Forwarding
(after a little more addressing)

EE122 Fall 2011

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Materials with thanks to Jennifer Rexford, Ion Stoica, Vern Paxson
and other colleagues at Princeton and UC Berkeley

Agenda

- Dealing with address scarcity: DHCP, NAT
- Address Aggregation
- Conceptual issues
- Forwarding

Follow-up from last time

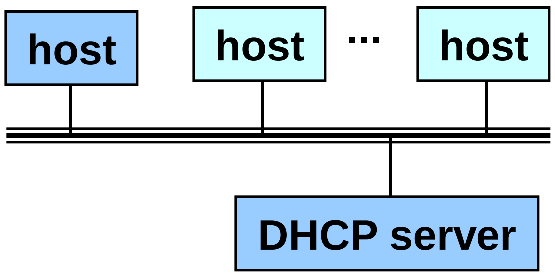
- **Giving back /8:**
  - That was Stanford, not Berkeley, that gave back a /8
  - Original ARPANET: UCLA, UCSB, Stanford, U. of Utah
  - LBL was involved in ARPANET later, but not Berkeley

- **Padding fragments?** (Offsets are multiples of 8)
  - Padding not needed!
  - Early fragments need to be multiples of 8
  - Last fragment need not be! Length field not multiple of 8
  - Put the leftover bits there….
  - Example: break 1303 bytes into 400+400+400+103

Dealing with Address Scarcity

Sharing a Block of Addresses

- Dynamic Host Configuration Protocol (DHCP)
  - Configures several aspects of hosts
  - Most important: assigns temporary address (lease)
  - Uses DHCP server to do allocation
  - Multiplexes block of addresses across users
- DHCP protocol:
  - Broadcast a server-discovery message (layer 2)
  - Server(s) sends a reply offering an address

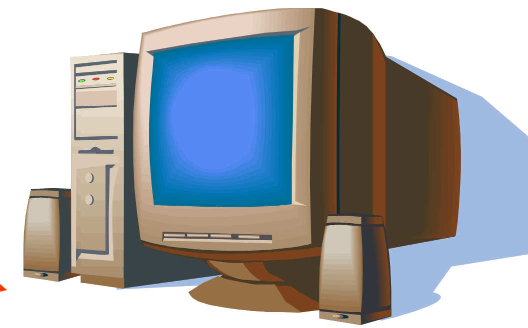


Response from the DHCP Server

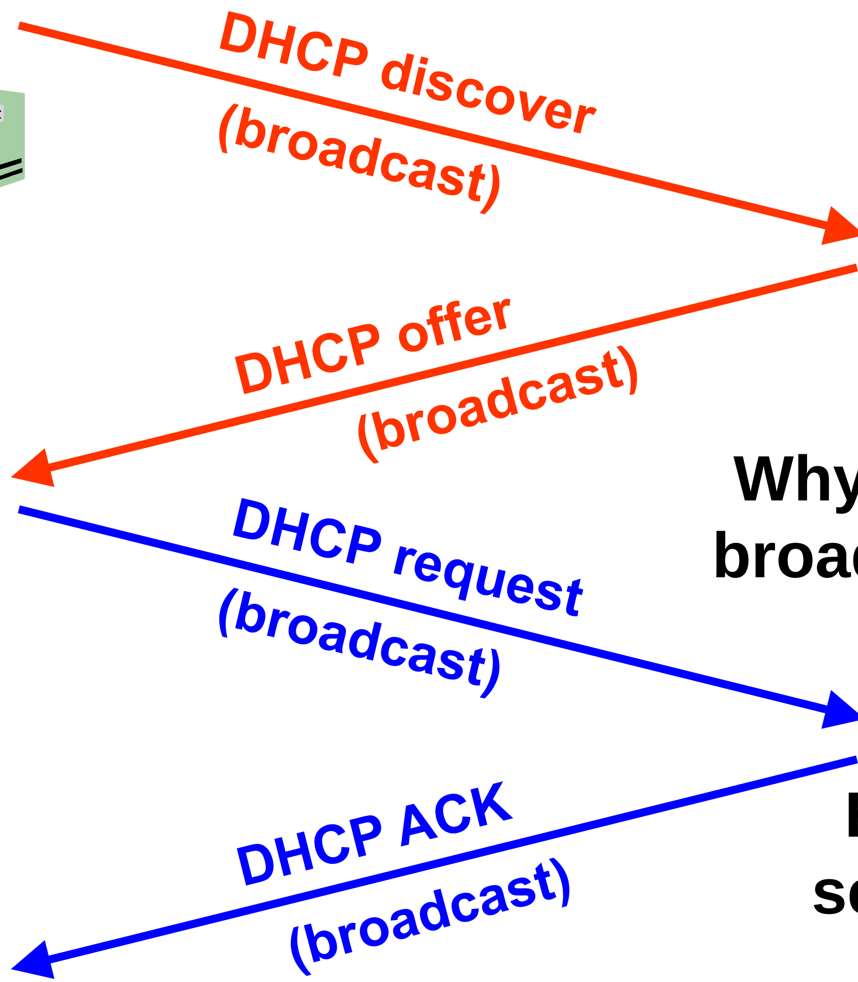
- DHCP "**offer**" message from the server
  - Configuration parameters (proposed IP address, mask, gateway router, DNS server, ...)
  - Lease time (duration the information remains valid)
- Multiple servers may respond
  - Multiple servers on the same broadcast network
  - Each may respond with an offer
- Accepting one of the offers
  - Client sends a DHCP "**request**" echoing the parameters
  - The DHCP server responds with an "**ACK**" to confirm
  - … and the other servers see they were **not** chosen

Dynamic Host Configuration Protocol

arriving
client



DHCP server
203.1.2.5



Why all the broadcasts?

How does DHCP send a broadcast?

Sending Broadcasts

- DHCP is at application layer
- Uses UDP transport protocol
- IP does not support global broadcasts
- And DHCP only wants local broadcast
- How to send local broadcast w/o violating layers?

Special-Purpose Address Blocks

- Limited broadcast
  - Sent to every host attached to the local network
  - Block: **255.255.255.255/32**
- Private addresses
  - By agreement, not routed in the public Internet
  - For networks not meant for general Internet connectivity
  - Blocks: **10.0.0.0/8**, **172.16.0.0/12**, **192.168.0.0/16**
- Link-local
  - By agreement, not forwarded by any router
  - Used for single-link communication only
  - Intent: autoconfiguration (especially when *DHCP* fails)
  - Block: **169.254.0.0/16**
- Loopback
  - Address blocks that refer to the local machine
  - Block: **127.0.0.0/8**
  - Usually only **127.0.0.1/32** is used

Back to DHCP: Uses "Soft State"

- Soft state: if not refreshed state will be forgotten
  - Install state with timer, reset timer when refresh arrives
  - Delete state if refresh not received when timer expires
  - Allocation of address is "soft state" (renewable lease)

- Why do you "lease" addresses?
  - Client can release the IP address (DHCP **RELEASE**)
    - E.g., "ipconfig /release" at the DOS prompt
    - E.g., clean shutdown of the computer
  - But, host might not release the address
    - E.g., the host crashes (blue screen of death!)
    - E.g., buggy client software
  - And you don't want the address to be allocated forever
  - *So if request isn't refreshed, server takes address back*

DHCP

- Allows you to share a set of addresses
  - As laptops come and go

- But does not solve problem when you have many permanent hosts and only one address….

