IPv6 / IP Routers

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cs168.io

Rob Shakir

Last Time

- A different class of routing protocols – *Link State*.
- Solving routing scalability – IP addressing.

IPv4

- 32 bits of address.

- Some number of fixed bits – **network address**.
- Remaining bits variable – **multiple host addresses.**

- Hierarchical.
  - Allows us to introduce “wildcard” matches – to *summarise* routes.
  - “All addresses” - 0.0.0.0/0 – the *default route*.

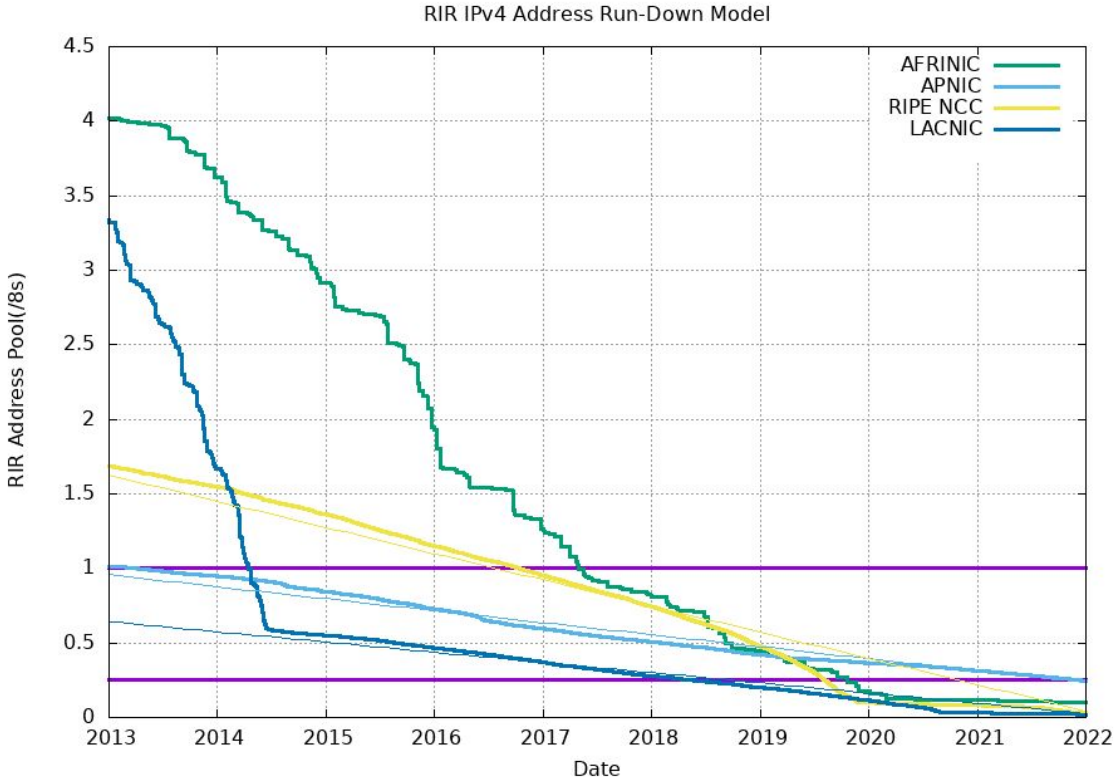
- Class-ful addressing to class-less addressing.
  - Making better use of the address space.

IPv6

IPv4

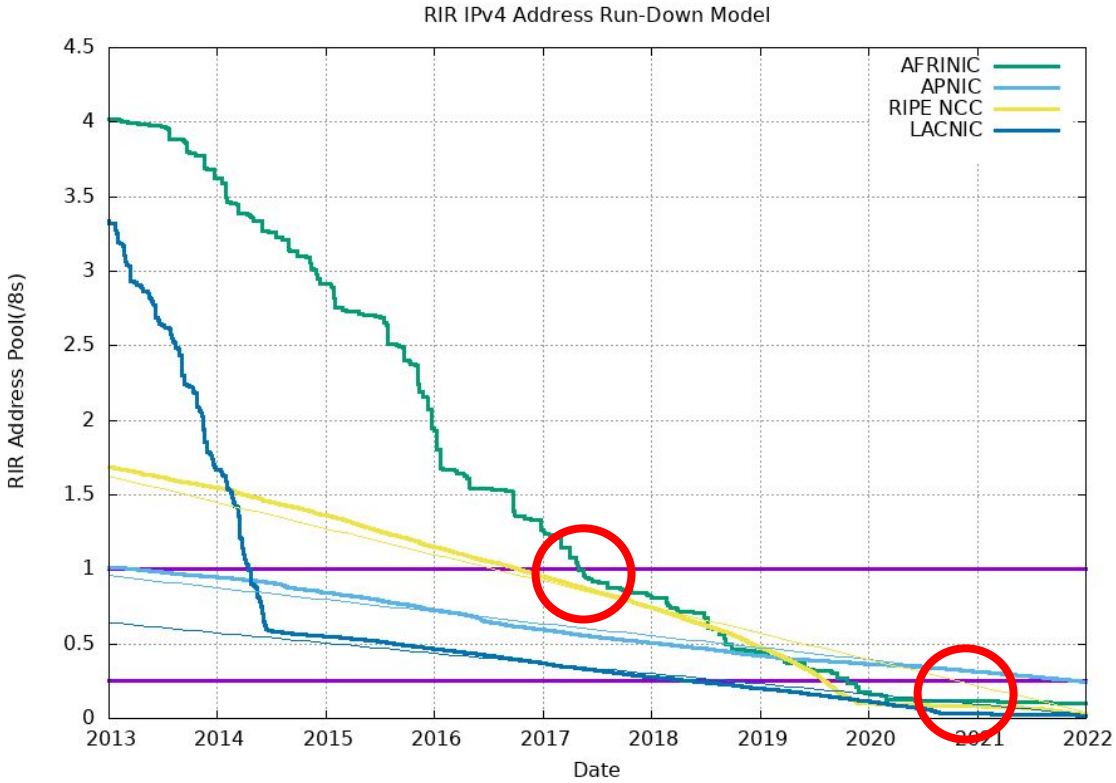
2^32 = 4294967296
addresses available.

Was 32 bits enough?



https://ipv4.potaroo.net/

Was 32 bits enough?



https://ipv4.potaroo.net/

NANOG 51 - February 2011

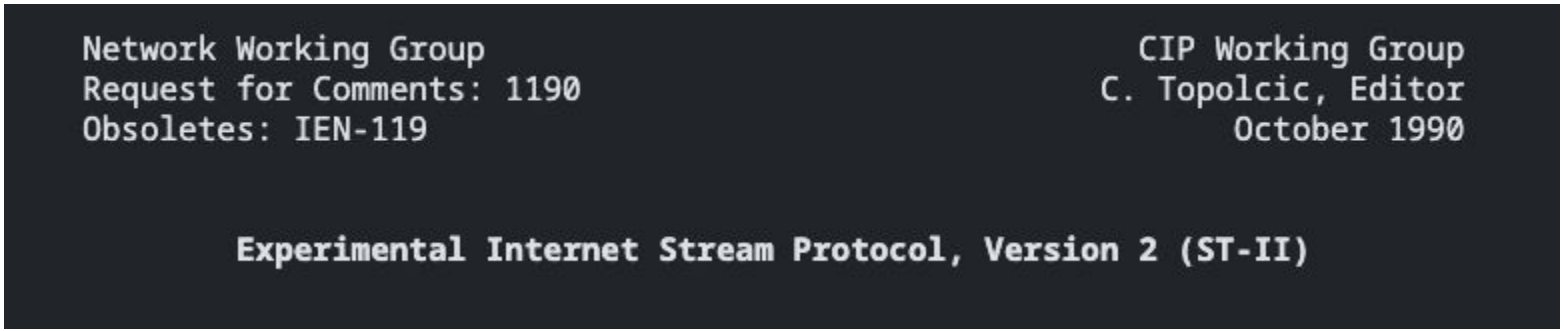
IP version 6

Network Working Group
Request for Comments: 2460
Obsoletes: 1883
Category: Standards Track

S. Deering
Cisco
R. Hinden
Nokia
December 1998

Internet Protocol, Version 6 (IPv6)
Specification

What happened to version 5?



Network Working Group
Request for Comments: 1190
Obsoletes: IEN-119

CIP Working Group
C. Topolcic, Editor
October 1990

Experimental Internet Stream Protocol, Version 2 (ST-II)

IPv6

- Fundamentally uses the same addressing structure as IP version 4.
- But with 128-bits of address space.
  - And some new requirements and rules…
  - Not relevant to our discussion.
- Went from 2^32 to 2^128 addresses.

IPv6

2^128 = 3.402823669209385e+38 addresses available.

IPv6

Number of seconds since the Universe began – 1e+21.

IPv6

- Switches to hexadecimal representation rather than longer dotted address.

- 2001:0DB8:CAFE:BEEF:DEAD:1234:5678:9012
- 2001:0DB8:0000:0000:0000:0000:0000:0001

- Can omit leading zeros: 2001:DB8:0:0:0:0:0:1
- Can omit repeated zeros *once per address:* 2001:DB8**::**1

IPv6

- Still uses *slash notation.*

- 128-bits fixed == /128.
- 32-bits fixed == /32.

IPv6

- Some changes!

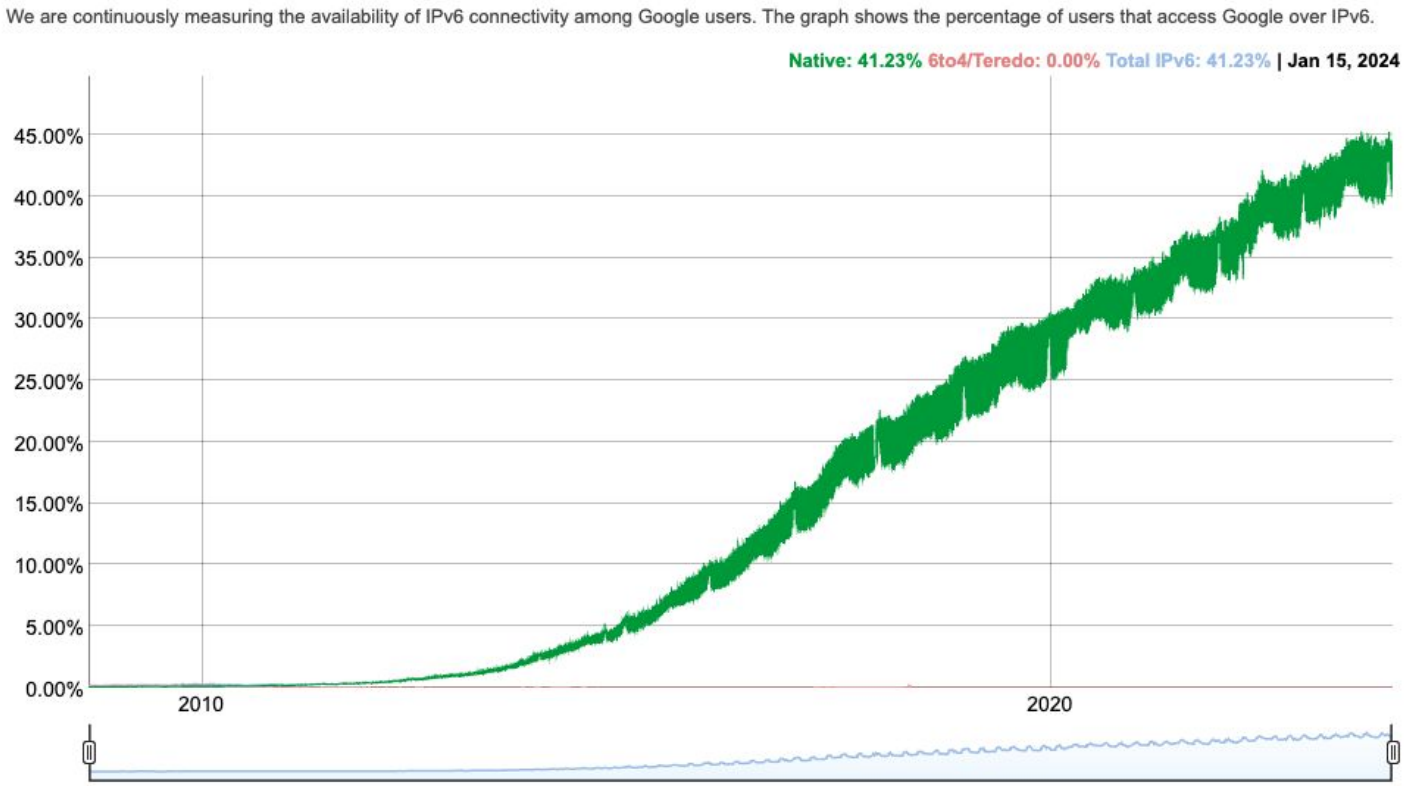
- We leave the last 64-bits of the address variable to allow for hosts to configure their own addresses.
  - **S**tate**L**ess **A**ddress **A**uto**C**onfiguration (SLAAC).

- This means practically, we don’t expect to see routes with /64 or *longer* (greater).
  - Although in special cases we might.

IPv6

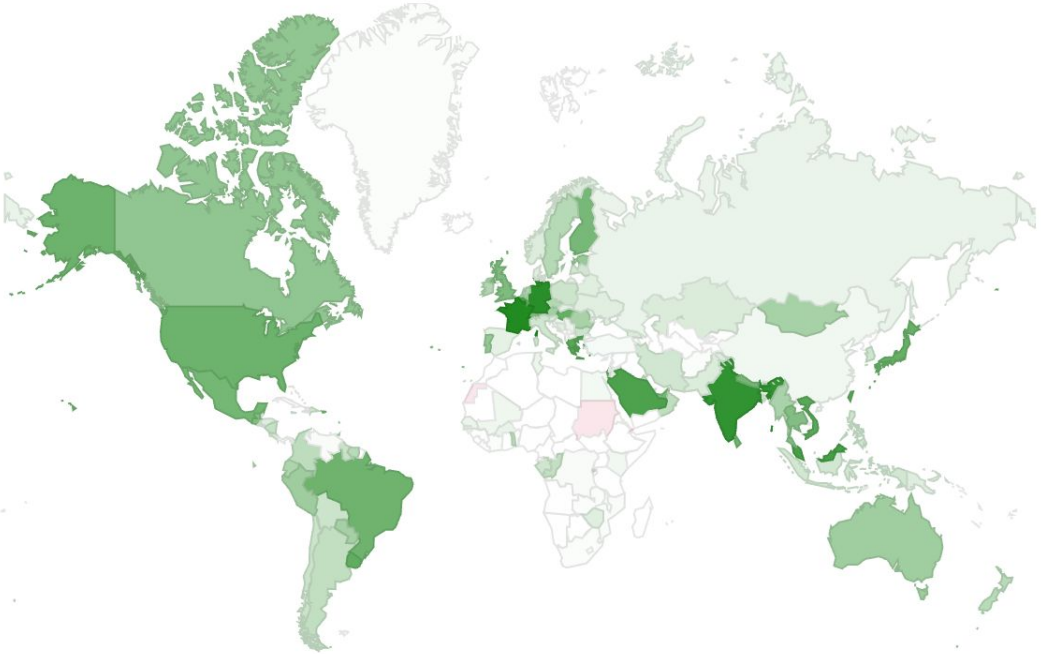
- The same hierarchical addressing approach is used in IPv6 and IPv4.
- We tend to use IPv4 for examples.
  - Because long strings of numbers are harder to remember.

