Missing pieces
+
Putting the pieces together

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Material thanks to Ion Stoica, Scott Shenker, Jennifer Rexford, Nick McKeown, and many other colleagues

Today

- Switched Ethernet (wrap-up)
  - Frames and framing
  - MAC addresses
  - Routing
  - Forwarding

- Missing pieces and putting the pieces together

Last Time

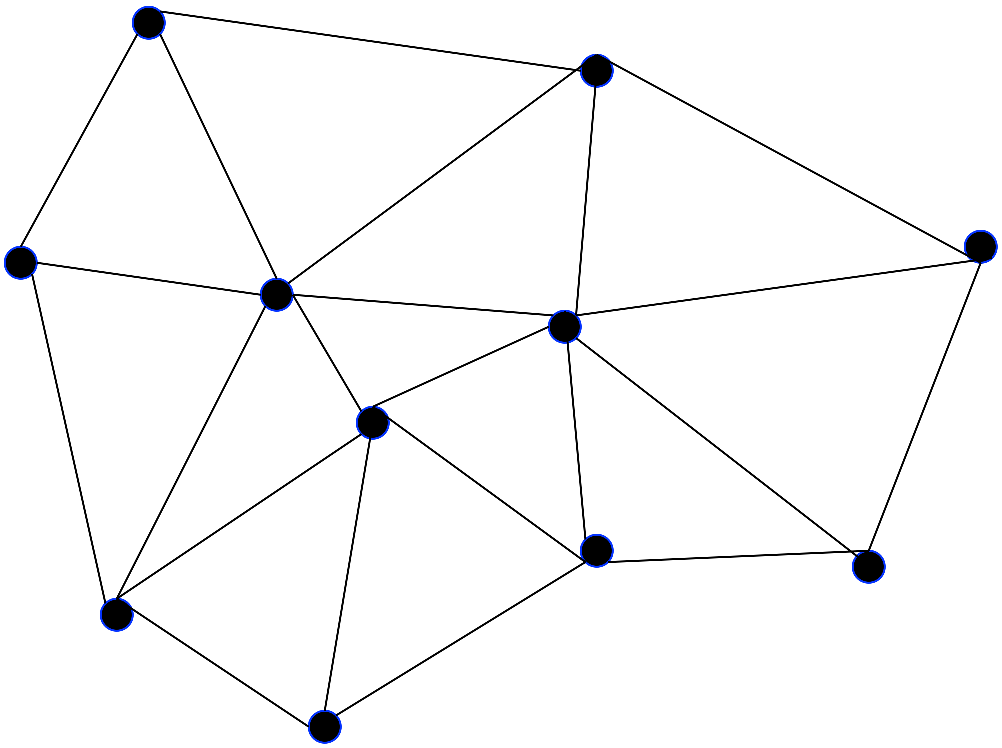
- Switched Ethernet
  - Frame formats
  - MAC addresses
  - Spanning Tree approach
    - Take arbitrary topology
    - Pick subset of links that form a spanning tree

- Today: how do we forward over the spanning tree?

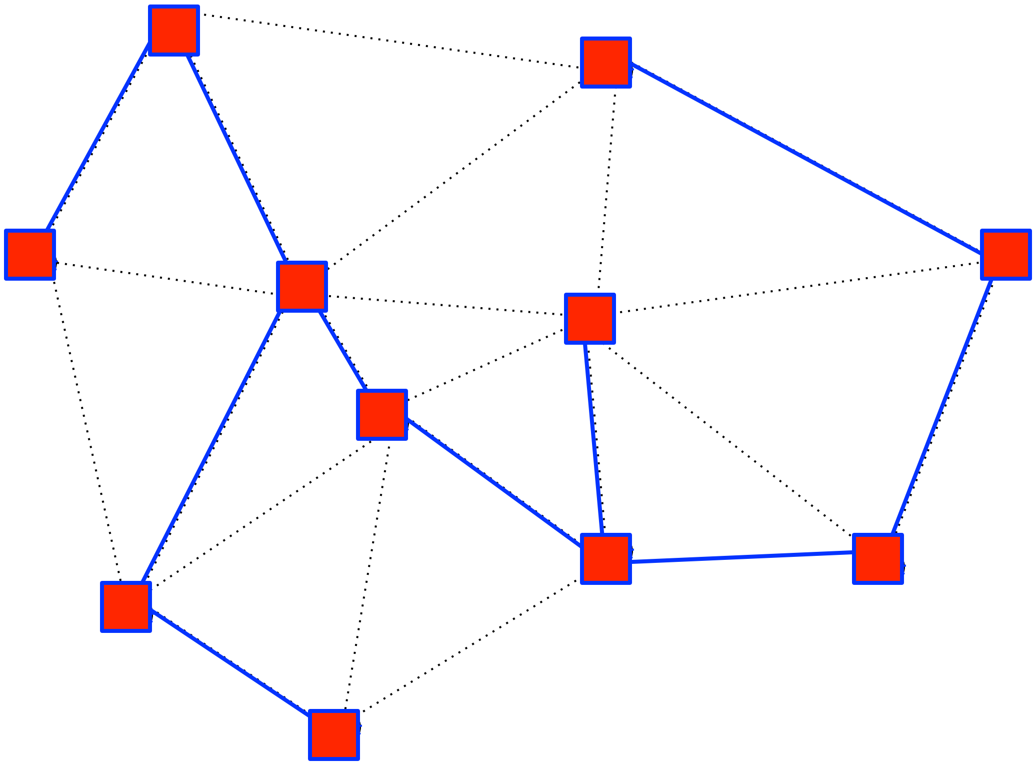
Flooding on a Spanning Tree

- Switches flood using the following rule:
  - (Ignoring all ports not on spanning tree!)
  - Originating switch sends packet out all ports
  - When a packet arrives on one incoming port, send it out <u>all</u> ports <u>other</u> than the incoming port

Flooding on Spanning Tree



Flooding on Spanning Tree



But isn't flooding wasteful?

- Yes, but we can use it to bootstrap more efficient forwarding
- Idea: watch the packets going by, and learn from them
  - If node A sees a packet from node B come in on a particular port, i**t knows what port to use to reach B!**
  - Works because there's only one path to B

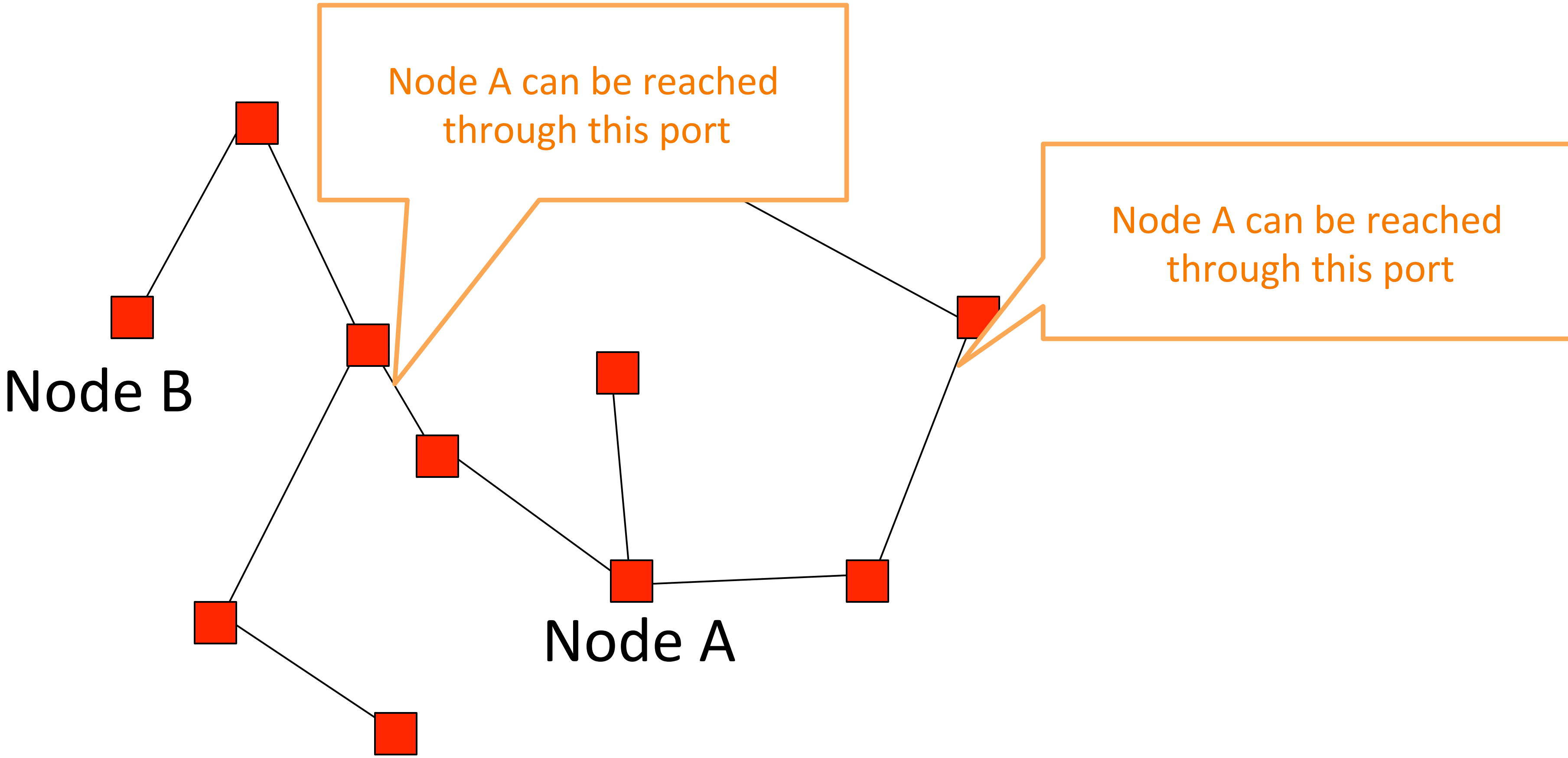
Nodes can "learn" routes

- Switch learns how to reach nodes by remembering where flooding packets came from
  - If flood packet <u>from</u> Node A entered switch on port 4, then switch uses port 4 to send to Node A

