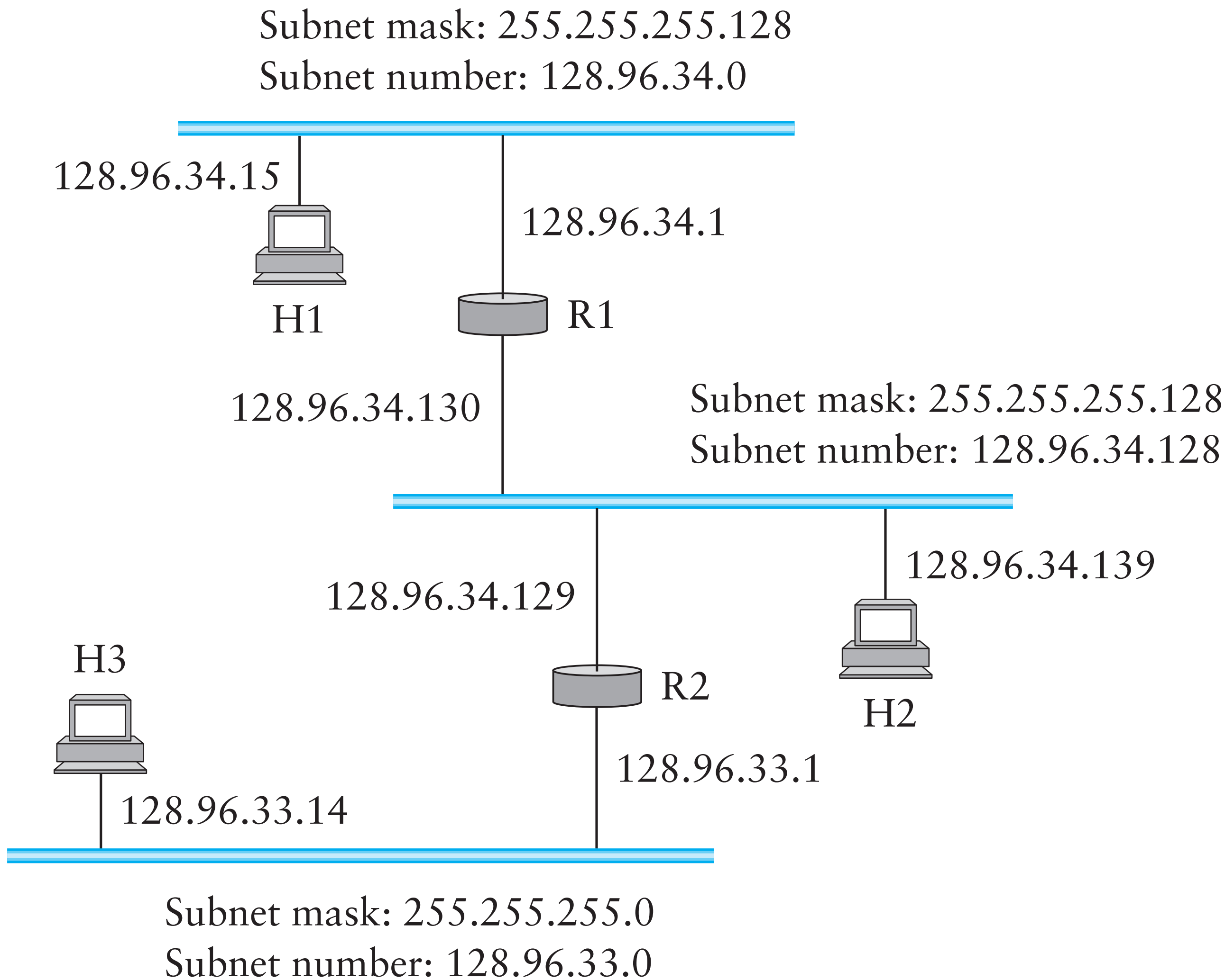
Obtaining IP Addresses

- **Blocks of IP addresses allocated hierarchically**
  - ISP obtains an *address block*, may subdivide

