CSCI1680
Network Layer: IP & Forwarding II

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

Administivia

- IP Project: out later today
  - Partner form: due TONIGHT by 11:59pm
  - You will get an email confirming your team tomorrow morning
- IP gearup: tonight 5-7pm, CIT368
- IP Milestone: meet with me/a TA on/before next Friday (October 4) to discuss your design
  - (No *working* code yet, just some serious plans/sketches)
- HW1 (short): Due next Thursday

Today

Continuing network layer

- IP forwarding mechanics
- About the IP project

Where we left off

- All hosts identified by an IP address

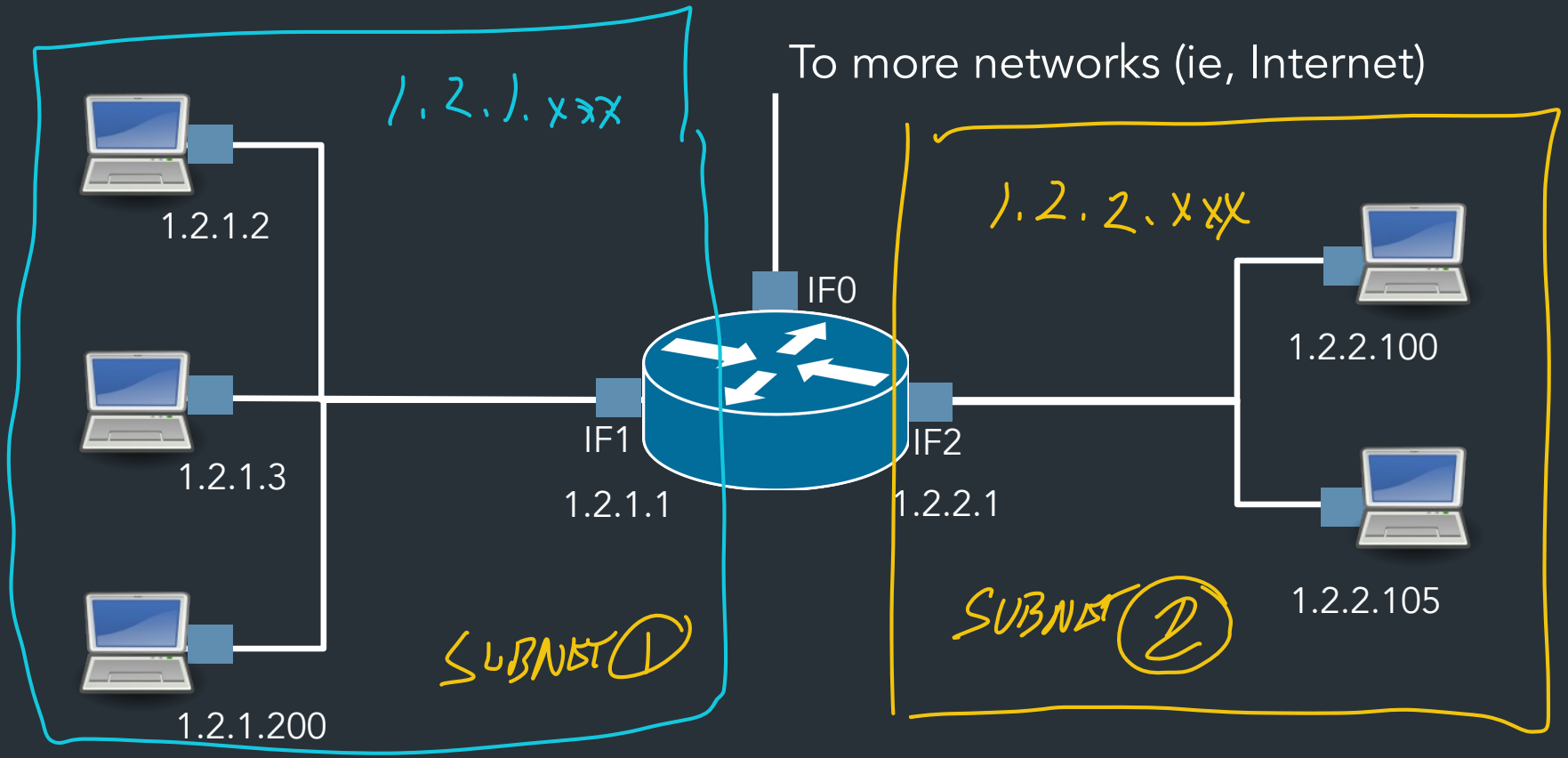
1.2.3.4

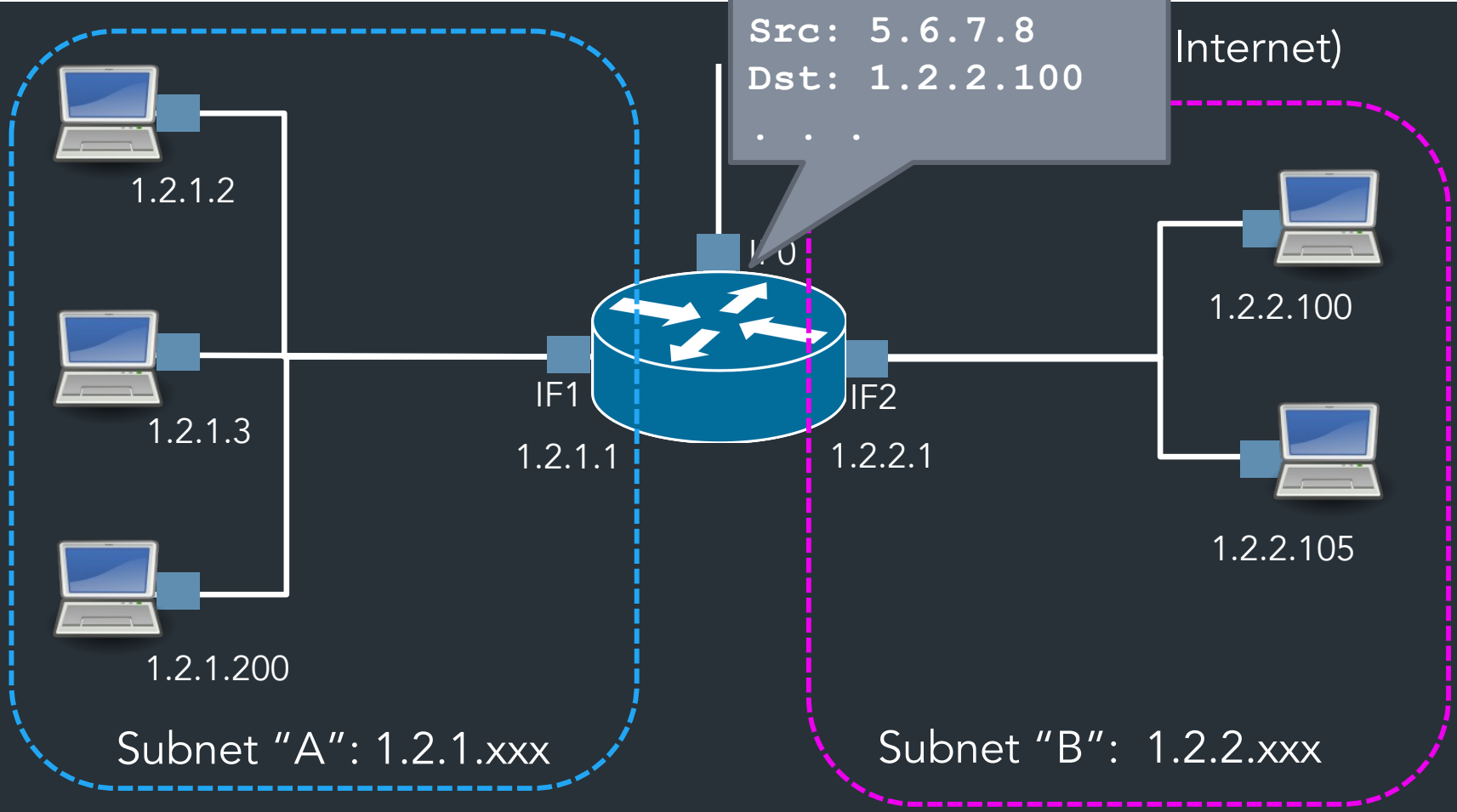
- IP address: a number with *structure*
  - *Network part* Identifies "Brown University"
  - *Host part* Identifies one host at...

- *Routers look at network part to forward packets between networks*

Warmup

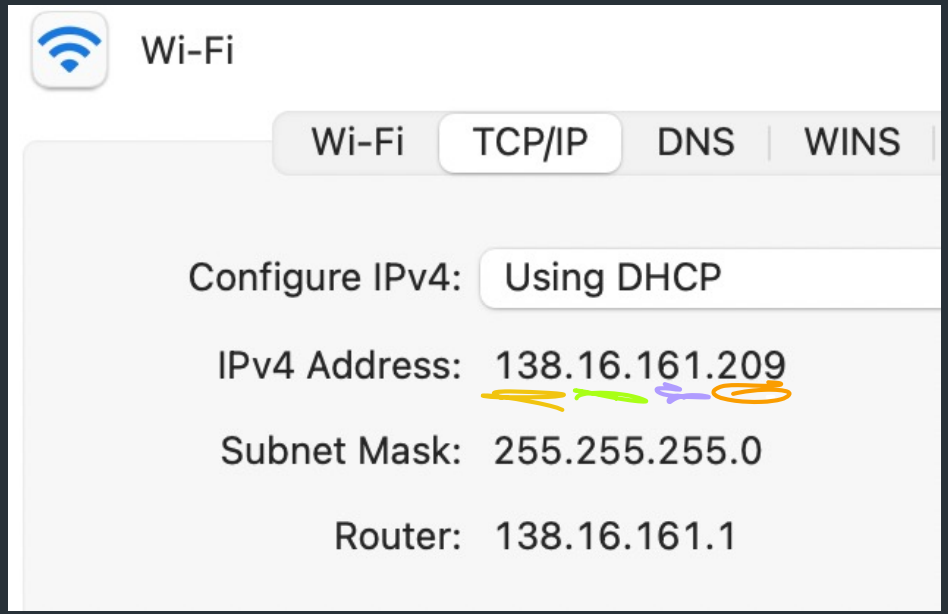
What are the two different networks? How would you describe them?




Src: 5.6.7.8
Dst: 1.2.2.100
. . .
Internet)
1.2.1.2
1.2.1.3
1.2.1.200
IF1
1.2.1.1
IF0
IF2
1.2.2.1
1.2.2.100
1.2.2.105
Subnet "A": 1.2.1.xxx
Subnet "B": 1.2.2.xxx

How do we specify an IP network (range of addresses)?

What does it mean for an address to be in a network?