IPv6 Adoption



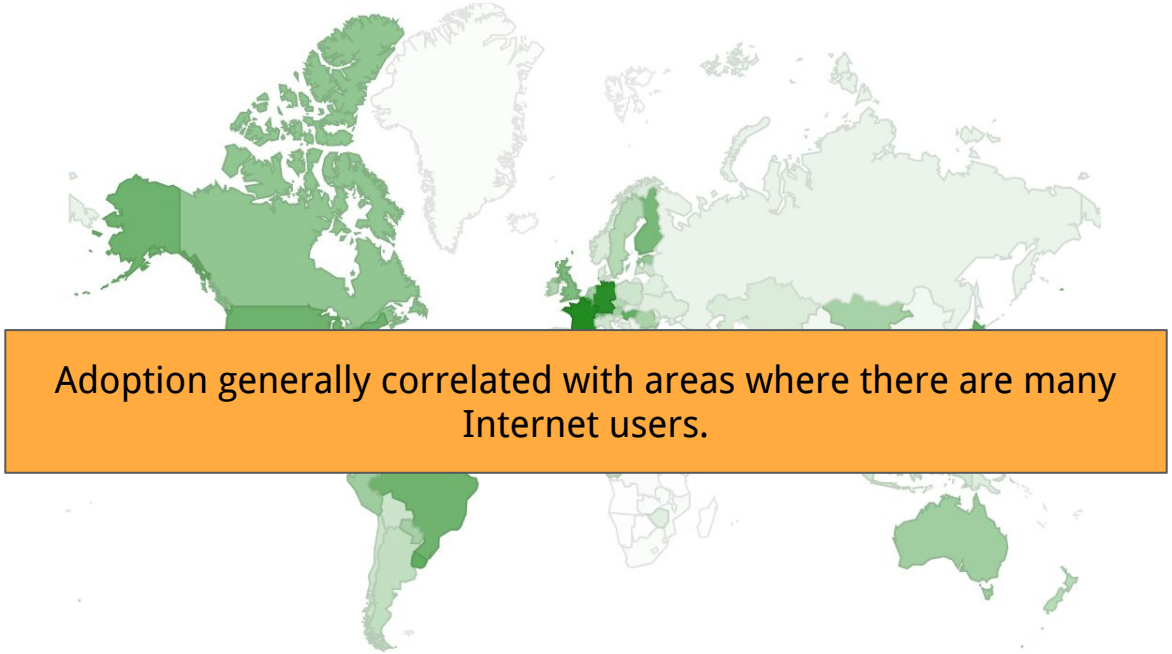
https://www.google.com/intl/en/ipv6/statistics.html

IPv6 Adoption



https://www.google.com/intl/en/ipv6/statistics.html

IPv6 Adoption



Adoption generally correlated with areas where there are many Internet users.

https://www.google.com/intl/en/ipv6/statistics.html

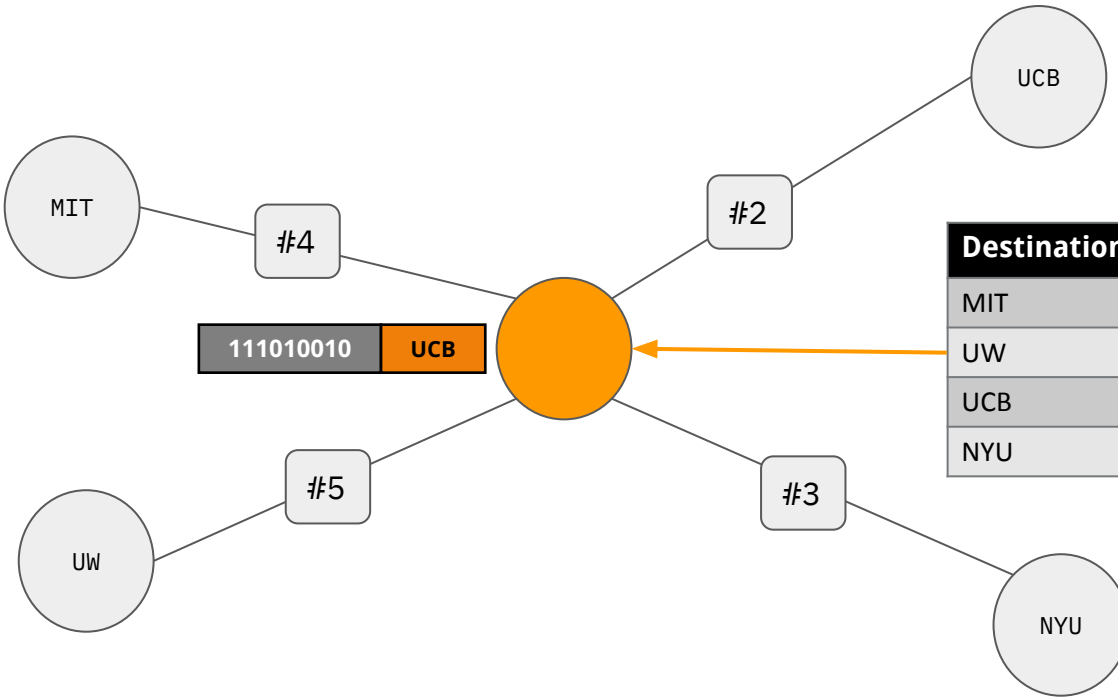
Challenges for IPv6 Adoption

- No smooth path
  - Hosts and ISPs need both addresses.
- Rebuilding the Internet.
  - Partial coverage where only some things are on IPv6.
- Coexistence.
  - If something is on IPv4 and IPv6 which should I use?
- Main driver for IPv6 adoption
  - We’re running out of IPv4 addresses!

Questions?

IP Routers

Recall: IP router purpose.



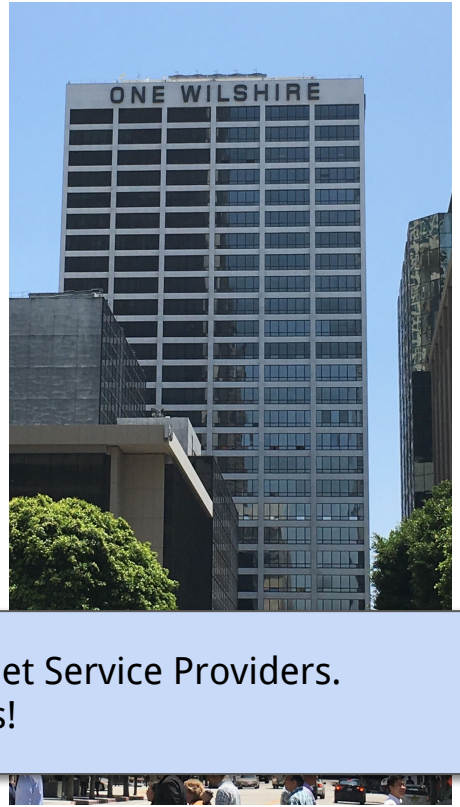
Destination	Next Hop Link
MIT	Link#4
UW	Link#5
UCB	Link#2
NYU	Link#3

Recall

- A router performs IPv4/IPv6 lookup against the destination IP of a packet.
- Routers run *routing protocols* to learn about routes.
- “Routes” are sets of destination IP addresses.

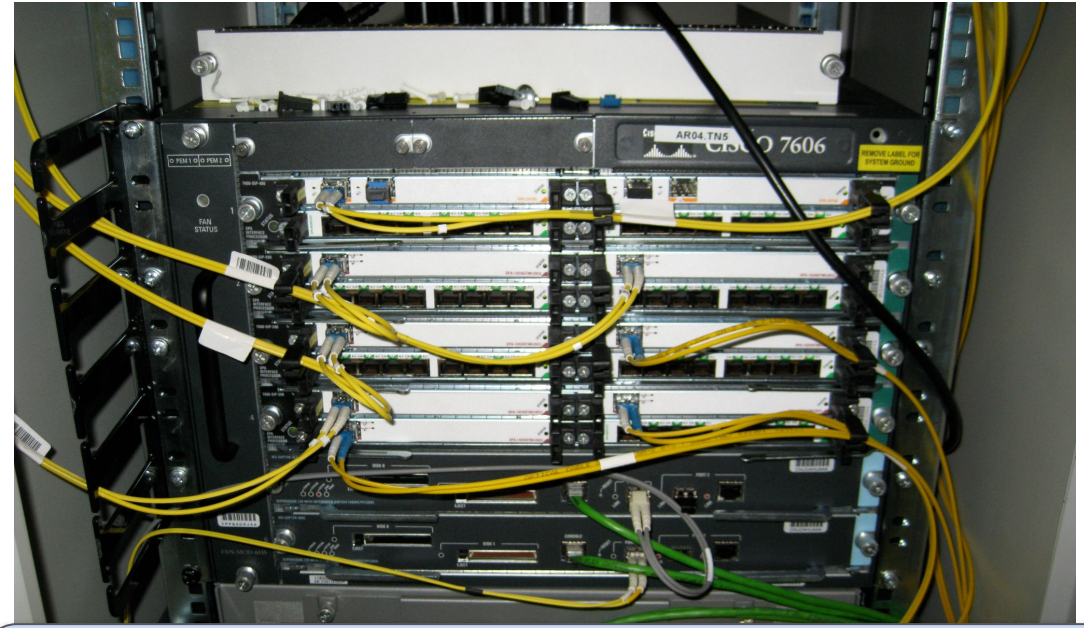
- **Today: What *is* a router?**

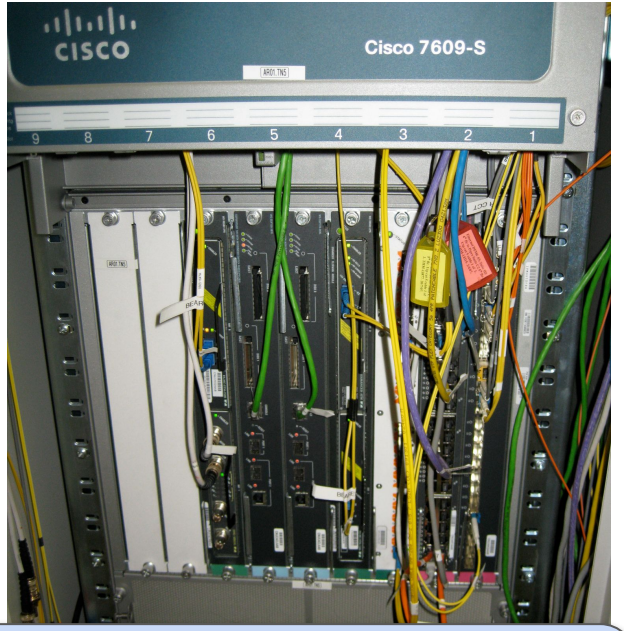
What makes up the Internet?



Colocation facilities: Datacenters housing multiple Internet Service Providers.
Many routers from different companies!

IP routers?





Computers specialised for forwarding packets.
Different sizes and configurations depending on requirements.

Different Sizes of IP Router.

Dimensions:

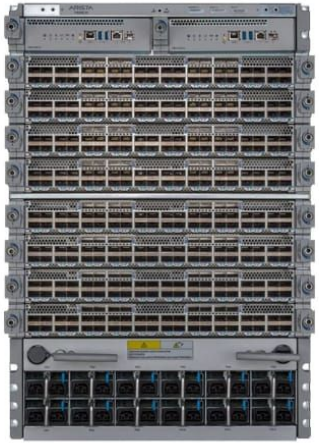
- Physical size
- Number of ports
- Bandwidth

Router Definitions

- N = number of external ports.
- R = speed (“line rate”) of a port
- Router Capacity = N x R

- N = 4, R = 100Mbps
- N = 1, R = 1Gbps
- Total: 0.4+1 = 1.4Gbps.

Today’s capacity.



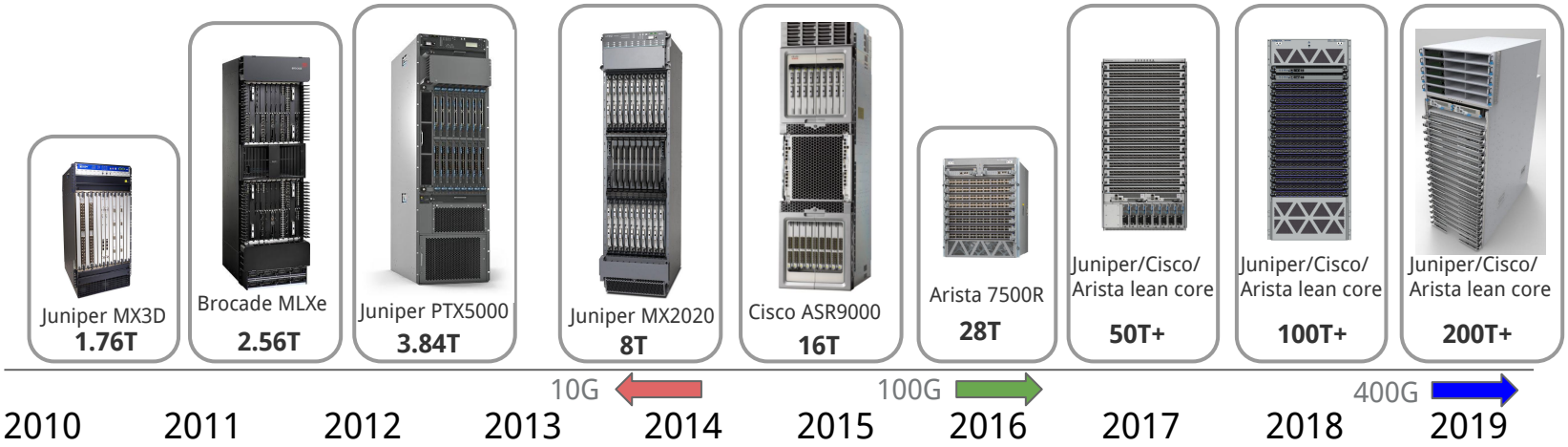
Today (400G linerate)

- 8 linecards, 36 ports each.
- N = 8 x 36 = 288
- R = 400Gbps
- Router Capacity = 288 * 400G = 115.2Tbps

Next Gen (800G linerate)

- 8 linecards, 36 ports each.
- N = 8 x 36 = 288
- R = 800Gbps
- Router Capacity = 288 * 800G = 230Tbps

