CSCI1680
Network Layer: IP & Forwarding

Nick DeMarinis

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

Administivia

- Snowcast: was due last night
- HW1: Out now, due next Wed (Feb 23)
- IP Project: Out tomorrow (Feb 18)
  - Fill out group preference form by 11:59pm tomorrow (Feb 18)

Today

Start of network layer

- Network layer: Internet Protocol (IP) (v4)
- Mechanics of IP forwarding
- Intro to IP project

Layers, Services, Protocols

Application

Service: user-facing application.
Application-defined messages

Transport

Service: multiplexing applications
Reliable byte stream to other node (TCP),
Unreliable datagram (UDP)

Network

Service: move packets to any other node in the network
Internet Protocol (IP)

Link

Service: move frames to other node across link.
May add reliability, medium access control

Physical

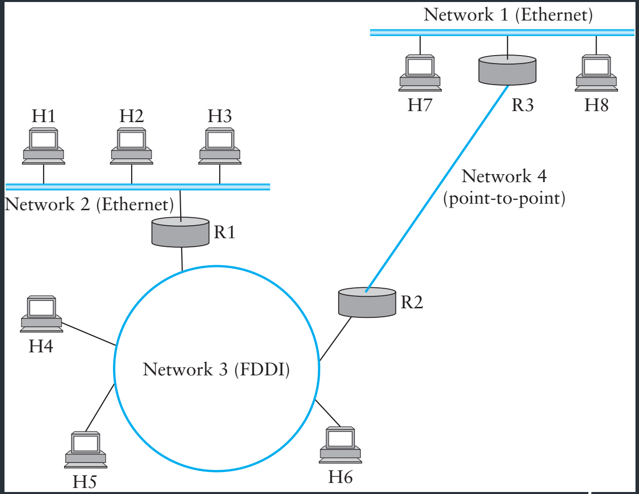
Service: move bits to other node across link

Internet Protocol (IP) Goals

How to connect *everyone*?

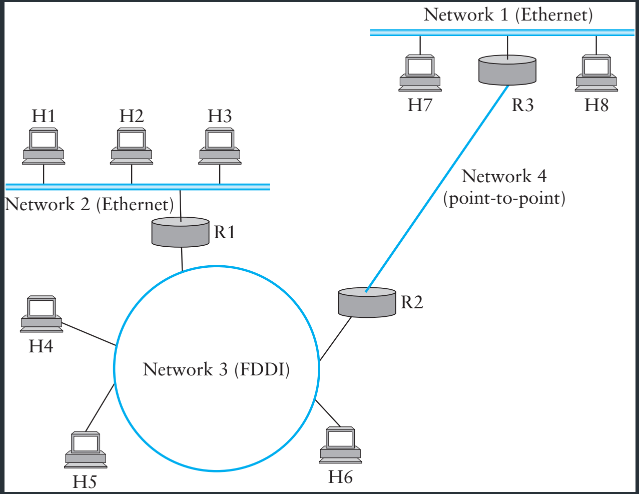
- Glue lower-level networks together
- A network of networks!
- Router: device that forwards packets between networks

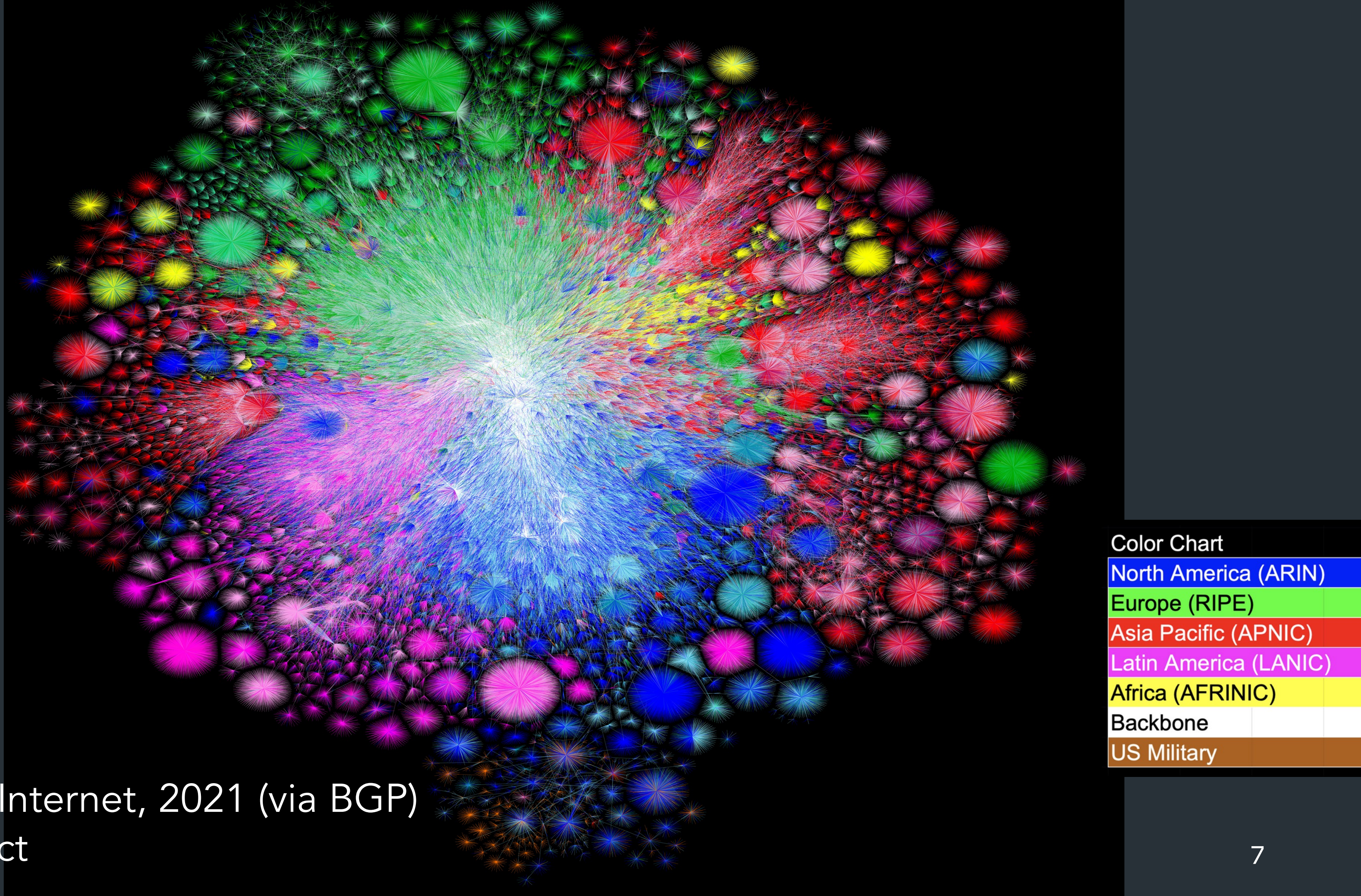
Doesn't this sound like switching?



Inter-networking Challenges

- Networks are heterogeneous (eg. Wifi vs. Ethernet)
  - Different frame formats
  - Different service models
  - Different packet sizes/bandwidths
- Scaling
  - Link-layer forwarding strategies don't scale to Internet!





Map of the Internet, 2021 (via BGP)
OPTE project

How would you design such a protocol?

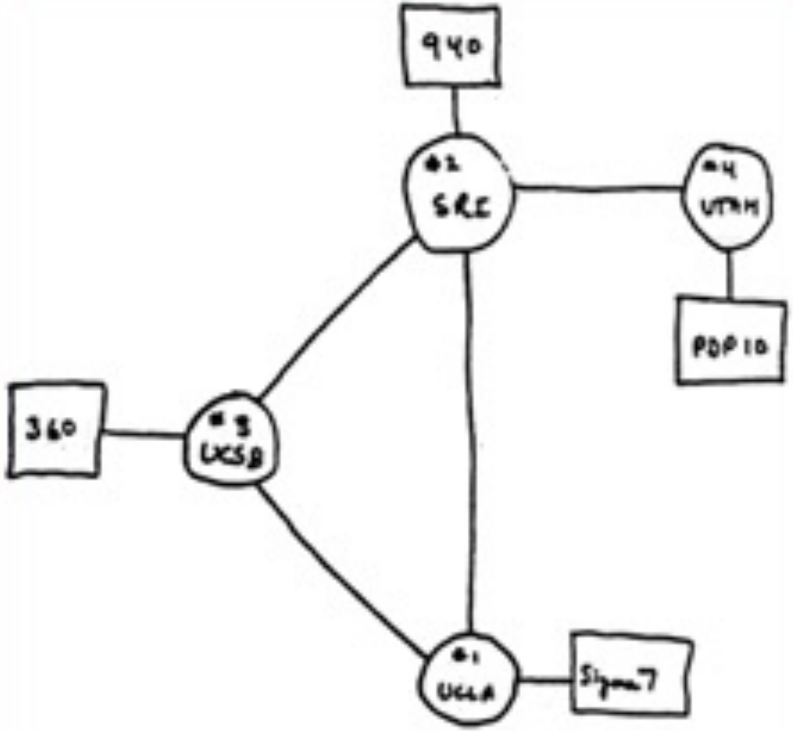
- Circuits or packets?
  - Predictability
- Service model
  - Reliability, timing, bandwidth guarantees
- Any-to-any communication
  - How do you find a particular host?
  - How do you get a message there?
  - What happens when a host joins/leaves?