Sharing Single Address Across Hosts

- Network Address Translation (NAT) enables many hosts to share a single address
  - Uses port numbers (fields in transport layer)
- Was thought to be an architectural abomination when first proposed, but it:
  - Probably saved us from address exhaustion
  - And reflects a modern design paradigm (indirection)
- But first, a word about ports….

How does a host handle packets?

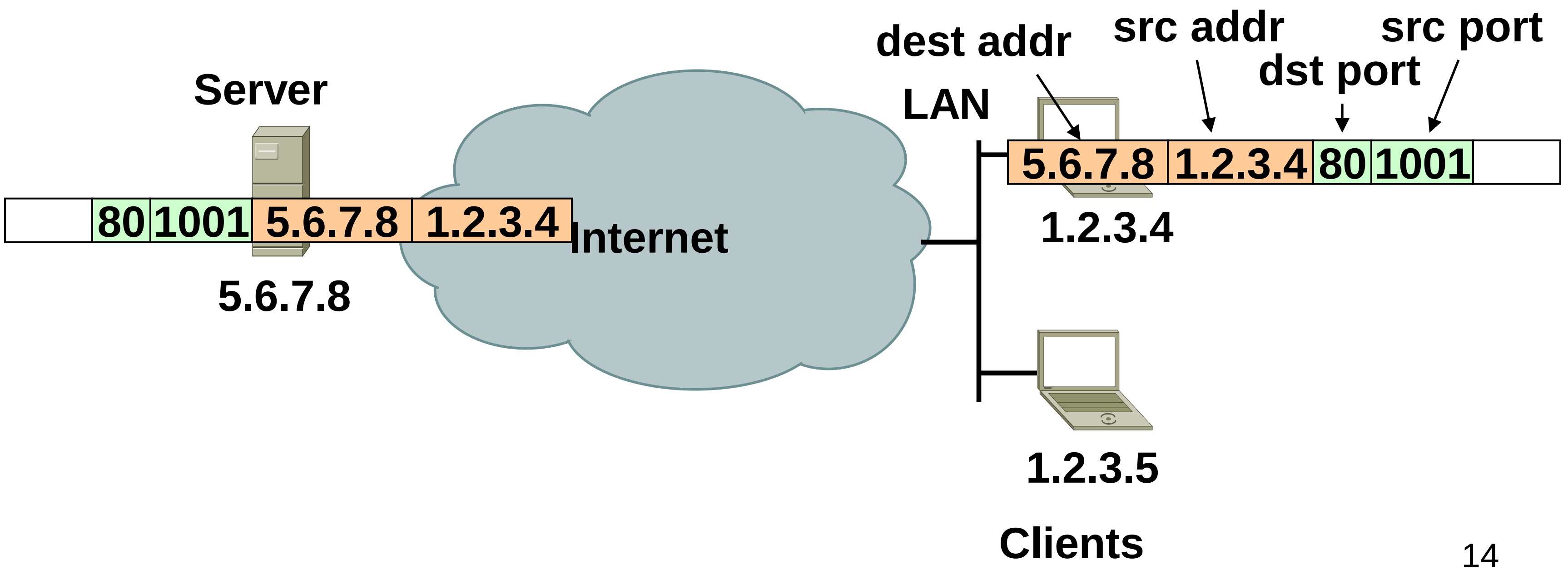
- Ethernet packet has EtherType field
  - Which protocol to hand payload to (e.g., IP)
- IP has Protocol field
  - Which protocol to hand payload to (e.g., UDP, TCP)
- Transport protocols have port numbers
  - **Which process to hand payload to**

Why?

- Source port and destination port both specified
  - Well-known ports: services such as HTTP (80), SSH (22)
    - What is port 17?
  - Ephemeral ports: for client instances, etc.

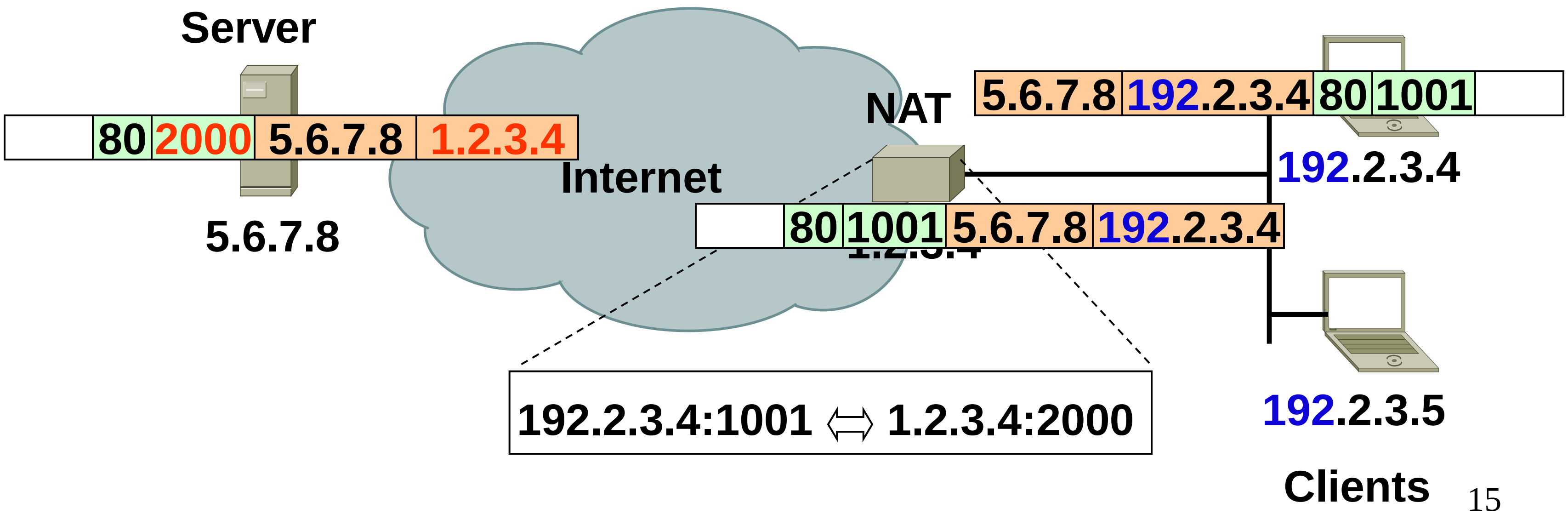
Network Address Translation (NAT)