General Approach

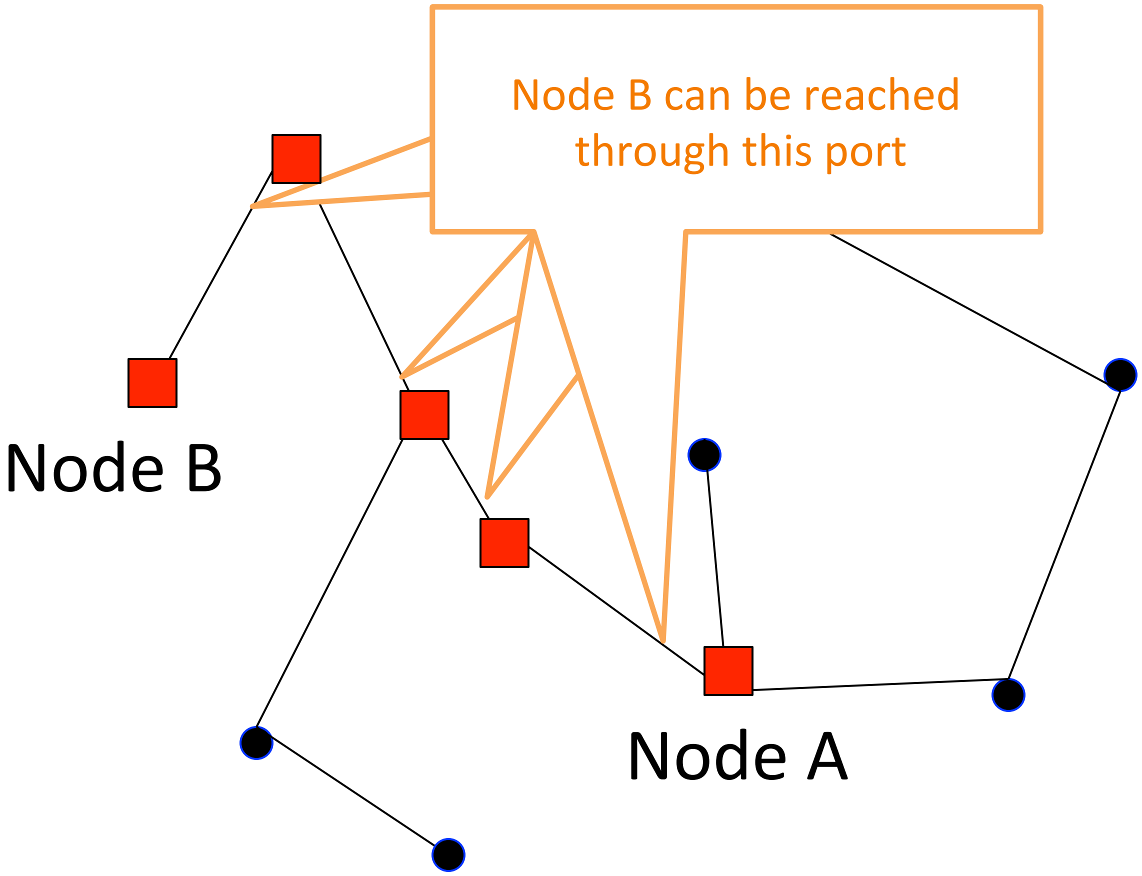
- Flood first packet to node you are trying to reach
- All switches learn where *you* are
- When destination responds, some switches learn where *it* is…
  - Only some switches, because packet to you follows direct path, and is not flooded

Learning from Flood Packets



Once a node has sent a flood message, all other switches know how to reach it….

Node B Responds

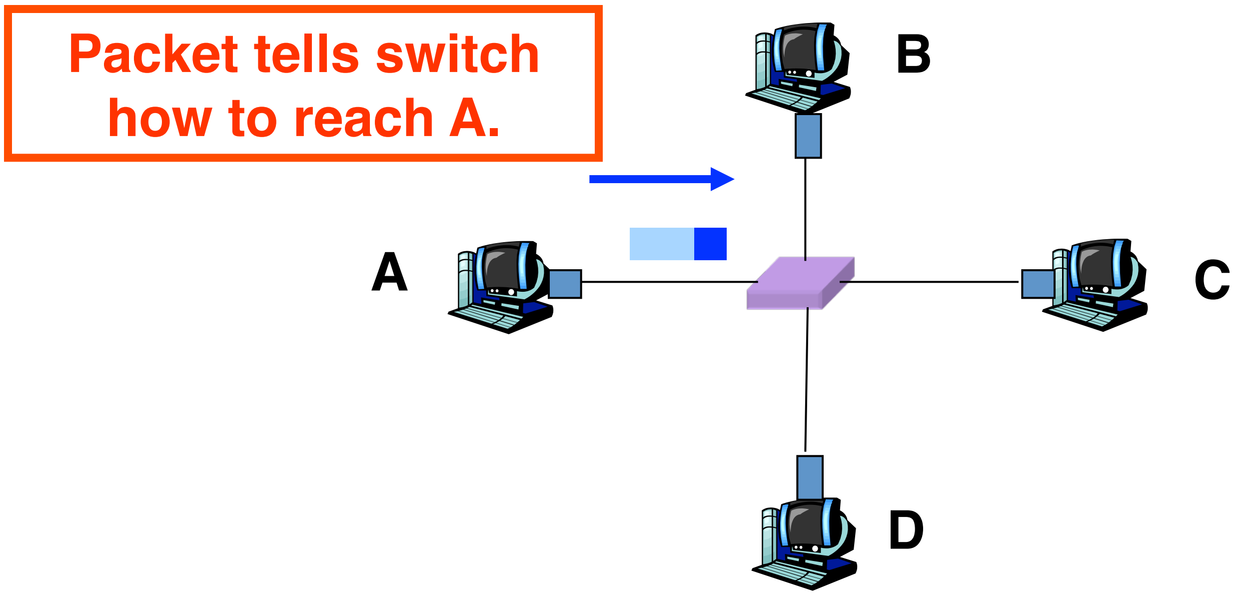


When a node responds, <u>some</u> of the switches learn where it is

Ethernet switches are "self learning"

When a packet arrives:

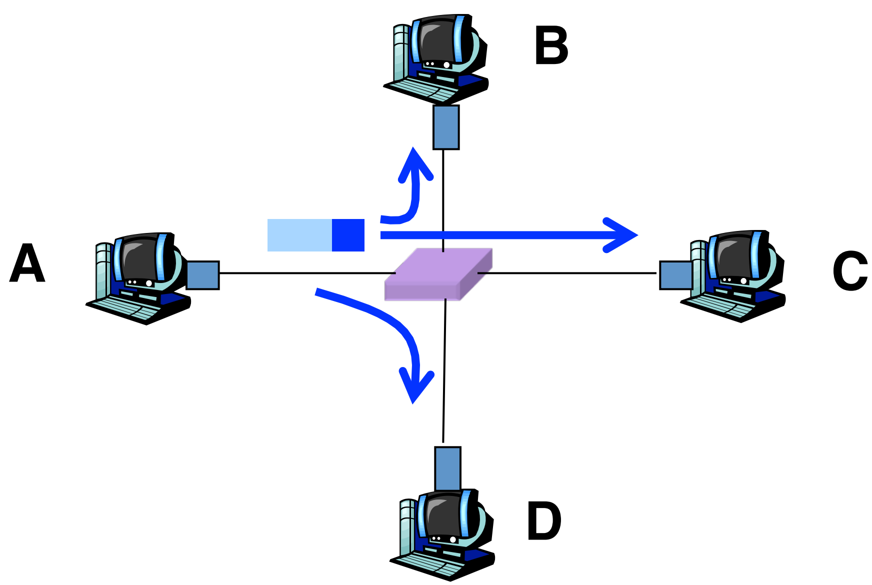
- Inspect *source* MAC address, associate with *incoming* port
- Store mapping in the switch table
- Use time-to-live field to eventually forget mapping



Self Learning: Handling Misses

When packet arrives with unfamiliar destination

- Forward packet out all other ports
- Response may teach switch about that destination



Hence: Forwarding Rule

<u>When switch receives a packet:</u>

index the switch table using destination MAC

if entry found for destination **{**

    if dest on port from which packet a

        then drop packet

    else forward packet on port indicated

}

else flood

Why do this?

forward on all but the port
on which the frame arrived

Summary of Learning Approach

- Avoids loop by restricting to spanning tree
- This makes flooding possible
- Flooding allows packet to reach destination
- And in the process switches learn how to reach source of flood
- No route "computation"
- Forwarding entries a consequence of traffic pattern

Contrast

- IP
  - Packets forwarded on all links
  - Aggregatable addresses
  - Routing protocol computes loop-free *paths*
  - Forwarding table computed by routing protocol
- Ethernet
  - Packets forwarded on subset of links (spanning tree)
  - Flat addresses
  - "Routing" protocol computes loop-free *topology*
  - Forwarding table derived from data packets (+SPT for floods)

Strengths of Ethernet's Approach?

- Plug-n-Play: zero-configuration / self-*
- Simple
- Cheap?

Weaknesses of This Approach?

- Much of the network bandwidth goes unused
  - Forwarding is only over the spanning tree
- Delay in reestablishing spanning tree
  - Network is "down" until spanning tree rebuilt
  - And rebuilt spanning tree may be quite different
- Slow to react to host movement
  - Entries must time out
- Poor predictability
  - Location of root and traffic pattern determines forwarding efficiency

Today

- Switched Ethernet (wrap-up)
  - Frames and framing
  - MAC addresses
  - Routing
  - Forwarding

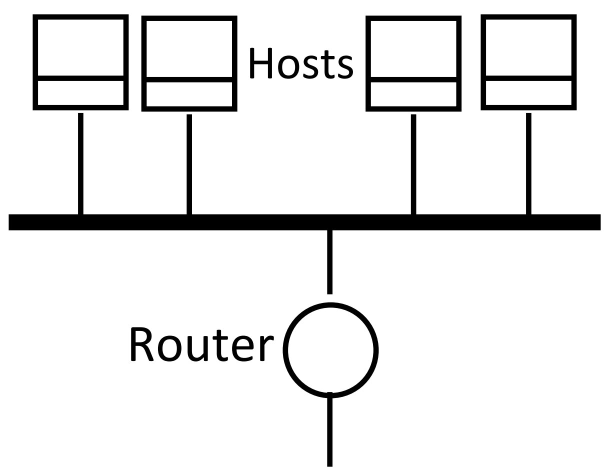
- Missing pieces and putting the pieces together

Discovery

- A host is “born” knowing only its MAC address
- Must discover lots of information before it can communicate with a remote host B
  - what is my IP address?
  - what is B’s IP address? (remote)
  - what is B’s MAC address? (if B is local)
  - what is my first-hop router’s address? (if B is not local)
  - …

ARP and DHCP

- Link layer discovery protocols
  - ARP → Address Resolution Protocol
  - DHCP → Dynamic Host Configuration Protocol
  - confined to a single local-area network (LAN)
  - rely on broadcast capability



ARP and DHCP

- Link layer discovery protocols
- Serve two functions
  - Discovery of local end-hosts
    - for communication between hosts on the same LAN

ARP and DHCP

- Link layer discovery protocols
- Serve two functions
  - Discovery of local end-hosts
  - Bootstrap communication with remote hosts
    - what's my IP address?
    - who/where is my local DNS server?
    - who/where is my first hop router?