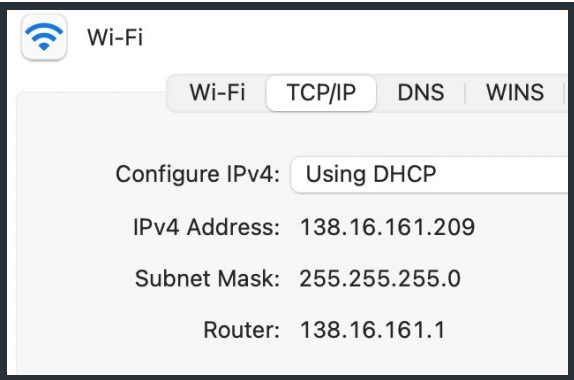


IN BINARY:

10001010 00010000 10100001 11010001

138 16 161 209

What network are we on?



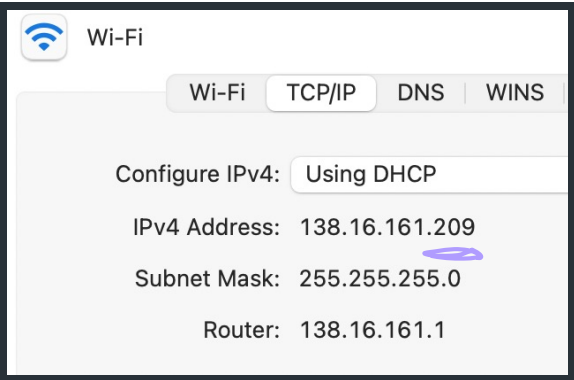
138.16.161.209

Addr:
138.16.161.209 **10001010 00010000 10100001 11010001**

Mask:
255.255.255.0 **11111111 11111111 11111111 00000000**

=> Bitmask used to "filter out" which part is for hosts on the same network

Identifying host and network



NETWORK

138.16.161.209 ← HOST

Addr:
138.16.161.209 **10001010 00010000 10100001 11010001**

Mask:
255.255.255.0 **&** **11111111 11111111 11111111 00000000**

"PREFIX" **10001010 00010000 10100001** **00000000**

24 bits

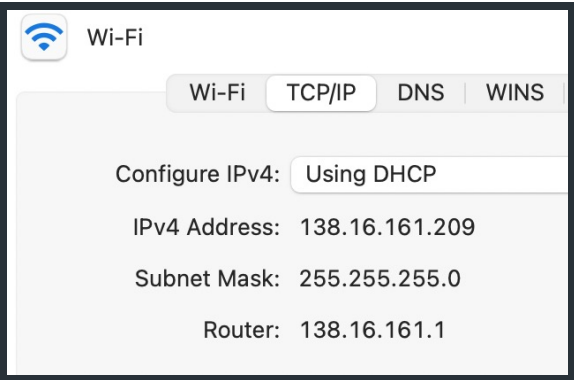
138.16.161.0

138.16.161.0/24

2^8 = 256 HOSTS

HOSTS ON THIS NET

All systems with an IP address have a configuration like this



138.16.161.209

Addr:
138.16.161.209 `10001010 00010000 10100001 11010001`

Mask:
255.255.255.0 `&` `11111111 11111111 11111111 00000000`

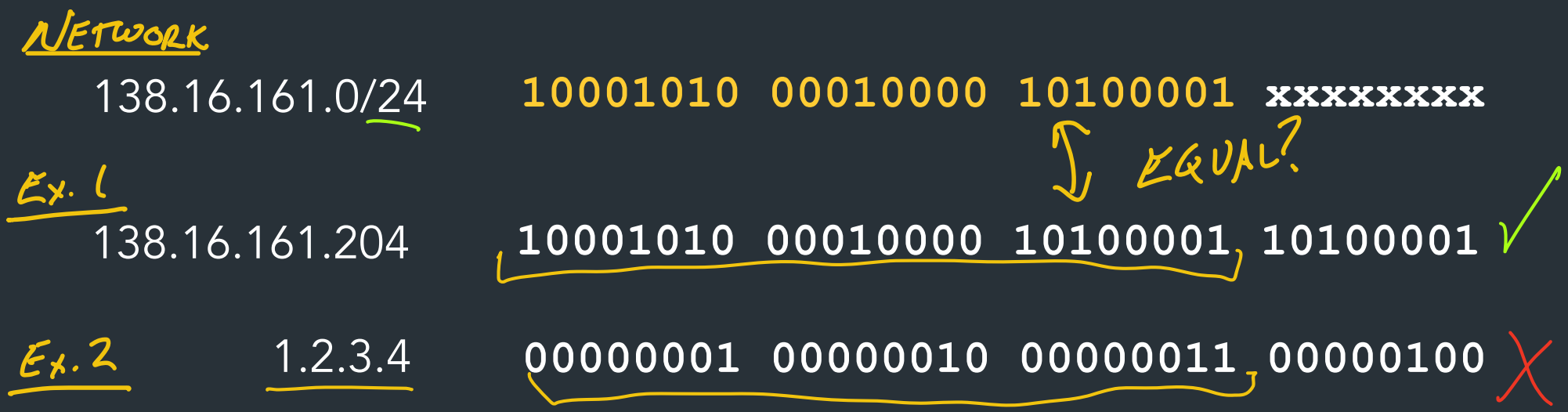
`10001010 00010000 10100001 00000000`

24 bits 138.16.161.0

Think: This host is on the network 138.16.161.0/24
=> "Prefix notation", or "CIDR notation"

How to decide if an address is part of a network?

=> Compare the network part of the addresses



⇒ The mask can be any size 0-32
Not just checking the first three digits!

How do we specify an IP network?

=> Range of addresses for a specific IP "prefix"

eg. 138.16.161.0/24

What does it mean for an address to be in a network?

=> Address must be within the range (based on the mask)

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

THIS CHART SHOWS THE IP ADDRESS SPACE ON A PLANE USING A FRACTAL MAPPING WHICH PRESERVES GROUPING -- ANY CONSECUTIVE STRING OF IPs WILL TRANSLATE TO A SINGLE COMPACT, CONTIGUOUS REGION ON THE MAP. EACH OF THE 256 NUMBERED BLOCKS REPRESENTS ONE /8 SUBNET (CONTAINING ALL IPs THAT START WITH THAT NUMBER). THE UPPER LEFT SECTION SHOWS THE BLOCKS SOLD DIRECTLY TO CORPORATIONS AND GOVERNMENTS IN THE 1990's BEFORE THE RIRs TOOK OVER ALLOCATION.

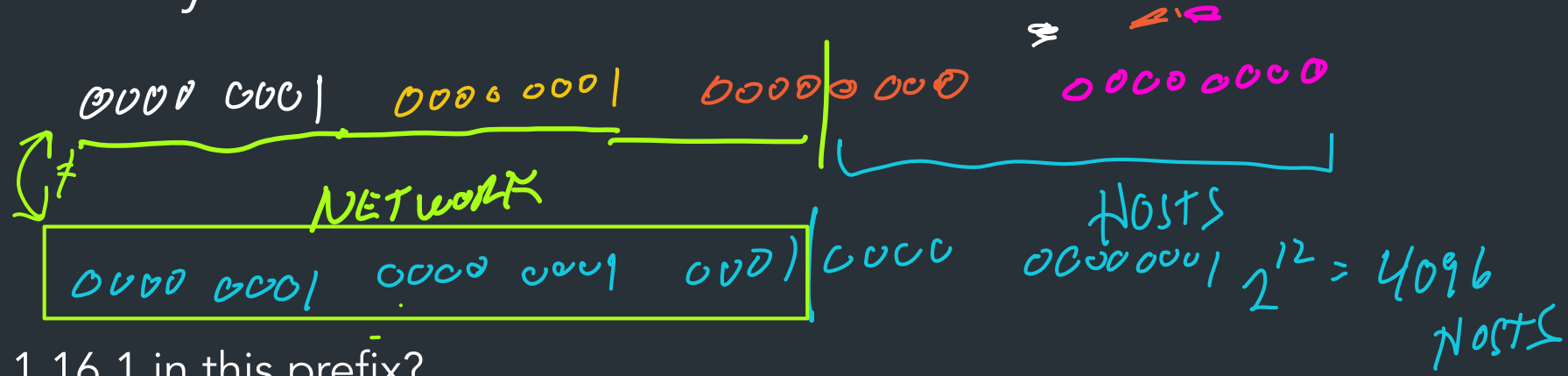
0 1 14 15 16 19 →
3 2 13 12 17 18
4 7 8 11
5 6 9 10

= UNALLOCATED BLOCK

https://xkcd.com/195/

Example

How many addresses are in the network 1.1.0.0/20?



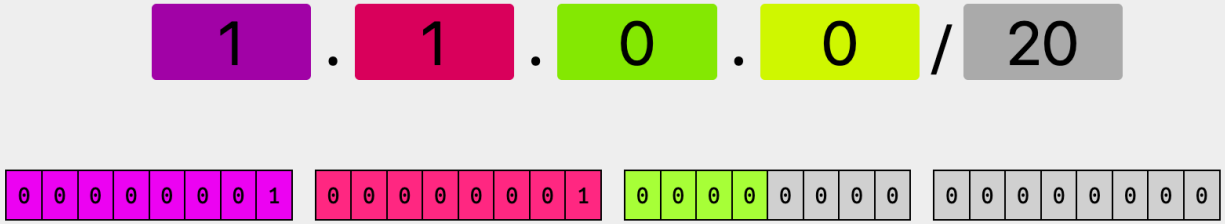
Is 1.1.16.1 in this prefix?

=> NO.

CIDR.xyz

AN INTERACTIVE IP ADDRESS AND CIDR RANGE VISUALIZER

CIDR is a notation for describing blocks of IP addresses and is used heavily in various networking configurations. IP addresses contain 4 octets, each consisting of 8 bits giving values between 0 and 255. The decimal value that comes after the slash is the number of bits consisting of the routing prefix. This in turn can be translated into a netmask, and also designates how many available addresses are in the block.



255.255.240.0
NETMASK

1.1.0.0
CIDR BASE IP

1.1.15.255
BROADCAST IP

4,096
COUNT

1.1.0.1
FIRST USABLE IP

1.1.15.254
LAST USABLE IP

* For routing mask values <= 30, first and last IPs are base and broadcast addresses and are unusable.