IP’s Decisions

- Packet switched
  - Unpredictability, statistical multiplexing
- Service model
  - Lowest common denominator: best effort, connectionless datagram
- Any-to-any communication
  - IP header: common message format
  - IP address: each host has an address, based on hierarchical structure of network

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 transfe
- Wanted to connect multiple networks
  - Not all reliable, different formats, etc…



THE ARPA NETWORK

DEC 1969

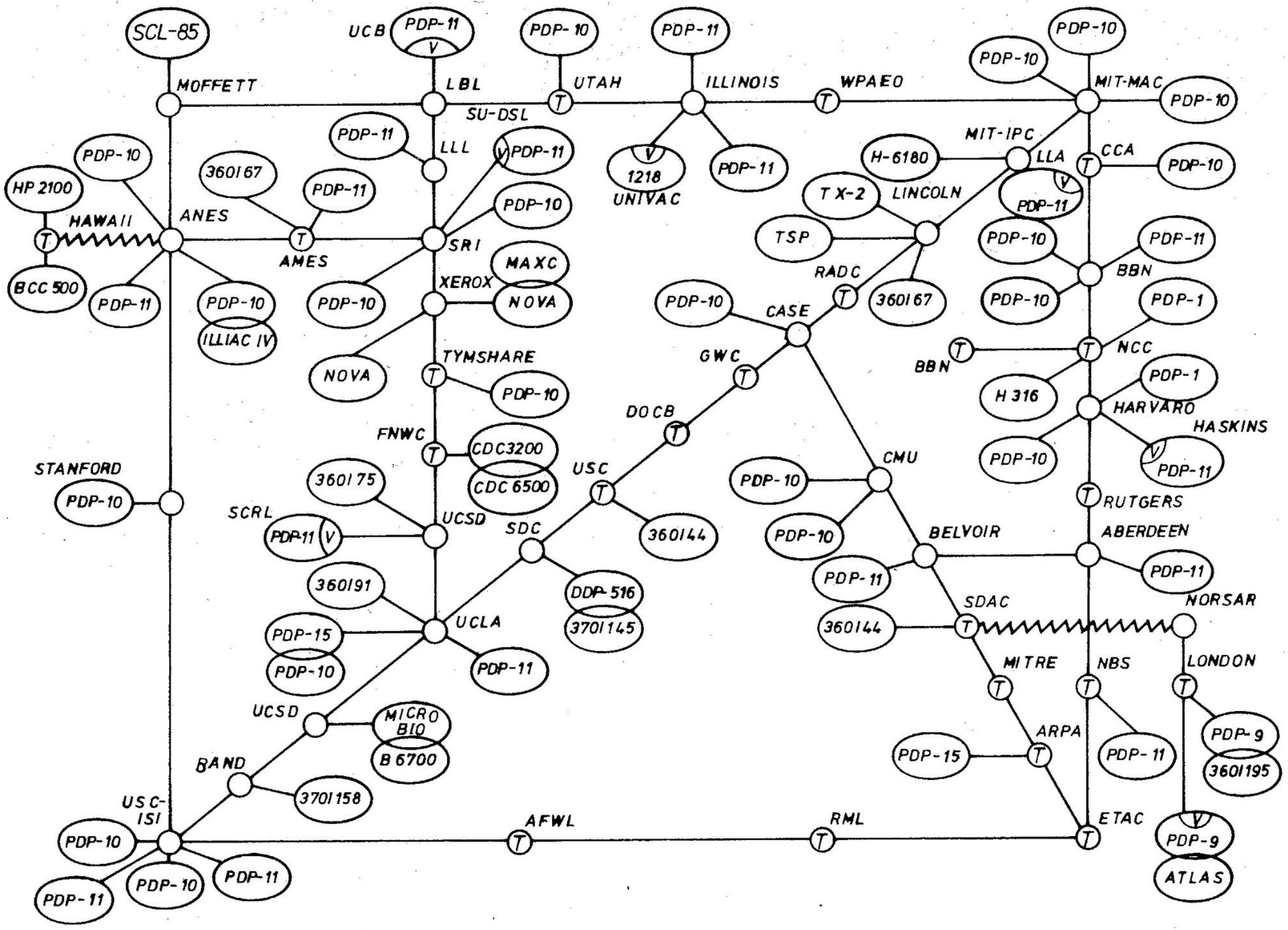


Abb. 4 ARPA NETwork, topologische Karte. Stand Juni 1974.

TCP/IP Introduced

- Vint Cerf, Robert Kahn build protocol to replace NCP
- Initial design: single protocol providing a unified reliable pipe
- 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

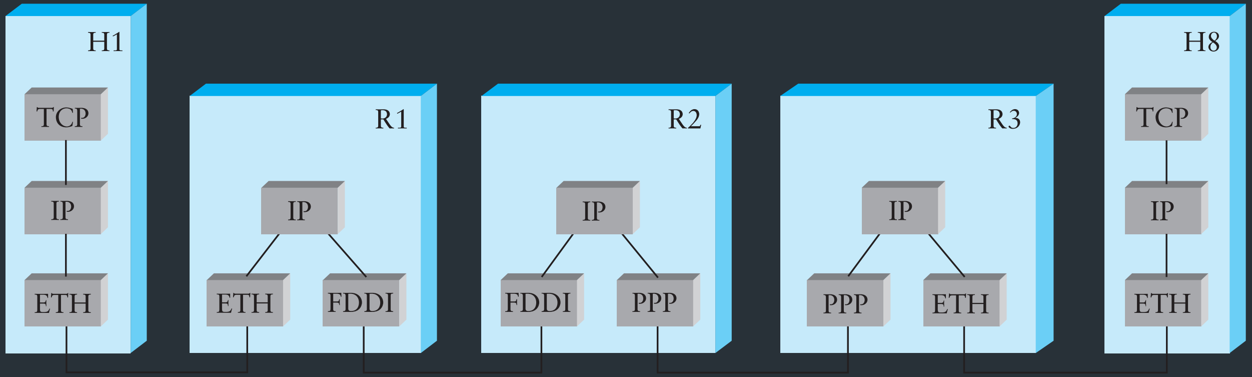
David D. Clark, “The design Philosophy of the DARPA Internet Protocols”, 1988

- 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 runs on all hosts and routers

- Provides *addressing*: how we name nodes in an IP network
- Provides *forwarding*: how routers move packets based on the destination address
- Later: *routing*: how routers build forwarding rules



IP’s 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…)

IP Addressing

IP Version 4: Each address is a 32-bit number:

```
10000000 10010100 00010000 00000111
```

128.148.16.7

Notation

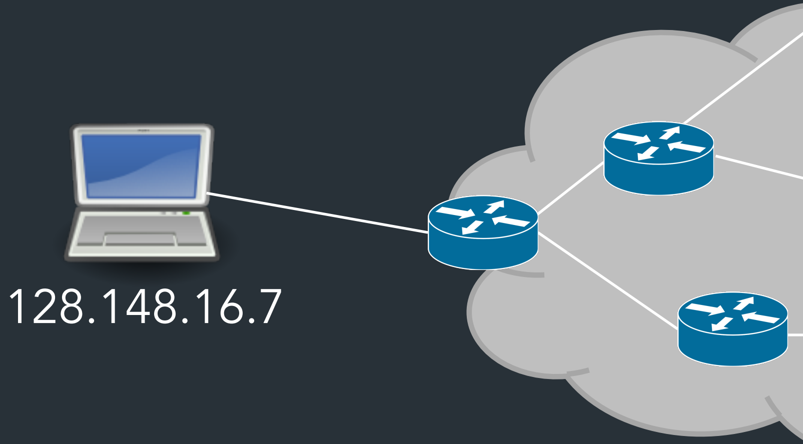
- Write each byte (“octet”) as a decimal number
- This is called “dotted decimal” or ”dotted quad” notation