Before NAT…every machine connected to Internet had unique IP address



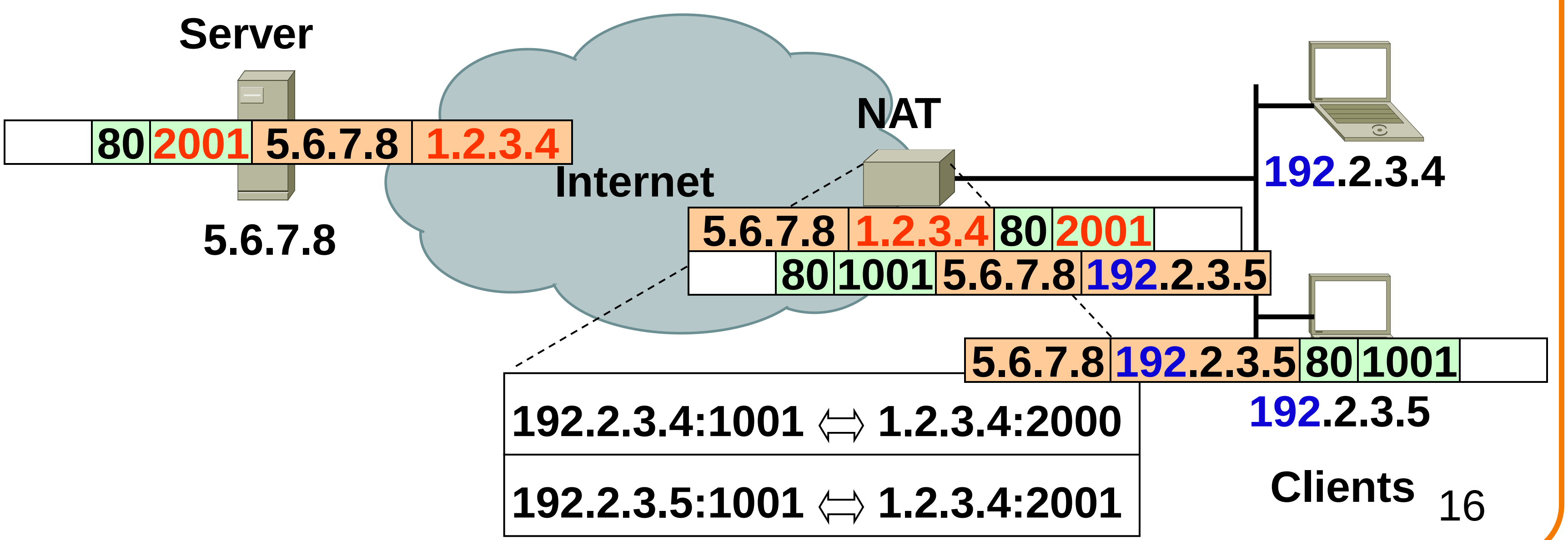
NAT (cont'd)

- Assign addresses to machines behind same NAT
  - Can be any private address range
  - e.g. **192.168.0.0/16**
- Use **port numbers** to multiplex single address



NAT (cont’d)

- Assign addresses to machines behind same NAT
  - Usually in address block **192.168.0.0/16**
- Use port numbers to multiplex single address



NAT: Early Example of "Middlebox"

- Boxes stuck into network to delivery functionality
  - NATs, Firewalls,….
- Don't fit into architecture, violate E2E principle
- But a very handy way to inject functionality that:
  - Does not require end host changes or cooperation
  - **Is under operator control (e.g., security)**
- An interesting architectural challenge:
  - How to incorporate middleboxes into architecture

More on Address Aggregation

Review of Addressing

- Notation: dotted quad (e.g., 16.45.231.117)
  - Set of four 8-bit numbers
- Structure: (prefix, suffix)
  - Network component (prefix)
  - Host component (suffix)
- Slash notation: /x means that prefix is x bits long
- Addressing schemes:
  - Original: prefix of length 8 (all addresses in /8s)
  - Classful: opening bits determined length of prefix

    E.g., 0 meant /8, 10 meant /16, 110 meant /24, 1110 meant mcast
  - **Classless (CIDR): explicit mask defines prefix**

CIDR Addressing

Use two 32-bit numbers to represent a network location
Address + Mask

IP Address : 12.4.2.1   IP Mask: 255.254.0.0

Address	00001100	00000100	00000010	00000001
Mask	11111111	11111110	00000000	00000000

|← Network Prefix →|← for hosts →|

CIDR Prefixes

Use two 32-bit numbers to represent a network prefix
Address + Mask

Prefix: 12.4.0.0 IP Mask: 255.254.0.0

Address	00001100	00000100	00000000	00000000
Mask	11111111	11111110	00000000	00000000

|← Network Prefix →|← for hosts →|

Written as 12.4.0.0/15 or 12.4/15

Allocation Done Hierarchically

- ICANN gives large blocks to...
- Regional Internet Registries, which give blocks to...
- Large institutions (ISPs), which give addresses to...
- Individuals and smaller institutions

- Examples:

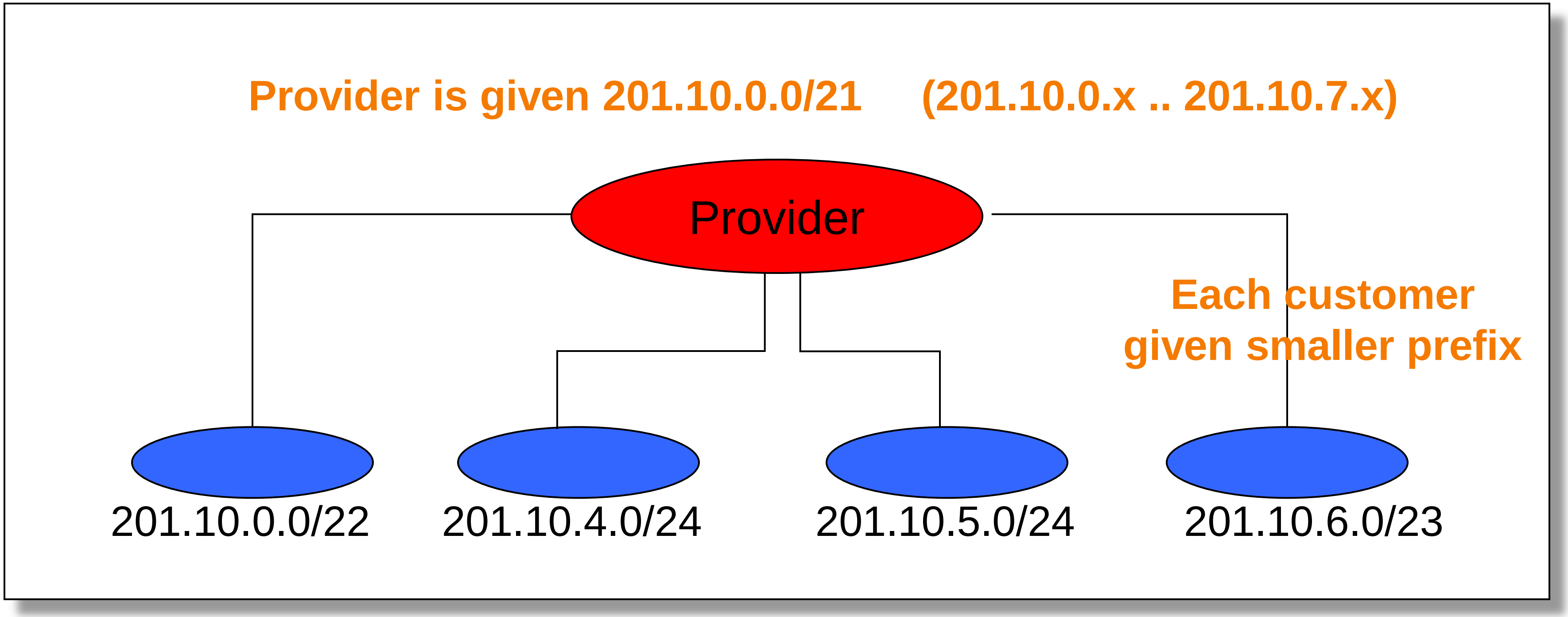
ICANN → ARIN → AT&T → Customer

ICANN → ARIN → UCB → Department

FAKE Example in More Detail

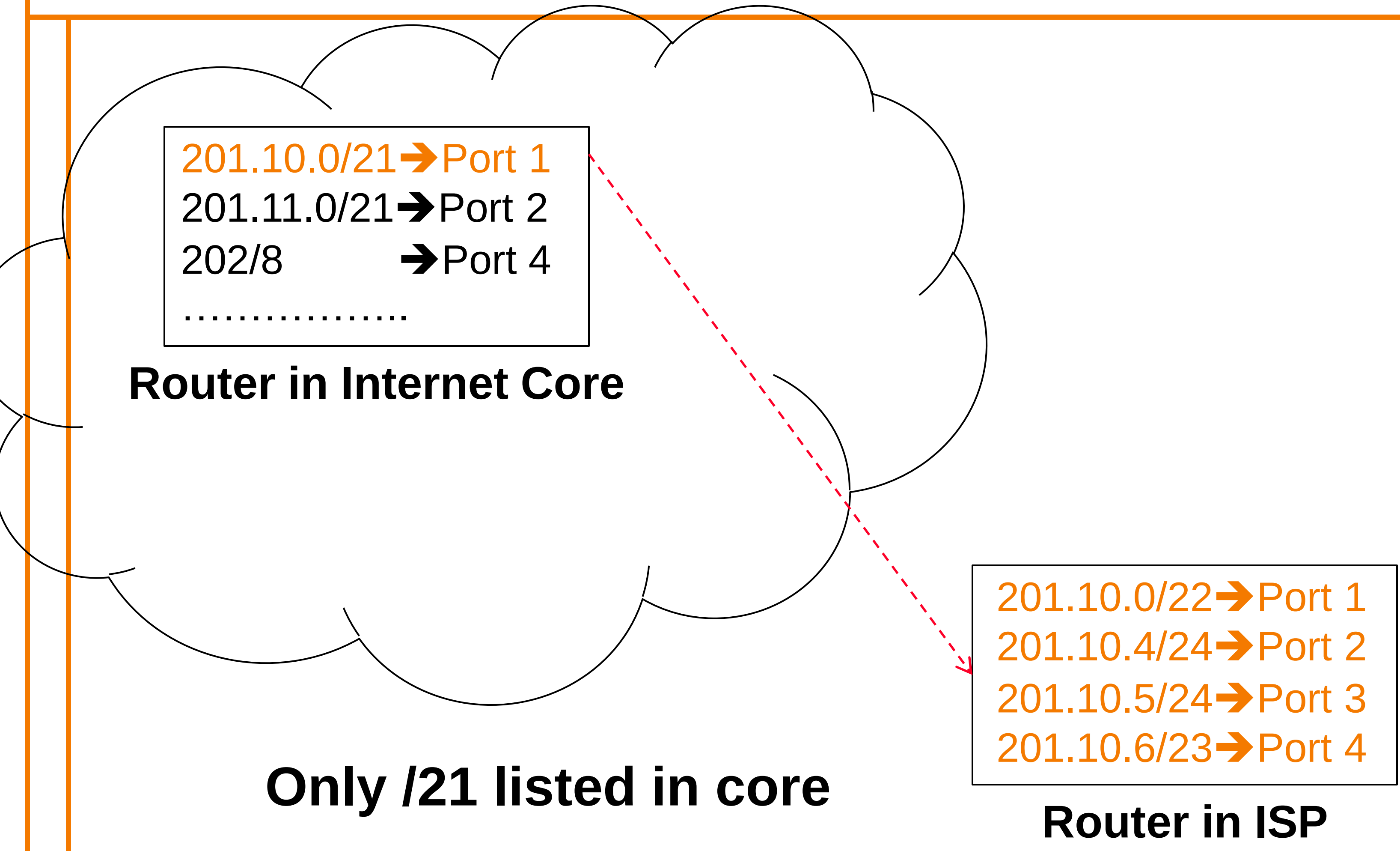
- ICANN gives ARIN several /8s, including **12.0/8**
  - **Network Prefix: 00001100**
- ARIN gives ACME Internet a /16, **12.197/16**
  - **Network Prefix: 0000110011000101**
- ACME give XYZ Hosting a /24, **12.197.45/24**
  - **Network Prefix: 000011001100010100101101**
- XYZ gives customer specific address **12.197.45.23**
  - **Address: 00001100110001010010110100010111**

Scalability via Address Aggregation



Routers in the rest of the Internet just need to know how to reach 201.10.0.0/21. The provider can direct the IP packets to the appropriate customer.

Global Picture



/22, /23, /24 only listed in ISP's router

Prefix Expansion

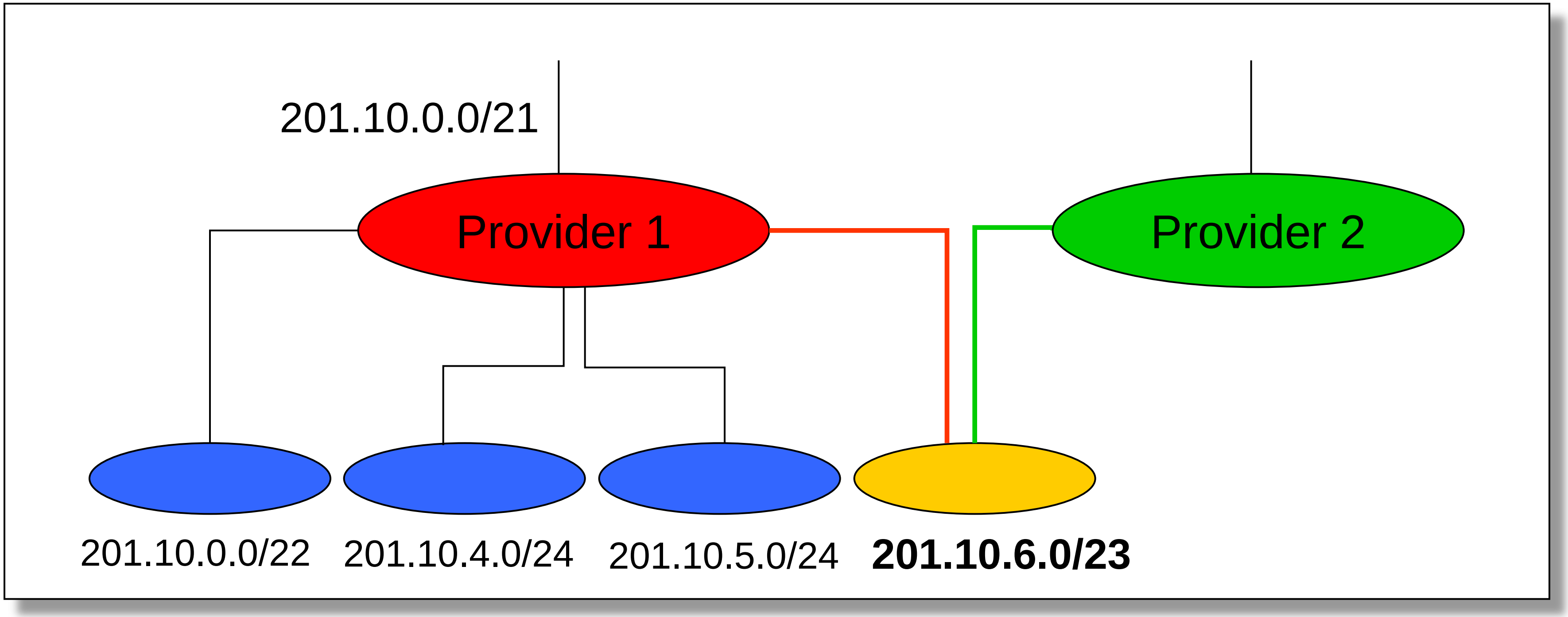
Original Prefix:

- 201.10.0/21=11001001|00001010|00000***|********

Subprefixes: (disjoint coverage of original prefix)

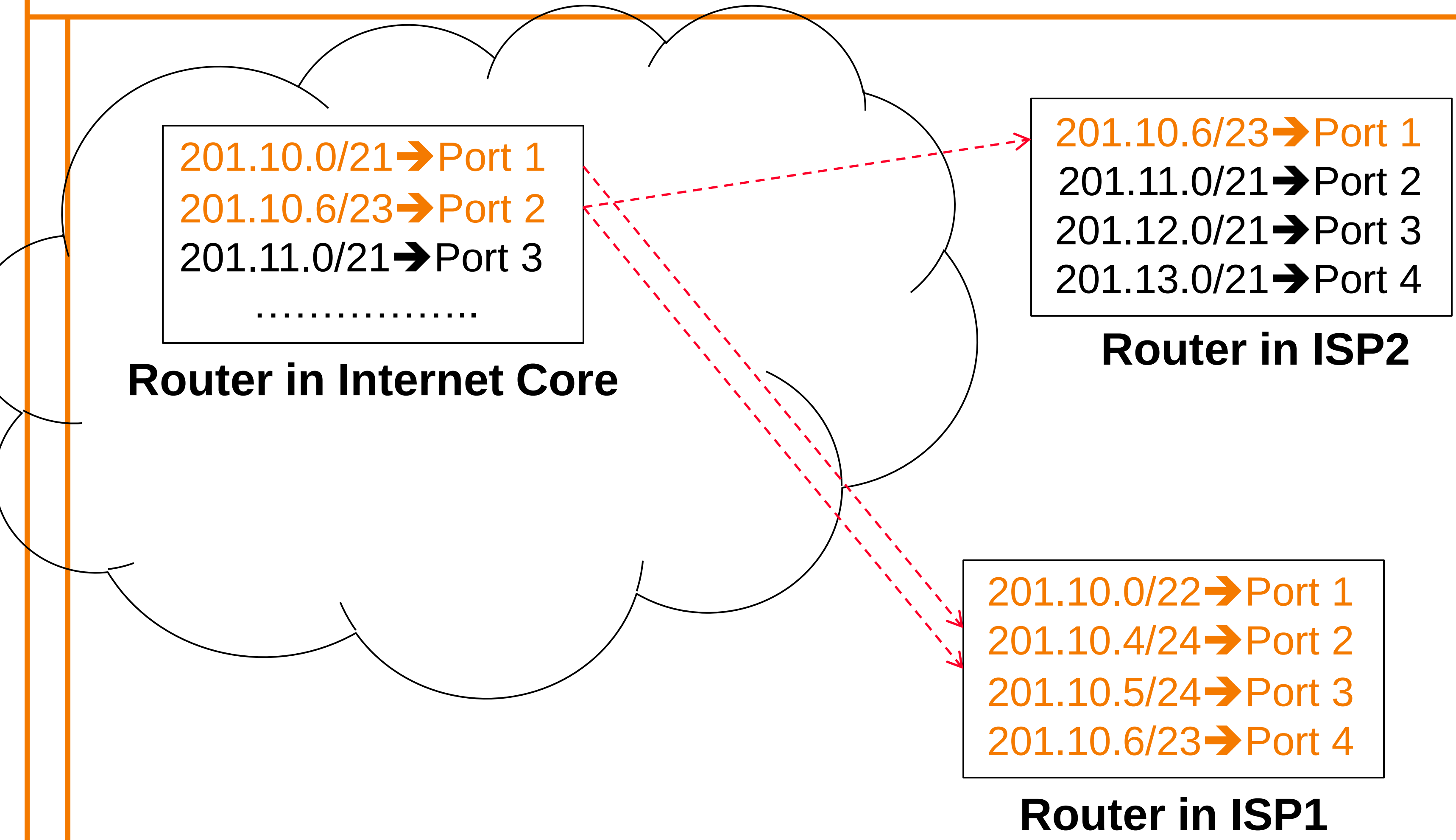
- 201.10.0/22=11001001|00001010|000000**|********
- 201.10.4/24=11001001|00001010|00000100|********
- 201.10.5/24=11001001|00001010|00000101|********
- 201.10.6/23=11001001|00001010|0000011*|********

Aggregation Not Always Possible



Multi-homed **customer with 201.10.6.0/23 has two providers. Other parts of the Internet need to know how to reach these destinations through *both* providers.**
⇒ /23 route must be globally visible

Multihoming Global Picture



Which ISP does core send 201.10.6/23 to?
It depends…..