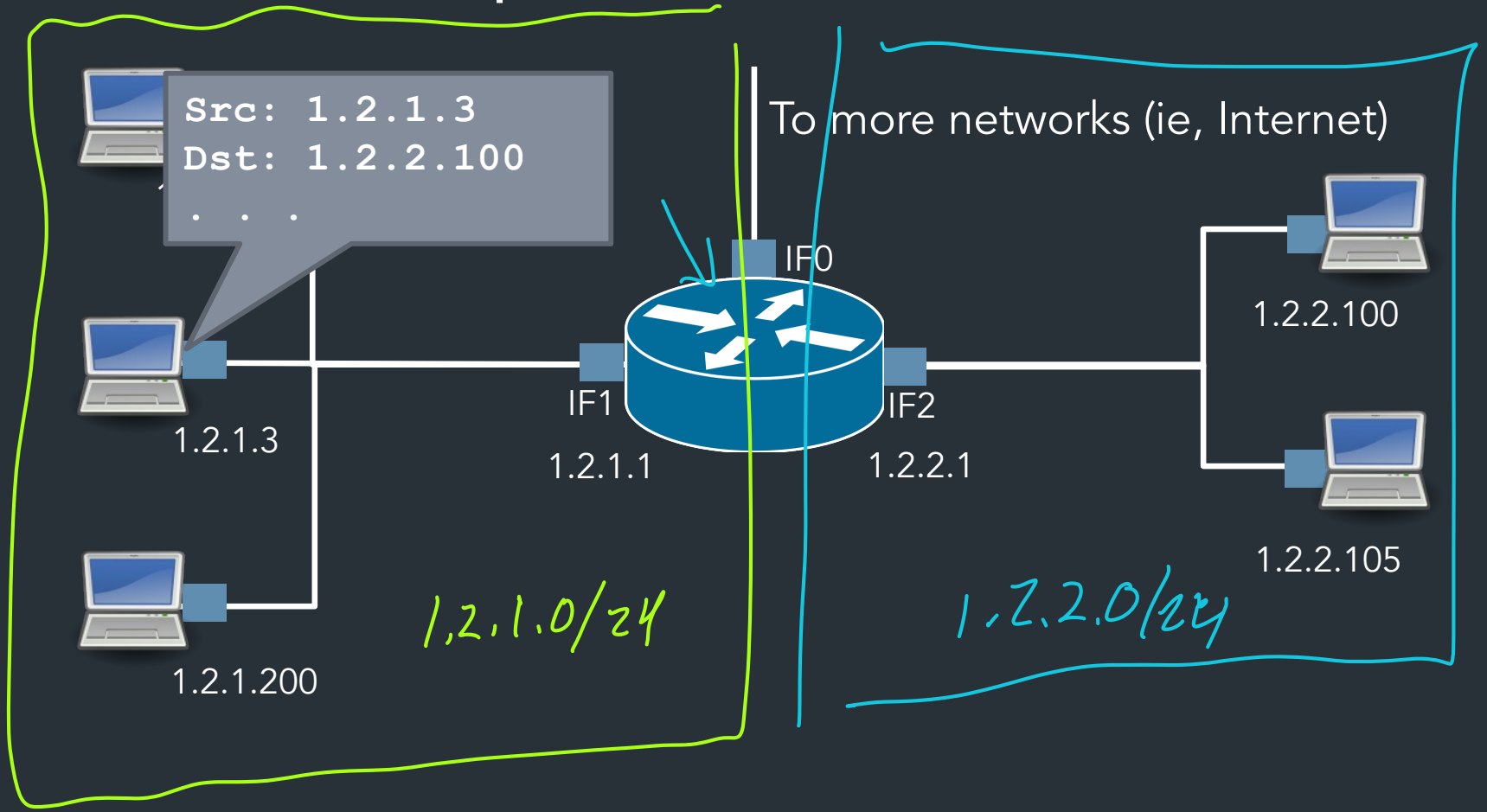
https://cidr.xyz

Created by Yuval Adam. Source available on Github.

Tools exist, use them!

How do we move
packets between networks?

Forwarding IP packets



IP forwarding

Decide where to send packets based on forwarding table

Prefix	Interface/Next hop
1.2.1.0/24	IF0
1.2.2.0/24	IF1
*	1.2.1.1

LOCAL NETS

"NEXT HOP"

Key Type: An IP prefix (1.2.1.0/24)

Value type: Multiple forms

- Interface (IF0): "This is my neighbor (on local net), link-layer can figure it out"

⇒ "LOCAL DELIVERY"

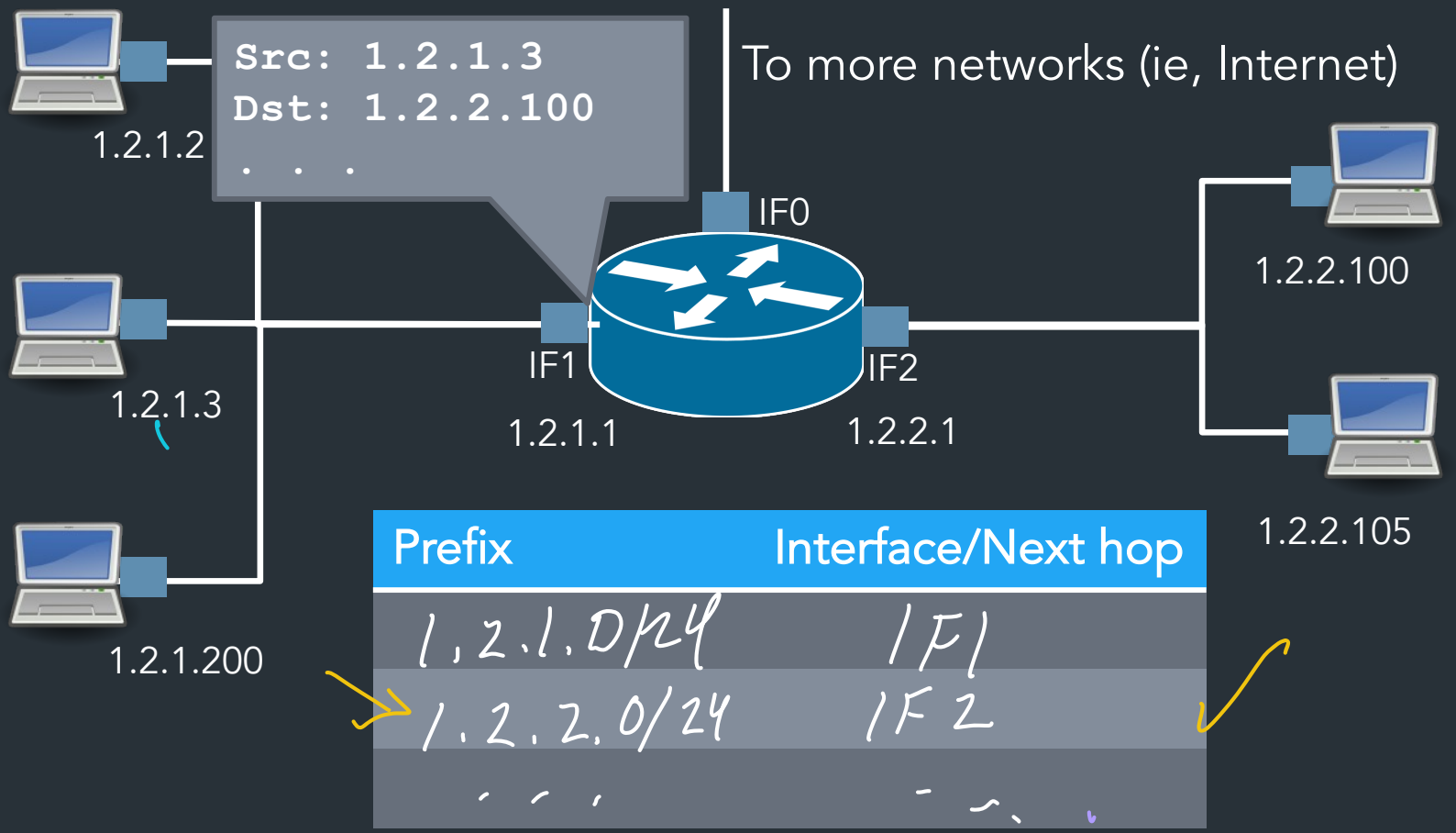
- Next hop IP (eg. 1.1.1.1): send packet to this IP instead

IP forwarding

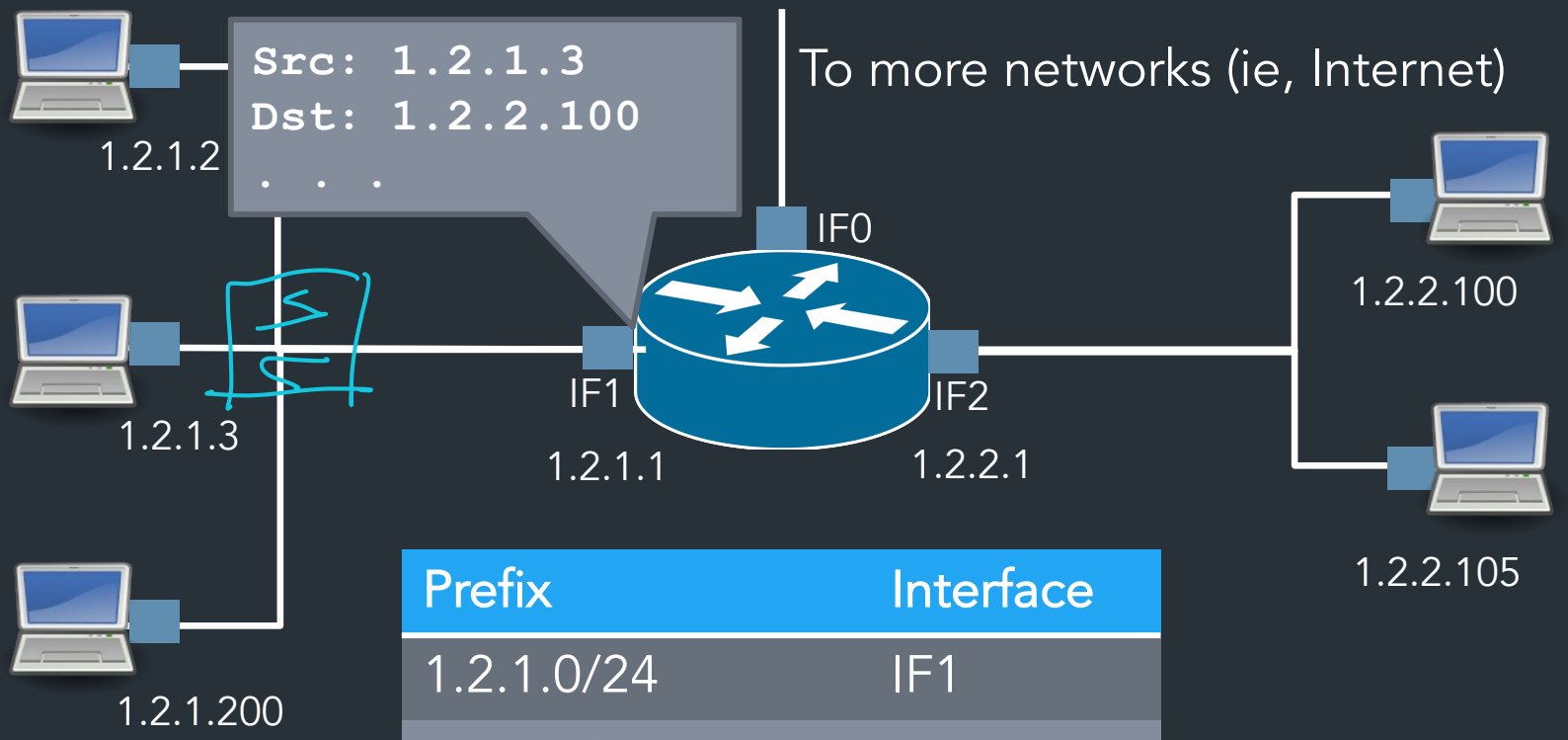
Decide where to send packets based on forwarding table

Key Type: An IP prefix (1.2.1.0/24)
Value type: Multiple forms
- Interface (IF0): "This is my neighbor (on local net), link-layer can figure it out"
  => "Local delivery"
- Next hop IP (eg. 1.1.1.1): send packet to this IP instead
  => Need to search for next hop in table!