DHCP

- "Dynamic Host Configuration Protocol"
  - defined in RFC 2131
- A host uses DHCP to discover
  - its own IP address
  - its netmask
  - IP address(es) for its local DNS name server(s)
  - IP address(es) for its first-hop "default" router(s)

DHCP: operation

1. One or more local DHCP servers maintain required information
   – IP address pool, netmask, DNS servers, *etc.*
   – application that listens on UDP port 67

DHCP: operation

1. One or more local DHCP servers maintain required information
2. Client broadcasts a DHCP discovery message
   - L2 broadcast, to MAC address FF:FF:FF:FF:FF:FF

DHCP: operation

1. One or more local DHCP servers maintain required information
2. Client broadcasts a DHCP discovery message
3. One or more DHCP servers responds with a DHCP "offer" message
   – proposed IP address for client, lease time
   – other parameters

DHCP: operation

1. One or more local DHCP servers maintain required information
2. Client broadcasts a DHCP discovery message
3. One or more DHCP servers responds with a DHCP “offer” message
4. Client broadcasts a DHCP request message
   - specifies which offer it wants
   - echoes accepted parameters
   - other DHCP servers learn they were not chosen

DHCP: operation

1. One or more local DHCP servers maintain required information
2. Client broadcasts a DHCP discovery message
3. One or more DHCP servers responds with a DHCP "offer" message
4. Client broadcasts a DHCP request message
5. Selected DHCP server responds with an ACK

DHCP: operation

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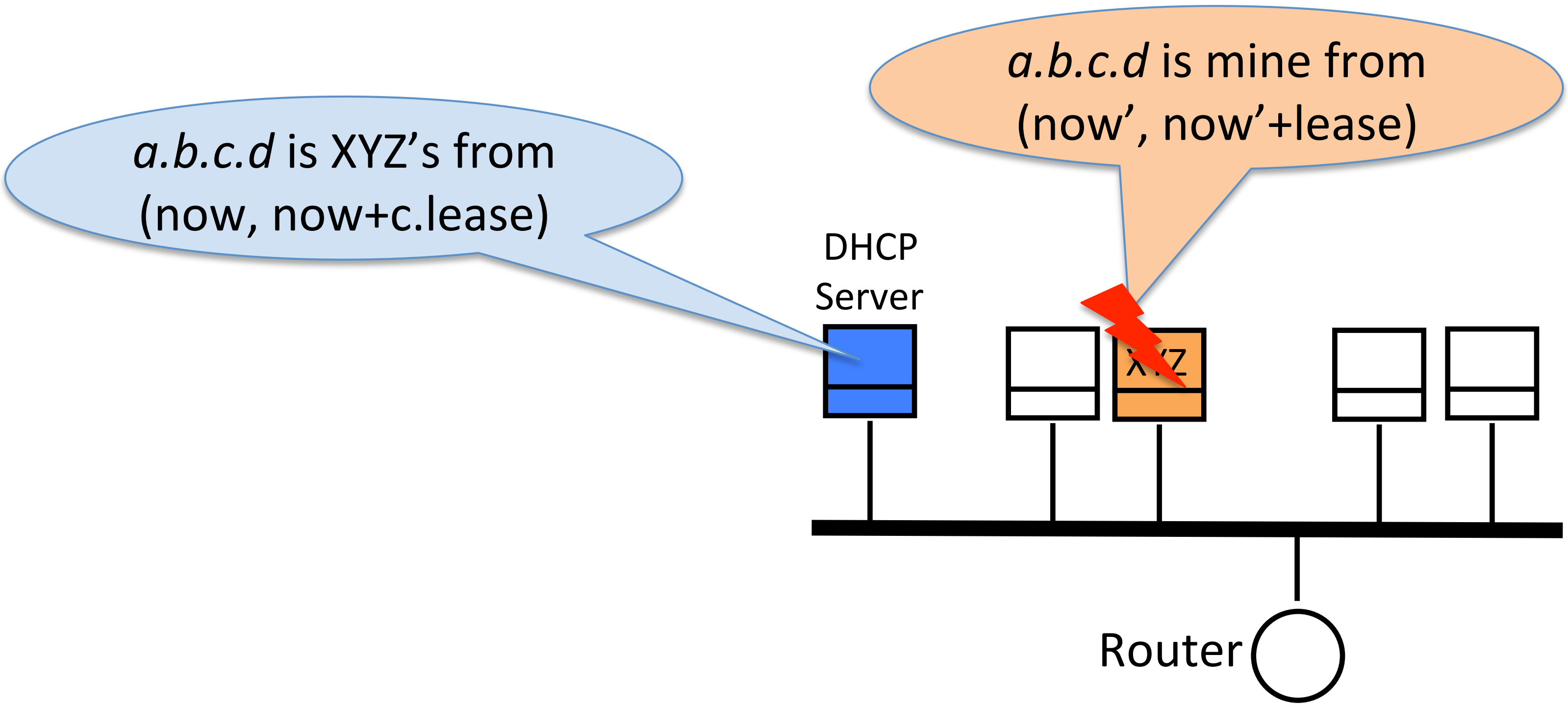
(DHCP "relay agents" used when the DHCP server isn't on the same broadcast domain -- see text)

DHCP uses "soft state"

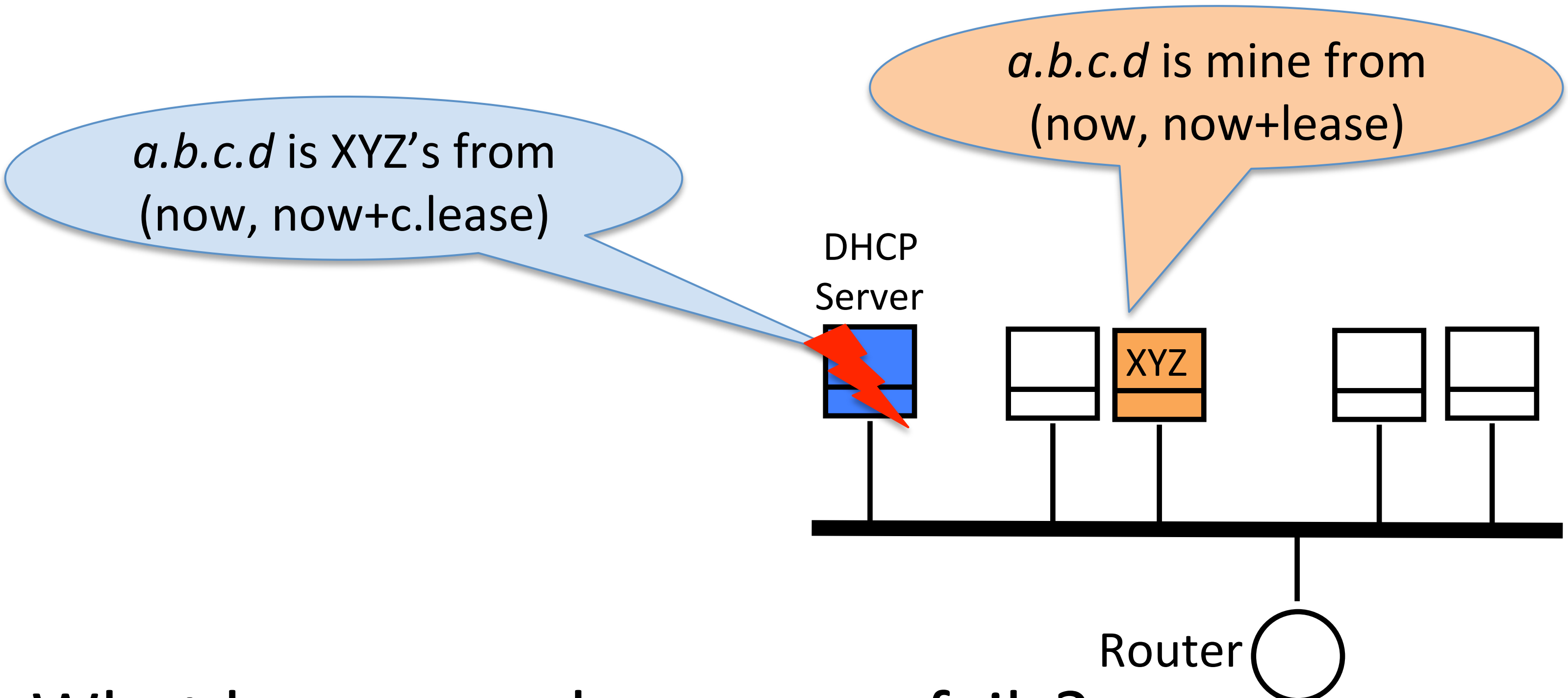
- Soft state: if not refreshed, state is forgotten
  - hard state: allocation is deliberately returned/withdrawn
  - e.g., used to track address allocation in DHCP
- Implementation:
  - address allocations are associated with a lease period
  - server: sets a timer associated with the record of allocation
  - client: must request a refresh before lease period expires
  - server: resets timer when a refresh arrives; sends ACK
  - server: reclaims allocated address when timer expires
- Simple, yet robust under failure
  - state always fixes itself in (small constant of) lease time

Soft state under failure



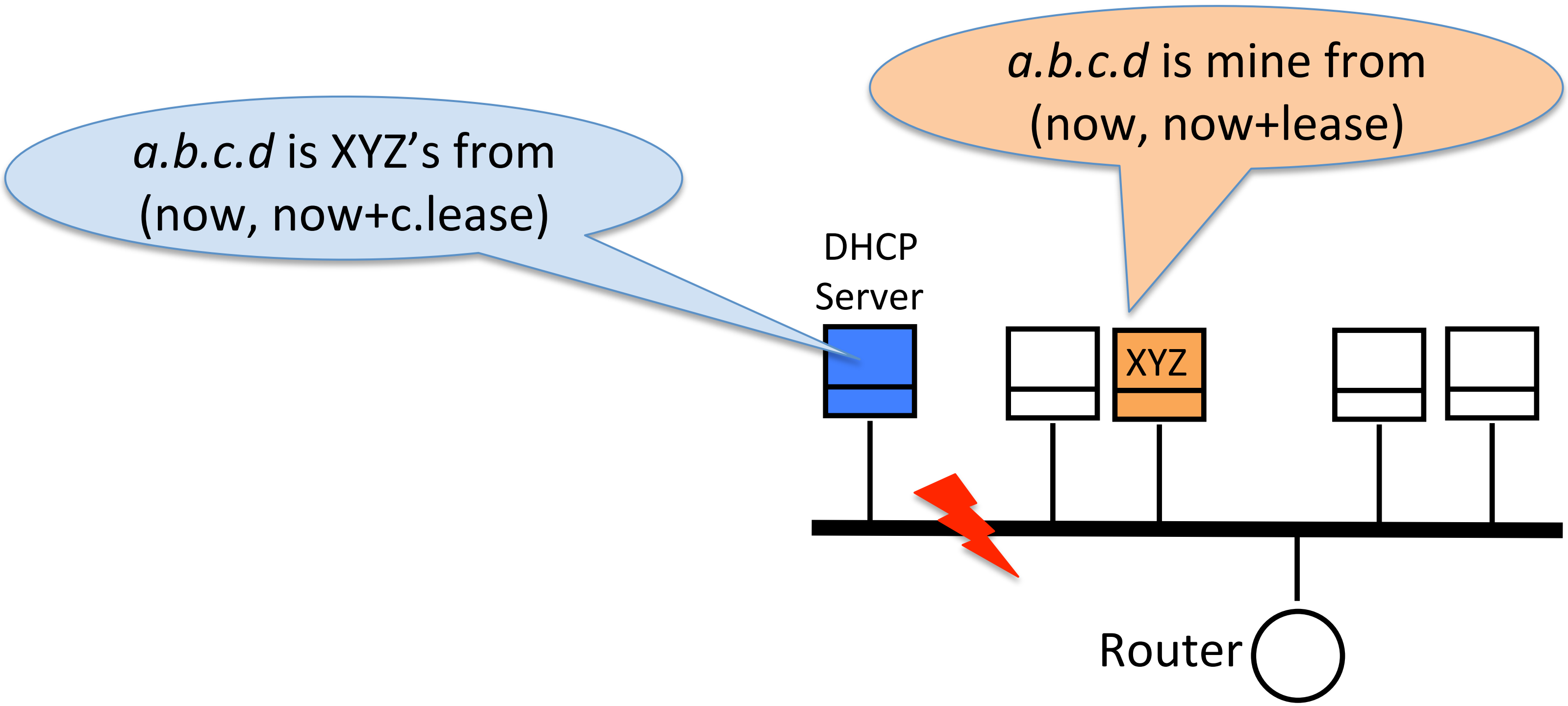
- What happens when host XYZ fails?
  - refreshes from XYZ stop
  - server reclaims *a.b.c.d* after O(lease period)