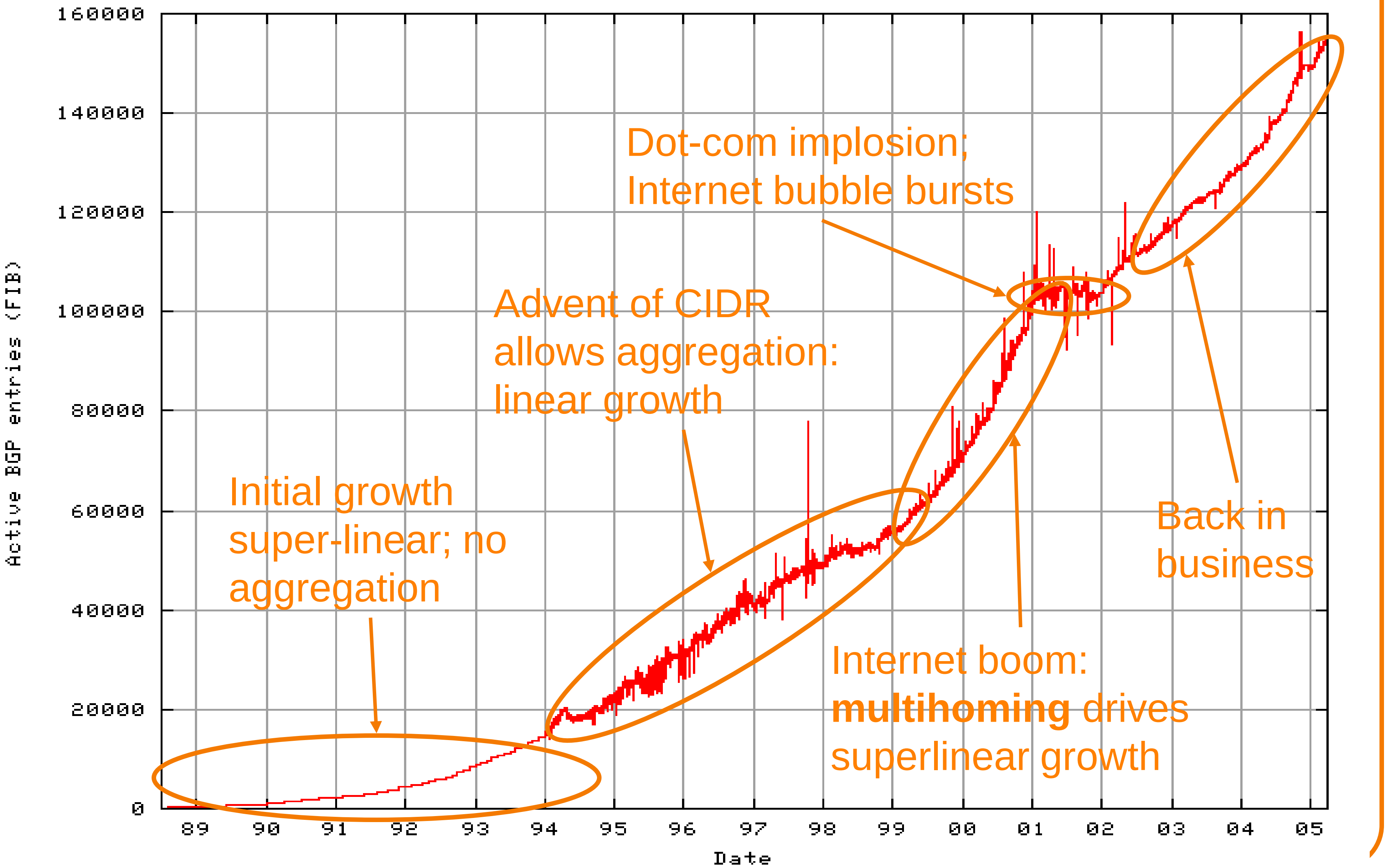
Addresses Advertised in Two Places?

- Provider 1 and Provider 2 both advertise prefix
  - That is, they both claim they can reach prefix
- What problems does this cause?
  - **None, in terms of basic connectivity!**
- DV: routers often offered two paths to destination
  - Pick the shorter path
- Here, situation is complicated by:
  - Length of prefix
  - Policy
- We will return to this example….
  - Focus now on multihoming as impediment to aggregation

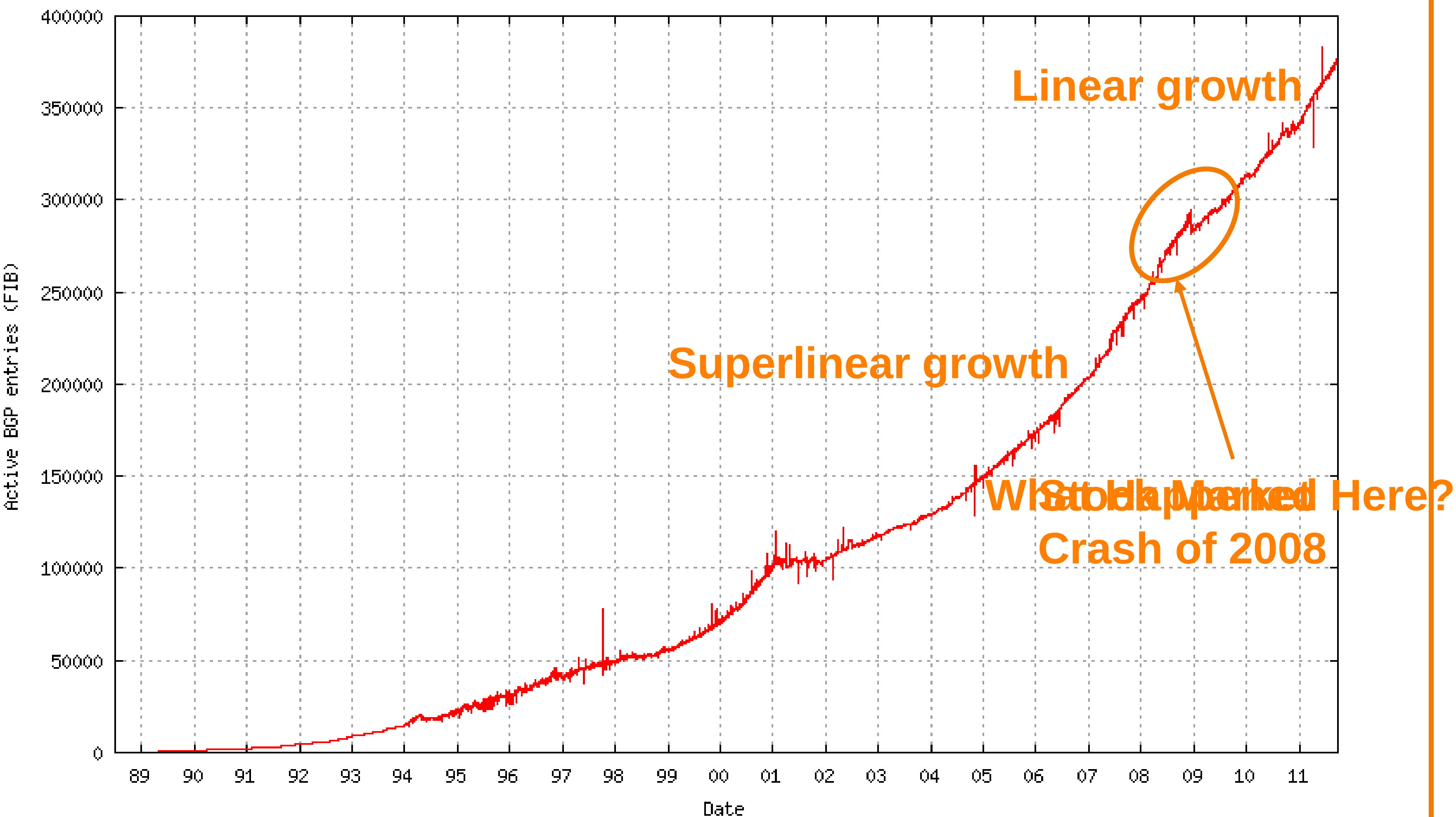
Two Countervailing Forces

- Aggregation reduces number of advertised routes
- Multi-homing increases number of routes

Growth in Routed Prefixes (1989-2005)



Same Table, Extended to Present



Summary of Addressing

- **Hierarchical** addressing
  - Critical for **scalable** system
  - Don't require everyone to know everyone else
  - Reduces amount of updating when something changes
- **Non-uniform** hierarchy
  - Useful for heterogeneous networks of different sizes
  - Class-based addressing was far too coarse
  - Classless InterDomain Routing (CIDR) more flexible
- **Any questions?**

Conceptual Problems with IP Addressing

What's Wrong with IP Addressing?