Forwarding IP packets



Forwarding IP packets



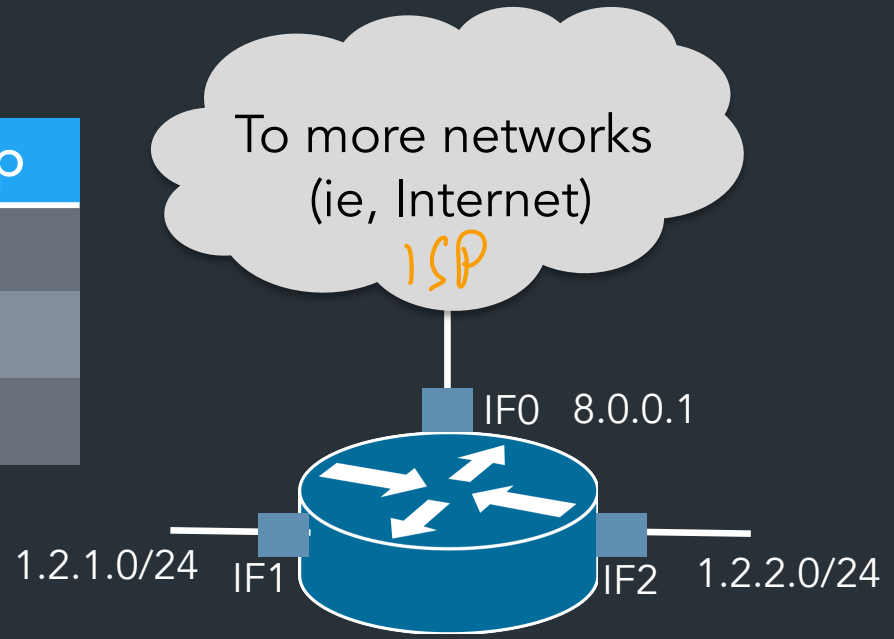
Prefix	Interface
1.2.1.0/24	IF1
1.2.2.0/24	IF2
…	…

What about the rest?

How to reach networks that aren't directly connected?

⇒ DEFAULT ROUTE

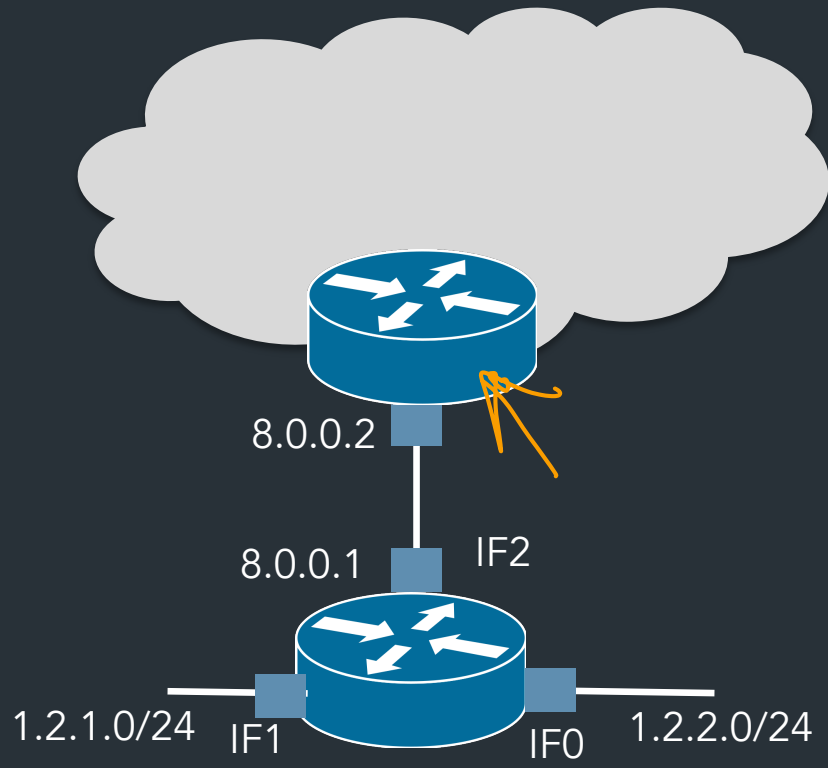
Prefix	Interface/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
<everything else>	



"Default route": where to send to reach anything not in the table

Gateway: device at the "edge" of a network (eg. Brown <-> Internet)

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
0.0.0.0/0	8.0.0.2



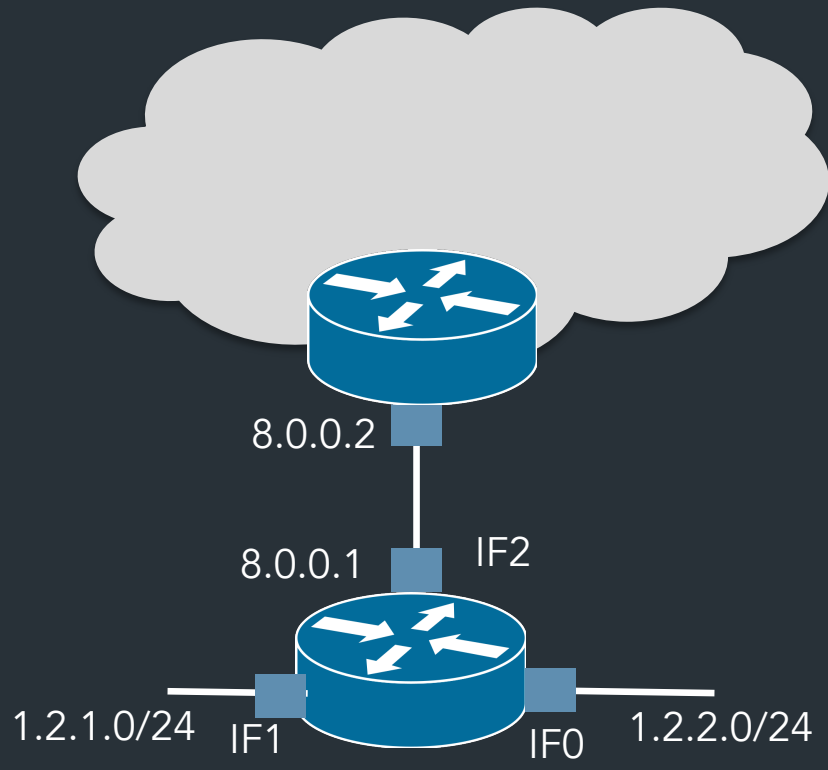
IF2

"Default route": where to send to reach anything not in the table

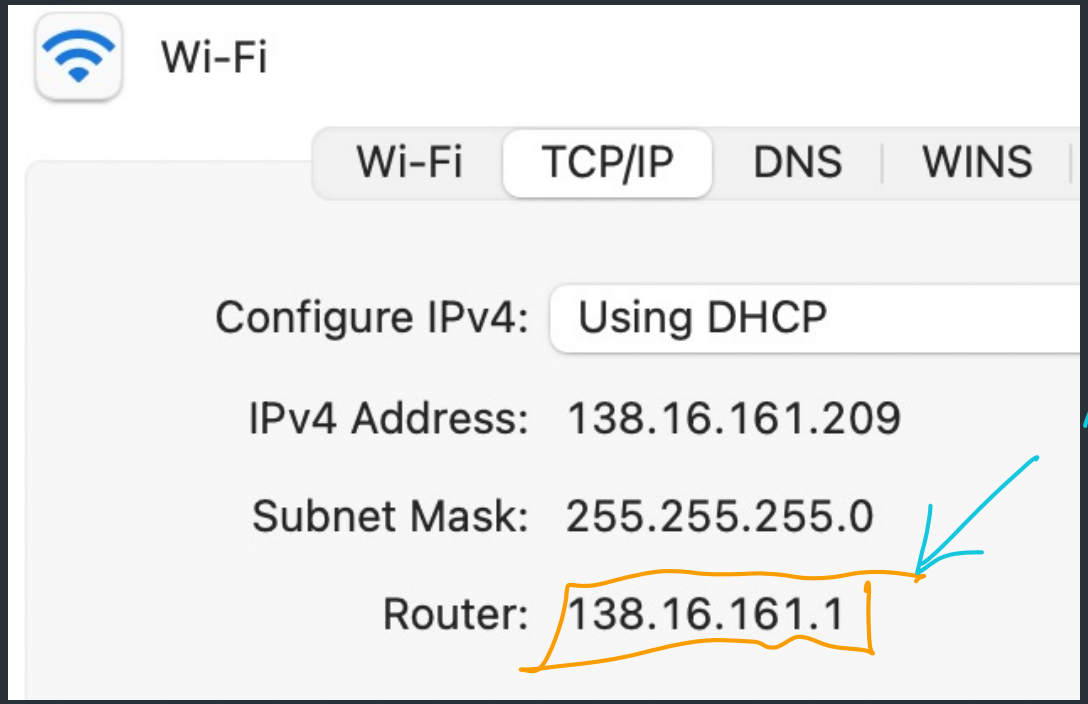
=> Use "Next hop IP" in table

Gateway: device at the "edge" of a network (eg. Brown <-> Internet)

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
0.0.0.0/0	8.0.0.2



⇒ 0.0.0.0 matches on everything! Problem?
Can have multiple matches in table => use the most specific (longest) prefix (more on this later)


Wi-Fi
Wi-Fi
TCP/IP
DNS
WINS
Configure IPv4:
Using DHCP
IPv4 Address:
138.16.161.209
Subnet Mask:
255.255.255.0
Router:
138.16.161.1
DEFAULT GATEWAY/ ROUTER.

Does it scale?

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
0.0.0.0/0	8.0.0.2

Does it scale?