ISP: 128.35.16/20 10000000 00100011 00010000 00000000
Client 1: 128.35.16/22 10000000 00100011 00010000 00000000
Client 2: 128.35.20/22 10000000 00100011 00010100 00000000
Client 3: 128.35.24/21 10000000 00100011 00011000 00000000

- **Blocks restricted to powers of 2**
- **Global allocation: ICANN, /8's (ran out!)**
- **Regional registries: ARIN, RIPE, APNIC, LACNIC, AFRINIC**

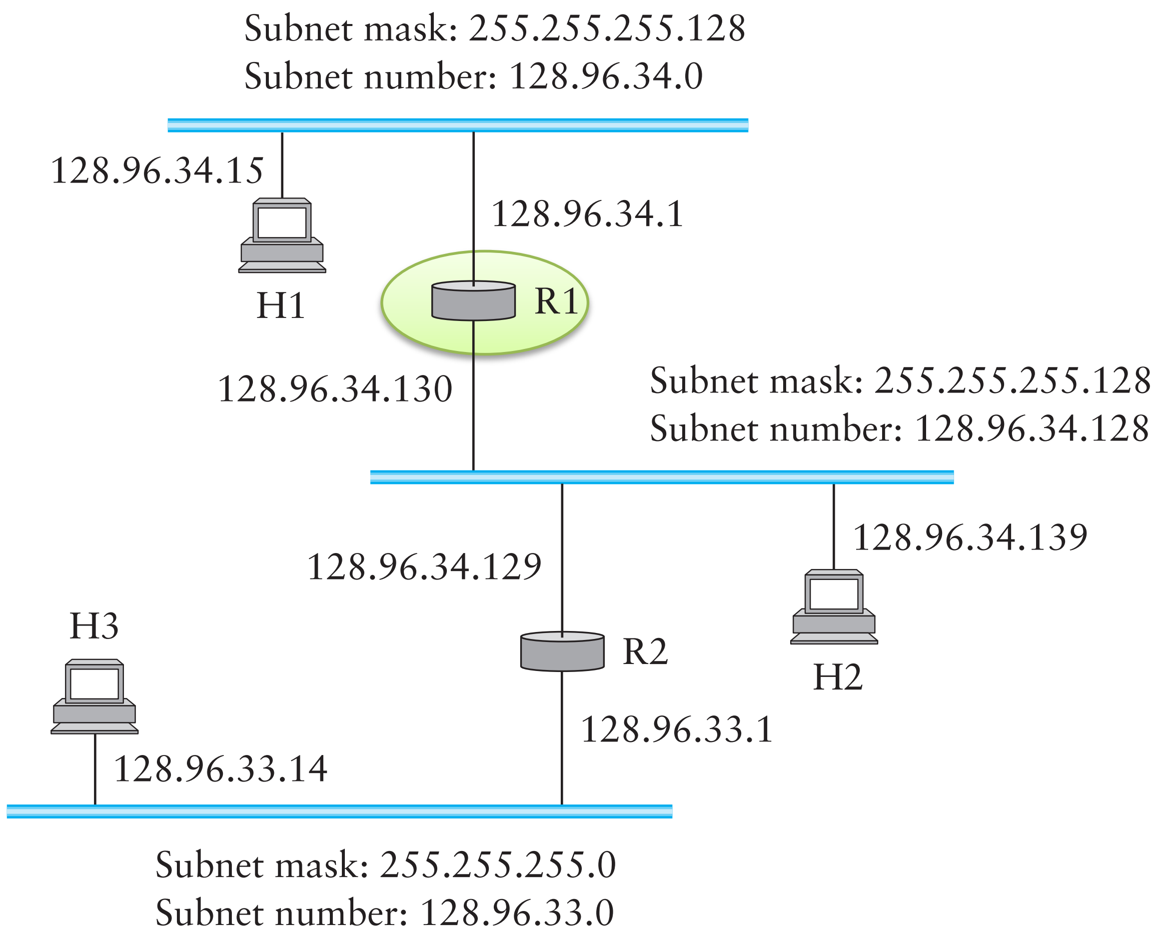
How does this really work?