- Multihoming not naturally supported
  - Causes aggregation problems
- No binding to identity (spoofing, etc.)
- Scarce (IPv6 solves this)
- Forwarding hard (discuss later)
- …..

Design Exercise:

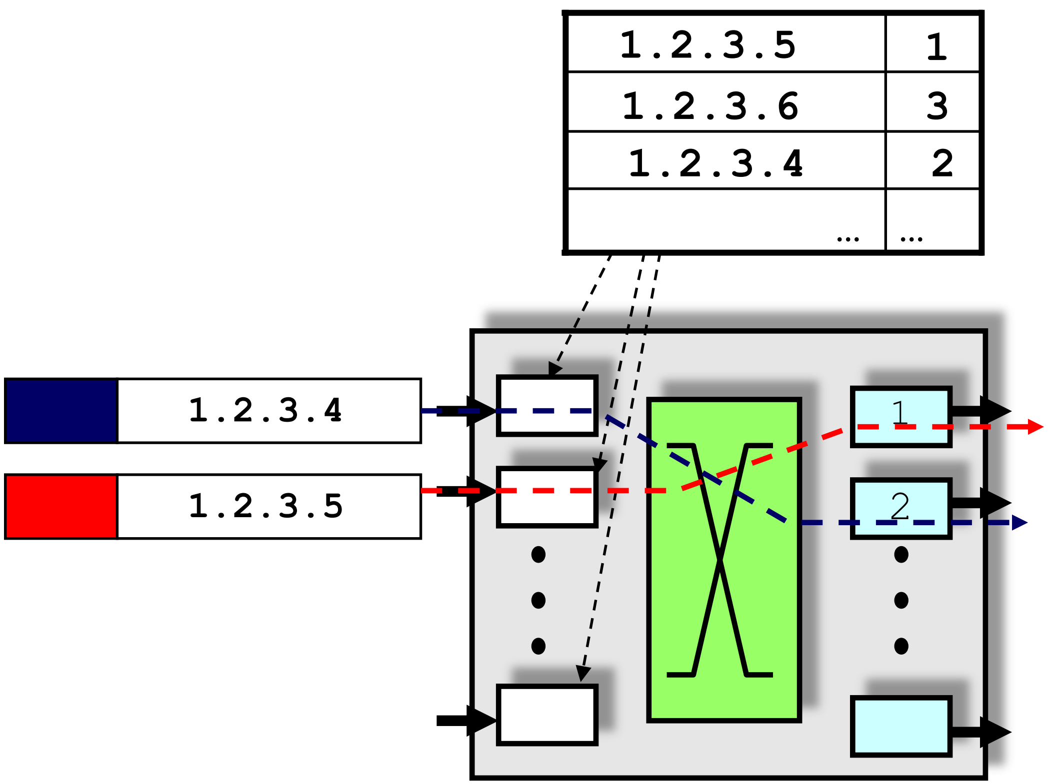
- Design better addressing scheme
- Take five minutes
- Work in groups
- Will take three proposals
- We will then vote on the winner….

5 Minute Break

Forwarding

Forwarding Table Plays Crucial Role

- Table maps IP addresses into output interfaces
- Forwards packets based on destination address



Hop-by-Hop Packet Forwarding

- Forwarding table derived from:
  - **Routing** algorithms (or static configuration)

- Upon receiving a packet
  - Inspect the destination IP address in the header
  - Index into the forwarding table
  - Forward packet out appropriate interface
  - If no match, take **default route**

- Default route
  - Configured to cover cases where no matches
  - Allows small tables at edge (w/o routing algorithms)
    - **if it isn't on my subnet, send it to my ISP**

Using the Forwarding Table

- With classful addressing, this is easy:
  - Early bits in address specify mask
    - Class A [0]: /8   Class B [10]: /16   Class C [110]: /24
  - Can find exact match in forwarding table
    - Use prefix as index into hash table

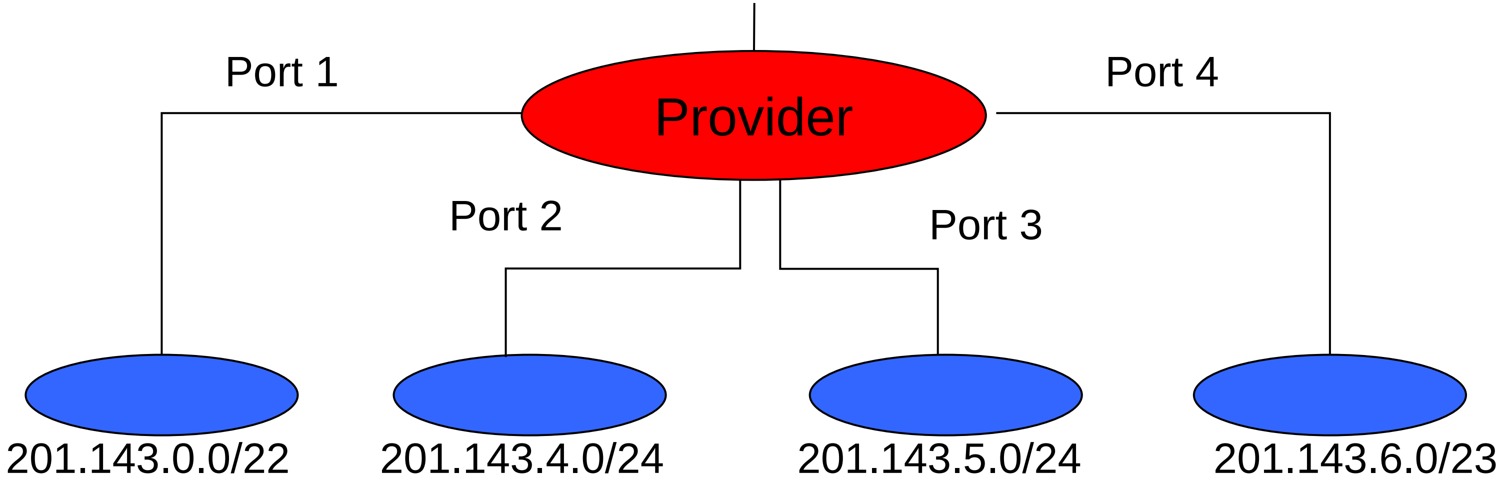
- Why won't this work for CIDR?
  - What's the network prefix in this address?