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
0.0.0.0/0	8.0.0.2

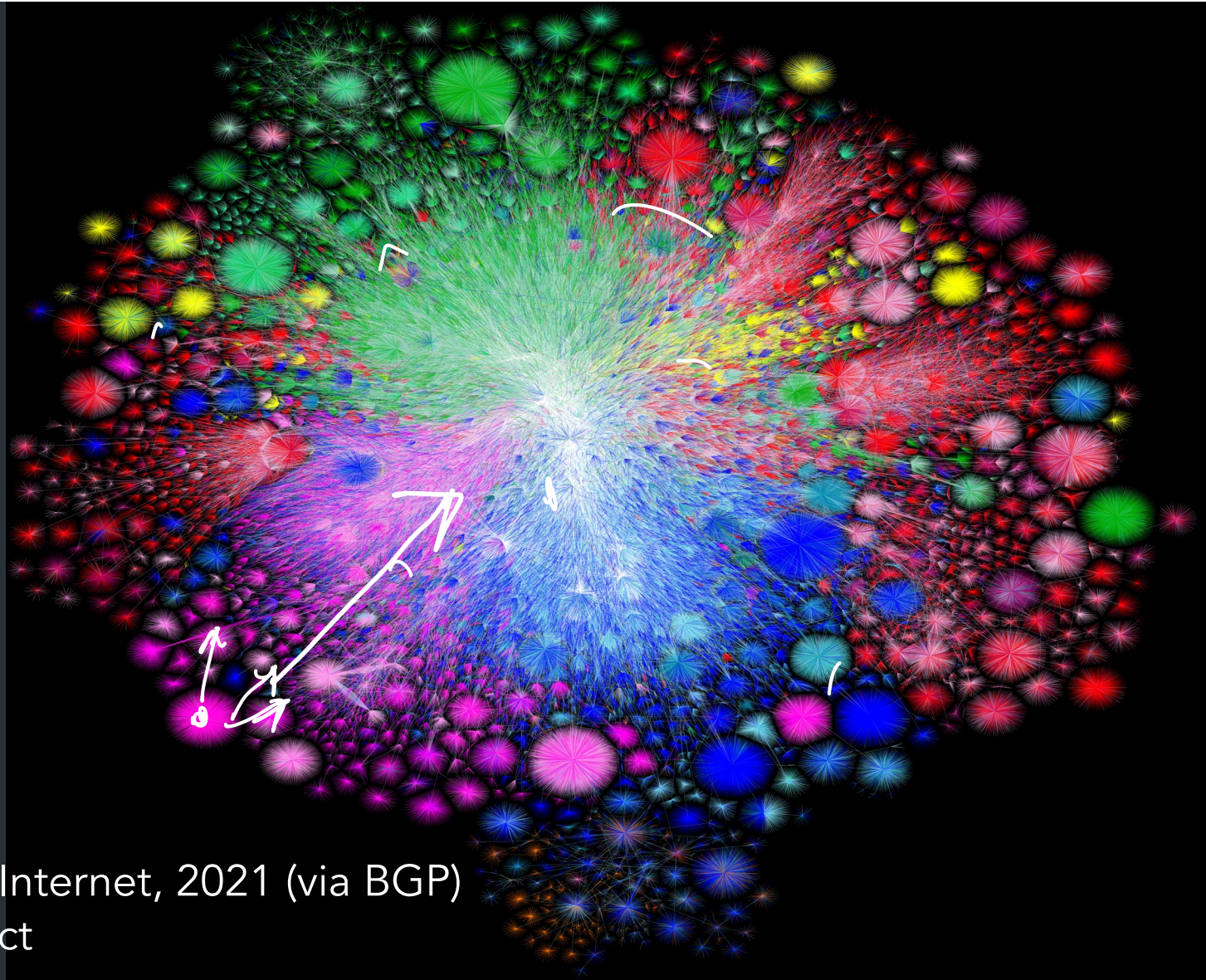
Yes! At least enough to make the Internet as we know it….

=> Forward packets based on IP prefixes

=> Don't need to keep track of every single host

=> Routers at the "edges" of the network don't need to know about every route

=> Larger, highly-connected routers ("core routers") do need very large tables, specialized hardware, optimization tricks…



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

A forwarding table (my laptop)

```
deemer@ceres ~ % ip route
default via 10.3.128.1 dev wlp2s0
10.3.128.0/18 dev wlp2s0 proto dhcp scope link src 10.3.135.44 metric 3003
172.18.0.0/16 dev docker0 proto kernel scope link src 172.18.0.1
192.168.1.0/24 dev enp0s31f6 proto kernel scope link src 192.168.1.1
```

A routing table

```
R6#sh ip ro
Gateway of last resort is 108.34.215.1 to network 0.0.0.0

S*    0.0.0.0/0 [1/0] via 108.34.215.1
      10.0.0.0/8 is variably subnetted, 7 subnets, 3 masks
C        10.1.0.0/24 is directly connected, wlan-ap0
L        10.1.0.2/32 is directly connected, wlan-ap0
O IA     10.1.44.1/32 [110/1001] via 10.20.30.33, 3w4d, Tunnel0
C        10.1.48.0/24 is directly connected, Loopback0
L        10.1.48.1/32 is directly connected, Loopback0
C        10.20.30.32/31 is directly connected, Tunnel0
L        10.20.30.32/32 is directly connected, Tunnel0
      108.0.0.0/8 is variably subnetted, 2 subnets, 2 masks
C        108.34.215.0/24 is directly connected, GigabitEthernet0/0
L        108.34.215.208/32 is directly connected, GigabitEthernet0/0
      172.16.0.0/16 is variably subnetted, 2 subnets, 2 masks
C        172.16.98.0/24 is directly connected, Vlan98
L        172.16.98.1/32 is directly connected, Vlan98
      172.17.0.0/16 is variably subnetted, 6 subnets, 3 masks
O IA     172.17.44.0/24 [110/1001] via 10.20.30.33, 3w4d, Tunnel0
C        172.17.48.0/24 is directly connected, Vlan20
L        172.17.48.1/32 is directly connected, Vlan20
C        172.17.49.0/25 is directly connected, Vlan50
```

A routing table

```
R6#sh ip ro
Codes: L - local, C - connected, S - static, R - RIP, M - mobile, B - BGP
       D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
       N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
       E1 - OSPF external type 1, E2 - OSPF external type 2
       i - IS-IS, su - IS-IS summary, L1 - IS-IS level-1, L2 - IS-IS level-2
       ia - IS-IS inter area, * - candidate default, U - per-user static route
       o - ODR, P - periodic downloaded static route, H - NHRP, l - LISP
       + - replicated route, % - next hop override


Gateway of last resort is 108.34.215.1 to network 0.0.0.0


S*    0.0.0.0/0 [1/0] via 108.34.215.1
      10.0.0.0/8 is variably subnetted, 7 subnets, 3 masks
C        10.1.0.0/24 is directly connected, wlan-ap0
L        10.1.0.2/32 is directly connected, wlan-ap0
O IA     10.1.44.1/32 [110/1001] via 10.20.30.33, 3w4d, Tunnel0
C        10.1.48.0/24 is directly connected, Loopback0
L        10.1.48.1/32 is directly connected, Loopback0
C        10.20.30.32/31 is directly connected, Tunnel0
L        10.20.30.32/32 is directly connected, Tunnel0
```