IP Addressing

An IP address identifies…

- *Who* a host is: A unique number
- *Where* it is on the Internet

- Networks are allocated ranges of IP addresses by global authority (ICANN)
  - Further subdivided by regions, ISPs, organizations…



eg. Brown owns 128.148.xxx.xxx, 138.16.xxx.xxx

*ICANN (Internet Corporation for Assigned Names and Numbers)

IP Addressing

Brown owns the range:

128.148.xxx.xxx

`10000000 10010100 xxxxxxxx xxxxxxxx`

<u>Network part</u>
Identifies Brown (to the Internet)

<u>Host part</u>
Denotes individual hosts
within the Brown Network

IP Addressing

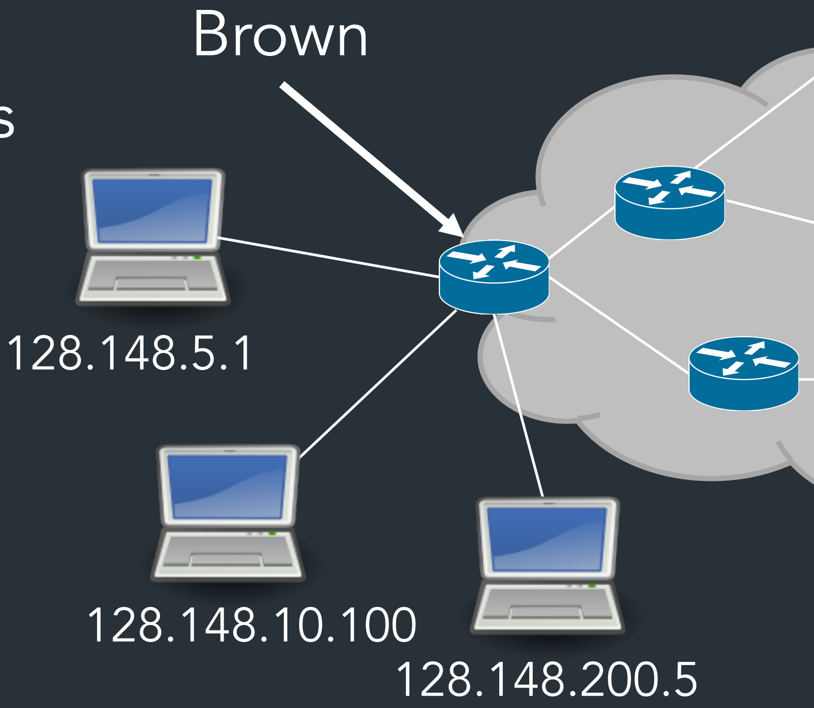
A network can designate IP addresses for its own hosts within its address range

For 128.148.xxx.xxx:

```
10000000 10010100 xxxxxxxx xxxxxxxx
```

Brown uses the the prefix 128.148.0.0/16

Some other ways to write this:
128.148/16
128.148.0.0 + subnet mask 255.255.0.0



Common prefixes

1.2.0.0/16	`00000001 00000010 xxxxxxxx xxxxxxxx`
8.0.0.0/8	`00001000 xxxxxxxx xxxxxxxx xxxxxxxx`
123.10.1.0/24	`01111011 00001010 00000001 xxxxxxxx`
201.112.10.200/30	`11001001 01110000 00001010 110010xx`

Example

How many addresses are in the network 192.1.0.0/20?

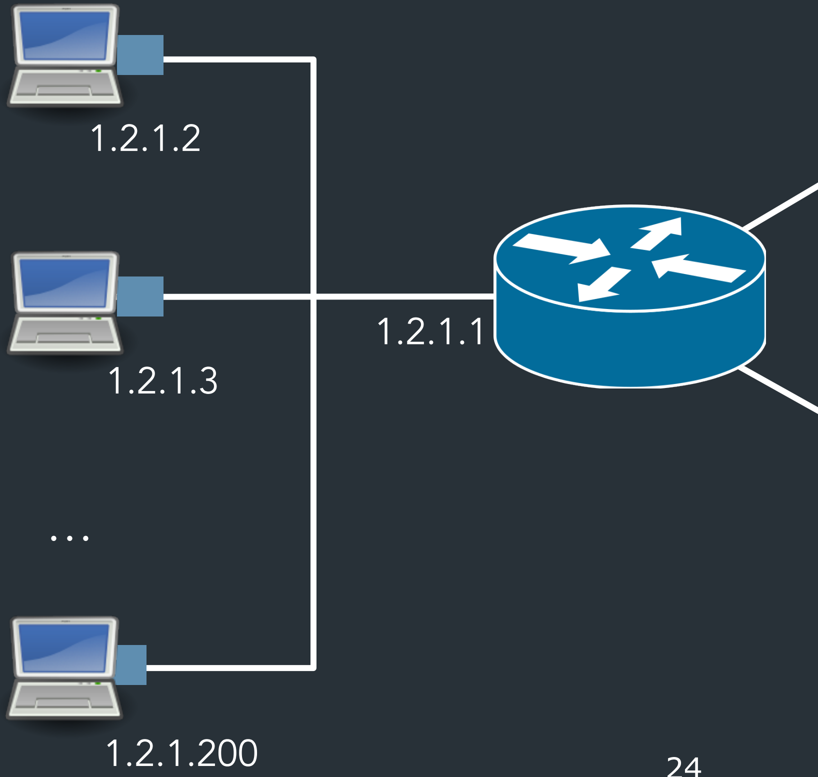
How do we move packets between networks?

IP forwarding

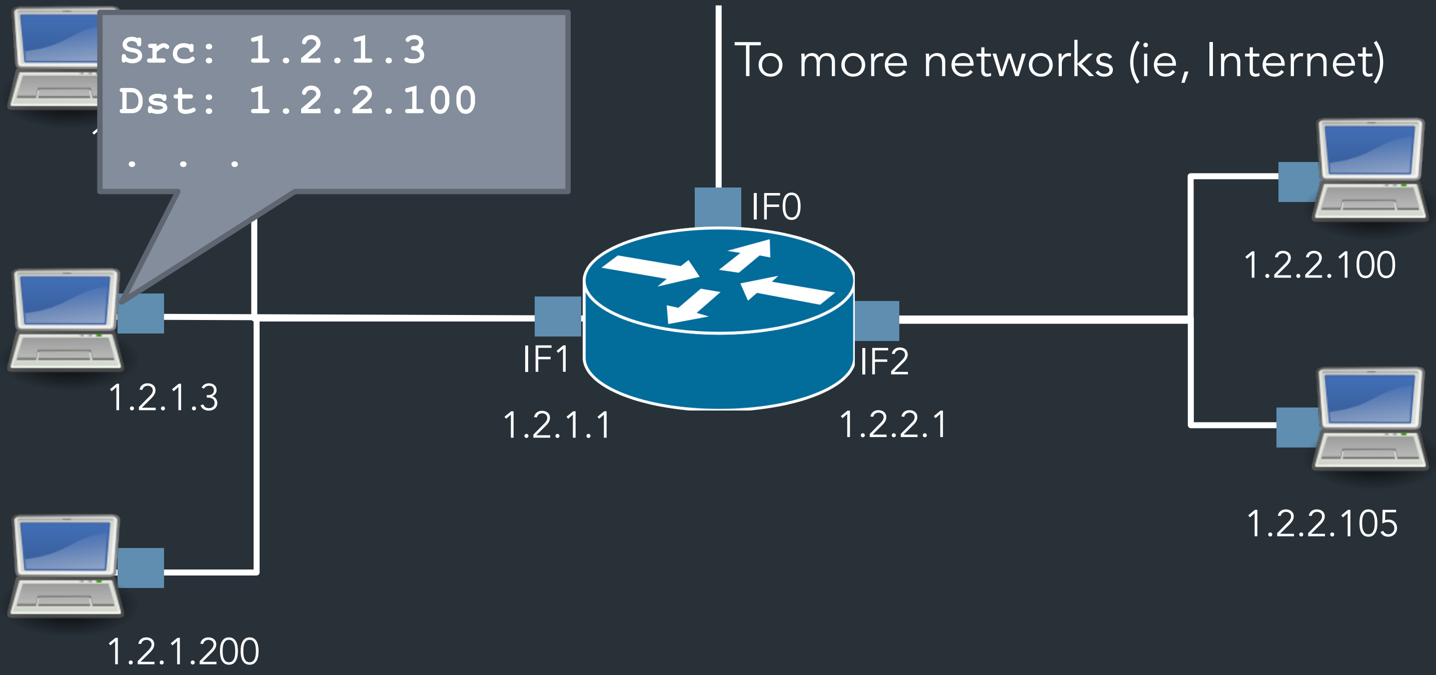
Consider the network 1.2.1.0/24:

- For IP, communicating on same network is easy—this is the link-layer's job!
- Need to map IP addresses to MAC addresses (more on this later)

To reach other networks, send packets to a router, which forwards IP packets to other networks



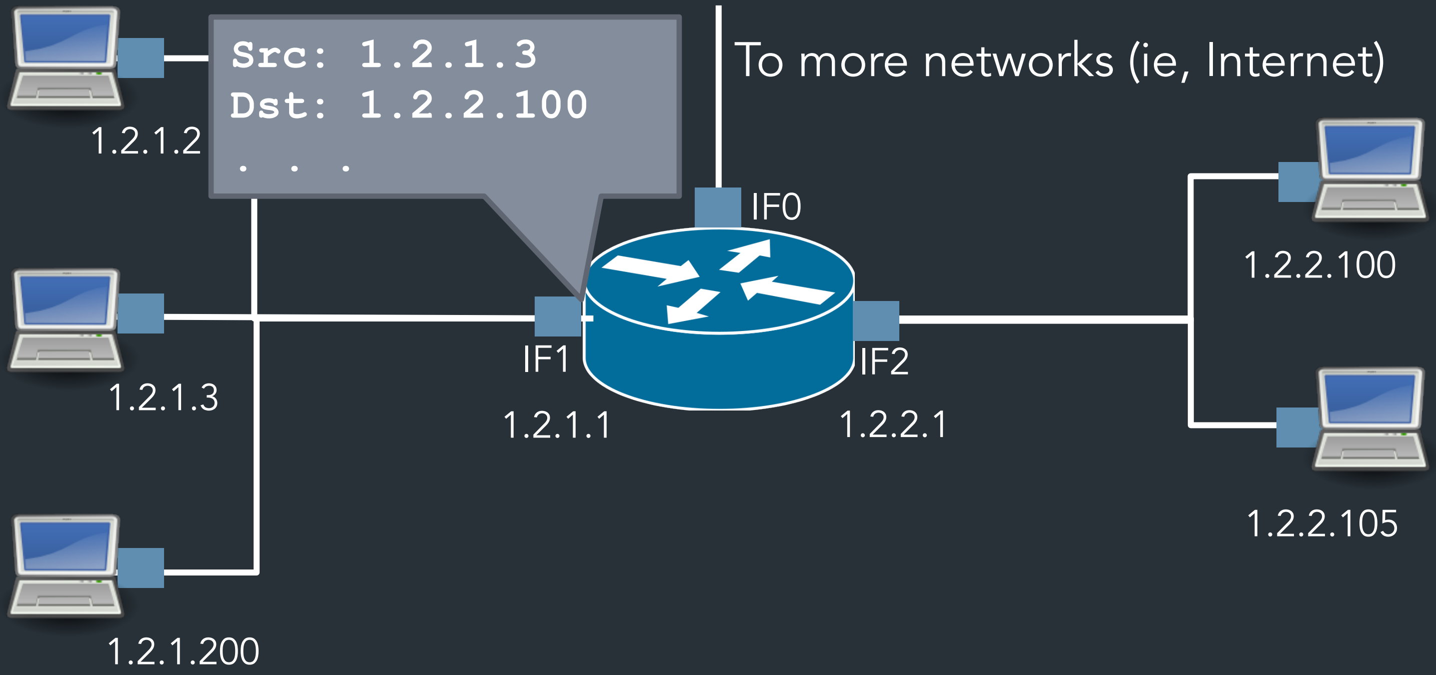
Forwarding IP packets



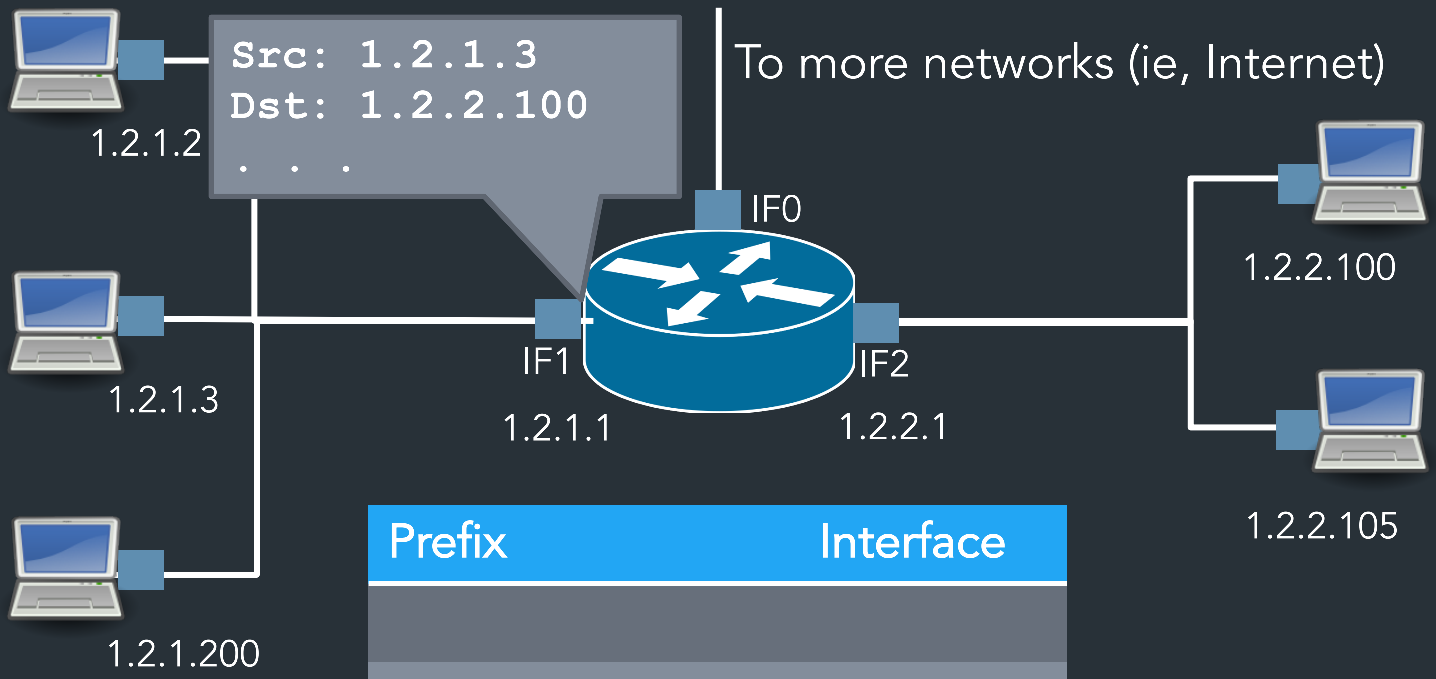
Src: 1.2.1.3
Dst: 1.2.2.100
. . .