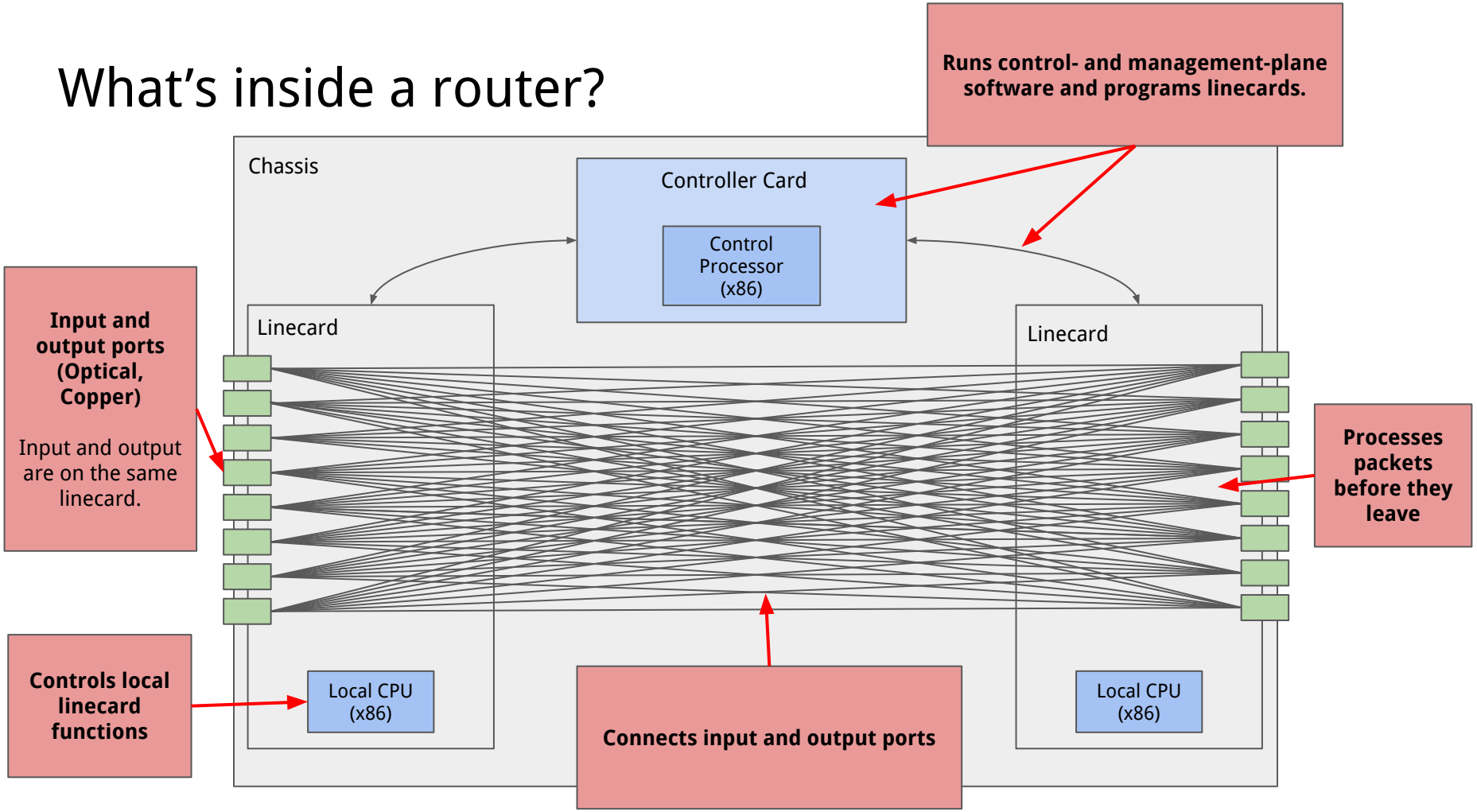
Evolution of Capacity…



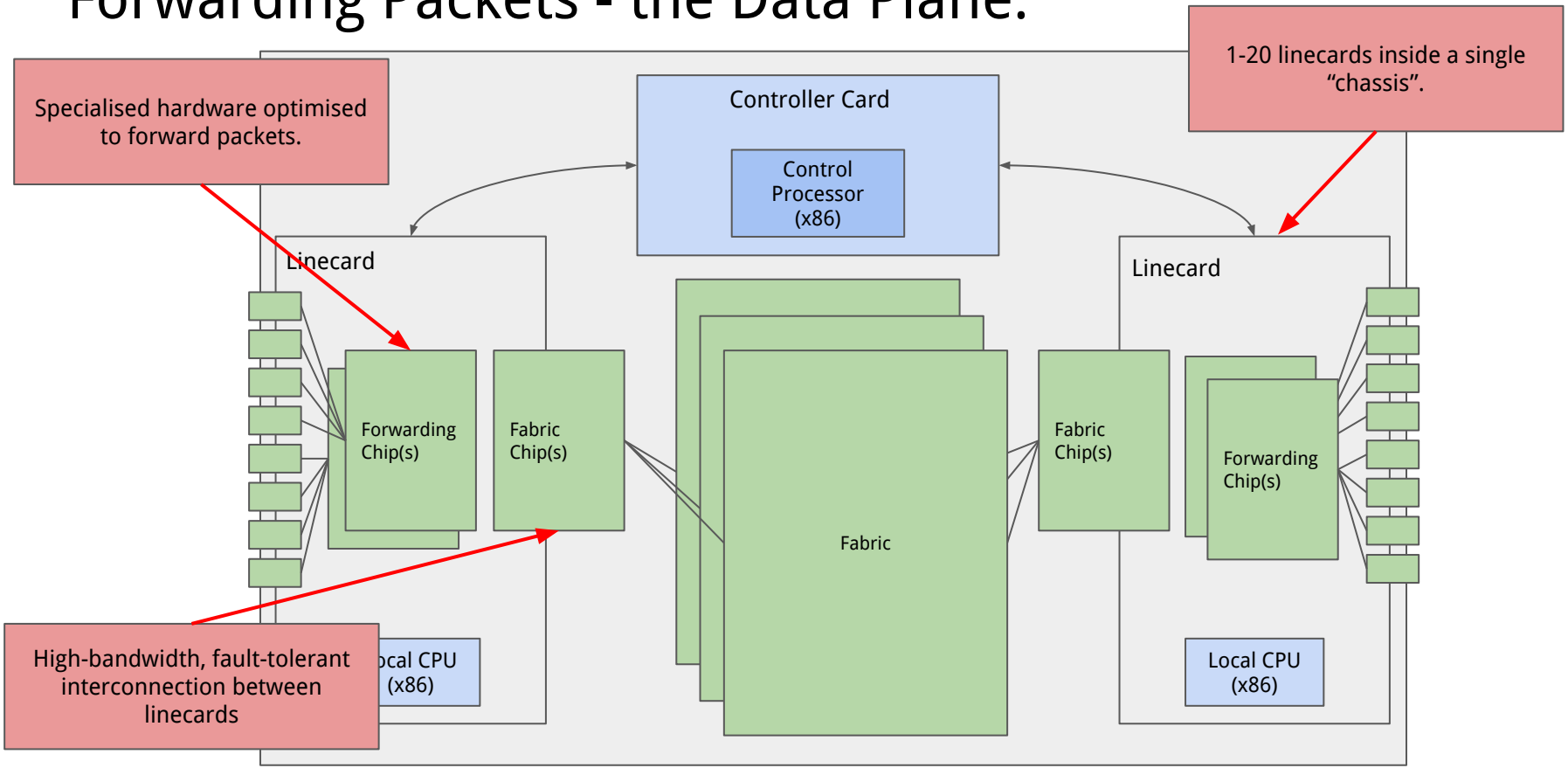
Note:

- Physical size (constrained by racks!)
- Impact of link speed (10G → 100G → 400G)

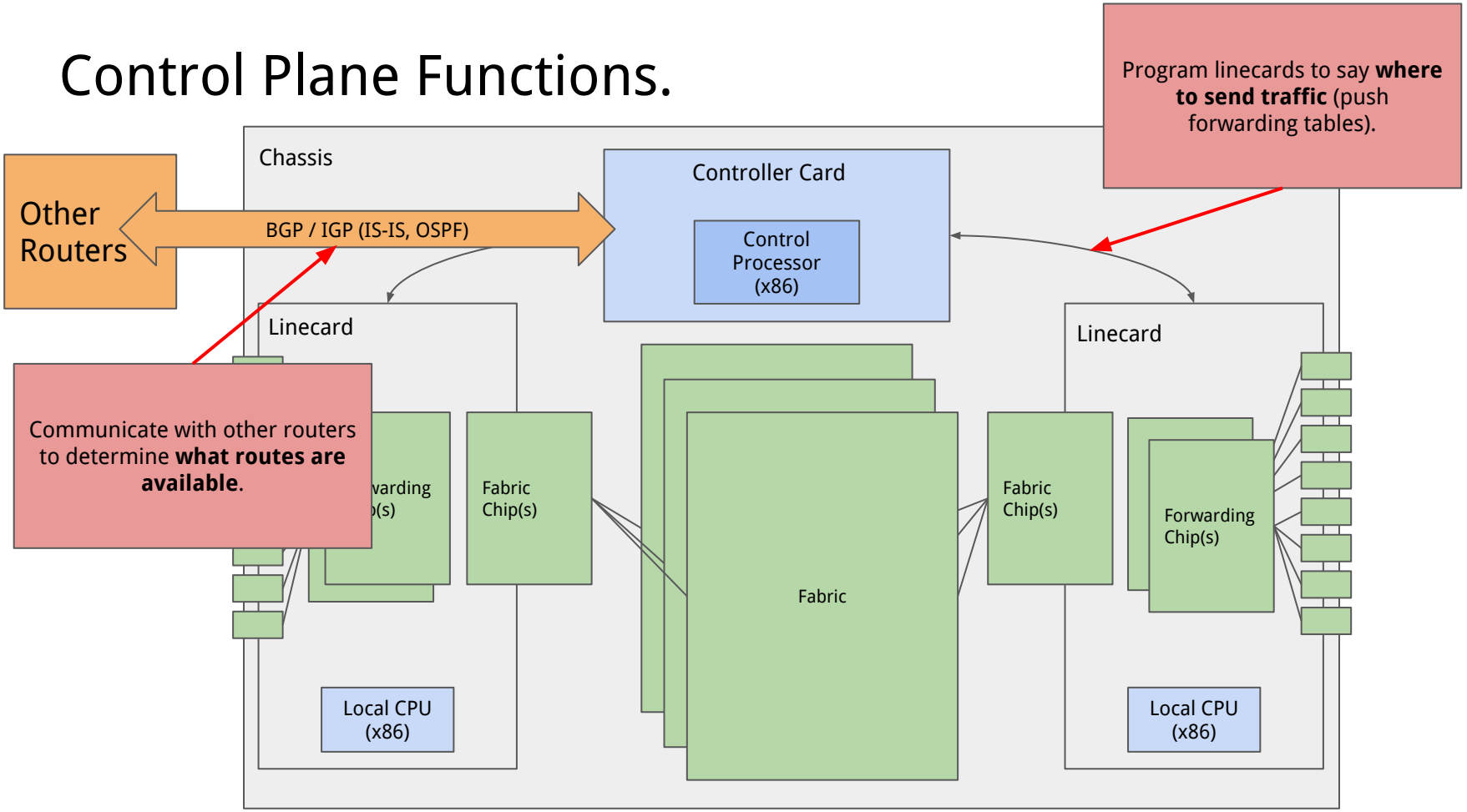
What's inside a router?



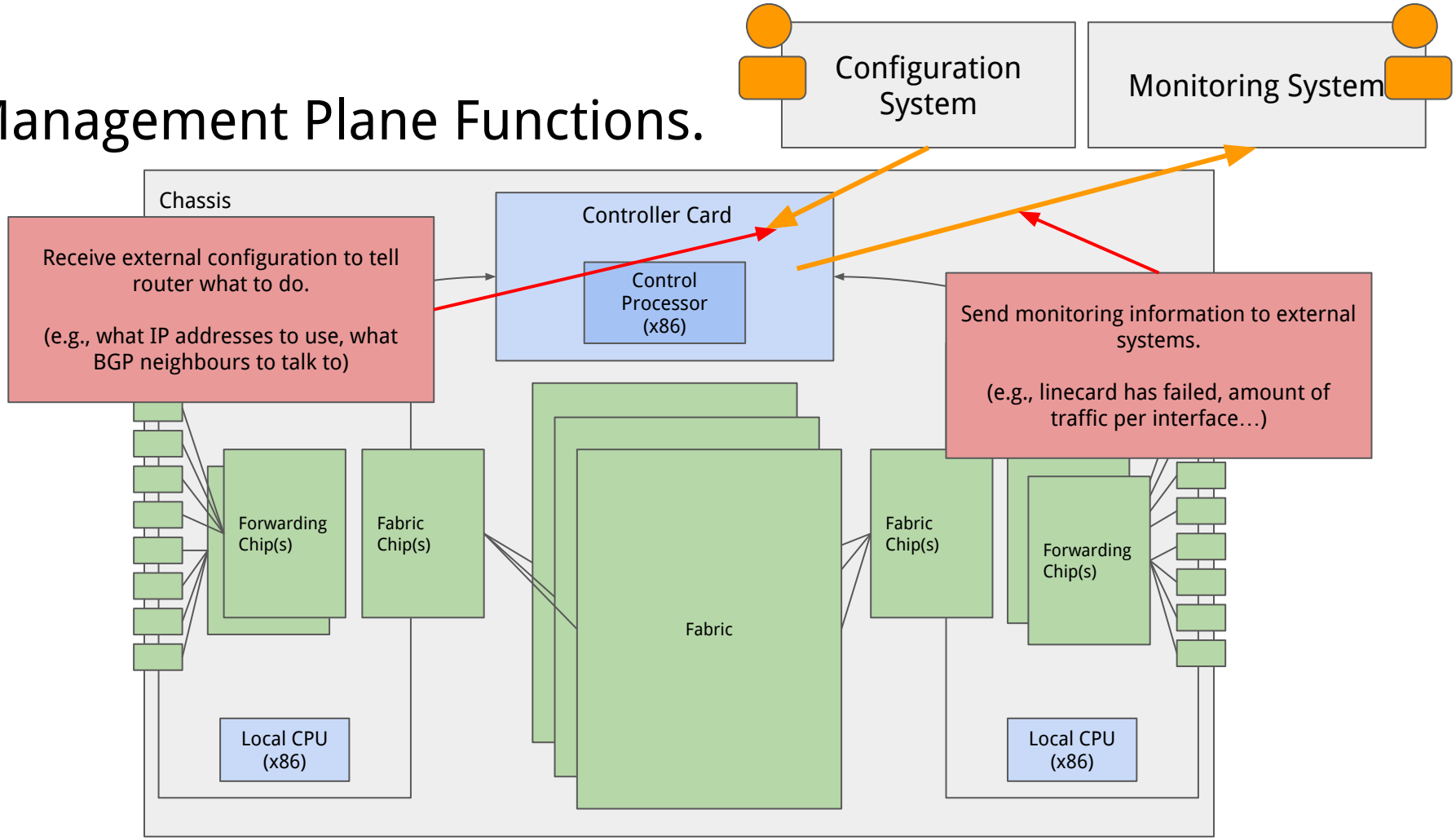
Forwarding Packets - the Data Plane.



Control Plane Functions.

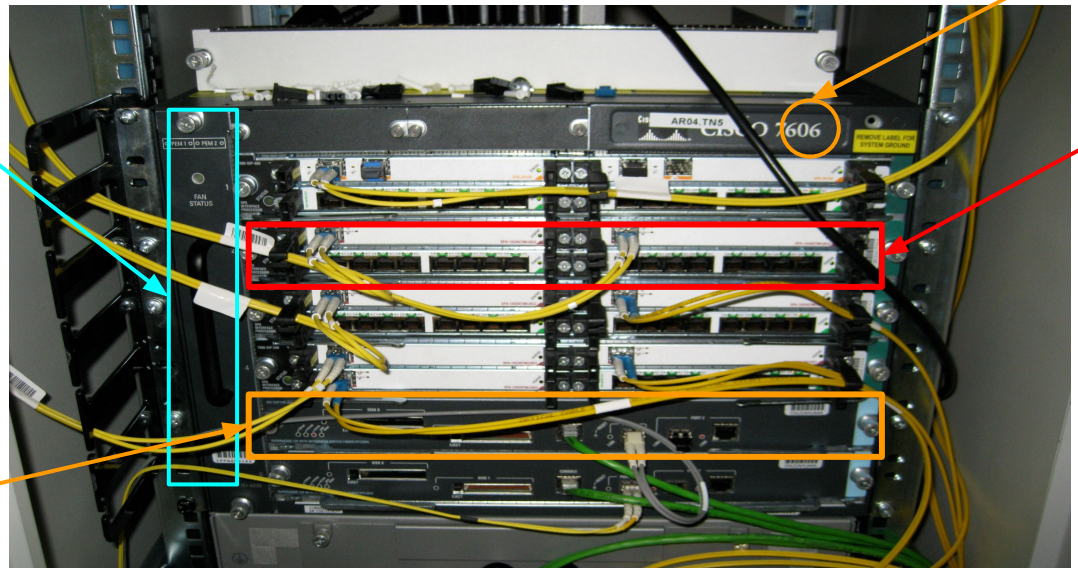


Management Plane Functions.



Questions?

Looking at a real router.



A small cluster of computers ~~Computers~~ specialised for forwarding packets.

Definitions

Control Plane

- Runs routing protocols to allow router to understand *where* to route packets.