Soft state under failure



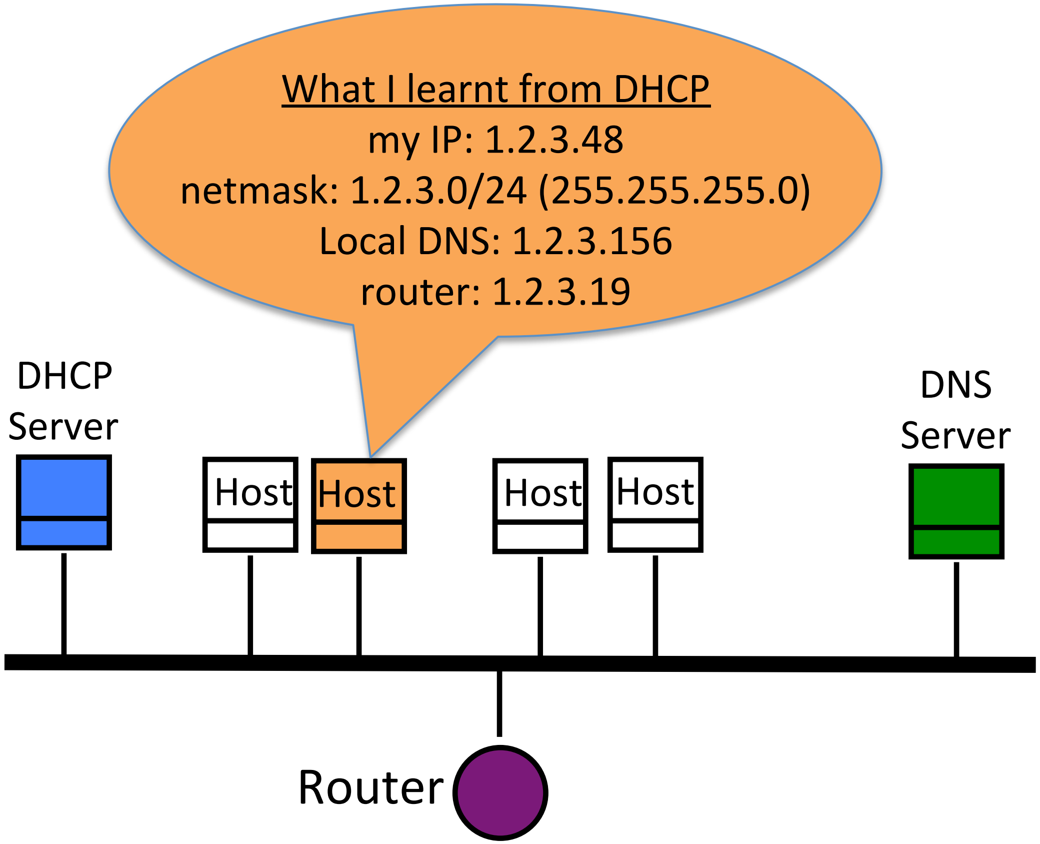
- What happens when server fails?
  - ACKs from server stop
  - XYZ releases address after O(lease period); send new request
  - A new DHCP server can come up from a `cold start' and we're back on track in ~lease time

Soft state under failure

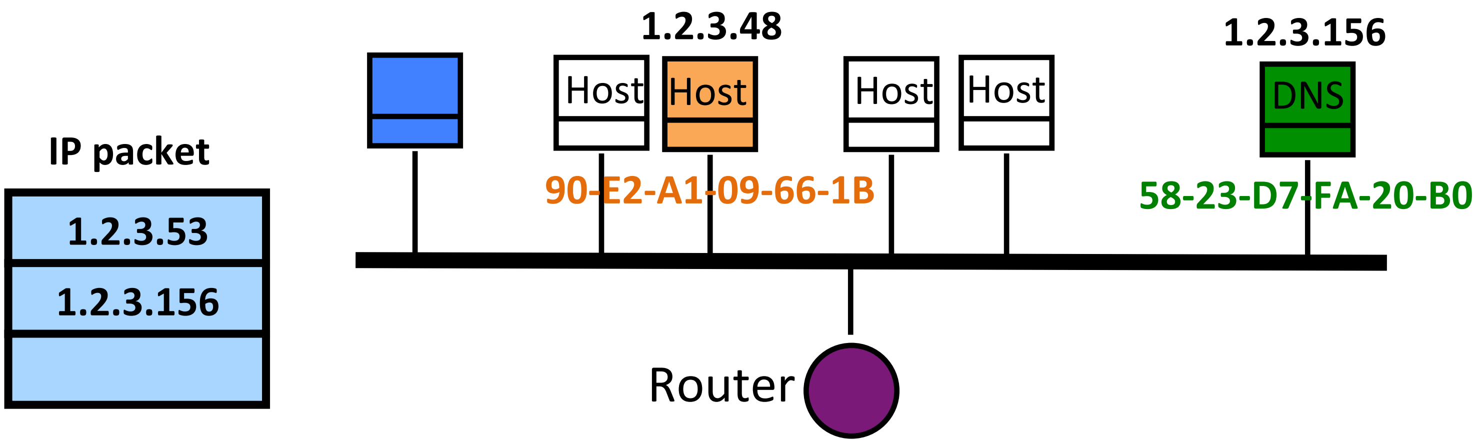


- What happens if the network fails?
  - refreshes and ACKs don't get through
  - XYZ release address; DHCP server reclaims it

Are we there yet?



Sending Packets Over Link-Layer



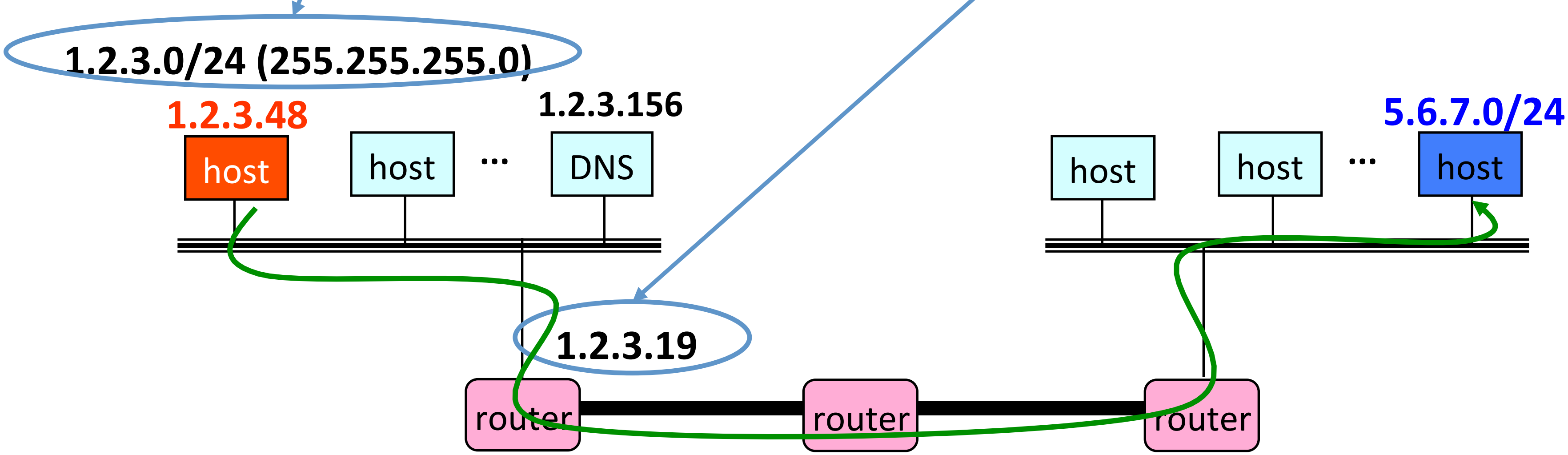
- Link layer only understands MAC addresses
  - Translate the destination IP address to MAC address
  - Encapsulate the IP packet in a link-level (Ethernet) frame