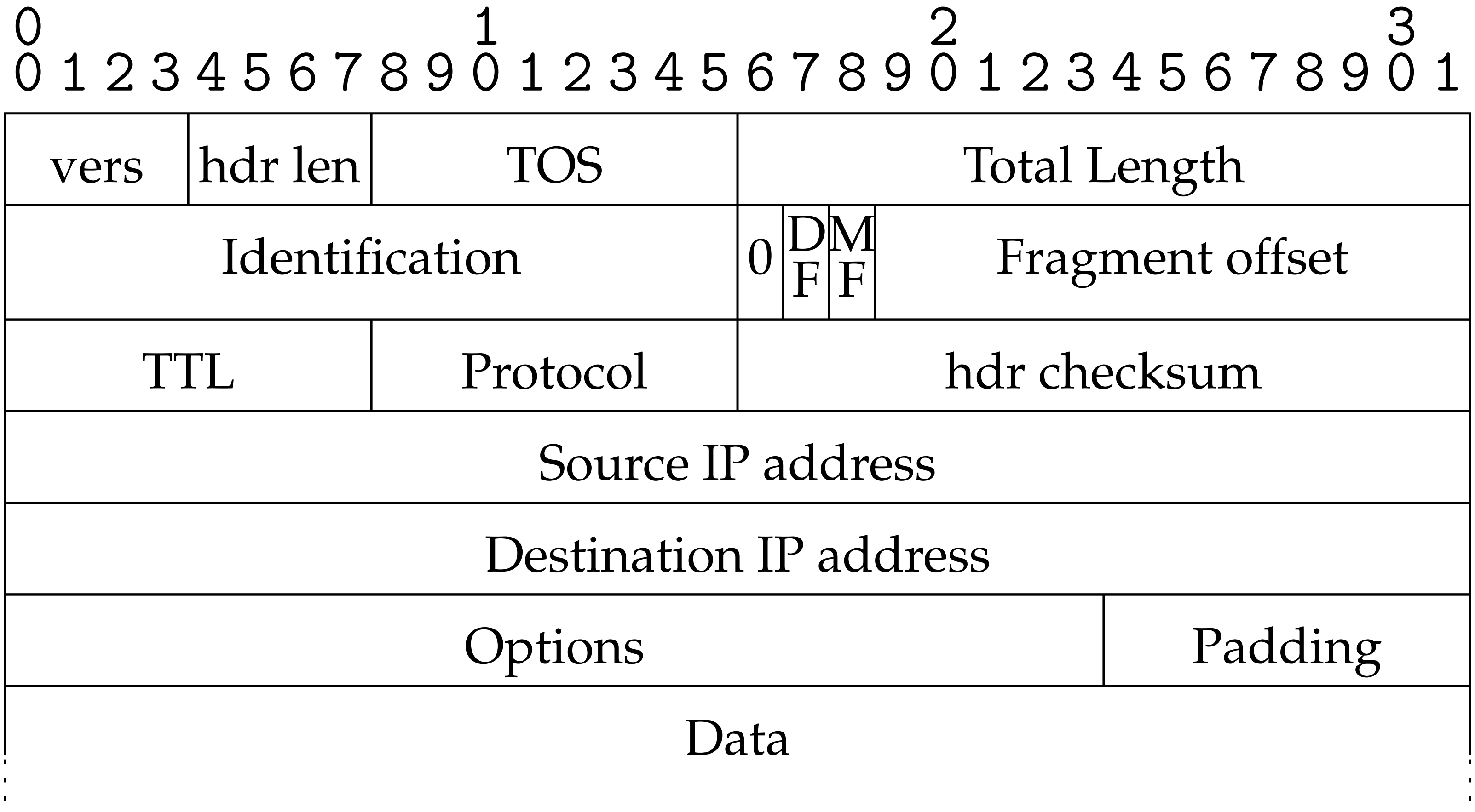
H1-> H2: H2.ip & H1.mask != H1.subnet => no direct path

R1's Forwarding Table

Network	Subnet Mask	Next Address
128.96.34.0	255.255.255.128	128.96.34.1
128.96.34.128	255.255.255.128	128.96.34.130
128.96.33.0	255.255.255.0	128.96.34.129