Management Plane

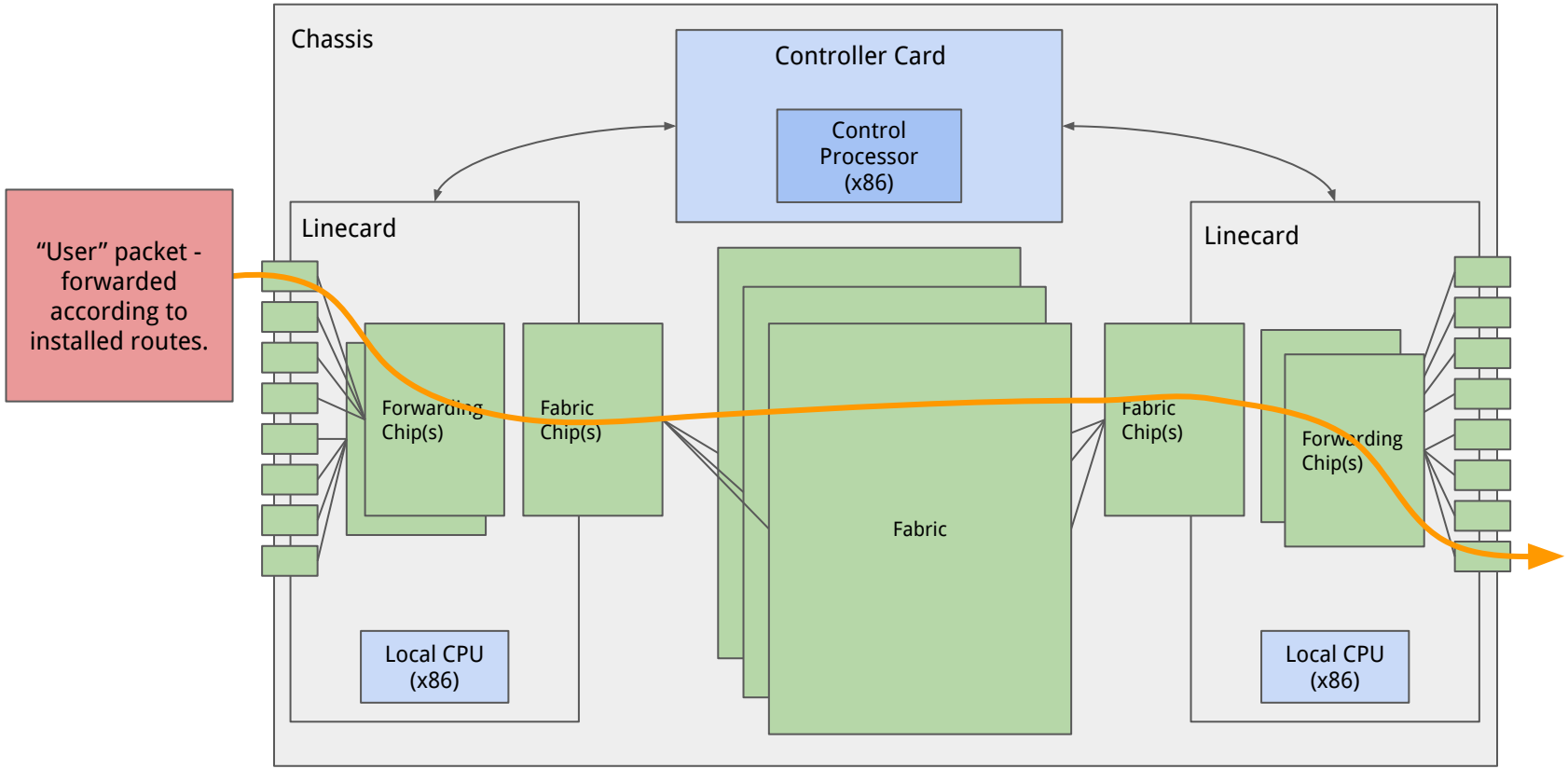
- Interacts with systems and humans to configure and monitor the device.

Data Plane

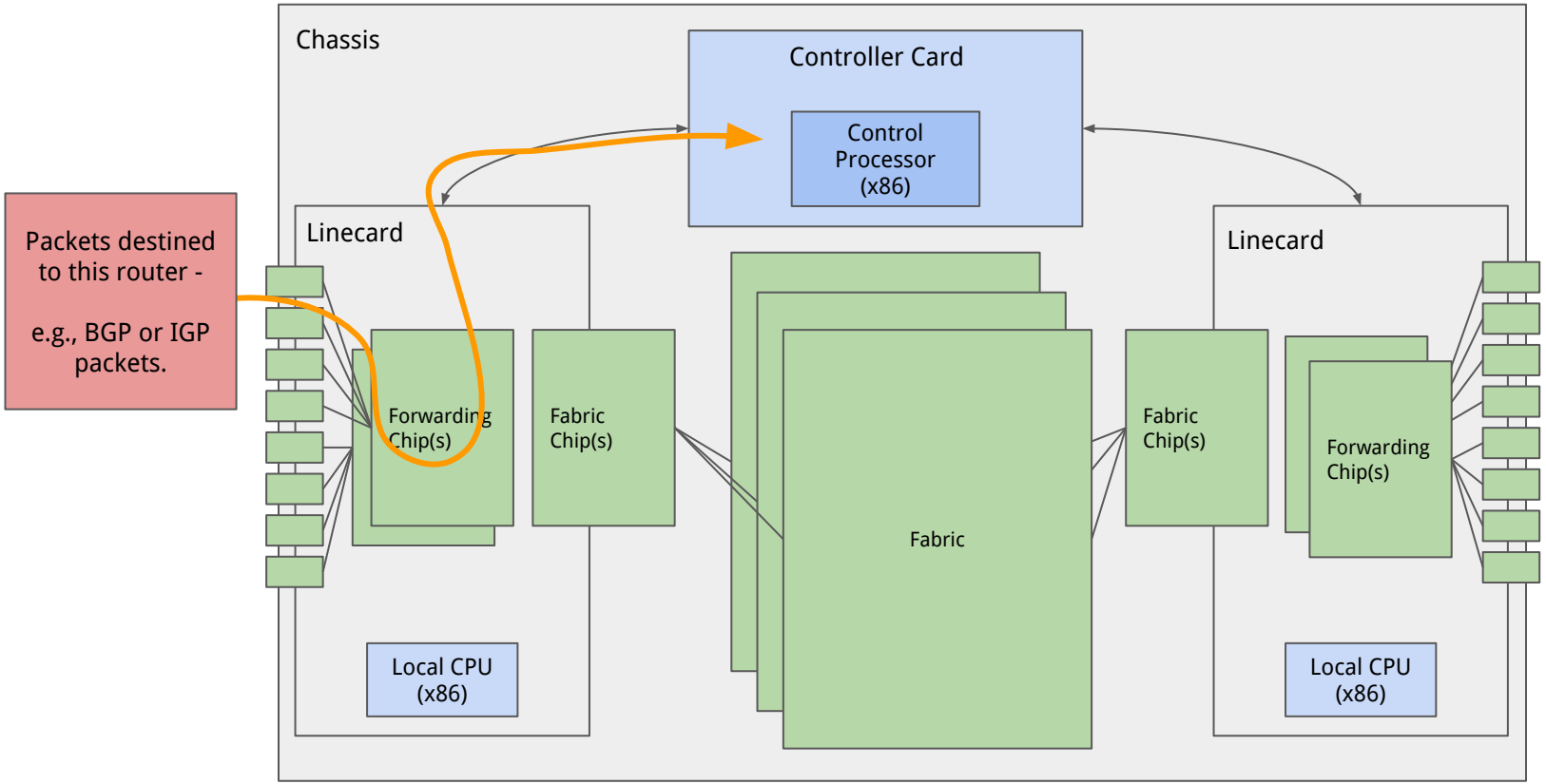
- Forwards packets.

We need all these to run a router in a real network!

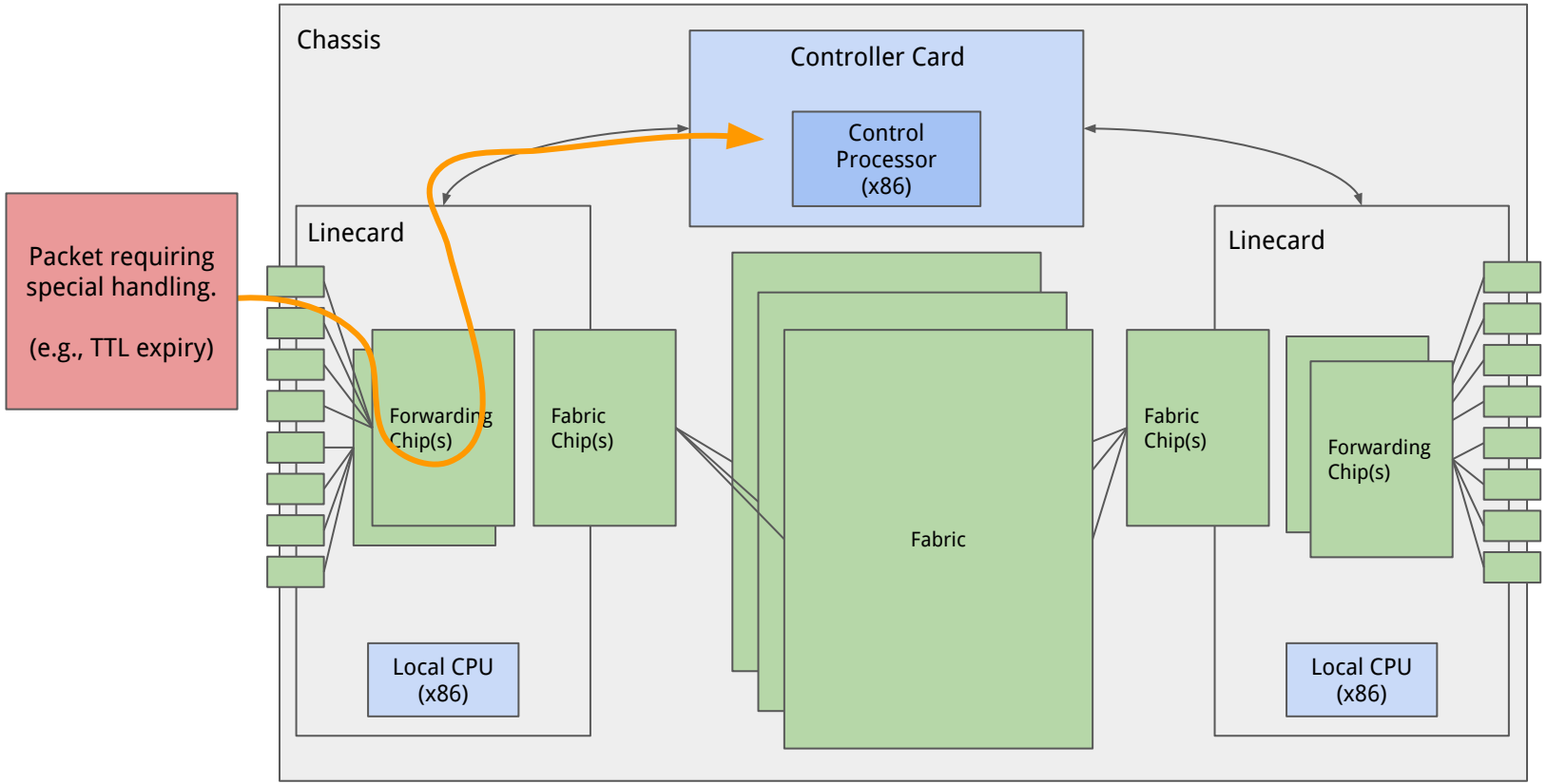
Types of Packets - “User” Traffic.



Types of Packets - Control Plane Traffic.



Types of Packets - “Punt” Traffic.

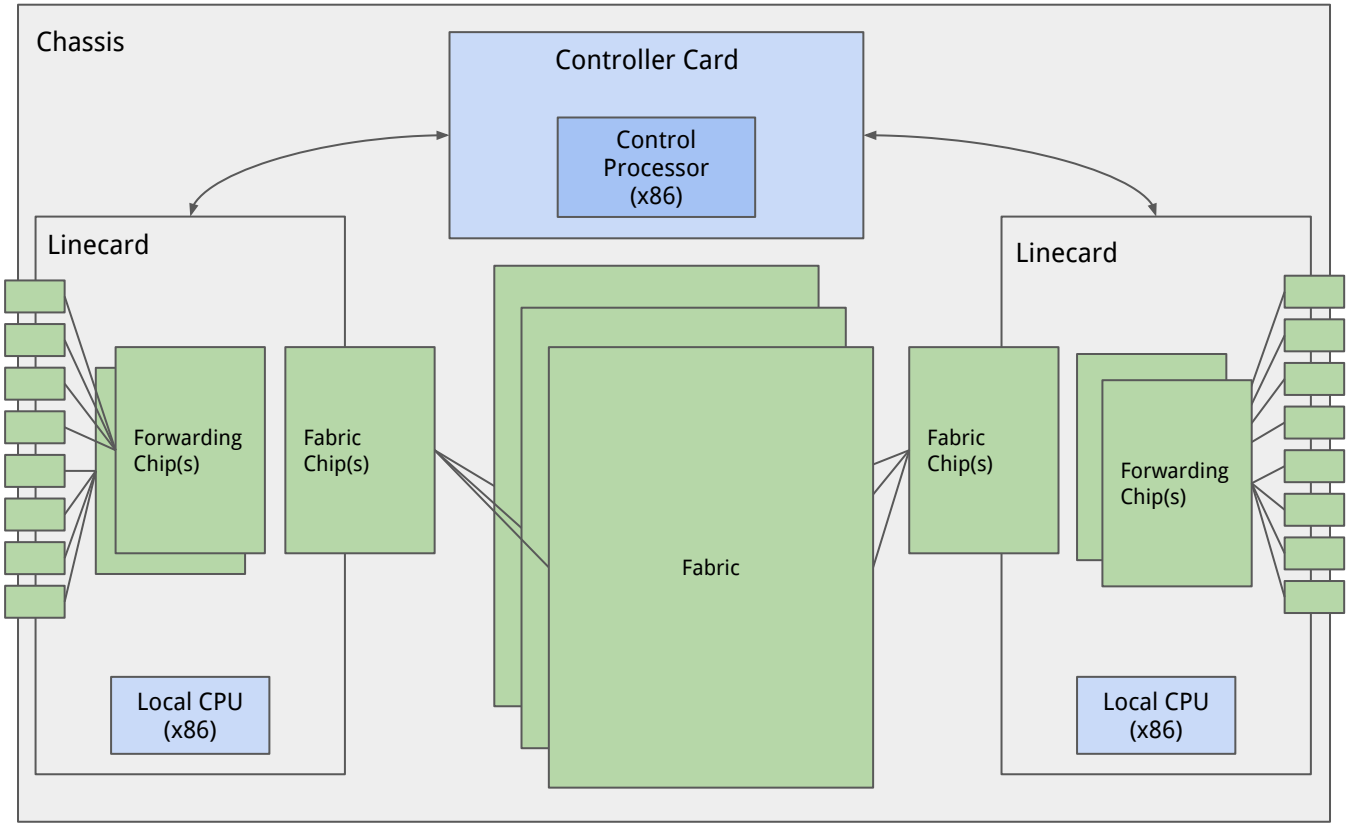


Why this architecture?

- Smallest Ethernet packet = 64 bytes.
- Current interface speed = 400 gigabits per second.
- $4x10^{11} / 64*8 = 781.25x10^{6}$ packets per second per direction.
- $1.5625x10^{9}$ packets per second x 36 ports = $56.25x10^{9}$ pps.
  - In practice a little lower… but a lot!

- Not achievable on a general purpose CPU.
  - ~millions of packets per second are.
  - “Slow path” used only when necessary.
- Forwarding hardware is the “fast path”.
  - Much more efficient (power, cost).

Any questions?



What does the input linecard do?

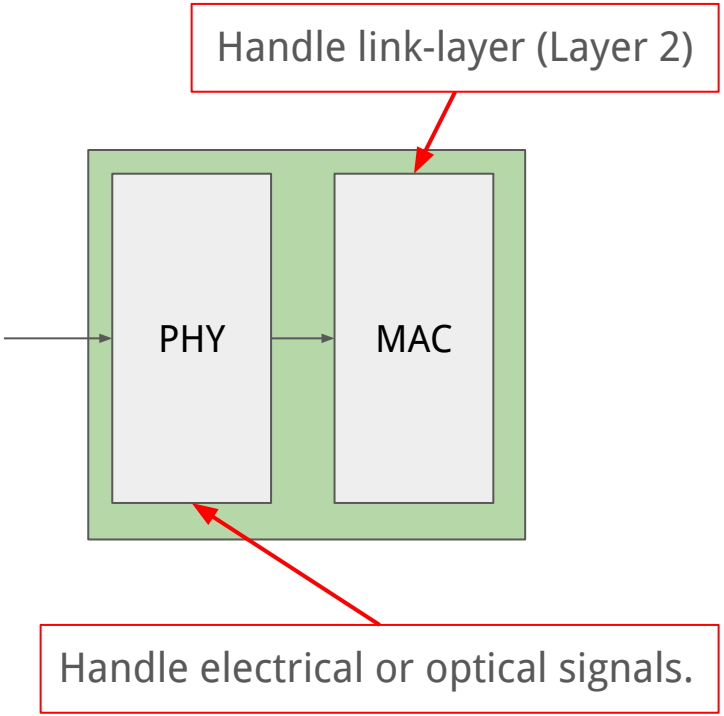
- Tasks
  - Receive incoming packets from other systems
    - Handle the physical layer (electrical, or optical) **- PHY**
    - On-the-wire encoding (Ethernet) - **MAC**
  - Update the IP header
    - TTL, checksum, options, fragment
  - Perform lookup for forwarding.