ARP: Address Resolution Protocol

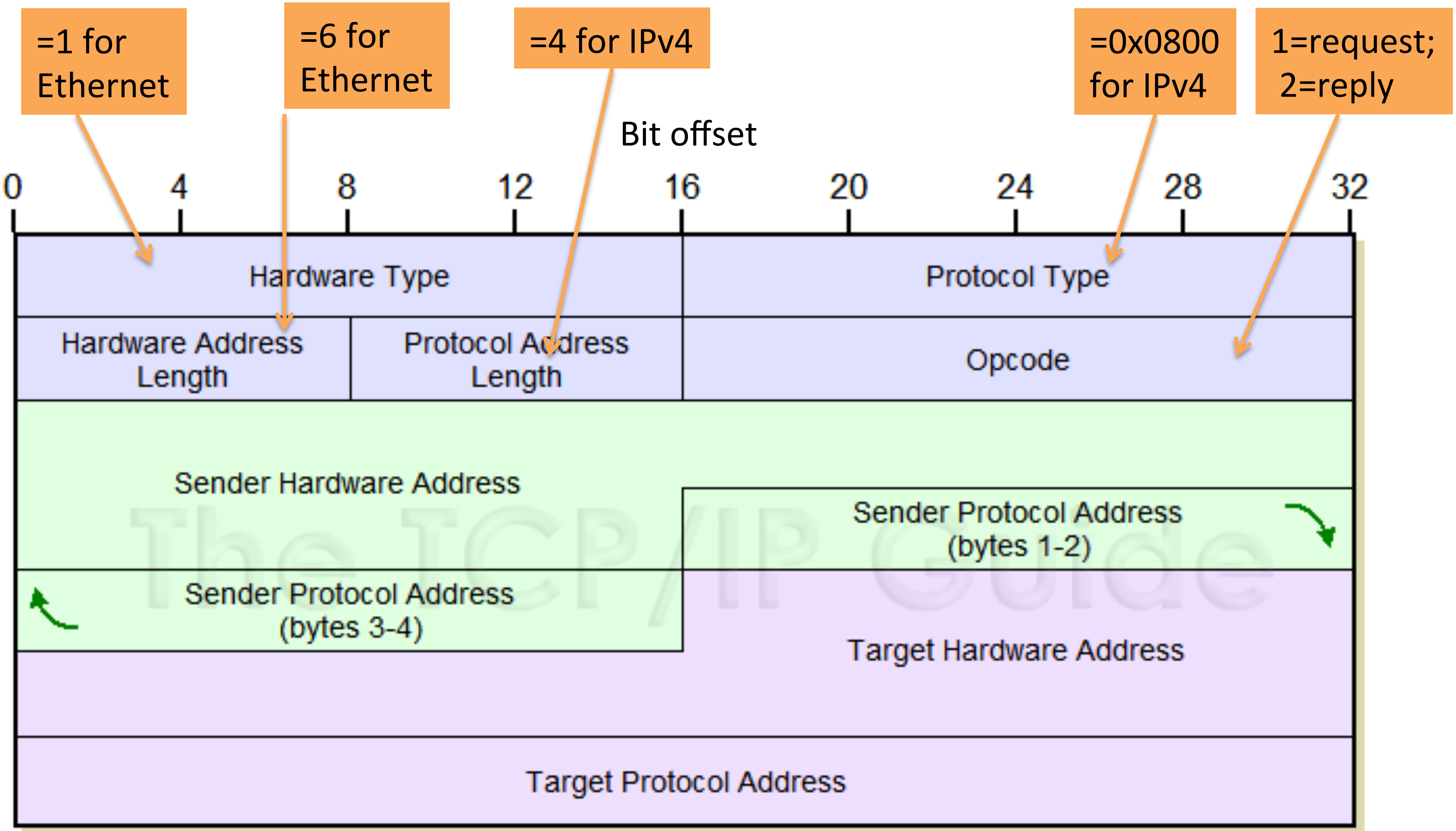
- Every host maintains an ARP table
  - list of (IP address → MAC address) pairs
- Consult the table when sending a packet
  - Map destination IP address to destination MAC address
  - Encapsulate the (IP) data packet with MAC header; transmit
- But: what if IP address not in the table?
  - Sender broadcasts: "**Who has IP address 1.2.3.156**?"
  - Receiver responds: "**MAC address 58-23-D7-FA-20-B0**"
  - Sender caches result in its ARP table

What if the destination is remote?

- Look up the MAC address of the first hop router
  - 1.2.3.48 uses ARP to find MAC address for first-hop router **1.2.3.19** rather than ultimate destination IP address
- How does the red host know the destination is not local?
  - Uses netmask (discovered via DHCP)
- How does the red host know about 1.2.3.19?
  - Also DHCP



ARP header



=1 for Ethernet
=6 for Ethernet
=4 for IPv4
=0x0800 for IPv4
1=request; 2=reply
Bit offset
0
4
8
12
16
20
24
28
32
Hardware Type
Protocol Type
Hardware Address Length
Protocol Address Length
Opcode
Sender Hardware Address
Sender Protocol Address (bytes 1-2)
Sender Protocol Address (bytes 3-4)
Target Hardware Address
Target Protocol Address
The TCP/IP Guide

Key Ideas in Both ARP and DHCP

- Broadcasting: Can use broadcast to make contact
  - Scalable because of limited size
- Caching: remember the past for a while
  - Store the information you learn to reduce overhead
- Soft state: eventually forget the past
  - Associate a time-to-live field with the information
  - … and either refresh or discard the information
  - Key for robustness in the face of unpredictable change

Taking Stock: Naming

Layer	Examples	Structure	Configuration	Resolution Service
App. Layer	www.cs.berkeley.edu	organizational hierarchy	~ manual	DNS
Network Layer	123.45.6.78	topological hierarchy	DHCP	ARP
Link layer	45-CC-4E-12-F0-97	vendor (flat)	hard-coded	

Discovery mechanisms

We've see two approaches

- Broadcast (ARP, DHCP)
  - flooding doesn't scale
  - no centralized point of failure
  - zero configuration
- Directory service (DNS)
  - no flooding / scalable
  - root of the directory is vulnerable (caching is key)
  - needs configuration to bootstrap (local, root servers, *etc.*)

Open: can we get Internet-scale yet zero config?

Steps in end-to-end communication

What do hosts need to know?

And how do they find out?

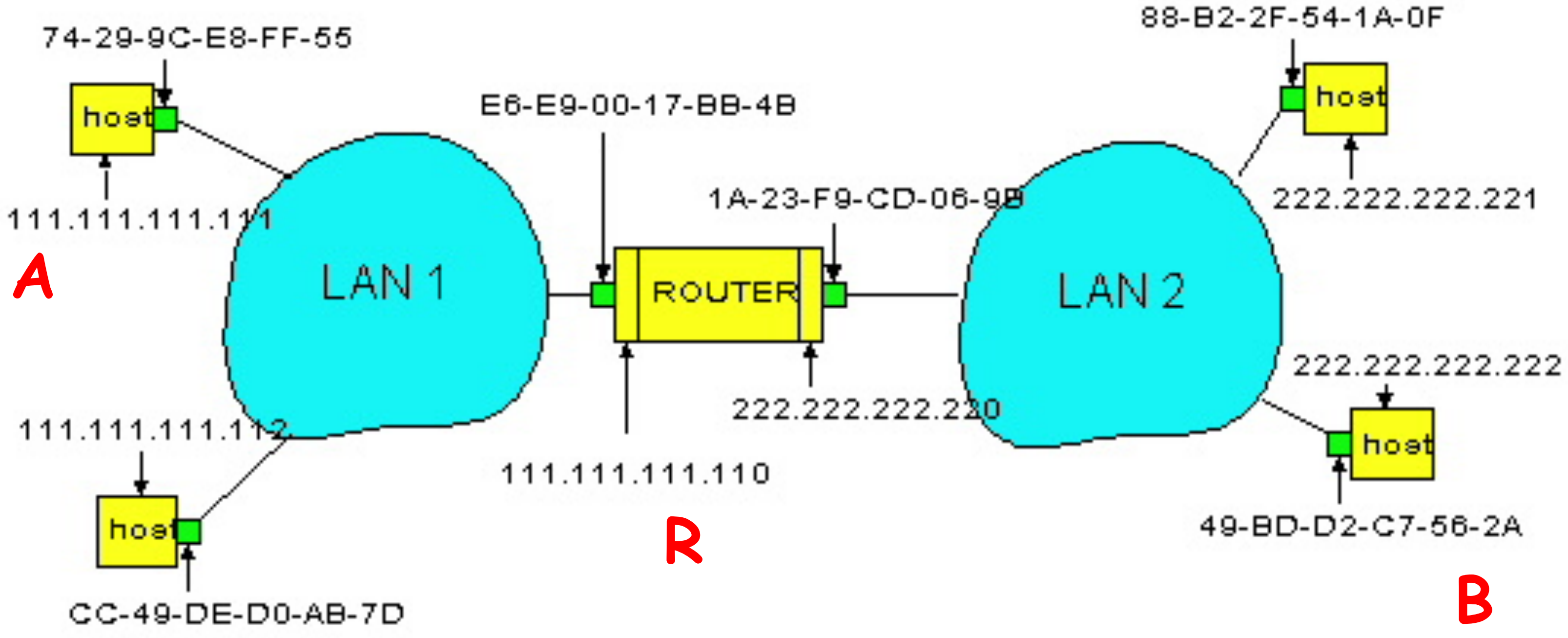
Steps in reaching a destination

- First look up destination's IP address
  - Need to know where my local DNS server is
    - **DHCP**
  - Also needs to know my own IP address
    - **DHCP**

Sending a Packet

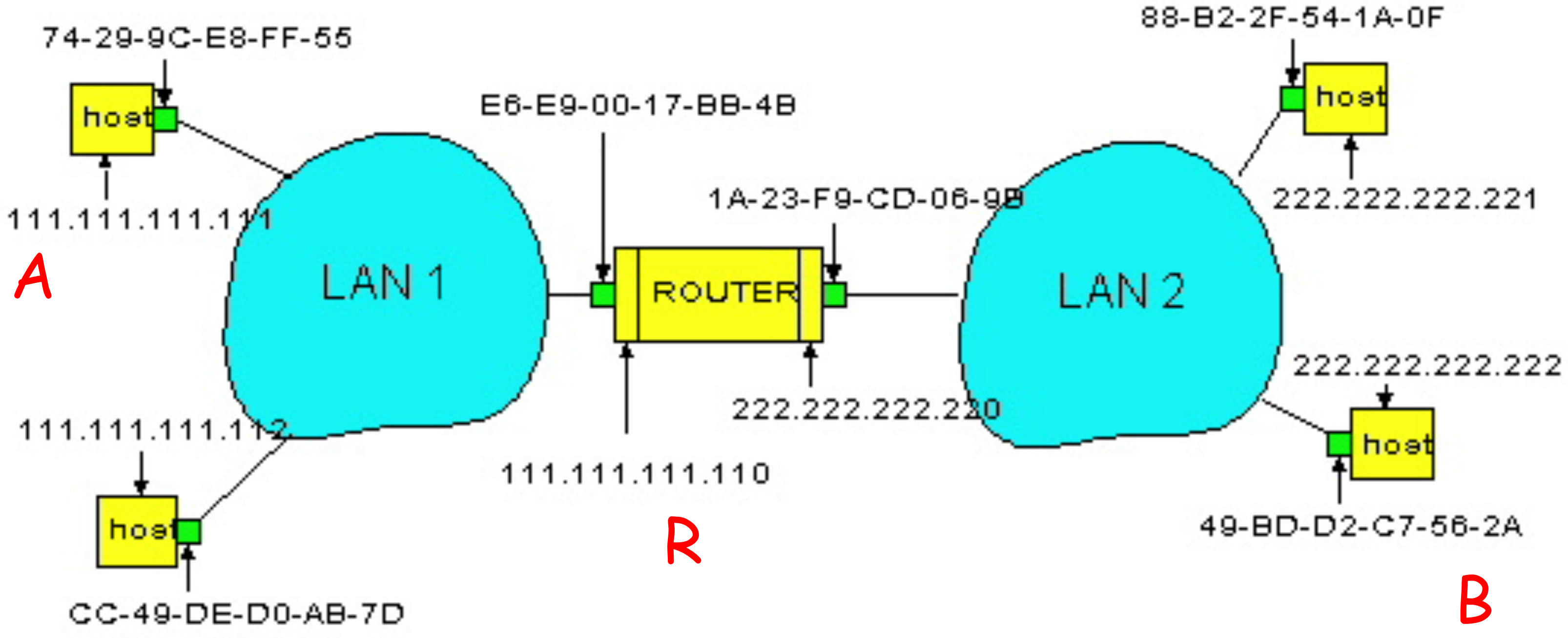
- On same subnet:
  - Use MAC address of destination
  - ***ARP***
- On some other subnet:
  - Use MAC address of first-hop router
  - ***DHCP + ARP***
- And how can a host tell whether destination is on same or other subnet?
  - Use the netmask
  - ***DHCP***

Example: A sending a packet to B



How does host A send an IP packet to host B?