To more networks (ie, Internet)

Forwarding IP packets



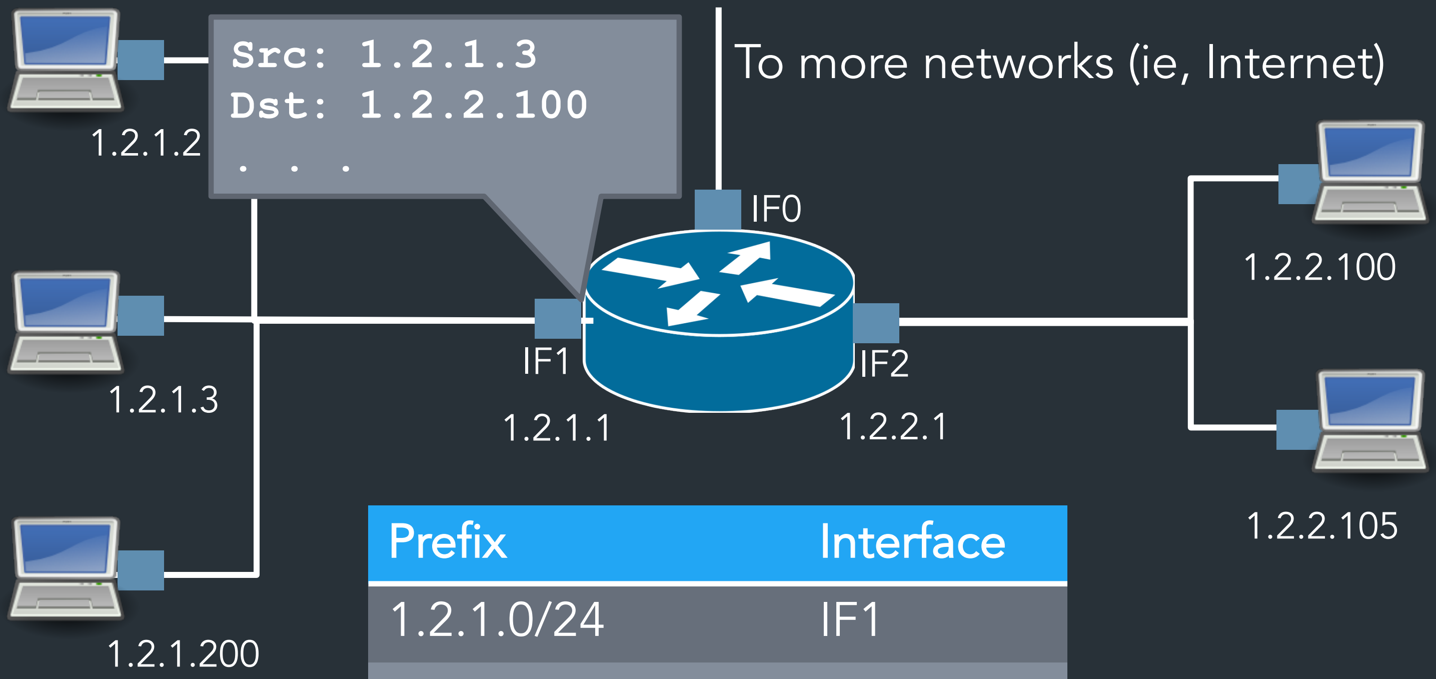
Forwarding IP packets



```
Src: 1.2.1.3
Dst: 1.2.2.100
. . .
```

Prefix	Interface

Forwarding IP packets



```
Src: 1.2.1.3
Dst: 1.2.2.100
. . .
```

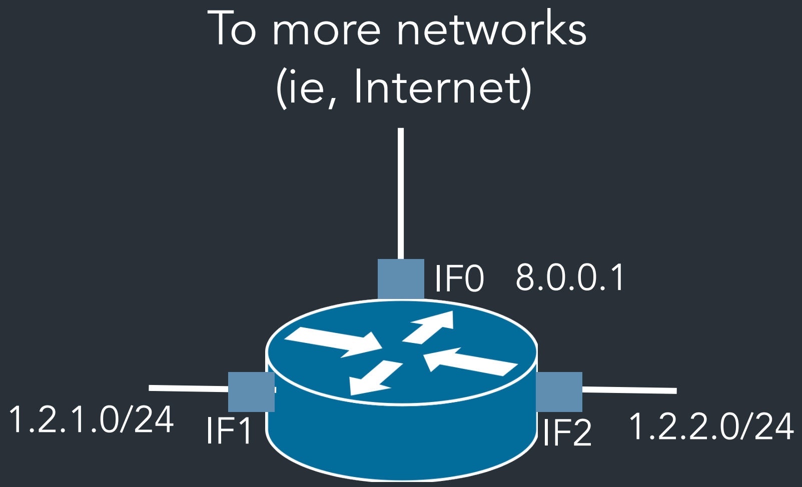
To more networks (ie, Internet)

Prefix	Interface
1.2.1.0/24	IF1
1.2.2.0/24	IF2
<everything else>	IF0

What about the rest?

How to reach networks that aren't directly connected?

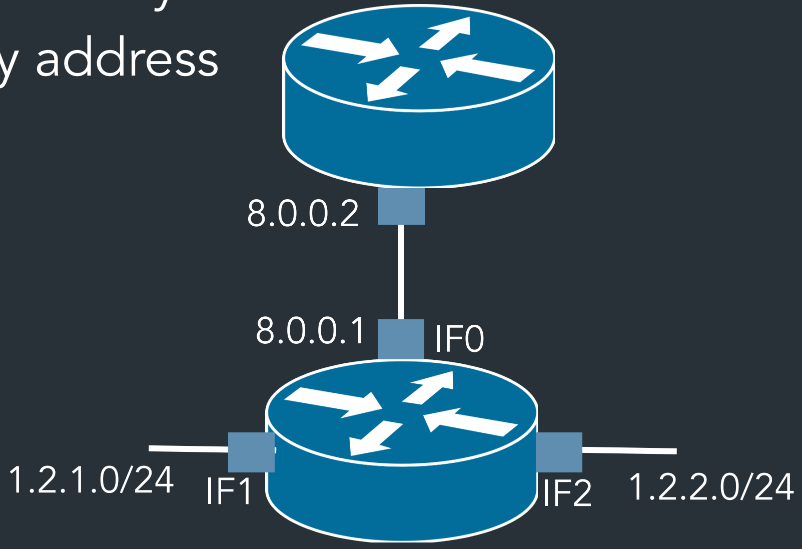
Prefix	Interface
1.2.1.0/24	IF1
1.2.2.0/24	IF2
<everything else>	IF0



What about the rest?

- Need IP of another router that knows about other networks
- This "next hop" IP must be reachable locally!
- "Default" => 0.0.0.0/0 refers to every address
  - Also called a *gateway*

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
Default	8.0.0.2



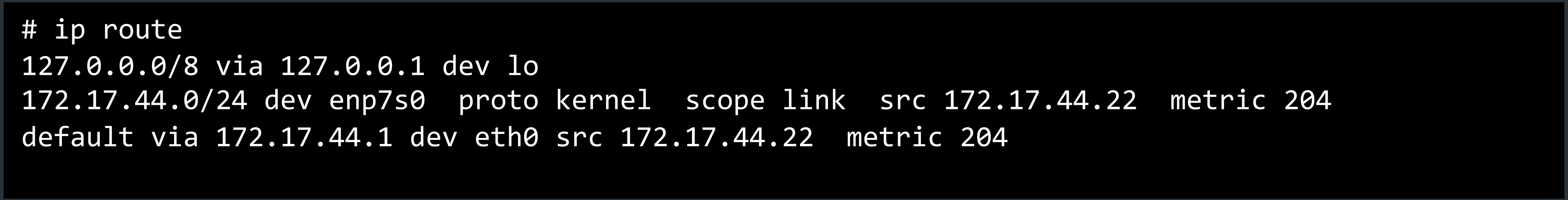
The forwarding table

- Exploits hierarchical structure of addresses: know how to reach *networks*, not individual hosts