Challenges for Input Linecards - Speed!

- We talked about packet rate - even with 250 byte packets - 1 packet per 5 nanoseconds.

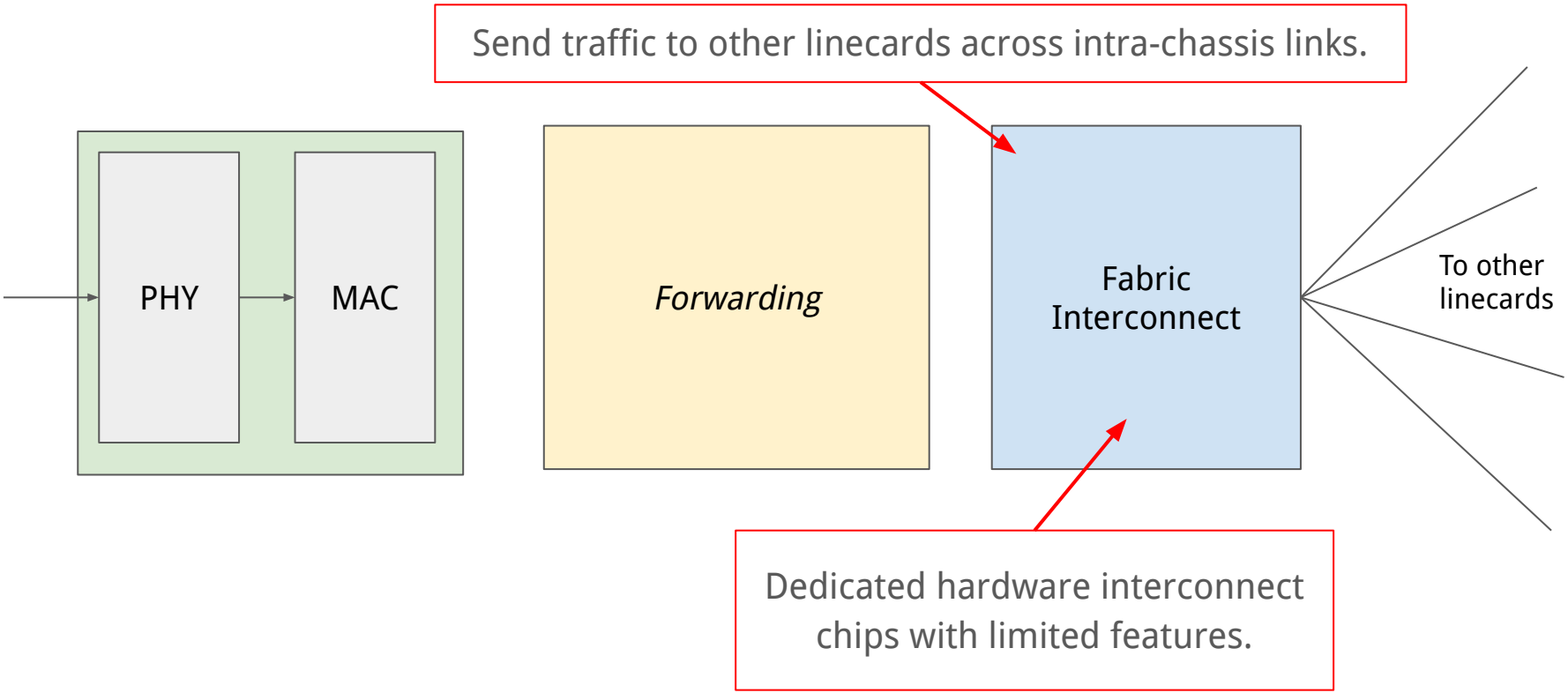
- Need to run at 0.2GHz for each port even with (the ideal of) one cycle per packet - but, we need to do multiple operations on each packet, and have many ports per chip.
  - Could we parallelise? Lots of CPU == lots of power.
  - Typically have specialised **network processors** - with some programmability, but with limited functions.
  - Special processing that can't be done there done at control processor (per linecard or central).

“Pipeline” For Packet Forwarding: Layer 1 + 2

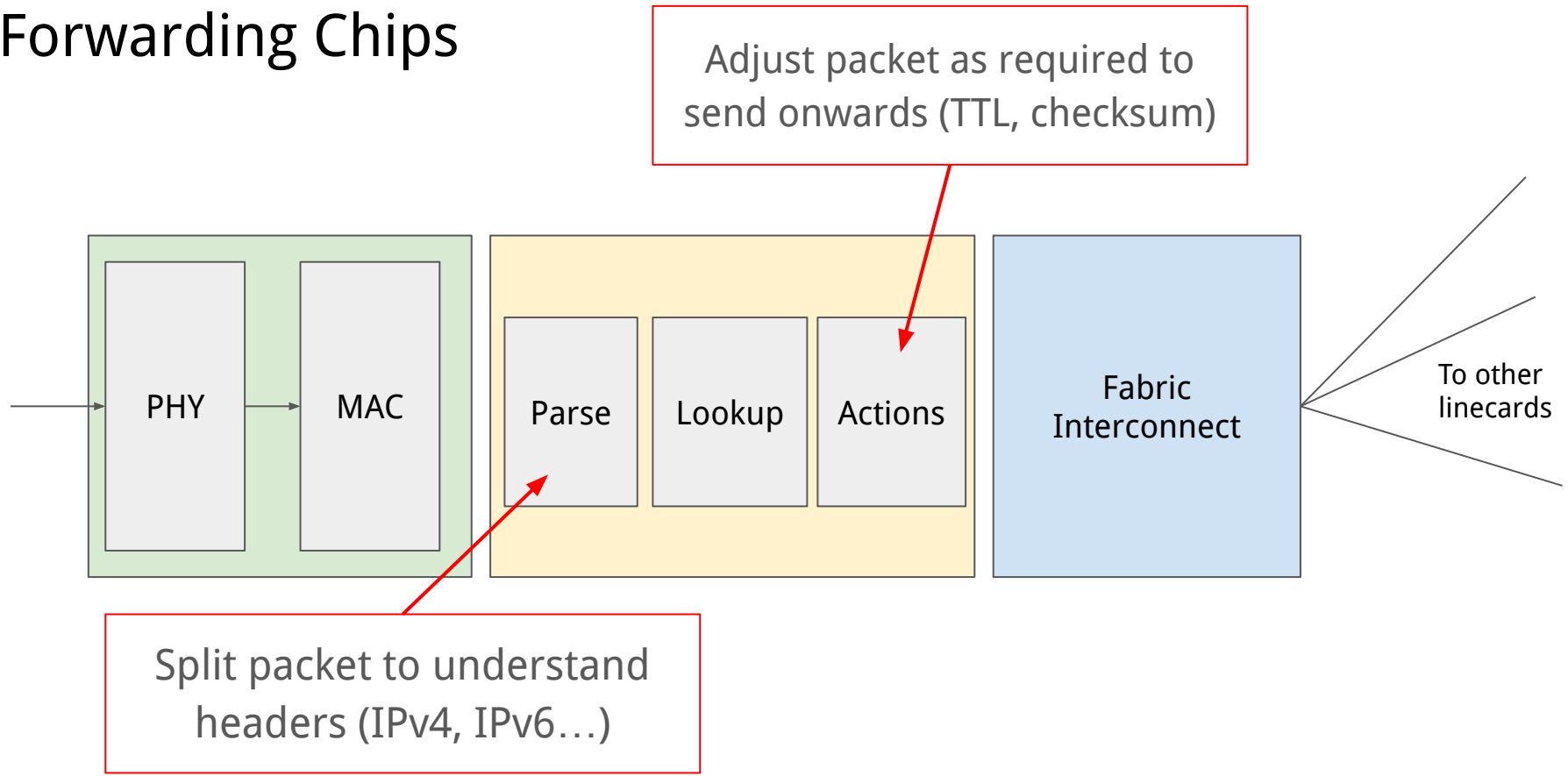


Implemented in hardware.

“Pipeline” For Packet Forwarding: Fabric



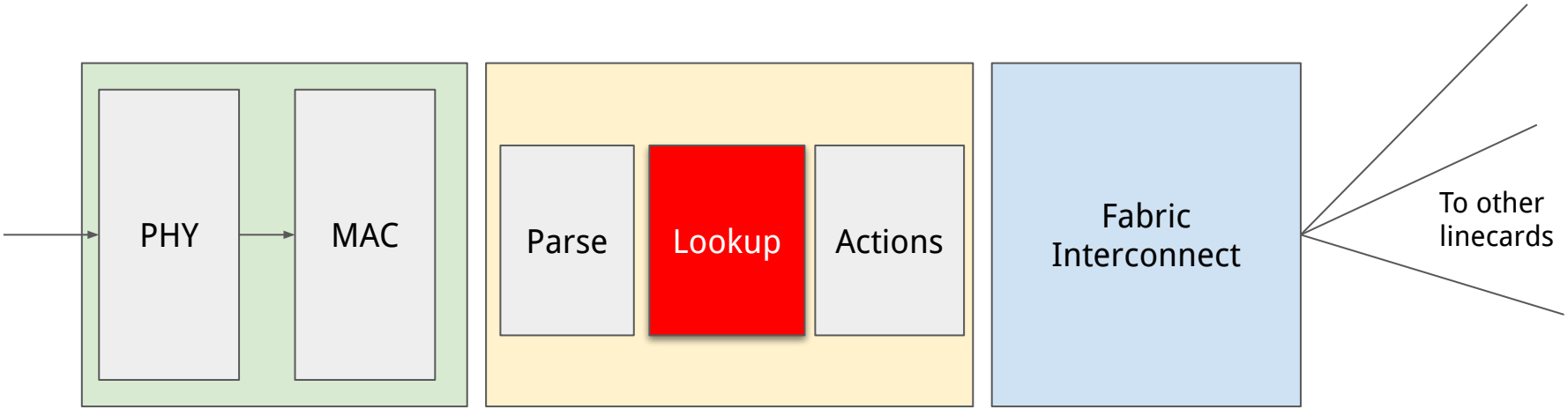
Forwarding Chips



Actions in Hardware

- **Easy to achieve:**
  - Checksum
  - Decrement TTL
- **More difficult:**
  - Options
    - Small number of cycles per packet on dedicated forwarding chips!
    - **Generally don’t use/allow options!**
  - Fragmentation
    - Achievable in hardware with some overhead.
    - **Typically avoided** (Internet MTU is 1500-bytes).

Focusing on lookups!



Core router functionality! This is our challenge!

Where should we send a packet?

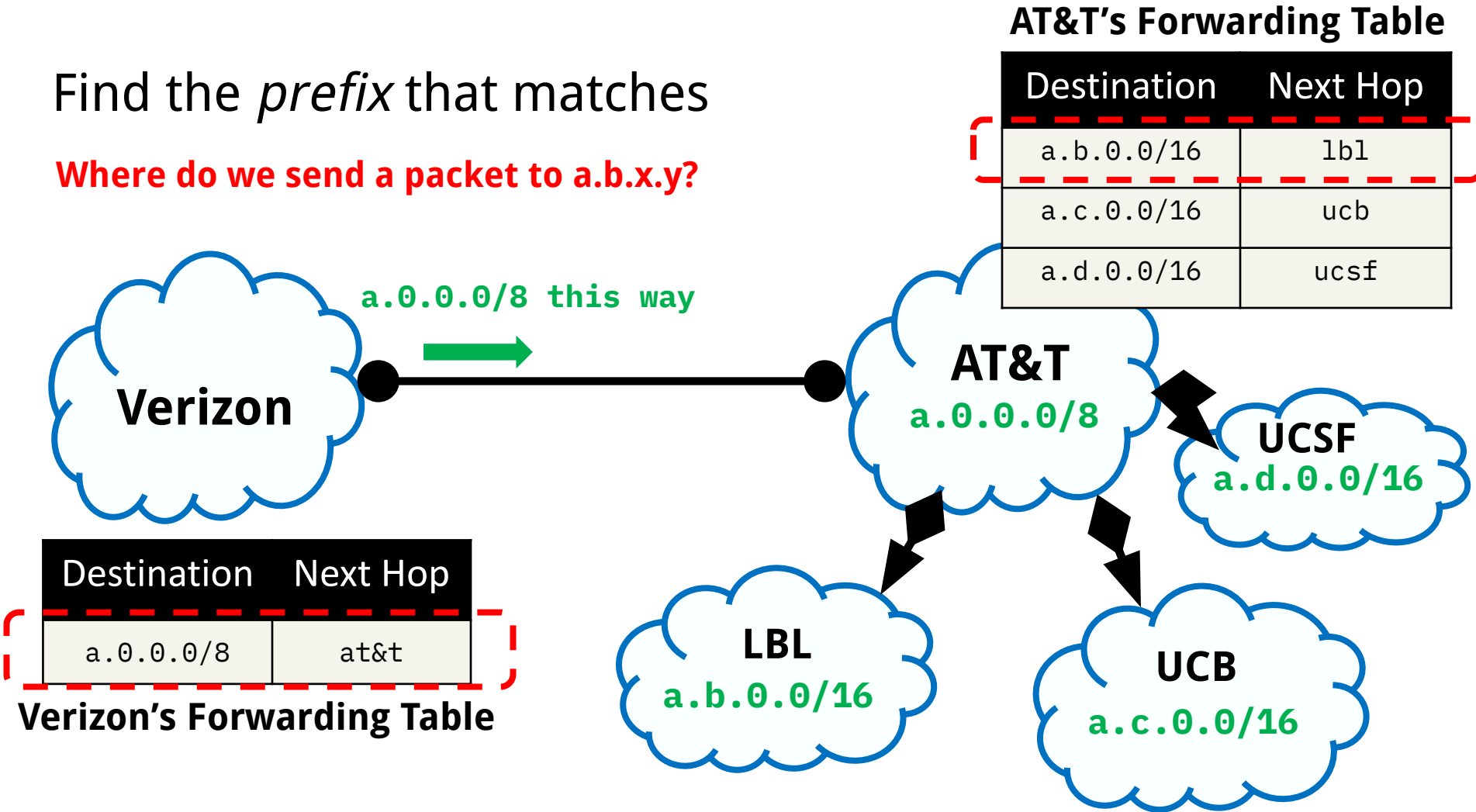
- Output lookups!

- Ideal? One lookup → forwarding entry.
  - Exact-match on destination IP - for O(1) lookups.
  - Forwarding table size?
  - Updating these tables - lots of entries to update!

- IP prefixes tend to be hierarchical.
  - Assigned IP addresses in a block to some ISP, and assigned to “downstream” networks.
  - Practically: /24 (256 address blocks) are the smallest we have on the Internet.
  - /32 (1 address) is the smallest internally though!
  - We can use compact tables that exploit this hierarchy – but lookups are more complex.

Find the *prefix* that matches

Where do we send a packet to a.b.x.y?