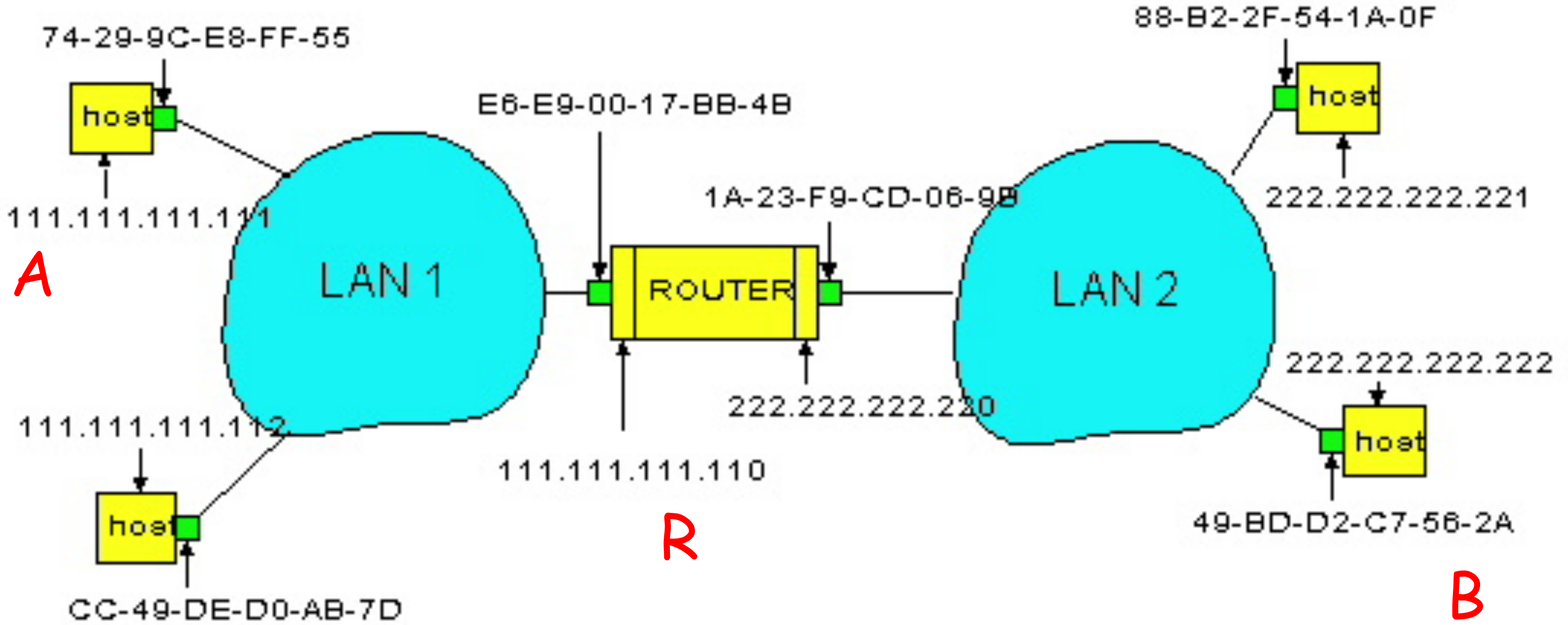
Example: A sending a packet to B



1. A sends packet to R.
2. R sends packet to B.

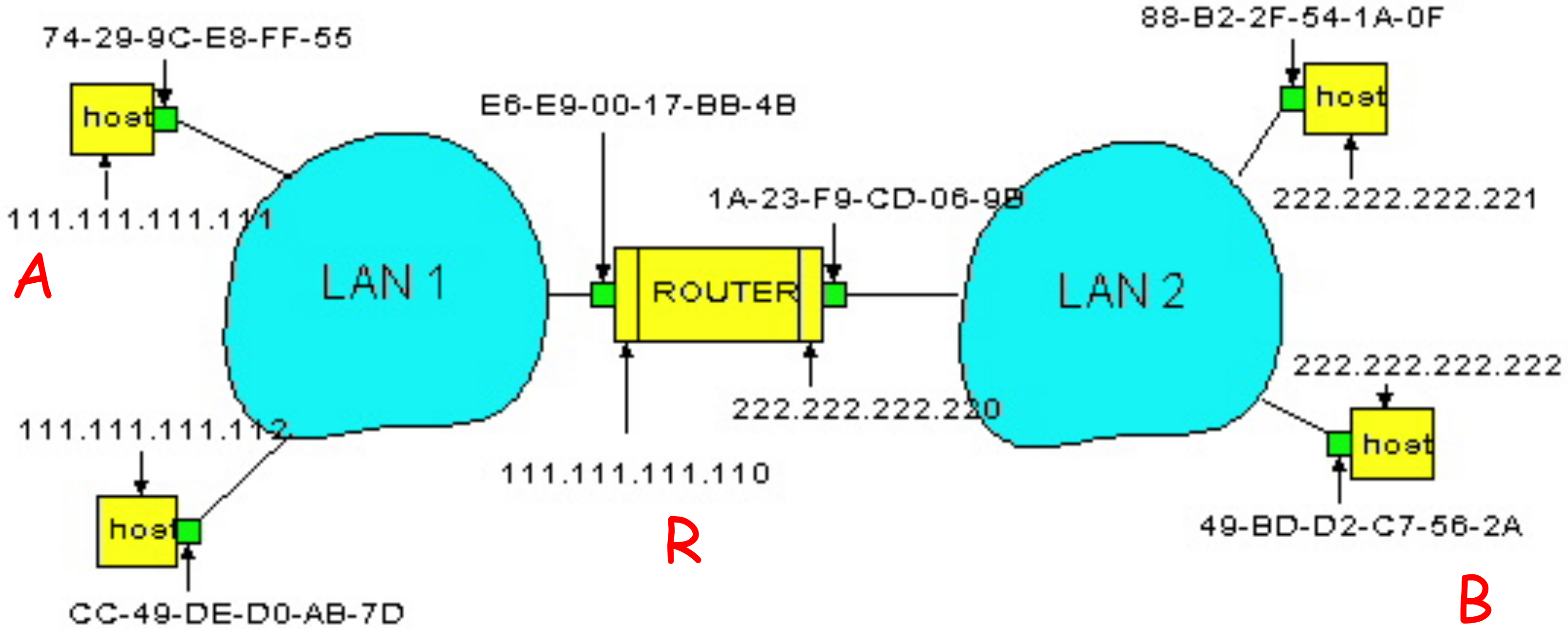
A sends packet through router R

- Host A constructs an IP packet to send to B
  - Source 111.111.111.111, destination 222.222.222.222
- Host A has a gateway router R
  - Used to reach destinations outside of 111.111.111.0/24
  - Address 111.111.111.110 for R learned via DHCP



A sends packet through router R

- Host A learns the MAC address of R's interface
  - ARP request: broadcast request for 111.111.111.110
  - ARP response: R responds with E6-E9-00-17-BB-4B
- Host A encapsulates the IP packet for B, and sends to R

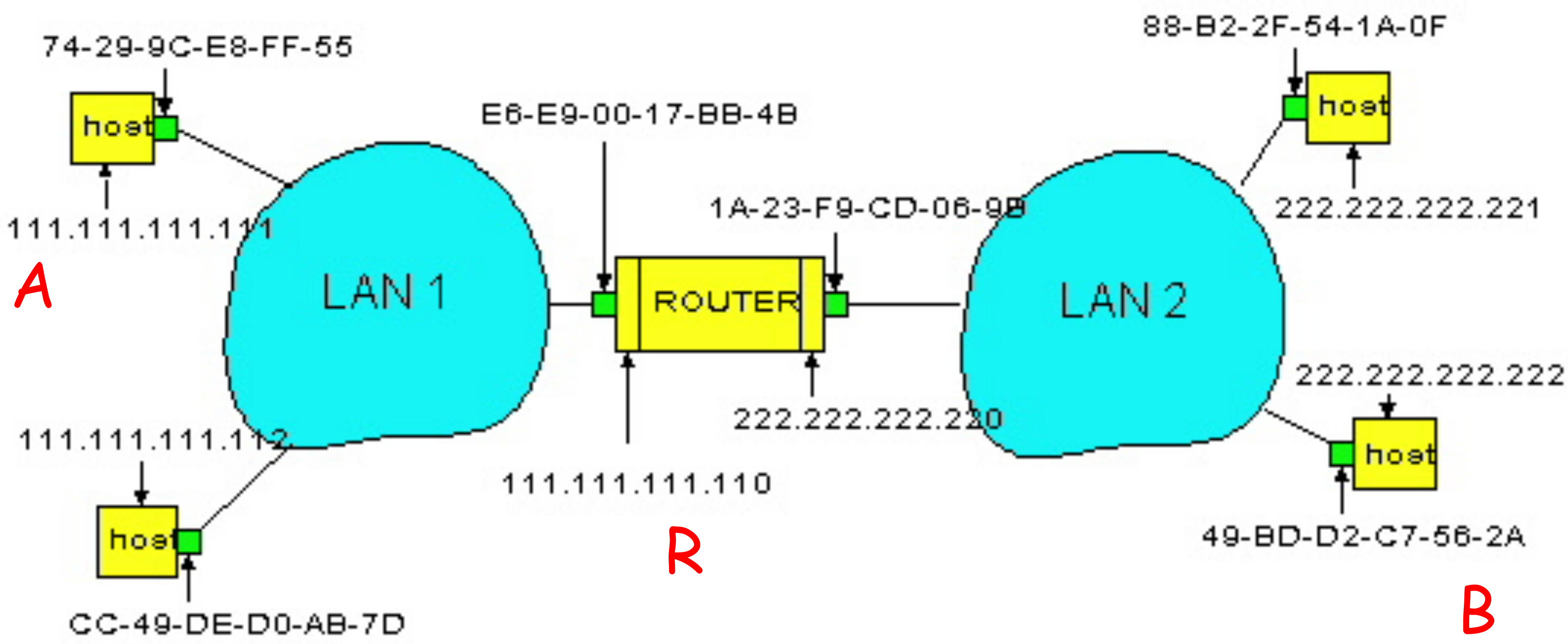


cket

Two points:

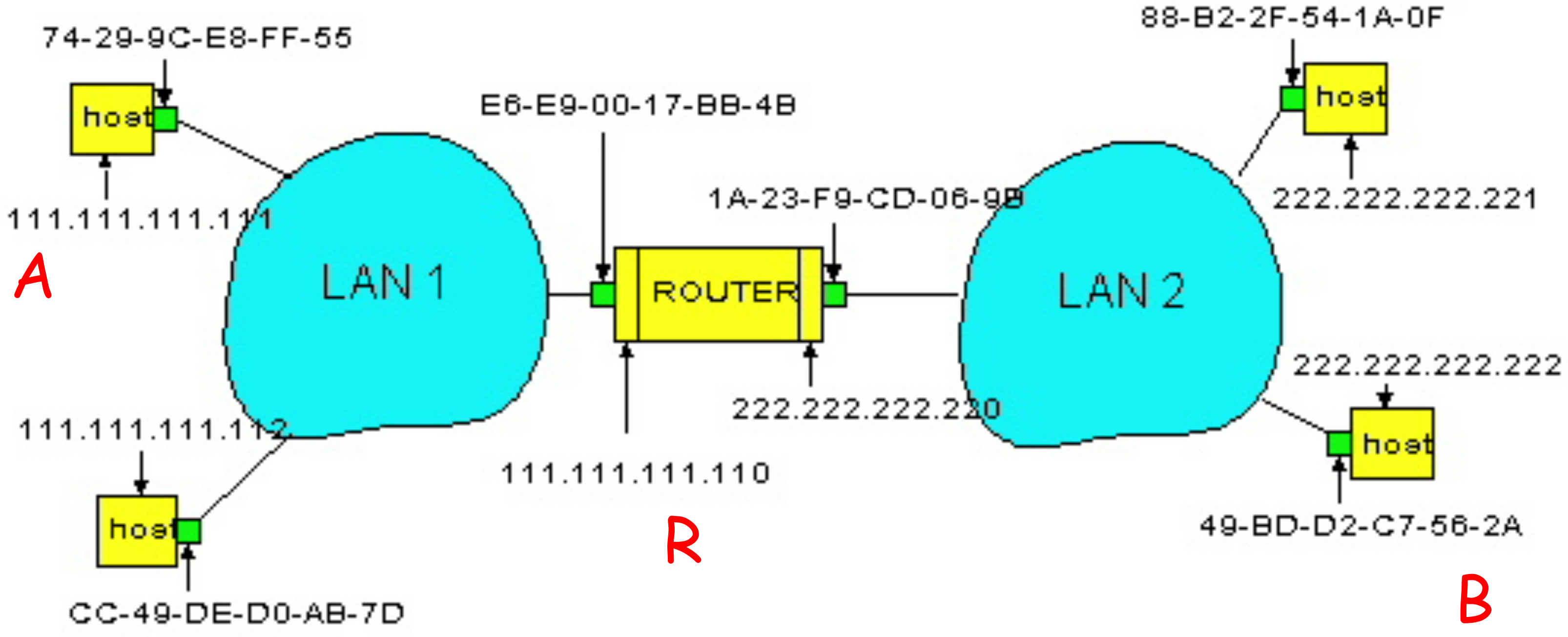
- IP routing table points to this port
- Destination address is within mask of port's address (i.e., local)

  - R sees t is destined to 222.222.222.222
- Router R consul s forwarding table
  - Packet matches 222.222.222.0/24 via other adapter (port)



R sends packet to B

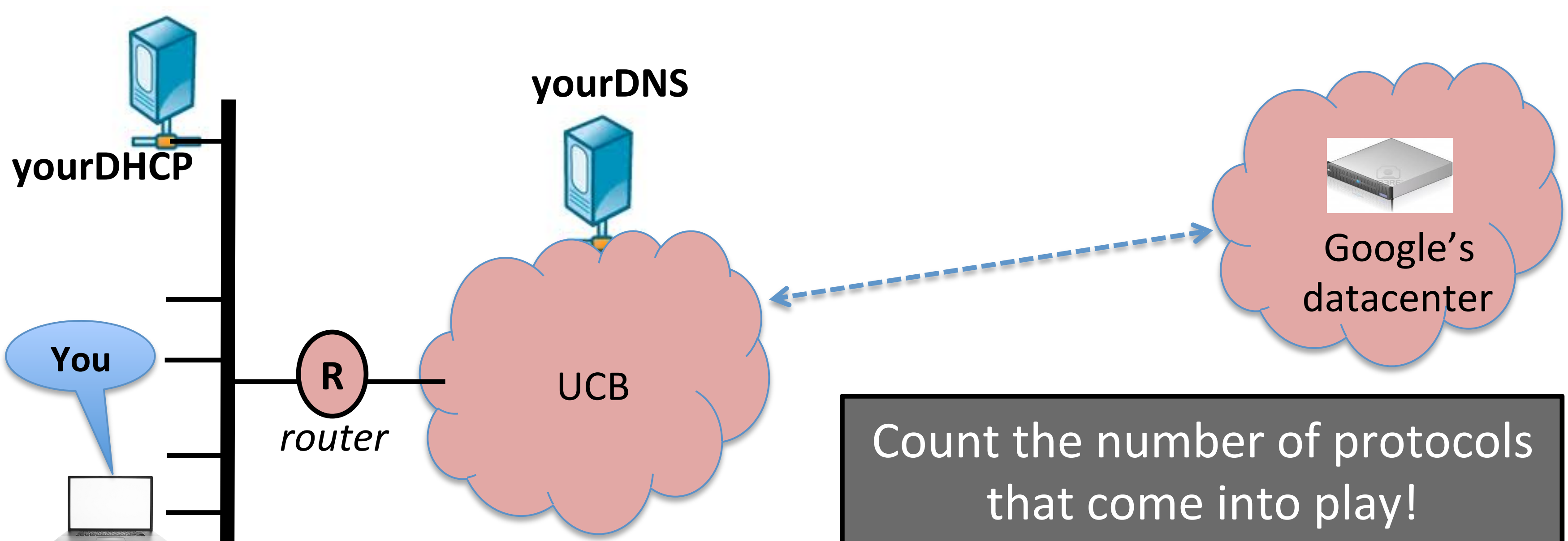
- Router R' s learns the MAC address of host B
  - ARP request: broadcast request for 222.222.222.222
  - ARP response: B responds with 49-BD-D2-C7-56-2A
- Router R encapsulates the packet and sends to B



- Are we there yet?
  - Yes!

Putting the pieces together

Walk through the steps required to download www.google.com/index.html from your laptop



Count the number of protocols that come into play!

- Assume: `cold start' -- nothing cached anywhere
- Assume: yourDNS on a different subnet from yourDHCP
- Ignore intra- and interdomain routing protocols

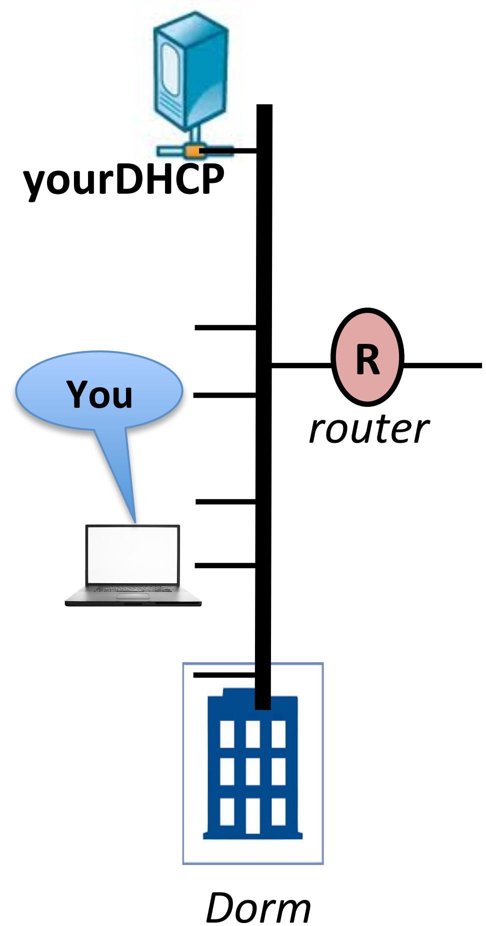
Step 1: Self discovery

- You use DHCP to discover bootstrap parameters
  - your IP addr (u.u.u.u)
  - your DNS server's IP (u.dns.ip.addr)
  - R's IP address (r.r.r.r)
  - ..

- Exchange between you and yourDHCP

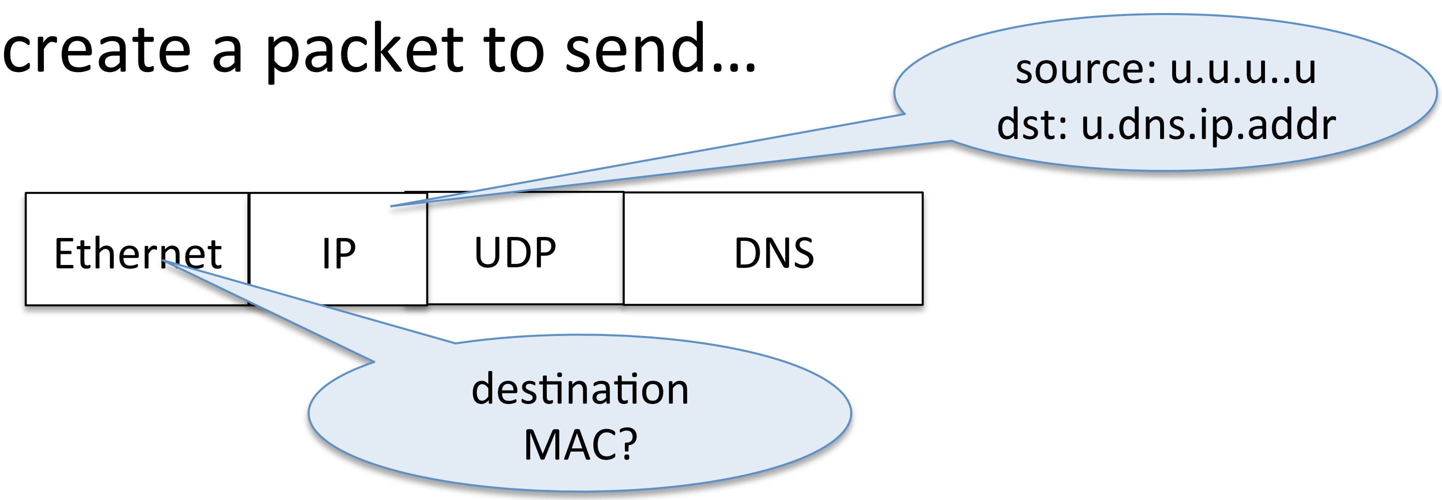
Ethernet	IP	UDP	DHCP

- Protocol count = 4



Next…

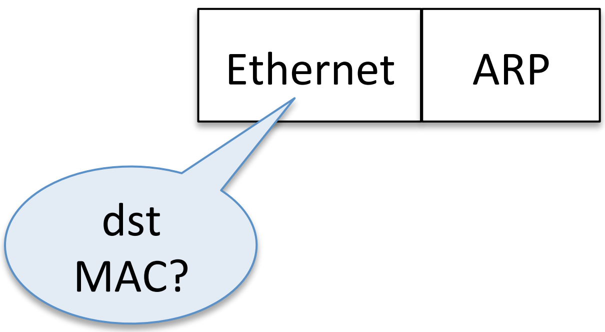
- You are ready to contact www.google.com
  → need an IP address for www.google.com
  → need to ask google's DNS server
  → need to ask my DNS server to ask google's DNS…
  → I know my DNS server's IP addr is u.dns.ip.addr
  → create a packet to send…