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
Default	8.0.0.2

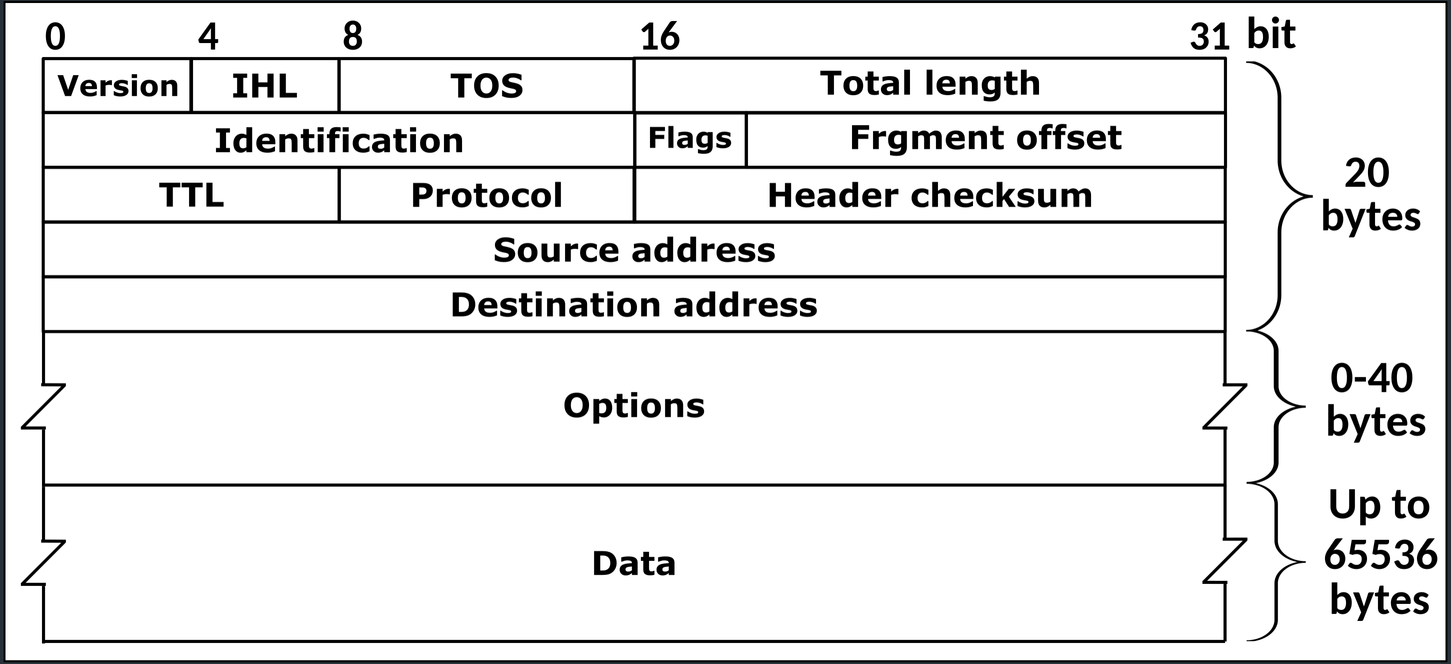
- Table is keyed is a network prefix, not a whole address
- Select best prefix with *longest prefix matching* (more on this later)

A forwarding table



```
# 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
```

The IPv4 Header



0 4 8 16 31 bit

Version | IHL | TOS | Total length

Identification | Flags | Frgment offset

TTL | Protocol | Header checksum

Source address

Destination address

Options

Data

20 bytes

0-40 bytes

Up to 65536 bytes

Defined by RFC 791
RFC (Request for Comment): defines network standard

Important fields

- Version: 4 for IPv4 packets, 6 for IPv6
- Destination address: used for forwarding
- TTL (time-to-live): decremented each hop
  - Can prevent forwarding loops (and do other stuff…)
- Checksum: computed over <u>header</u> (very weak!)
- Protocol identifier: describes what's in the packet
  - 6: TCP, 17: UDP, 1: ICMP, …
  - Defines the type of the payload

Less important fields

- Header length: in 32-bit units
  - >5 implies use of IP options
  - Almost all routers ignore IP options
- Fragmentation
  - Network can fragment a packet if next link requires a small frame
  - Most routers don’t fragment (or reassemble fragments)
- We won’t talk about…
  - Type of Service (TOS): basic traffic classification
  - Identifier: might have special meaning on some networks

Forwarding mechanics

When an IP packet arrives at a host/router:

- Is it valid? Verify checksum over *header*
- **Is it for me?** If dest IP == your address, send to OS
- If not, where should it go?
  - Consult forwarding table => find next hop
  - Decrement TTL
  - Send packet to next hop

Traceroute

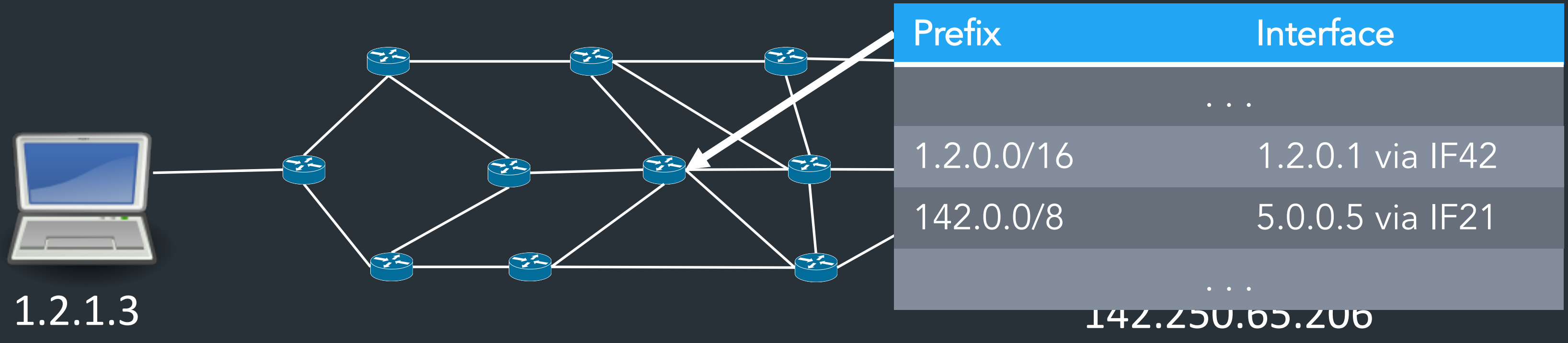
- When TTL reaches 0, router may send back an error
  - ICMP TTL exceeded
- If it does, we can identify a path used by a packet!

Coming up…

- ARP: Mapping IPs to MAC addresses
- How are addresses assigned?
- NAT: When it gets complicated
- Routing algorithms: how to build forwarding tables

Fill out the group preference survey for the IP project (announcement soon) by tomorrow (Feb 18) by 11:59PM

Putting it all together…



Prefix	Interface
. . .	
1.2.0.0/16	1.2.0.1 via IF42
142.0.0/8	5.0.0.5 via IF21
. . .	

- The more connected a router becomes, the more complex its forwarding table… and the more it may change!

- Routing algorithms: routers exchange path information to their forwarding tables (more on this later)

Goal: find the most specific (ie, longest) prefix matching the destination

Prefix	Interface
1.2.1.0/24	IF1
1.2.2.0/24	IF2
0.0.0.0/0	IF0

How to reach 1.2.2.100?

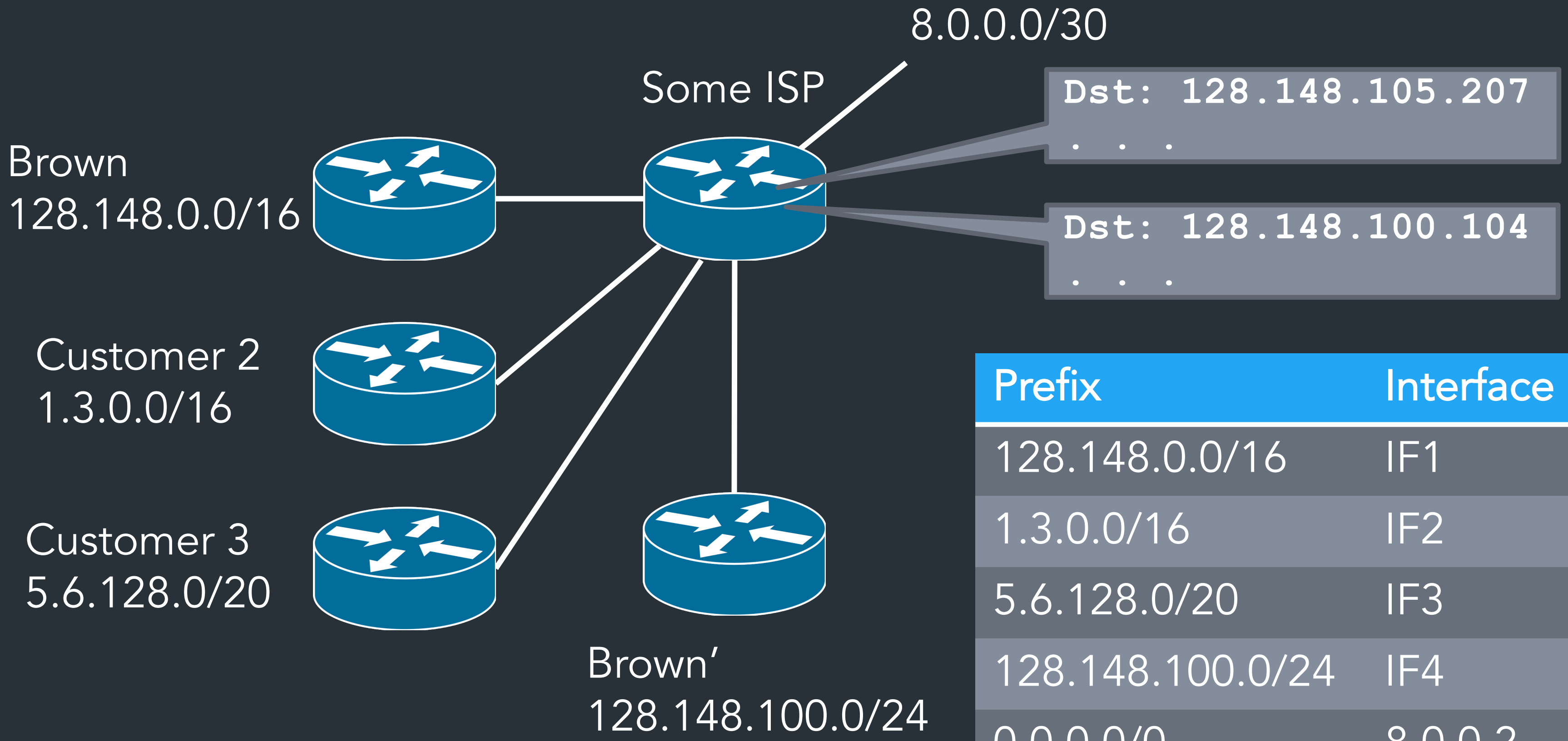
```
1.2.2.100       00000001.00000010.00000010.01100100
                                ?=
1.2.1.0/24      00000001.00000010.00000001.xxxxxxxx

1.2.2.0/24      00000001.00000010.00000010.xxxxxxxx

0.0.0.0/0       xxxxxxxx.xxxxxxxx.xxxxxxxx.xxxxxxxx
```