IP v4 packet format



IP header details

- **Forwarding based on destination address**
- **TTL (time-to-live) decremented at each hop**
  - Originally was in seconds (no longer)
  - Mostly prevents forwarding loops
  - Other cool uses…
- **Fragmentation possible for large packets**
  - Fragmented in network if crossing link w/ small frame
  - MF: more fragments for this IP packet
  - DF: don't fragment (returns error to sender)
- **Following IP header is "payload" data**
  - Typically beginning with TCP or UDP header

Other fields

- **Version: 4 (IPv4) for most packets, there's also 6**
- **Header length: in 32-bit units (>5 implies options)**
  - 4 bits * 4 bytes = 64KiB max
- **Type of service (won't go into this)**
- **Protocol identifier (TCP: 6, UDP: 17, ICMP: 1, …)**
- **Checksum over the *header***

Translating IP to lower level addresses or… How to reach these *local* addresses?

- **Map IP addresses into physical addresses**
  - E.g., Ethernet address of destination host
  - or Ethernet address of next hop router
- **Techniques**
  - Encode physical address in host part of IP address (IPv6)
  - Each network node maintains lookup table (IP->phys)

ARP – *address resolution protocol*

- Dynamically builds table of IP to physical address bindings for a *local network*
- Broadcast request if IP address not in table
- All learn IP address of requesting node (broadcast)
- Target machine responds with its physical address
- Table entries are discarded if not refreshed

ARP Ethernet frame format

0	8	16 31
Hardware type = 1		ProtocolType = 0x0800
HLen = 48	PLen = 32	Operation
SourceHardwareAddr (bytes 0–3)		
SourceHardwareAddr (bytes 4–5)		SourceProtocolAddr (bytes 0–1)
SourceProtocolAddr (bytes 2–3)		TargetHardwareAddr (bytes 0–1)
TargetHardwareAddr (bytes 2–5)		
TargetProtocolAddr (bytes 0–3)		

- **Why include source hardware address?**

Obtaining Host IP Addresses - DHCP

- **Networks are free to assign addresses within block to hosts**
- **Tedious and error-prone: e.g., laptop going from CIT to library to coffee shop**
- **Solution: Dynamic Host Configuration Protocol**
  - Client: DHCP Discover to 255.255.255.255 (broadcast)
  - Server(s): DHCP Offer to 255.255.255.255 (why broadcast?)
  - Client: choose offer, DHCP Request (broadcast, why?)
  - Server: DHCP ACK (again broadcast)
- **Result: address, gateway, netmask, DNS server**

Network Address Translation (NAT)

- Despite CIDR, it's still difficult to allocate addresses (2^{32} is only 4 billion)
- We'll talk about IPv6 later
- NAT "hides" entire network behind one address
- Hosts are given *private* addresses
- Routers map outgoing packets to a free address/port
- Router reverse maps incoming packets
- Problems?

Internet Control Message Protocol (ICMP)