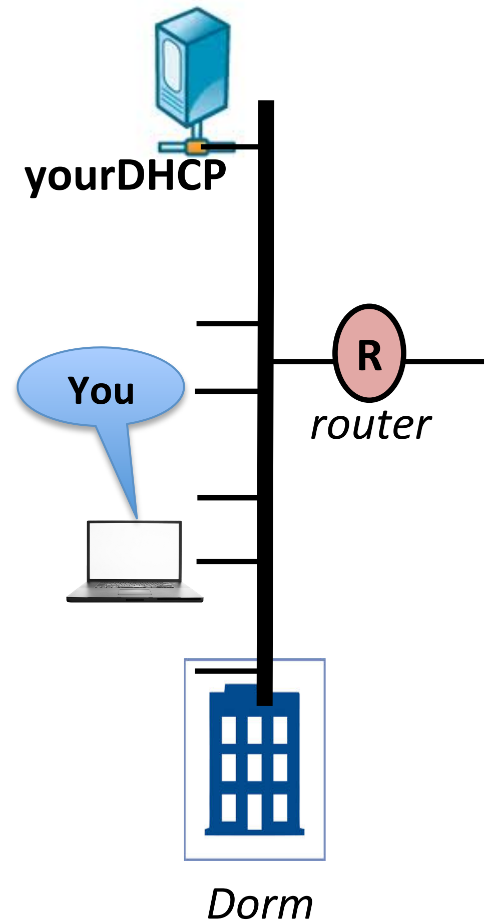
Step 2: Getting out the door

- You use ARP to discover the MAC address of R

- Exchange between you and R

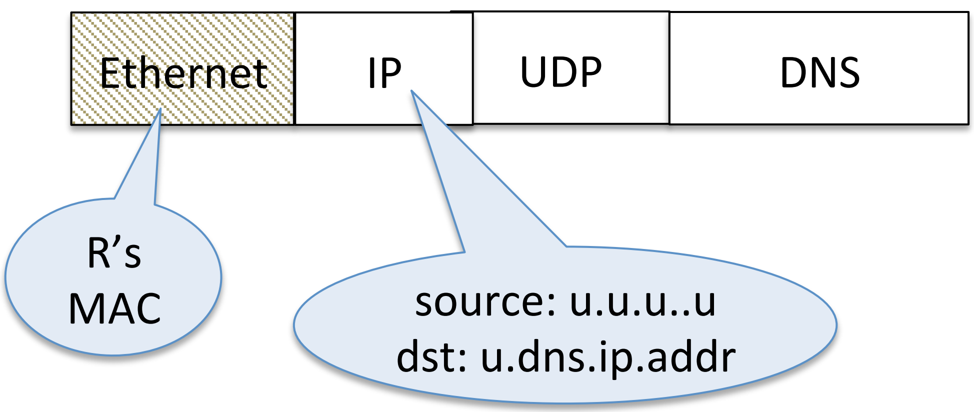


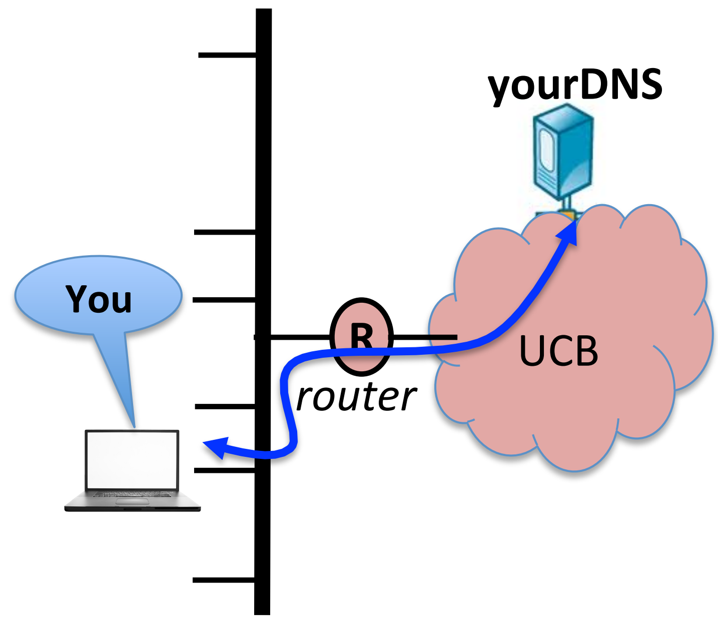
- Protocol count = 5



Step 3: Send a DNS request

- Exchange between you and yourDNS
- Now ready to send that packet

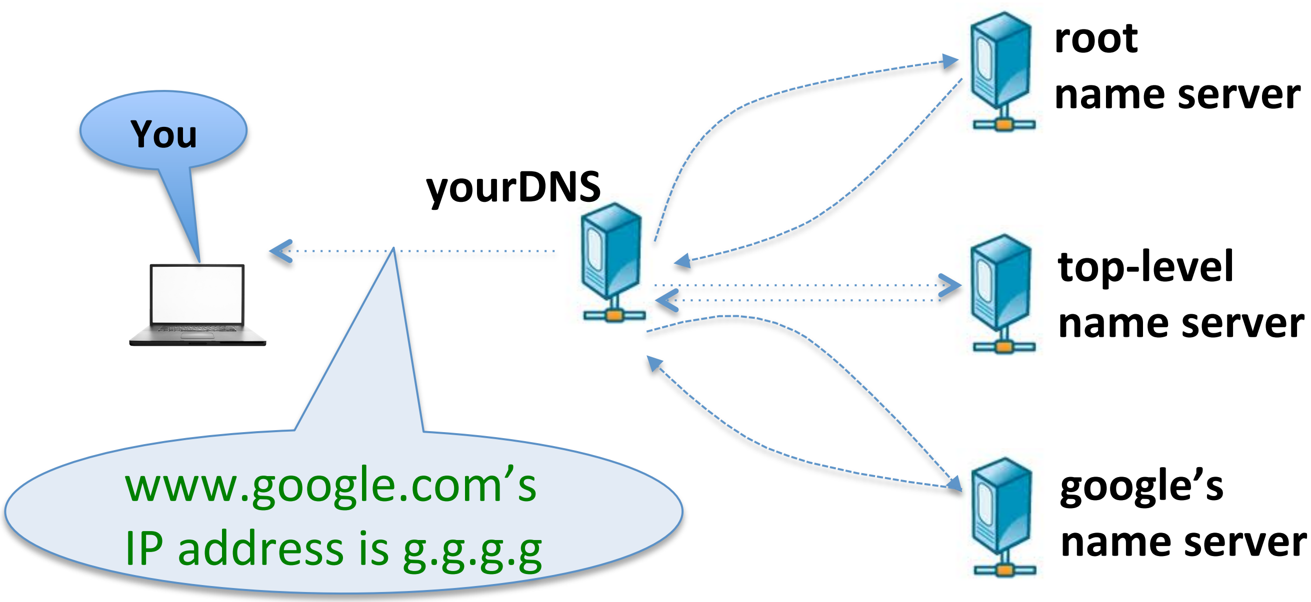




- Protocol count = 6

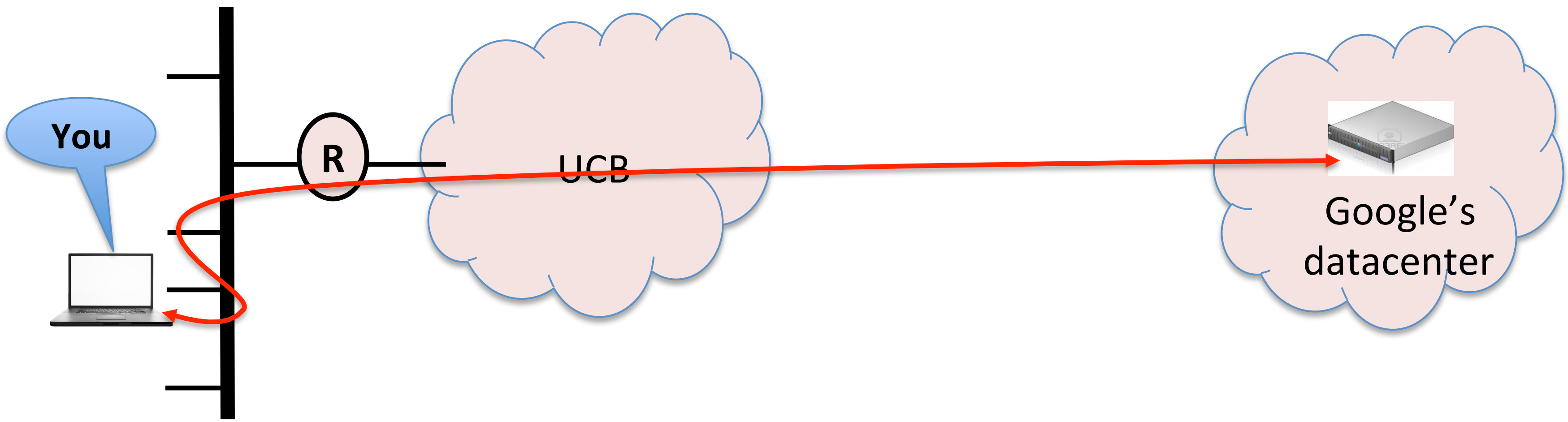
Step 4: yourDNS does its thing

- yourDNS resolves www.google.com

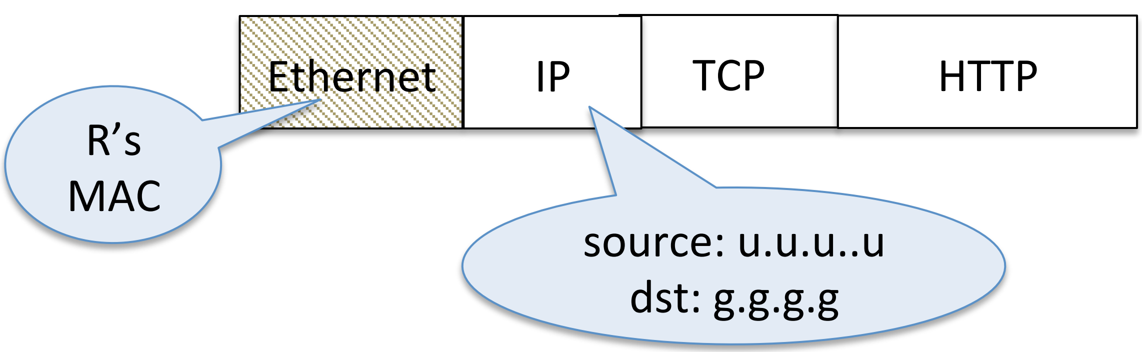


- Protocol count = 6

Step 5: Getting the content (at last)



- Exchange between you and google's server at g.g.g.g



- Protocol count = 8

Recap: Name discovery/resolution

- MAC addresses?
  - my own: hardcoded
  - others: ARP (given IP address)
- IP addresses?
  - my own: DHCP
  - others: DNS (given domain name)
    - how do I bootstrap DNS communication? (DHCP)
- Domain names?
  - search engines