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
```

A forwarding table (my laptop)

SOME ROUTER AT BROWN.

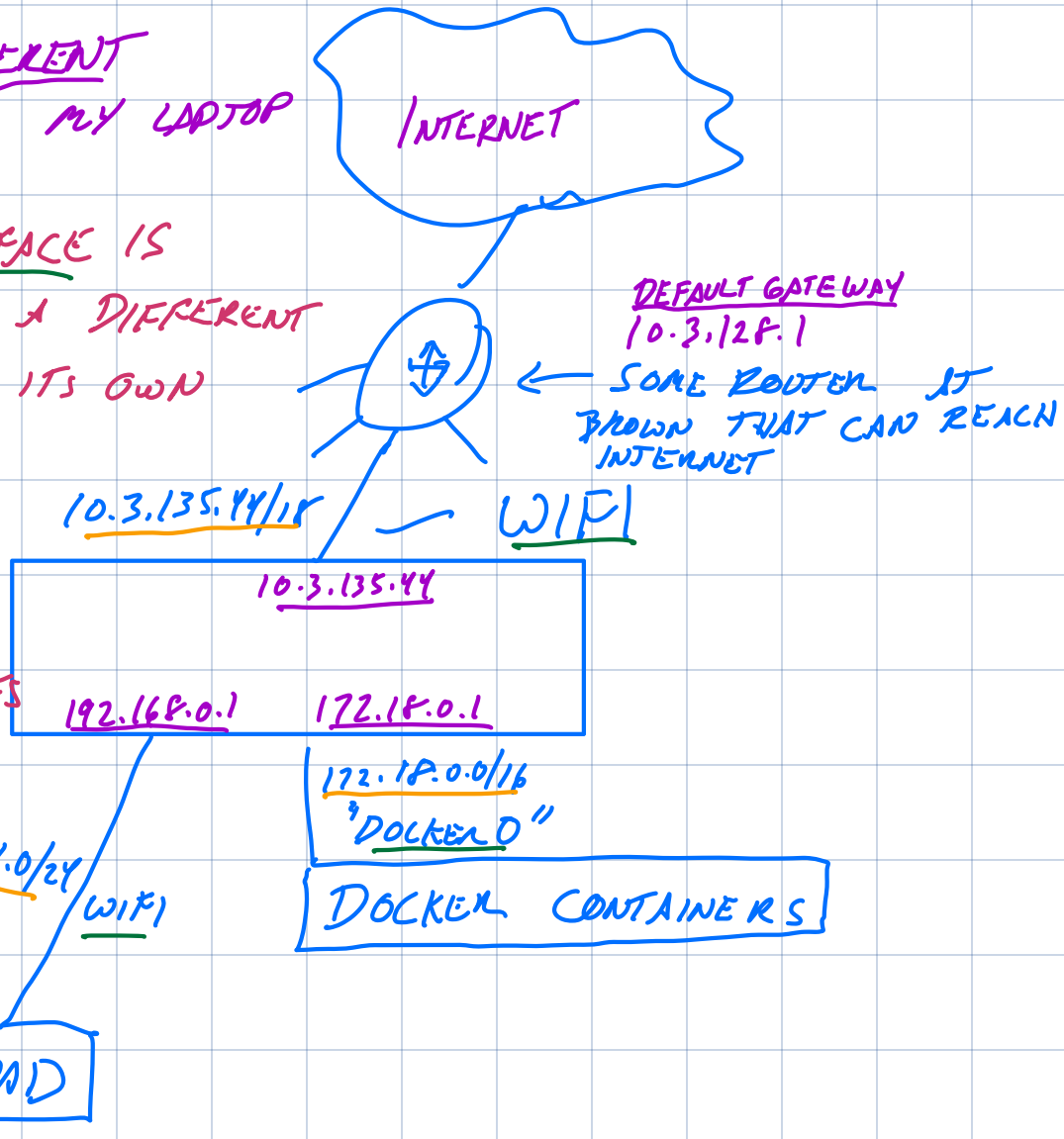
```
deemer@ceres ~ % ip route
default via 10.3.128.1 dev wlp2s0
10.3.128.0/18 dev wlp2s0 proto dhcp scope link src 10.3.135.44 metric
3003
172.18.0.0/16 dev docker0 proto kernel scope link src 172.18.0.1
192.168.1.0/24 dev enp0s31f6 proto kernel scope link src 192.168.1.1
```

WIFI

ETHERNET

LET'S BREAK THIS DOWN FURTHER... →

EXAMPLE: DIFFERENT NETWORKS ON MY LAPTOP



- EACH INTERFACE IS CONNECTED TO A DIFFERENT NETWORK + HAS ITS OWN IP ADDRESS
- LAPTOP DECIDES HOW TO FORWARD PACKETS TO INTERFACES

WHAT WOULD THE TABLE LOOK LIKE?

PREFIX	INTERFACE/NEXT
10.3.128.0/16	WIFI
192.168.0.0/24	ETHERNET
172.18.0.0/16	DOCKER
*	10.3.128.1

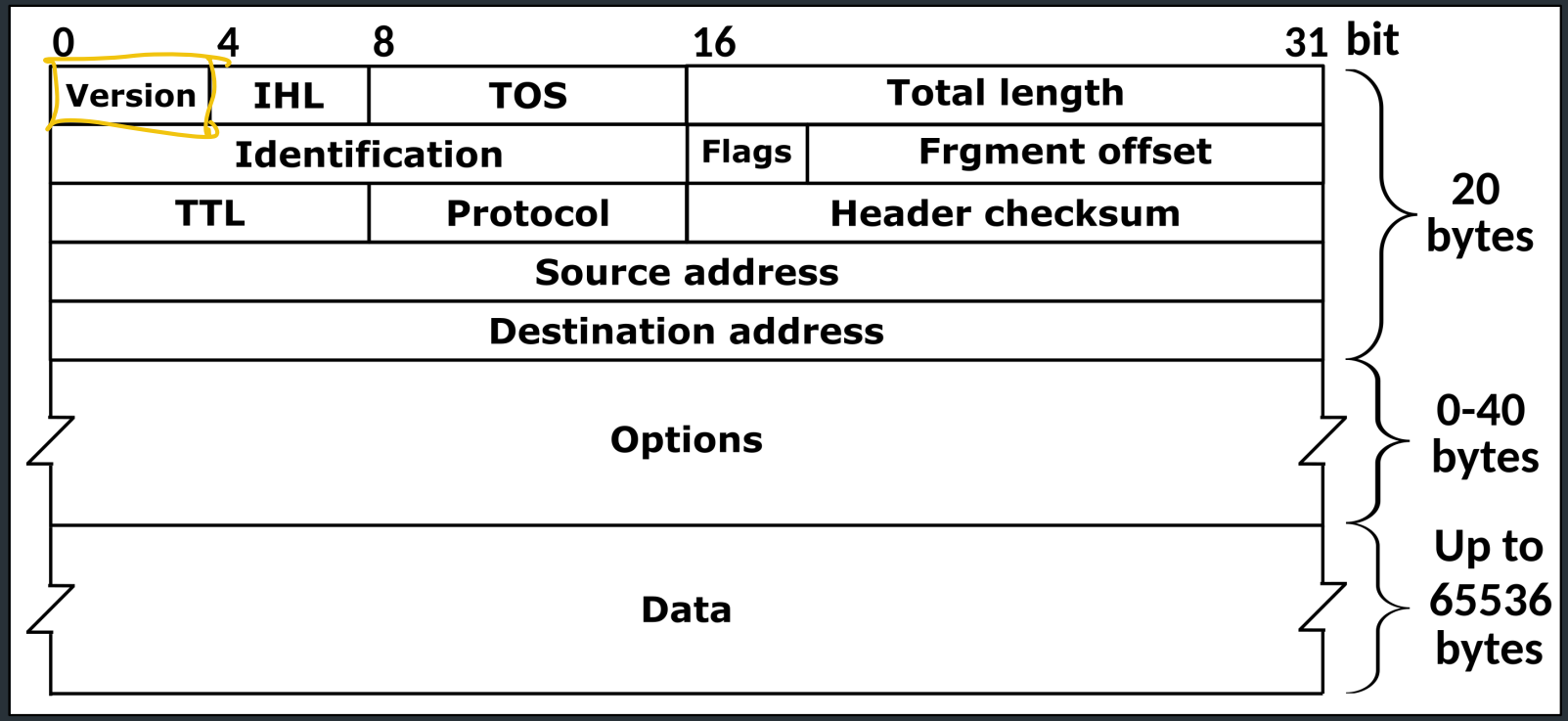
EXAMPLES

IP: 192.168.0.2 ⇒ ETHERNET

IP: 8.8.8.8 → DEFAULT, NEED TO LOOK UP 10.3.128.1 ⇒ WIFI.

How does forwarding actually work?

The IPv4 Header



Defined by RFC 791

RFC (Request for Comment): defines network standard

Most Important fields

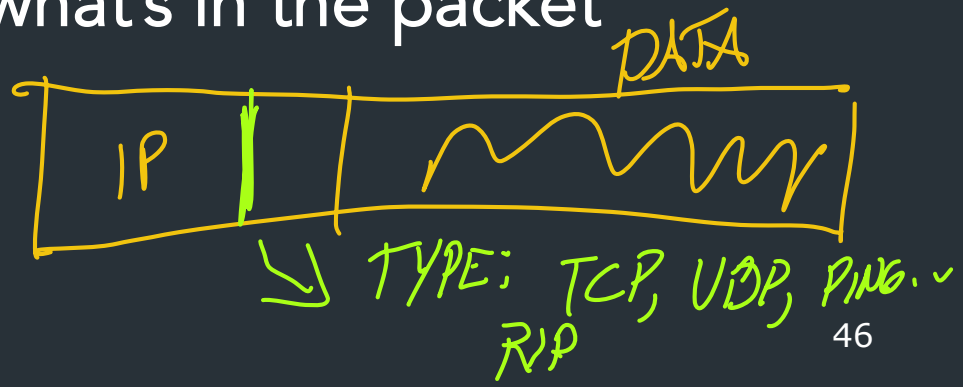
- Version: 4 for IPv4 packets, 6 for IPv6
- Source address: where the packet came from 1.2.3.4
- Destination address: where the packet is going 5.6.7.8

ROUTER MUST LOOK AT THIS TO FORWARD.

(continued…)

More important fields

- TTL (time-to-live): decremented each hop
  - Can prevent forwarding loops (and do other stuff…)