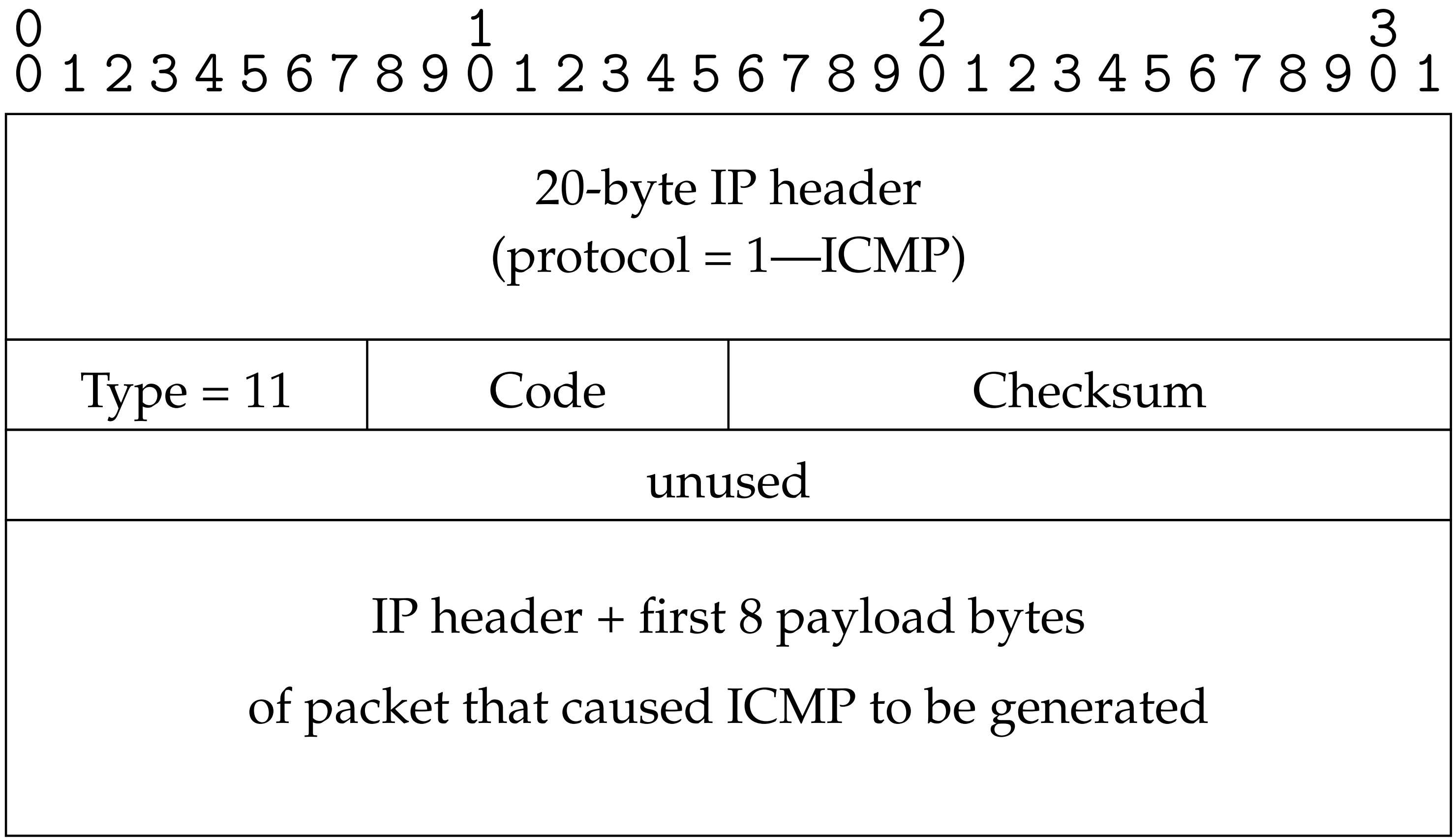
- Echo (ping)
- Redirect
- Destination unreachable (protocol, port, or host)
- TTL exceeded
- Checksum failed
- Reassembly failed
- Can't fragment
- Many ICMP messages include part of packet that triggered them
- See http://www.iana.org/assignments/icmp-parameters

ICMP message format

```
0                   1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
```

20-byte IP header (protocol = 1—ICMP)		
Type	Code	Checksum
depends on type/code		

Example: Time Exceeded



- **Code usually 0 (TTL exceeded in transit)**
- **Discussion: traceroute**

Example: Can't Fragment

- **Sent if DF=1 and packet length > MTU**
- **What can you use this for?**
- **Path MTU Discovery**
  – Can do binary search on packet sizes
  – But better: base algorithm on most common MTUs

Coming Up

- **Routing: how do we fill the routing tables?**
  - Intra-domain routing: Tuesday, 10/4
  - Inter-domain routing: Thursday, 10/6

Example

```
# arp -n
Address                  HWtype  HWaddress           Flags Mask            Iface
172.17.44.1              ether   00:12:80:01:34:55   C                     eth0
172.17.44.25             ether   10:dd:b1:89:d5:f3   C                     eth0
172.17.44.6              ether   b8:27:eb:55:c3:45   C                     eth0
172.17.44.5              ether   00:1b:21:22:e0:22   C                     eth0
```

```
# ip route
127.0.0.0/8 via 127.0.0.1 dev lo
172.17.44.0/24 dev enp7s0  proto kernel  scope link  src 172.17.44.22  metric 204
default via 172.17.44.1 dev eth0 src 172.17.44.22  metric 204
```