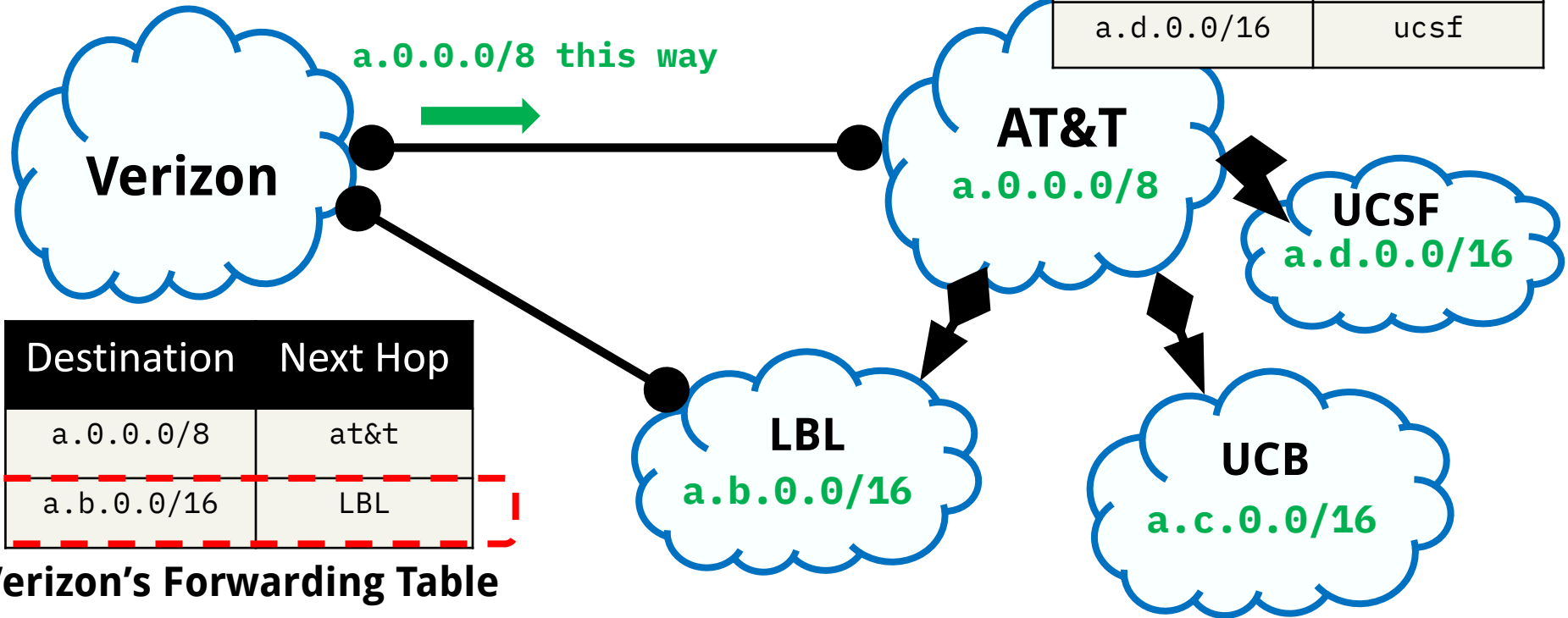


Find the **longest** *prefix* that matches

Where do we send a packet to a.b.x.y?

AT&T's Forwarding Table

Destination	Next Hop
a.b.0.0/16	lbl
a.c.0.0/16	ucb
a.d.0.0/16	ucsf



Destination	Next Hop
a.0.0.0/8	at&t
a.b.0.0/16	LBL

Verizon's Forwarding Table

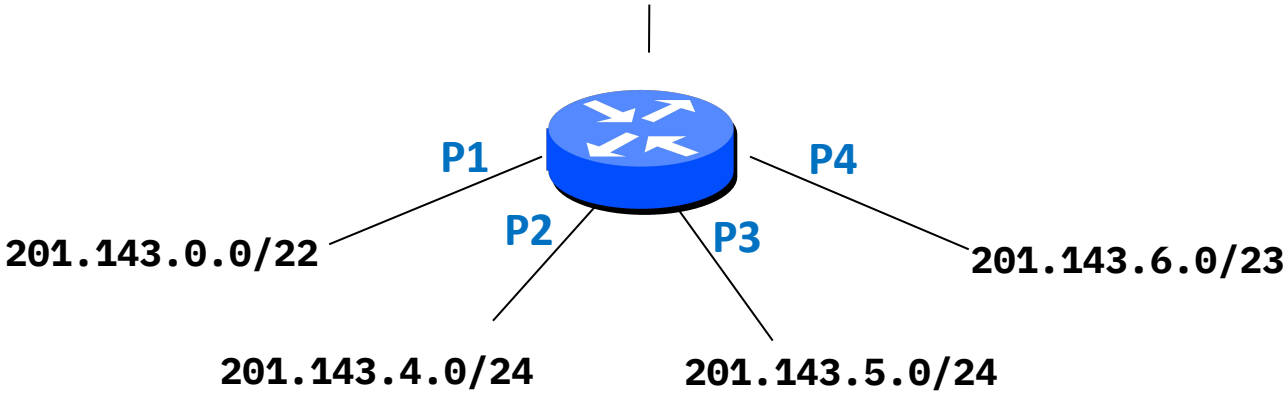
Longest Prefix Match (LPM)

Take the **most specific** route that matches.

- If address matches multiple prefixes, then take the **longest** match.
- If the address matches no prefixes, take the default route.
- If there’s no default route, drop the packet!

Questions?

Example #1: 4 prefixes, 4 ports



Prefix	Port
201.143.0.0/22	P1
201.143.4.0.0/24	P2
201.143.5.0.0/24	P3
201.143.6.0/23	P4

Finding a Matching Route

- Incoming packet destination: 201.143.7.210

Prefix	Port
201.143.0.0/22	P1
201.143.4.0.0/24	P2
201.143.5.0.0/24	P3
201.143.6.0/23	P4

Finding a Matching Route: Convert to Binary

- Incoming packet destination: 201.143.7.210

11001001	10001111	00000111	11010010

Routing table

201.143.0.0/22	11001001	10001111	000000––	–––––––
201.143.4.0/24	11001001	10001111	00000100	–––––––
201.143.5.0/24	11001001	10001111	00000101	–––––––
201.143.6.0/23	11001001	10001111	0000011–	–––––––

Finding a Matching Route: Convert to Binary

- Incoming packet destination: 201.143.7.210

11001001	10001111	00000111	11010010

Routing table

~~201.143.0.0/22~~	11001001	10001111	000000--	--------
201.143.4.0/24	11001001	10001111	00000100	-------
201.143.5.0/24	11001001	10001111	00000101	-------
201.143.6.0/23	11001001	10001111	000001--	-------

Finding a Matching Route: Convert to Binary

- Incoming packet destination: 201.143.7.210

11001001	10001111	00000111	11010010

Routing table

~~201.143.0.0/22~~	11001001	10001111	000000--	--------
~~201.143.4.0/24~~	11001001	10001111	00000100	
~~201.143.5.0/24~~	11001001	10001111	00000101	
201.143.6.0/23	11001001	10001111	00000110	-------

Longest Prefix Match

- Incoming packet destination: 201.143.7.210

Check an address against all prefixes and select the longest prefix it matches with

Routing table

201.143.0.0/22	11001001	10001111	000000--	
201.143.4.0/24	11001001	10001111	00000100	
201				
201				

NOT Check an address against all prefixes and find the one it matches *most bits* with

Finding a Match Efficiently

- Looking up against each entry scales poorly.
  - On average O(number of entries)
  - IPv4 Internet is ~1M prefixes!

- We can leverage the tree structure of binary strings.

Prefix	Port
11001001100011110000**0**********	1
11001001100011110000**100**********	2
11001001100011110000**101**********	3
11001001100011110000**11***********	4

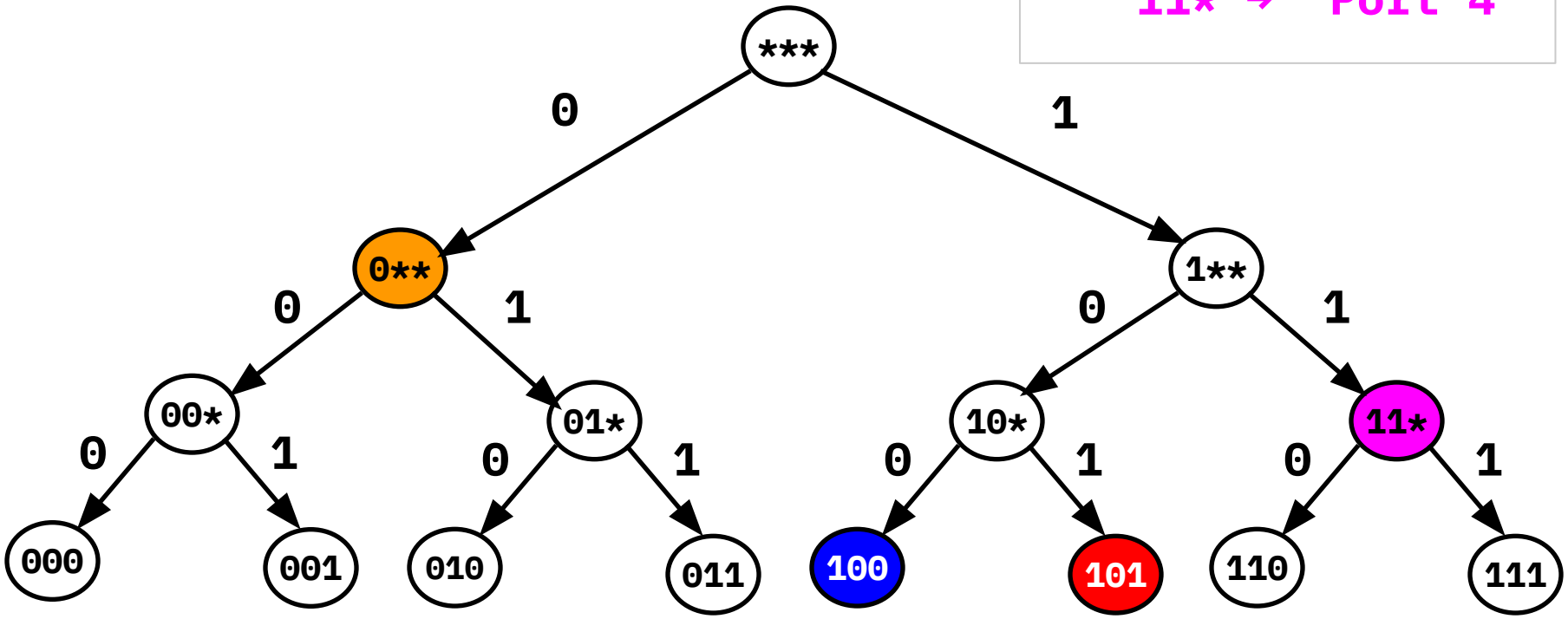
Considering the 3-bit prefixes…

- (We'll focus on where the differences are)

- `0**` → `Port 1`
- `100` → `Port 2`
- `101` → `Port 3`
- `11*` → `Port 4`

Prefix Tree

0** → Port 1
100 → Port 2
101 → Port 3
11* → Port 4



Prefix Tree

0** → Port 1
100 → Port 2
101 → Port 3
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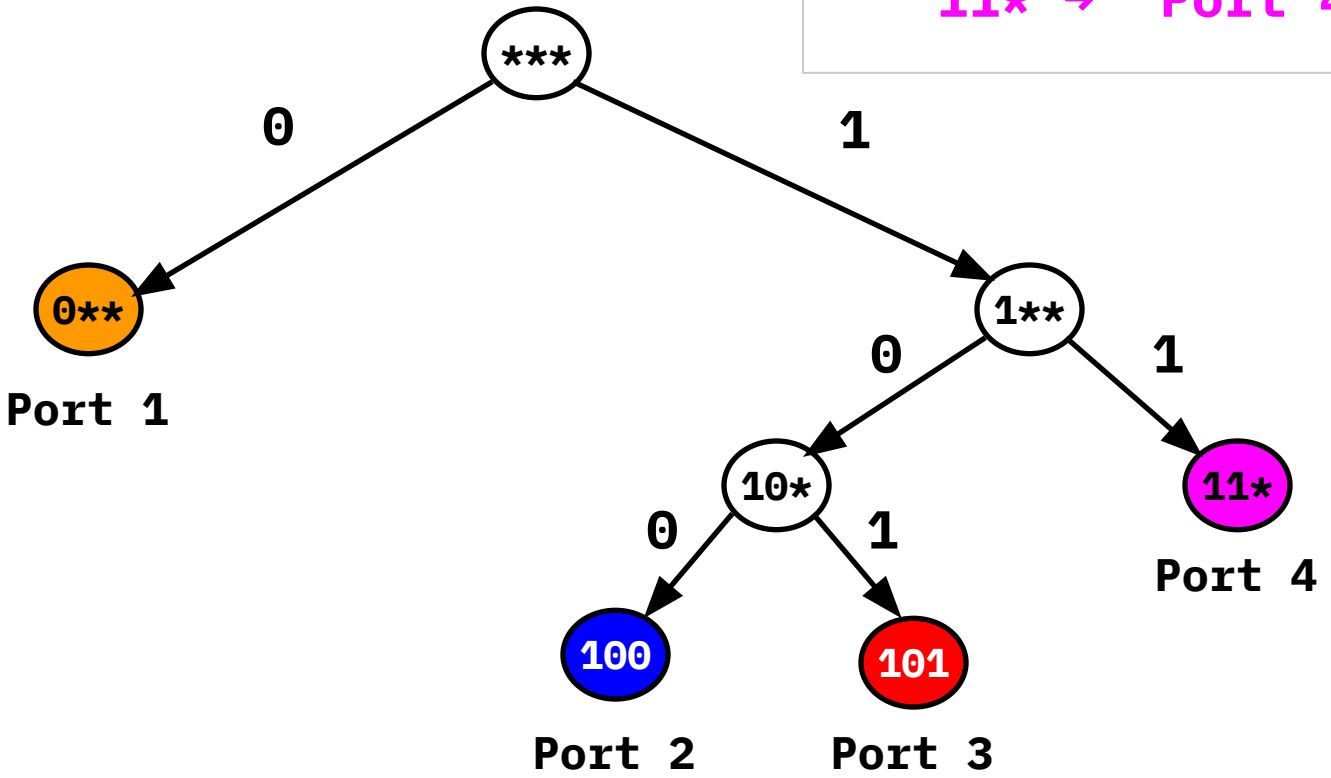
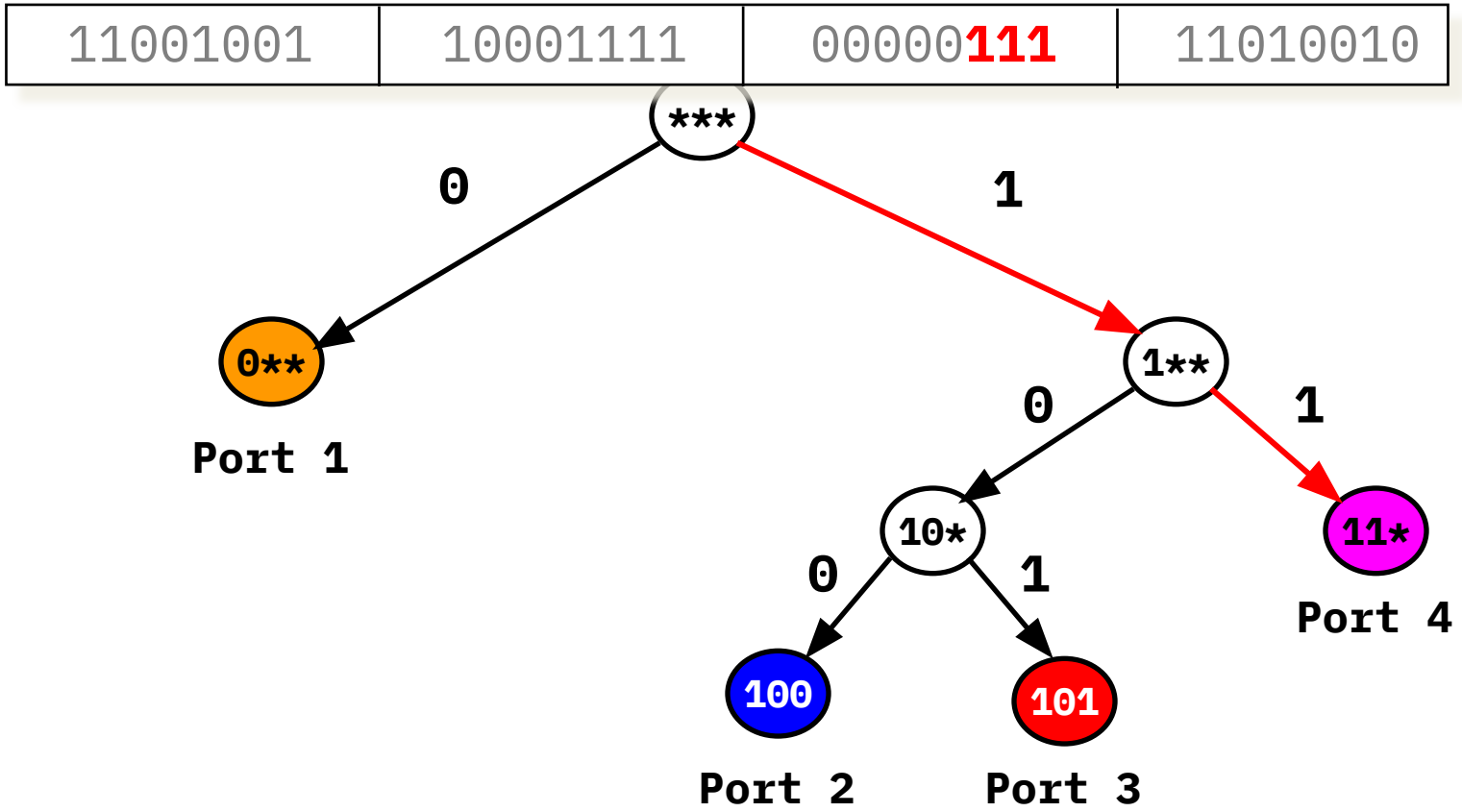