- Checksum: computed over header (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

NO ONE USES THIS.

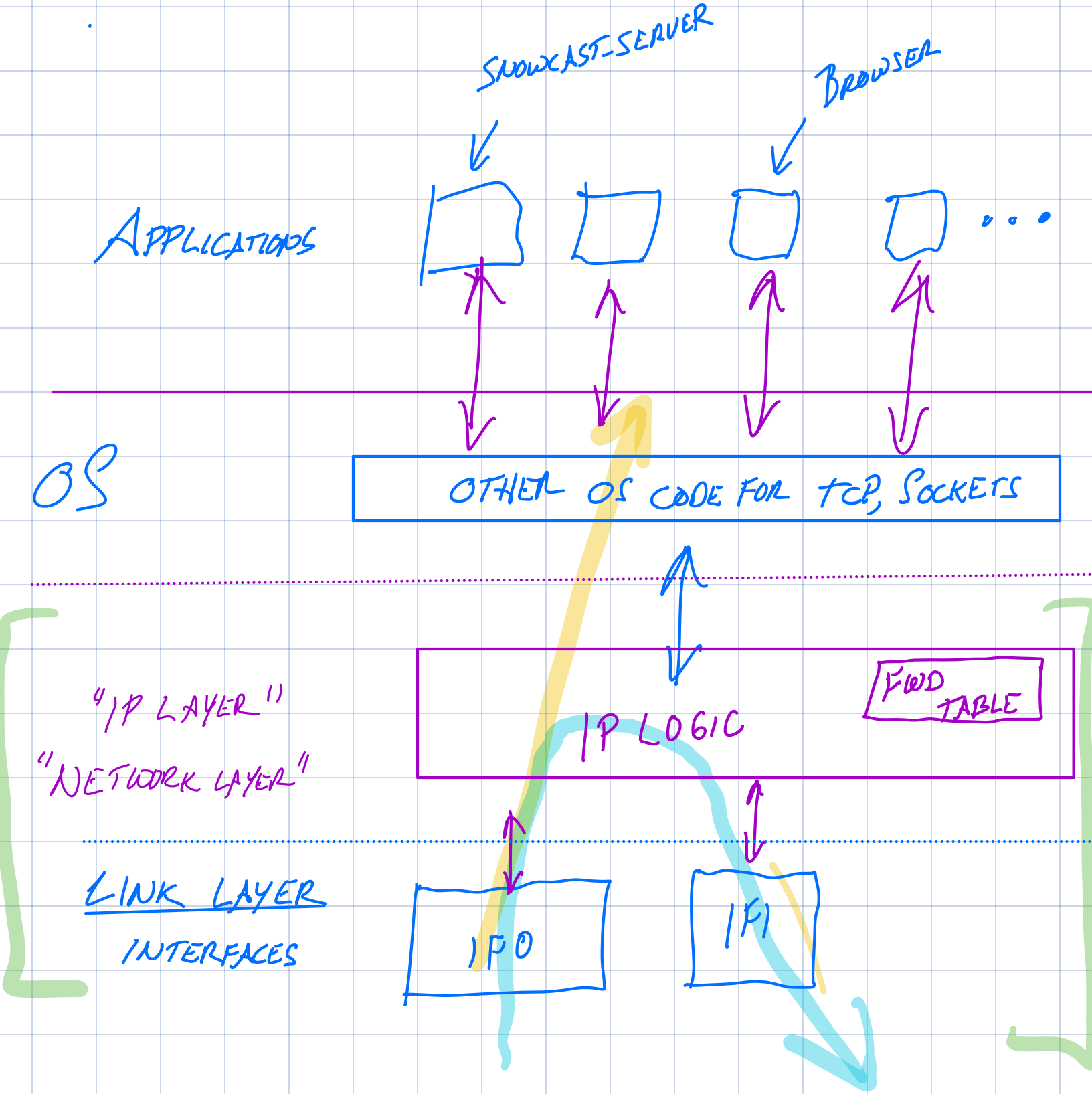
A "networking stack"

Logic on a device (host or router) responsible for handling packets:

- On a host: parts of the OS code that handles networking, sockets, etc.
- On a router: same logic, though per-packet processing is done with purpose-built hardware for maximum performance

=> Regardless of implementation, the core logic for handling IP packets is pretty much the same across both hosts and routers! (Which you'll see in the project!!)

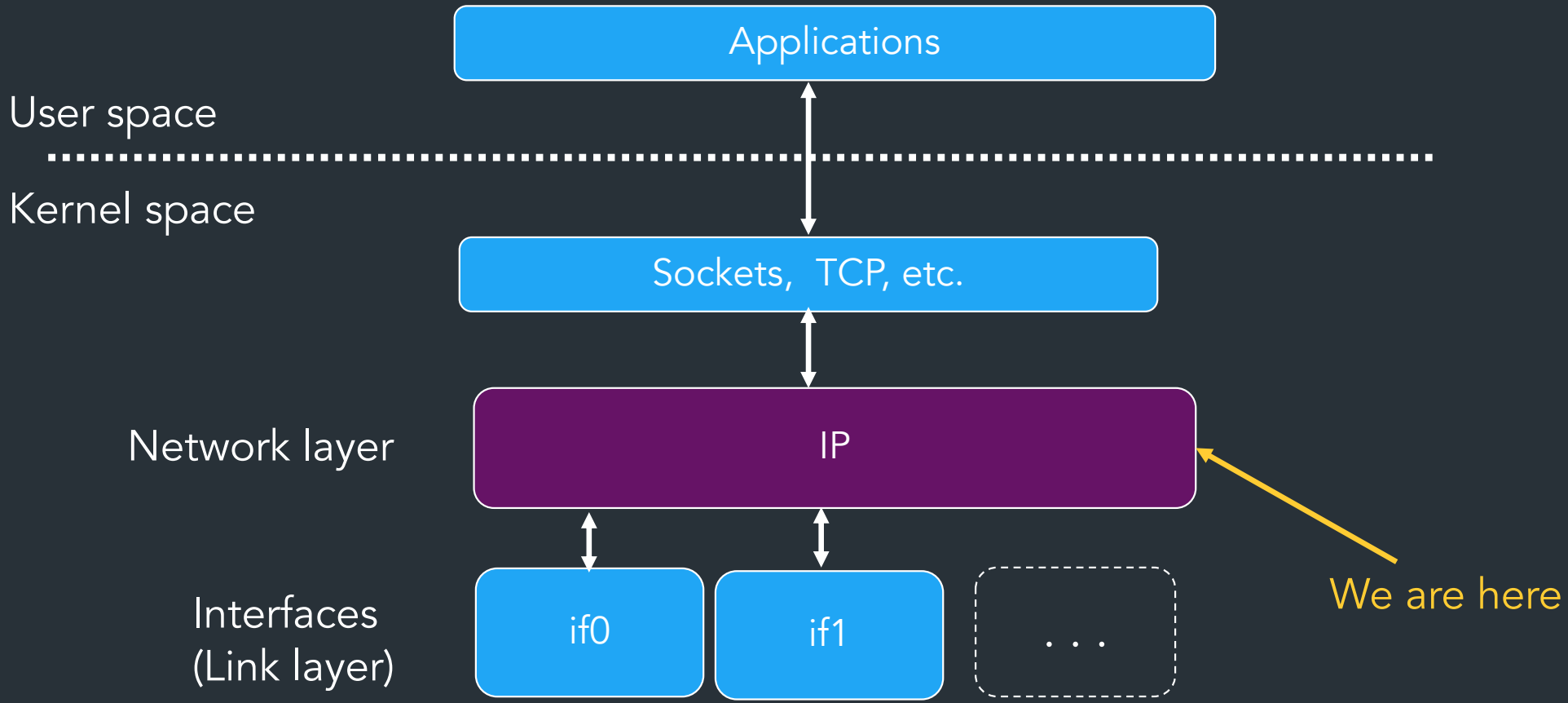
THINKING ABOUT A NETWORKING STACK.



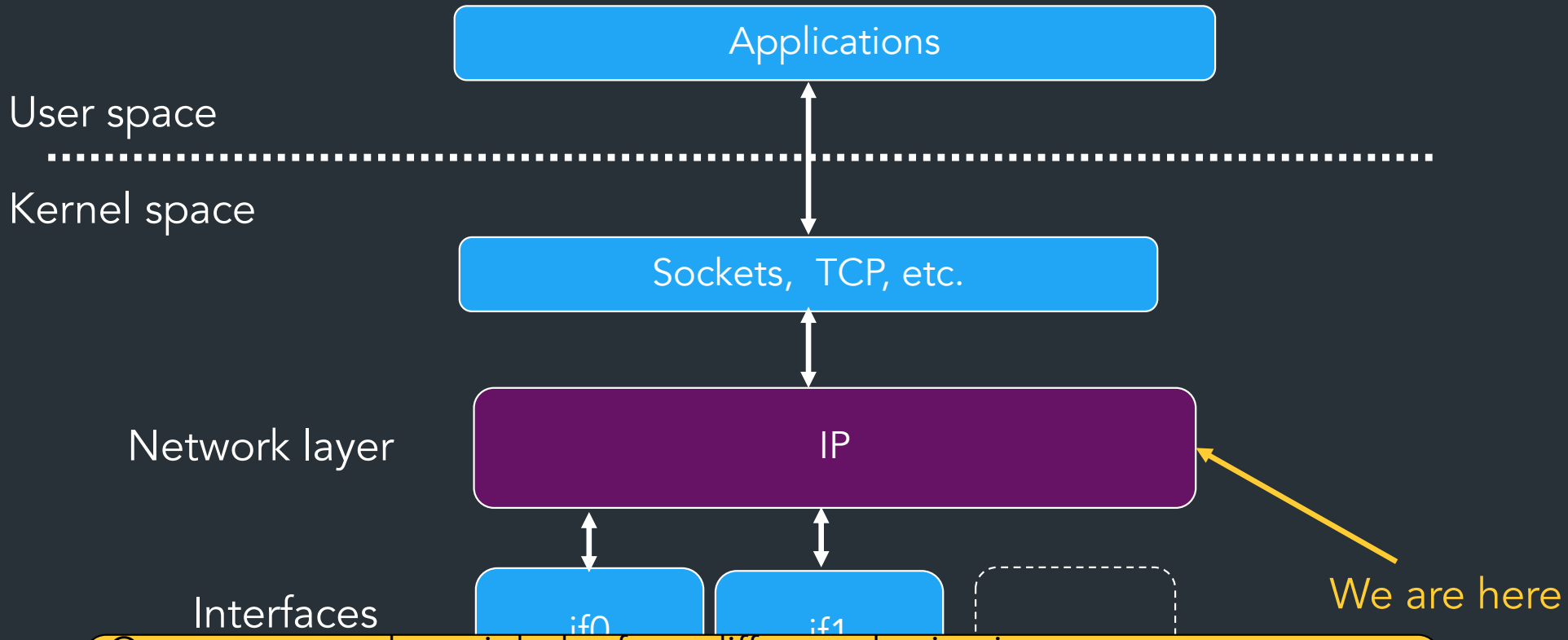
Core logic for making forwarding decisions (and some abstraction for interfaces) is the same for all devices using IP (hosts, routers)

- Hosts will have more logic at "higher" layers to figure out how to map packets to applications
- Routers are primarily geared towards forwarding packets from one interface to another (hosts can do this too, with a bit of configuration)

A "networking stack"

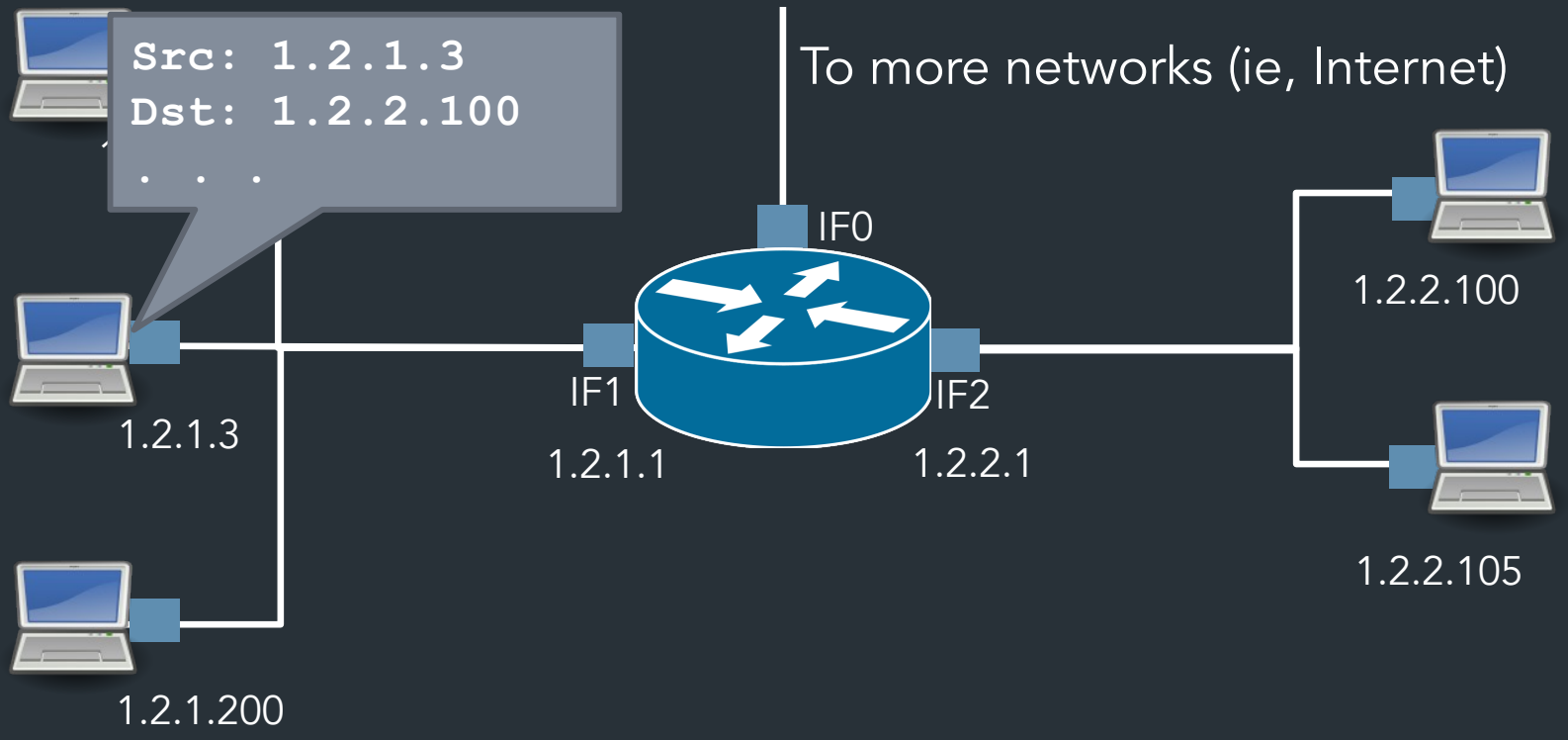


A "networking stack"



On a router: packet might be for a different destination
=> send out another interface
If it's for one for an IP assigned to this device, send to higher layer

Forwarding IP packets



Forwarding steps