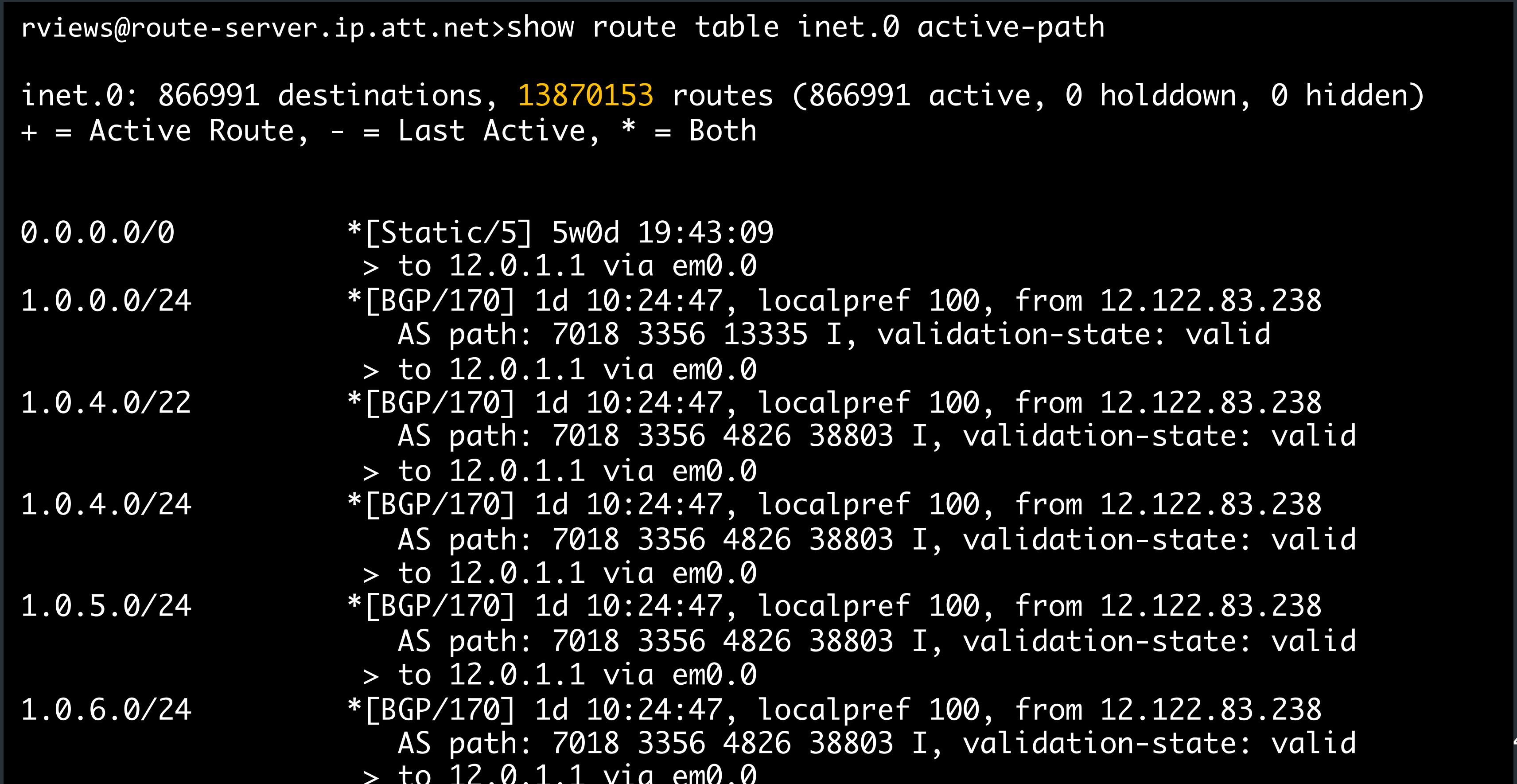
Output: IF2

Longest Prefix Matching (LPM): can represent entire IP space in (small) table!



Prefix	Interface
128.148.0.0/16	IF1
1.3.0.0/16	IF2
5.6.128.0/20	IF3
128.148.100.0/24	IF4
0.0.0.0/0	8.0.0.2

A large table

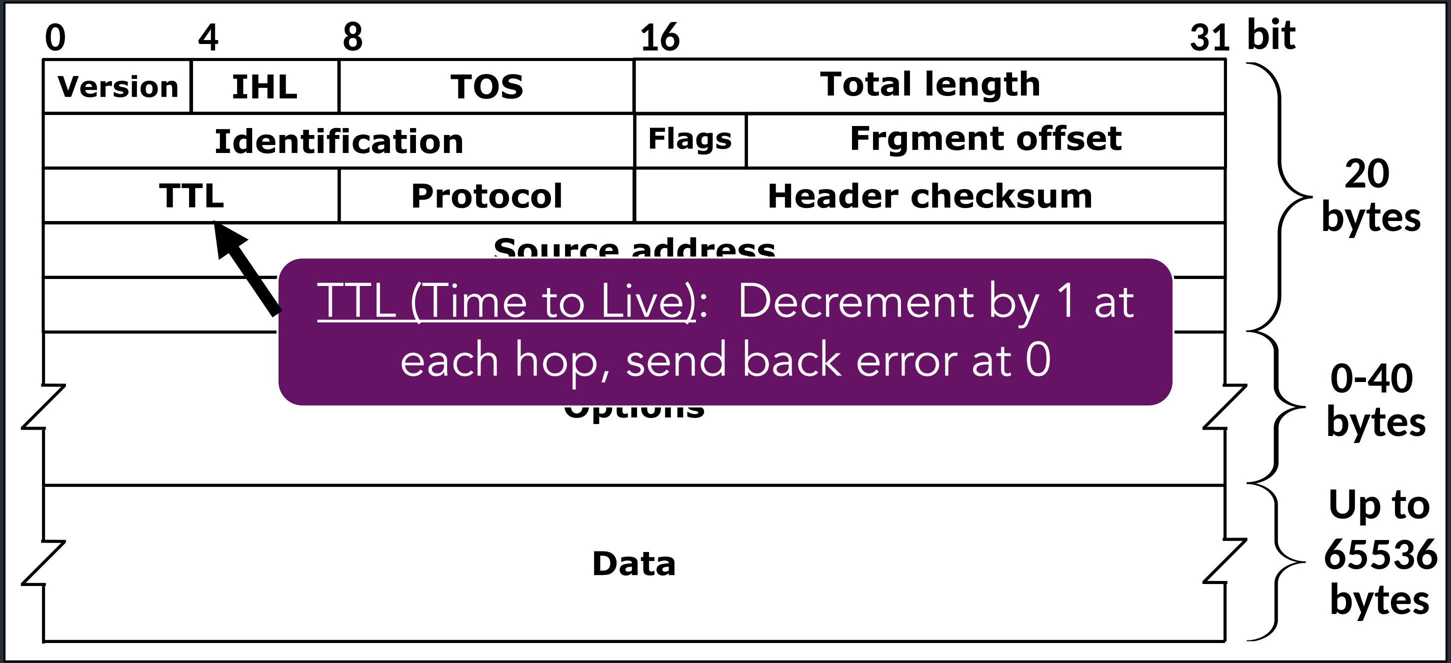


```
rviews@route-server.ip.att.net>show route table inet.0 active-path

inet.0: 866991 destinations, 13870153 routes (866991 active, 0 holddown, 0 hidden)
+ = Active Route, - = Last Active, * = Both


0.0.0.0/0          *[Static/5] 5w0d 19:43:09
                    > to 12.0.1.1 via em0.0
1.0.0.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 13335 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.4.0/22         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.4.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.5.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.6.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
```