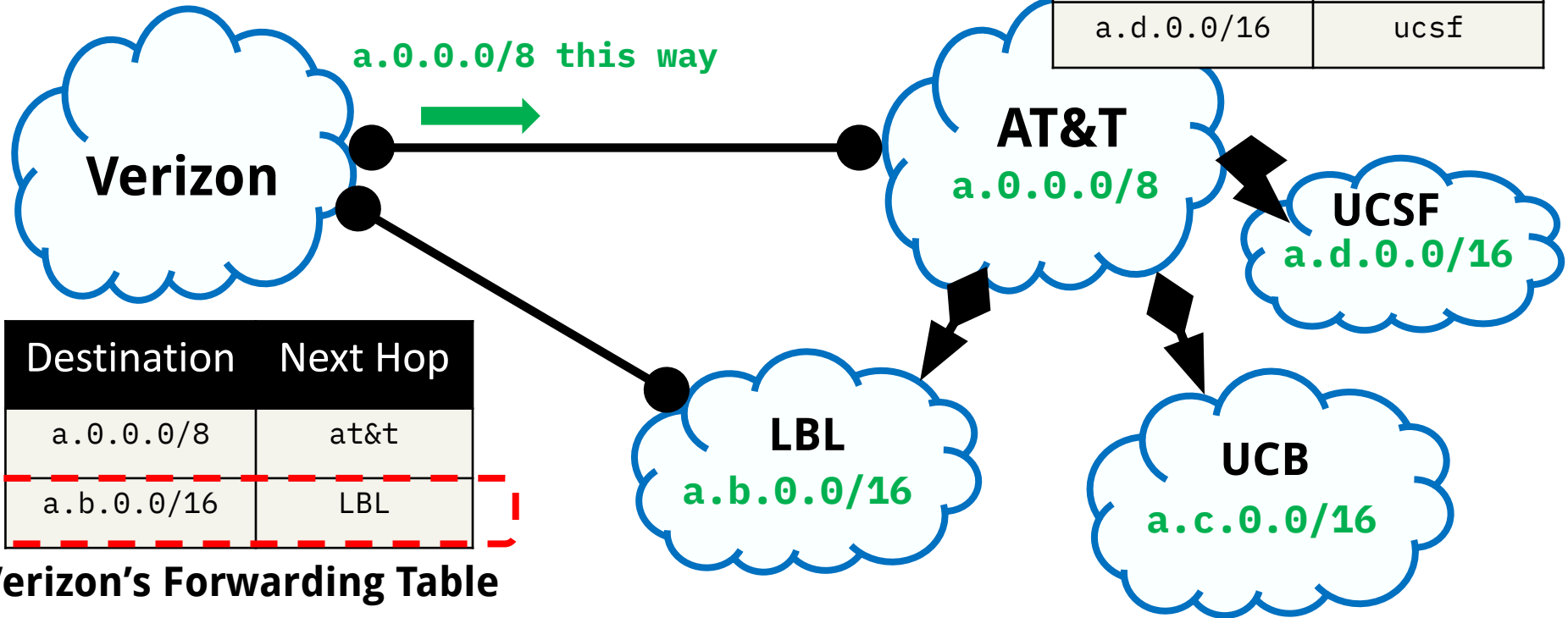
Prefix Match in the Tree



What about **multi-homing?**

AT&T's Forwarding Table

Destination	Next Hop
a.b.0.0/16	lbl
a.c.0.0/16	ucb
a.d.0.0/16	ucsf



Destination	Next Hop
a.0.0.0/8	at&t
a.b.0.0/16	LBL

Verizon's Forwarding Table

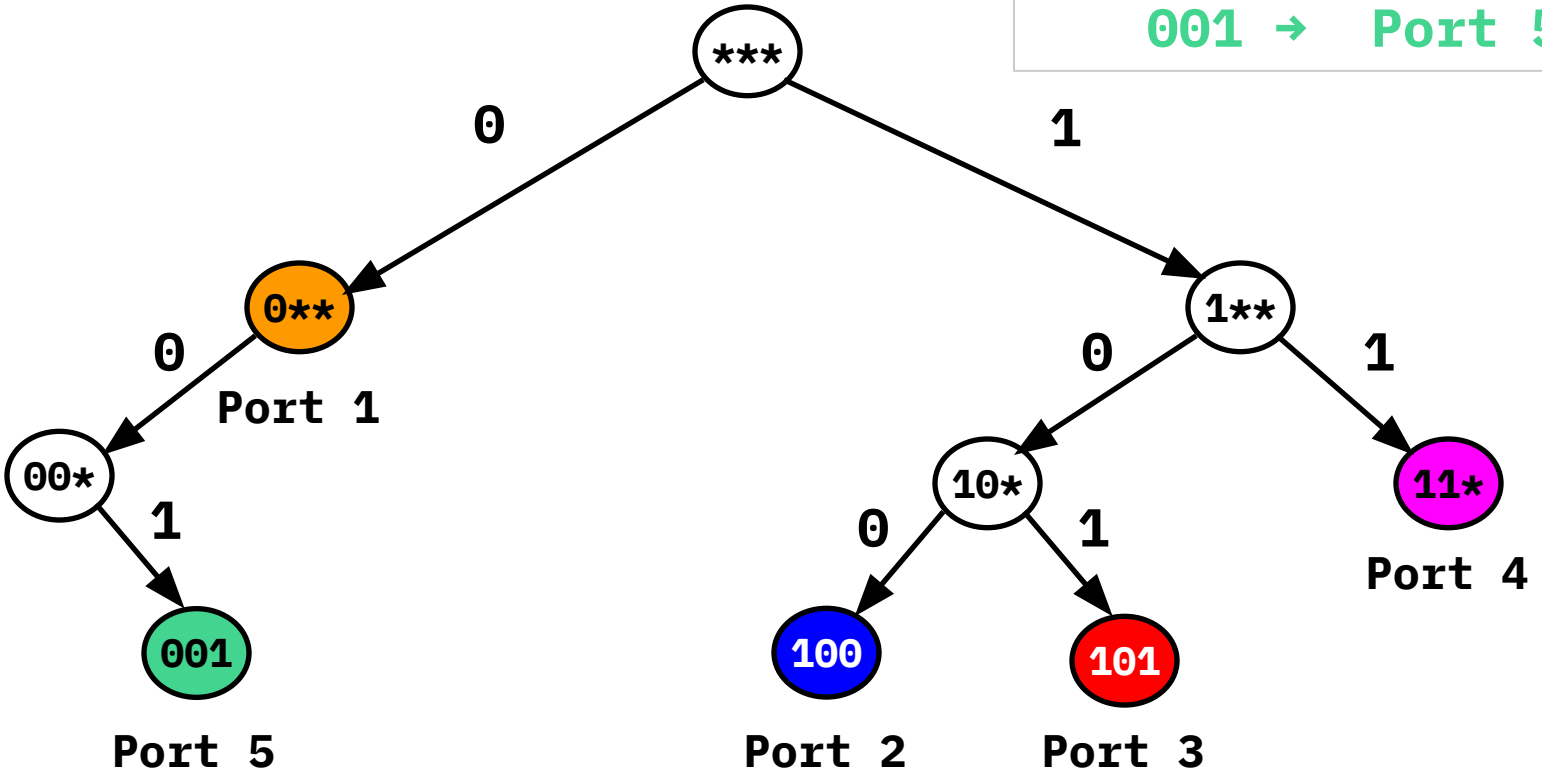
Some prefixes overlap

- Slightly different example - like Verizon.

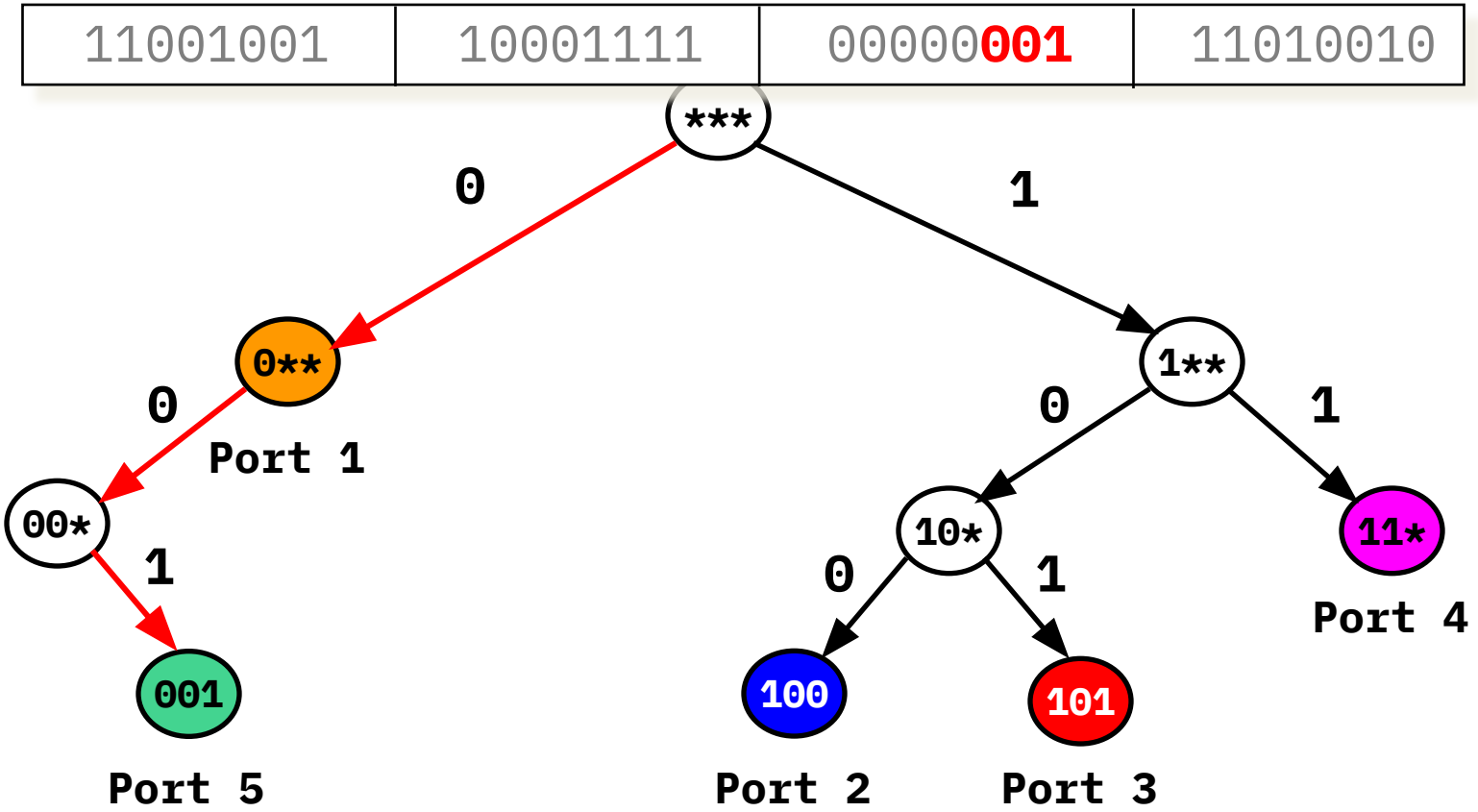
- `0** → Port 1`
- `100 → Port 2`
- `101 → Port 3`
- `11* → Port 4`
- `001 → Port 5`

Tree with overlapping entries.

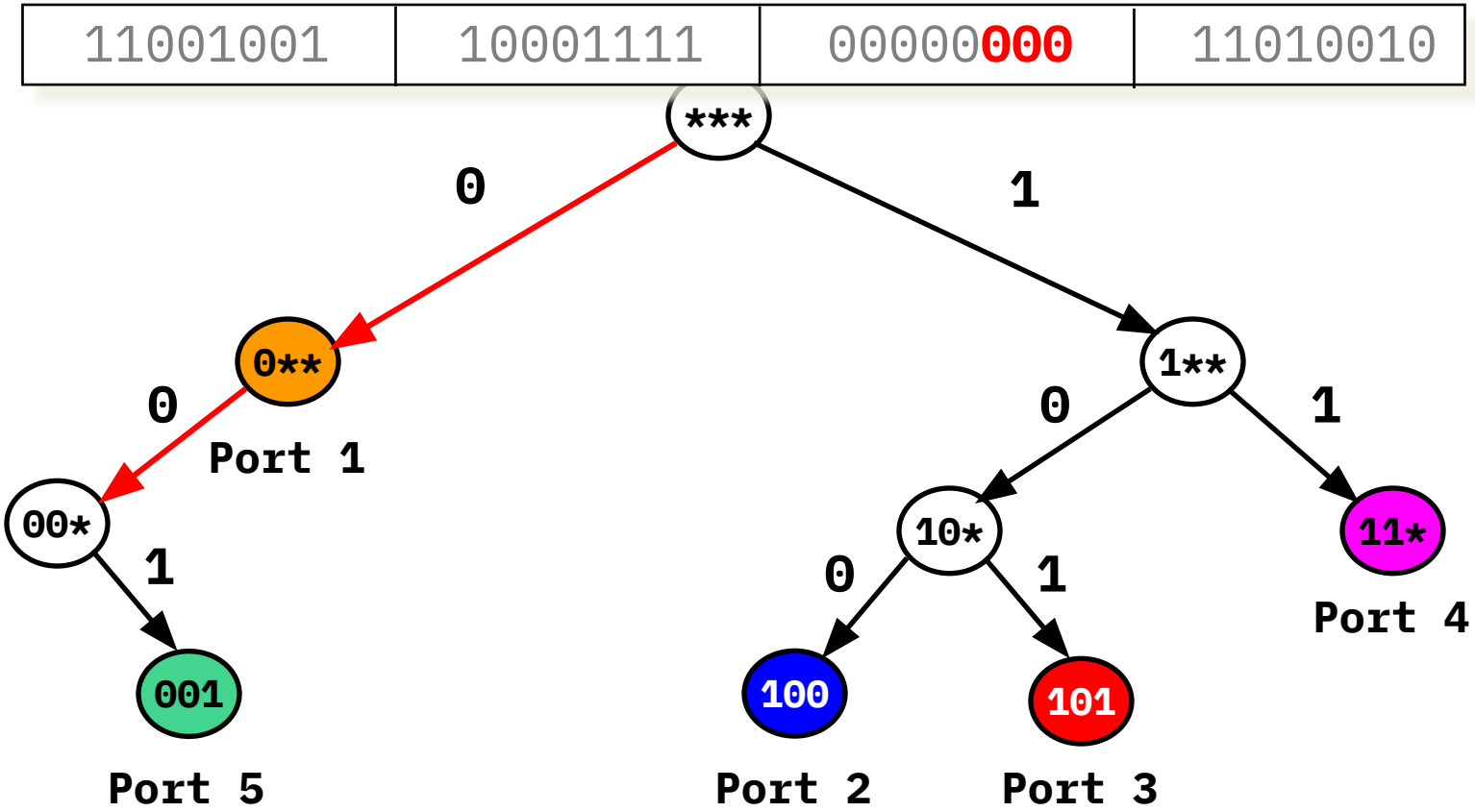
0**	→	Port 1
100	→	Port 2
101	→	Port 3
11*	→	Port 4
001	→	Port 5