What does a device do when it receives a packet?

Device: host, router, …

Forwarding steps

What does a *device* do when it receives a packet?

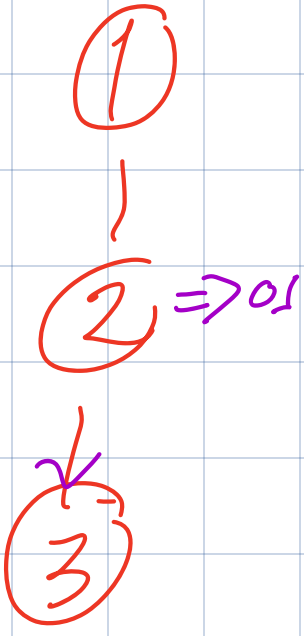
Device: host, router, …

(CLEANER VERSION OF THIS PAGE FROM LAST YEAR)

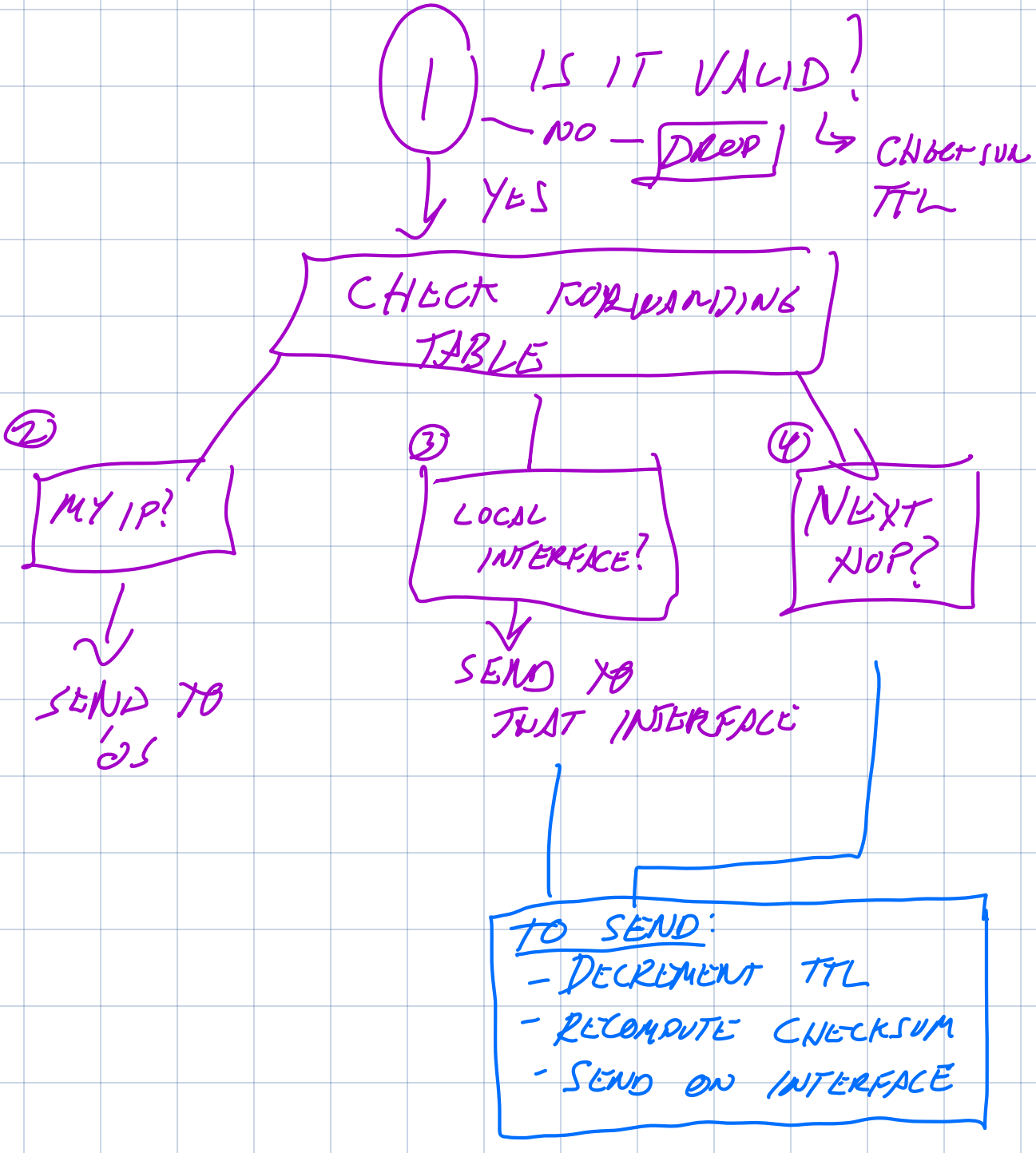
IP FORWARDING: STEPS

WHAT DO YOU DO WHEN YOU GET A PACKET?

1. IS THE PACKET VALID?
   - IS CHECKSUM VALID? ⇒ IF NO, DROP
   - IS TTL 0? ⇒ DROP
2. IS IT FOR ME? ⇒ IF DEST IP == (ANY LOCAL IP) ⇒ SEND IT TO "OS"
   - CHECK IF DEST ADDR IS FOR THIS HOST.
   - IF YES, SEND "UPSTREAM" TO OS. ⇒ OS CONSIDERS PROTOCOL FIELD: TCP, UDP, ...
3. IS IT FOR A LOCAL NETWORK? ⇒ CONSIDER DEST IP
   - DOES PACKET MATCH ANY NETWORKS IN FORWARDING TABLE?
   - IF YES, SEND ON THAT INTERFACE.
4. DO I HAVE A NEXT HOP? ⇒ IF SO, LOOKUP INTERFACE FOR NEXT HOP IP.



LOOKING AT IT IN A DIFFERENT WAY. -

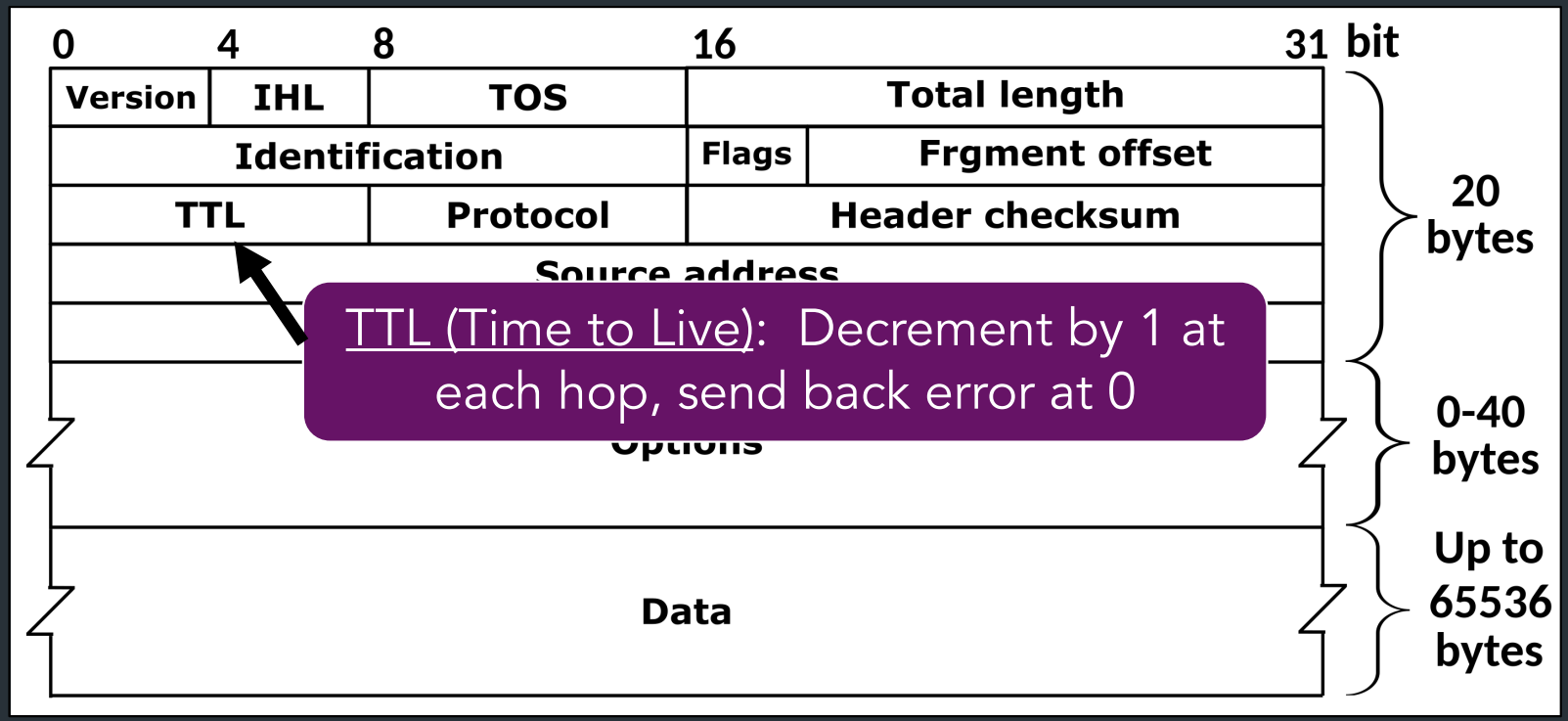


Forwarding mechanics

When an IP packet arrives at a host/router:

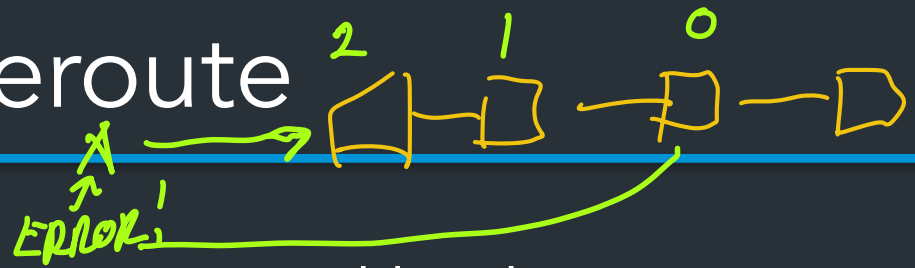
- Is it valid? Verify checksum over *header*
- **Is it for me?** If dest IP == your address, send to OS
- If not, where should it go?
  - Consult forwarding table => find next hop
  - Decrement TTL
  - Send packet to next hop

How to avoid loops?



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

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!

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
```