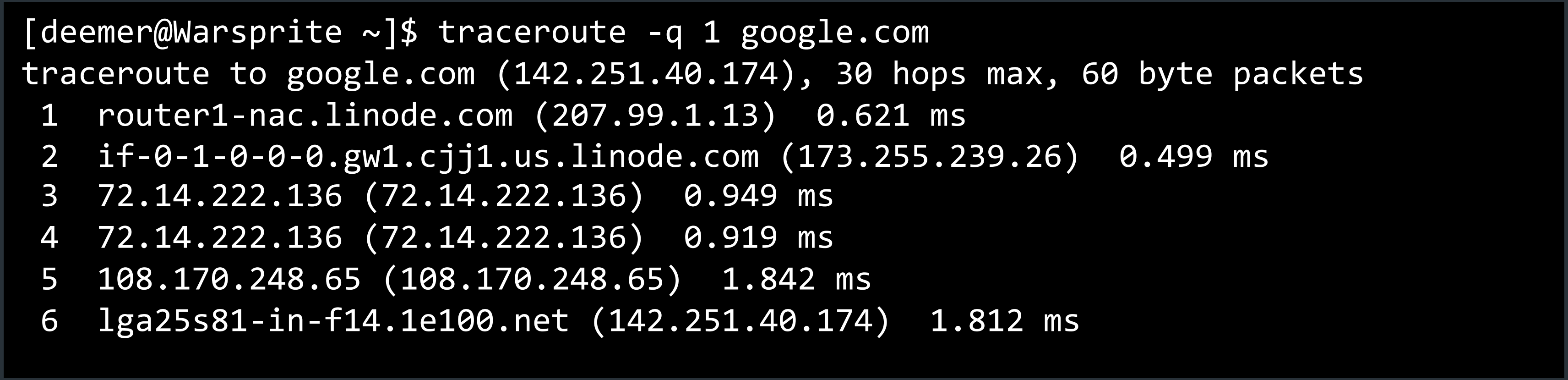
How to avoid loops?



TTL (Time to Live): Decrement by 1 at each hop, send back error at 0

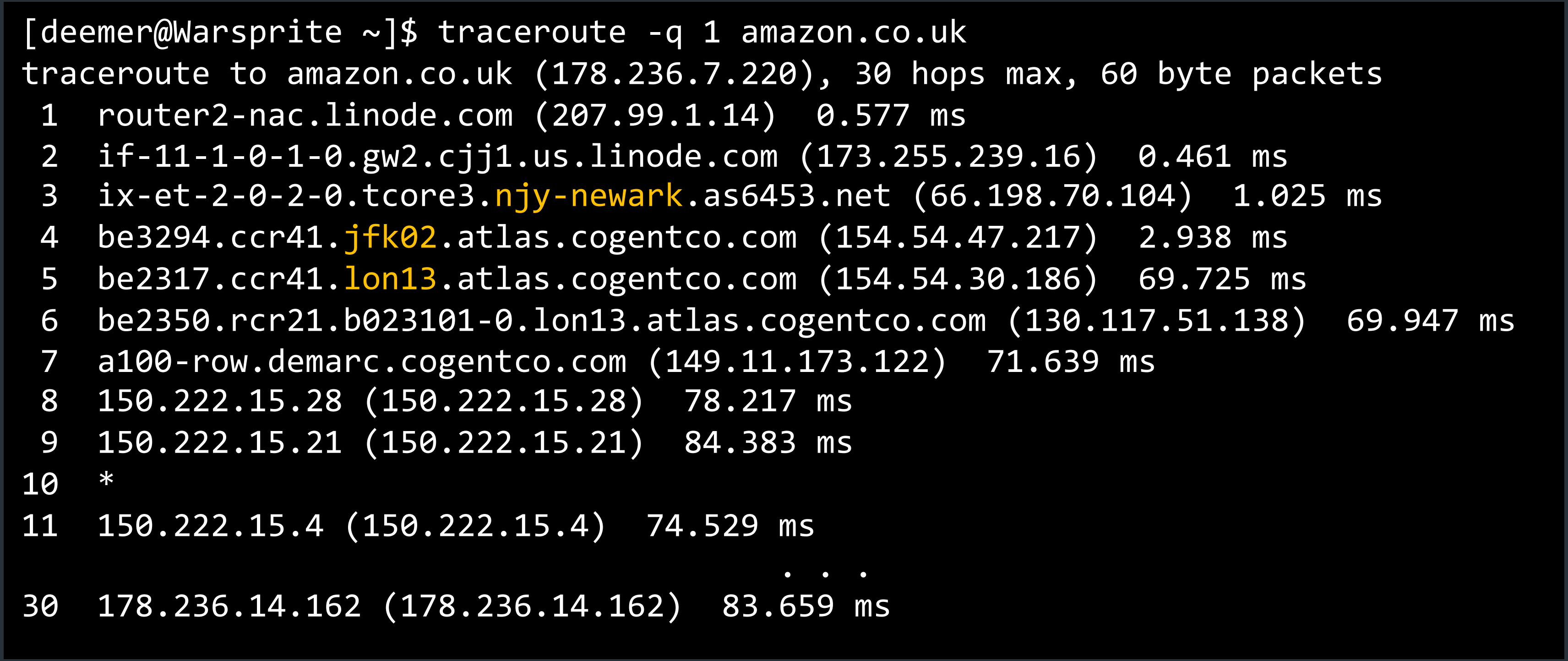
`traceroute`: tool to send packets with increasing TTLs
=> can learn about network paths!

Traceroute example



```
[deemer@Warsprite ~]$ traceroute -q 1 google.com
traceroute to google.com (142.251.40.174), 30 hops max, 60 byte packets
 1  router1-nac.linode.com (207.99.1.13)  0.621 ms
 2  if-0-1-0-0-0.gw1.cjj1.us.linode.com (173.255.239.26)  0.499 ms
 3  72.14.222.136 (72.14.222.136)  0.949 ms
 4  72.14.222.136 (72.14.222.136)  0.919 ms
 5  108.170.248.65 (108.170.248.65)  1.842 ms
 6  lga25s81-in-f14.1e100.net (142.251.40.174)  1.812 ms
```

Traceroute example



```
[deemer@Warsprite ~]$ traceroute -q 1 amazon.co.uk
traceroute to amazon.co.uk (178.236.7.220), 30 hops max, 60 byte packets
 1  router2-nac.linode.com (207.99.1.14)  0.577 ms
 2  if-11-1-0-1-0.gw2.cjj1.us.linode.com (173.255.239.16)  0.461 ms
 3  ix-et-2-0-2-0.tcore3.njy-newark.as6453.net (66.198.70.104)  1.025 ms
 4  be3294.ccr41.jfk02.atlas.cogentco.com (154.54.47.217)  2.938 ms
 5  be2317.ccr41.lon13.atlas.cogentco.com (154.54.30.186)  69.725 ms
 6  be2350.rcr21.b023101-0.lon13.atlas.cogentco.com (130.117.51.138)  69.947 ms
 7  a100-row.demarc.cogentco.com (149.11.173.122)  71.639 ms
 8  150.222.15.28 (150.222.15.28)  78.217 ms
 9  150.222.15.21 (150.222.15.21)  84.383 ms
10  *
11  150.222.15.4 (150.222.15.4)  74.529 ms
                                        . . .
30  178.236.14.162 (178.236.14.162)  83.659 ms
```