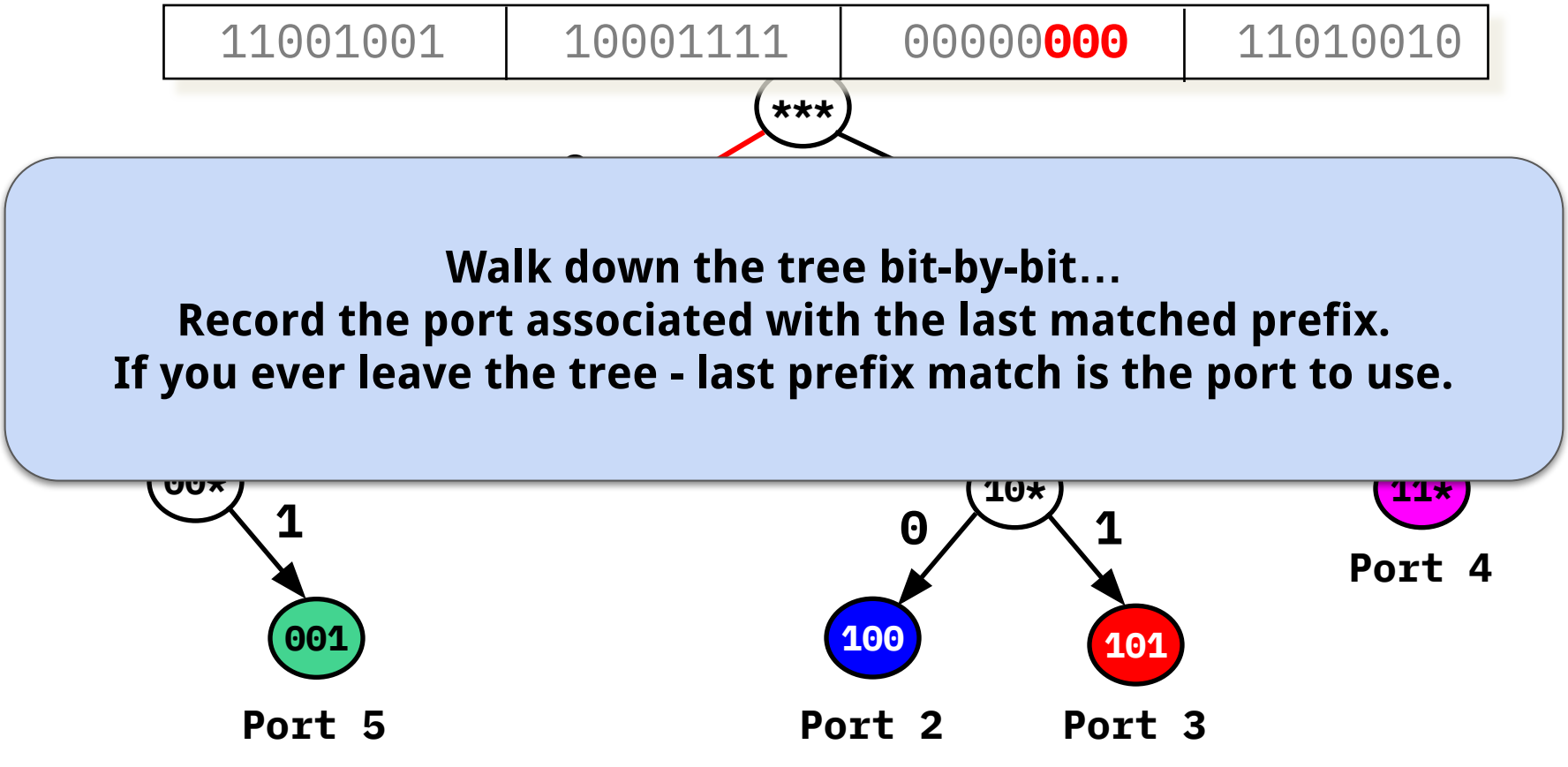
Example 1


11001001
10001111
00000001
11010010
***
0
1
0**
1**
0
Port 1
0
1
00*
10*
11*
1
0
1
Port 4
001
100
101
Port 5
Port 2
Port 3

Example 2


11001001
10001111
00000000
11010010
***
0
1
0**
0
Port 1
1**
0
1
00*
1
10*
11*
0
1
Port 4
001
100
101
Port 5
Port 2
Port 3

Longest Prefix Match



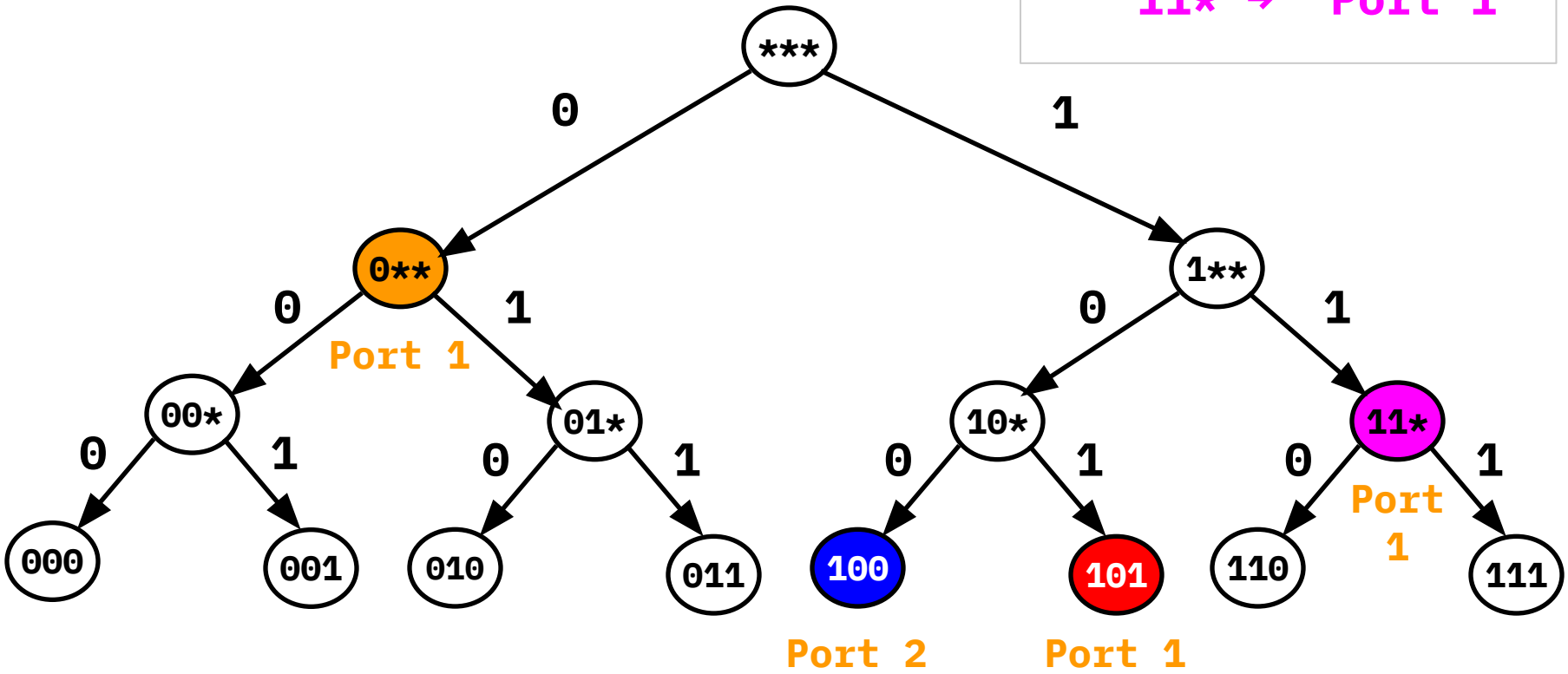
Several prefixes to the same port.

- More realistic Internet scenario.

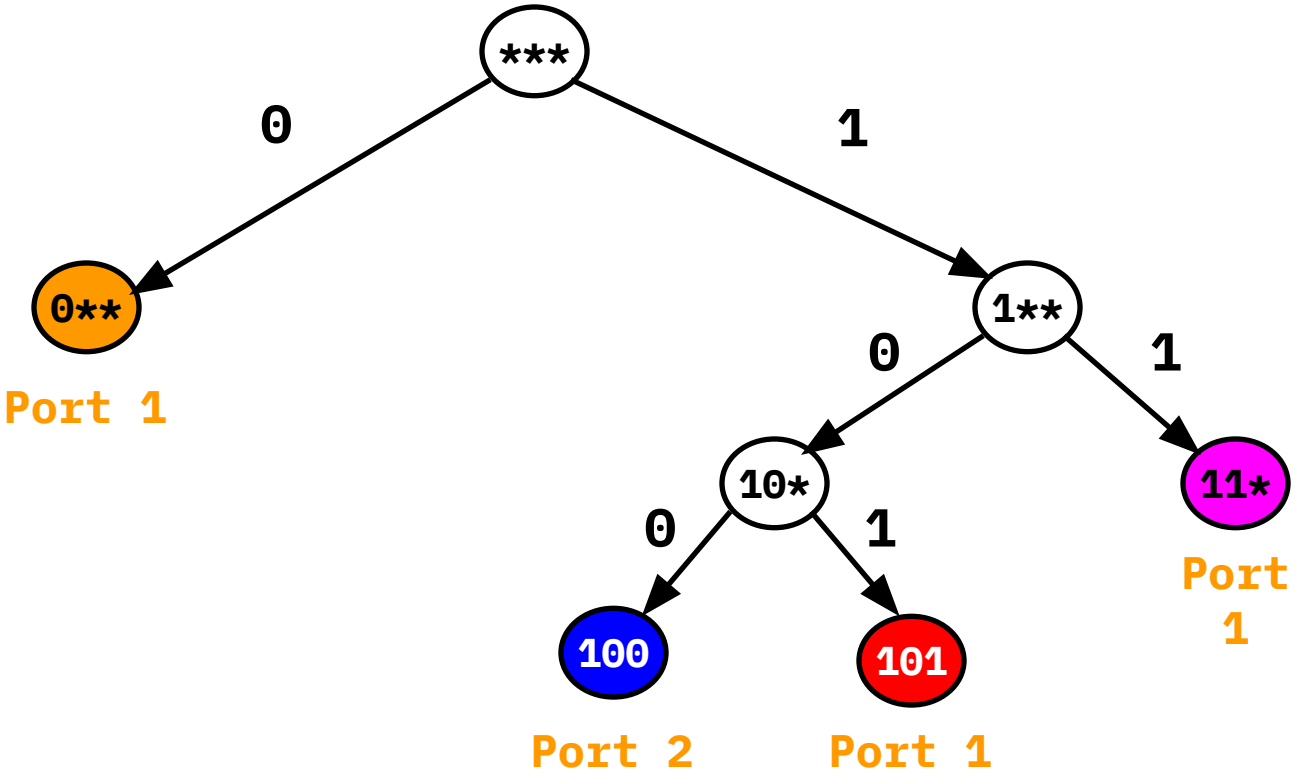
- `0** → Port 1`
- `100 → Port 2`
- `101 → Port 1`
- `11* → Port 1`

Prefix Tree

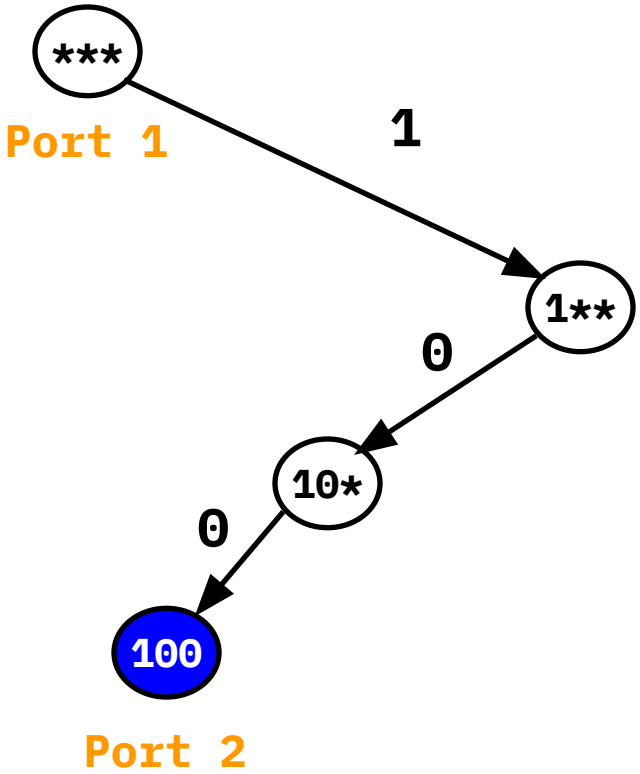
0** → Port 1
100 → Port 2
101 → Port 1
11* → Port 1



Normal Prefix Tree



A more compact representation.

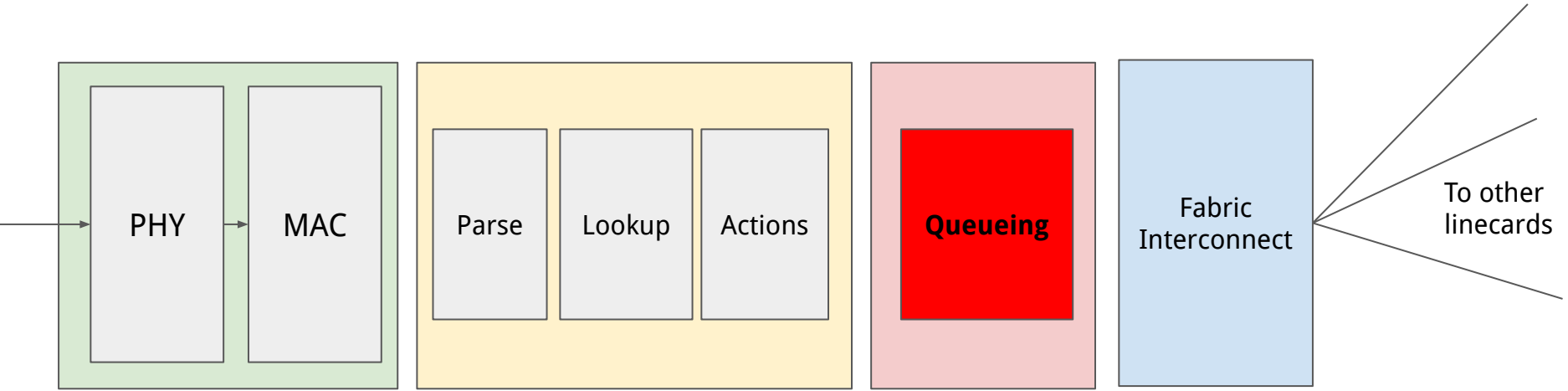


LPM in real routers

- All routers have this LPM functionality.
  - But use more advanced/complex solutions.

- Heuristics and optimisations can be made based on what is seen in the real internet.
  - Some destinations more popular than others.
  - Some ports have more destinations
  - Typical prefix sizes (recall: smallest IPv4 Internet prefix is /24).
  - Speed of update required.

Output Linecards: A wider picture



Packet Queueing

- Classification: what queue should this packet be put in to.
  - One queue per input port, one queue per marking on the packet (DSCP?)
- Buffer management.
  - Should we drop packets?
- Scheduling.
  - When should we transmit packets?

Traffic and queue management?

Our picture assumes the simplest possible!

- *No* classification
- *Drop-tail* buffer management: if the buffer is full, just drop the packet.
- *FIFO* scheduler - just send the packets in the order they arrive.

Many alternate (complex) scenarios - used to implement business objectives.

Recap: IP Routers

- Have different “planes”:
  - Control plane - programming forwarding entries and exception packets.
  - Management plane - configure and monitor router functionality.
  - Data plane - packet forwarding!

- Data plane leverages tradeoffs in software vs hardware packet processing.
  - Software: flexible but slow
  - Hardware: inflexible but fast

- Data plane challenges: speed!
  - Update packet header (easy)
  - LPM lookup on destination address (harder).