11001001100011110000010111010010

Finding Matches

- If address fields contained masks…
  - …we could do an exact match on network portion!
- But address in packet doesn't specify mask!
  - **Would just take five bits!**
- All delicacy of forwarding lookups due to CIDR
  - ***Lack of mask prevents easy exact match over prefix***

Example #1: Provider w/ 4 Customers



Prefix	Port
201.143.0.0/22	Port 1
201.143.4.0.0/24	Port 2
201.143.5.0.0/24	Port 3
201.143.6.0/23	Port 4

Finding the Match (at ISP's Router)

- No address matches more than one prefix
  - But can't easily find match

Prefix				
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-	--------

- Consider 11001001100011110000010111010010
  - First 21 bits match 4 partial prefixes
  - First 22 bits match 3 partial prefixes
  - First 23 bits match 2 partial prefixes
  - First 24 bits match exactly one full prefix

Finding Match Efficiently

- Testing each entry to find a match scales poorly
  - On average: (number of entries) × ½ (number of bits)
- Leverage tree structure of binary strings
  - Set up tree-like data structure
- Return to example:

Prefix	Port
1100100110001111000000************	1
110010011000111100000100********	2
110010011000111100000101********	3
11001001100011110000011*********	4

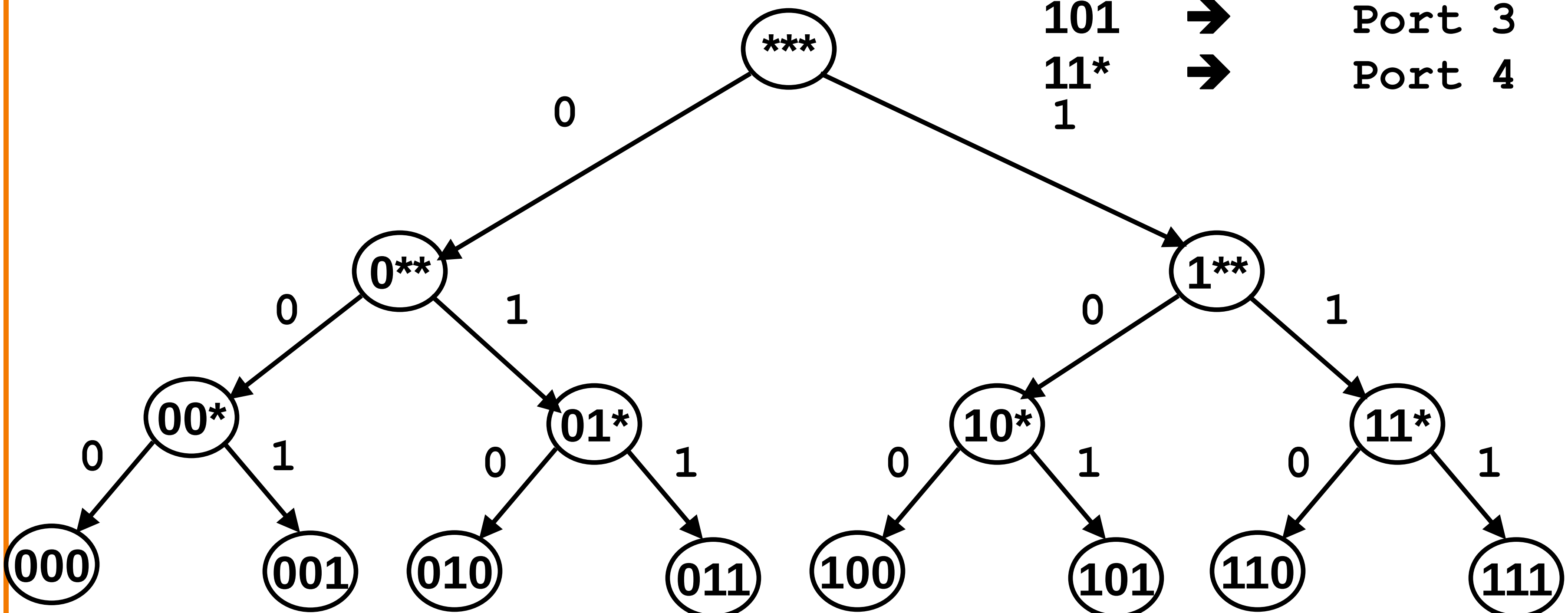
Consider four three-bit prefixes

- Just focusing on the bits where all the action is….

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

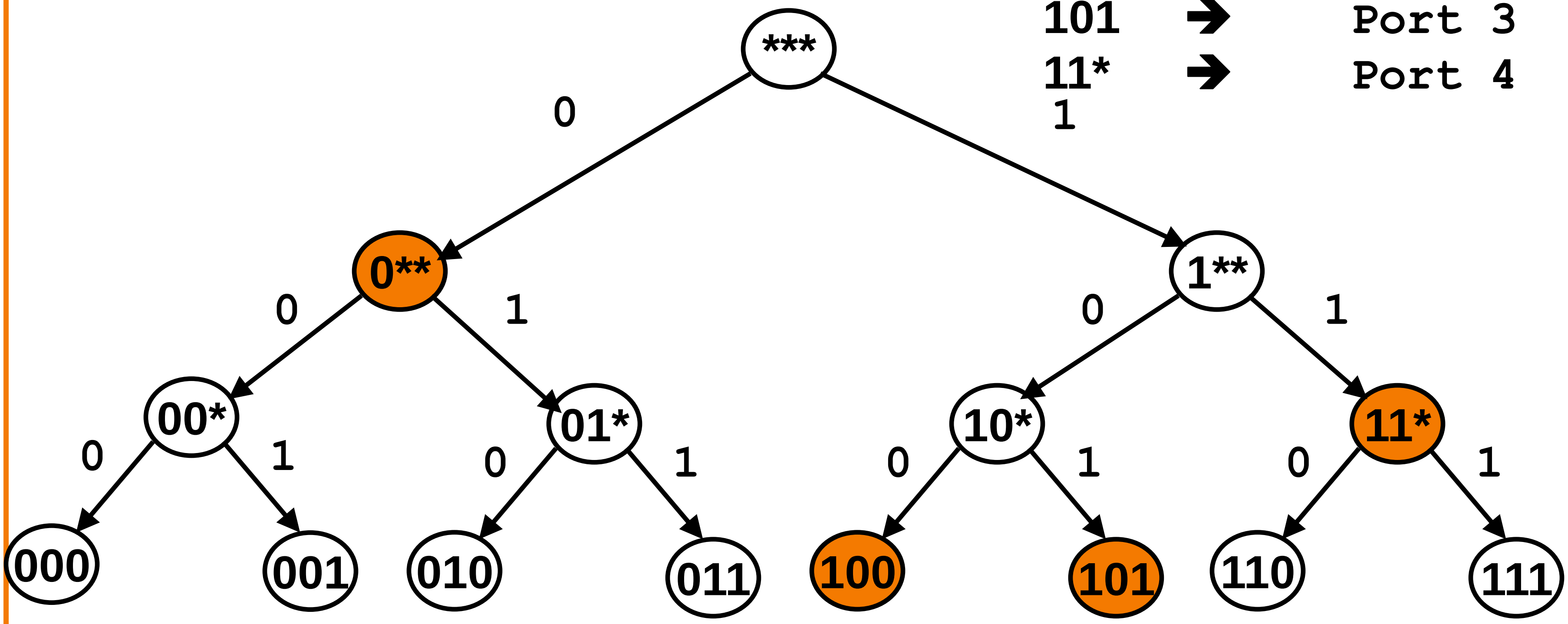
Tree Structure

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



Walk Tree: Stop at Prefix Entries

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



Walk Tree: Stop at Prefix Entries

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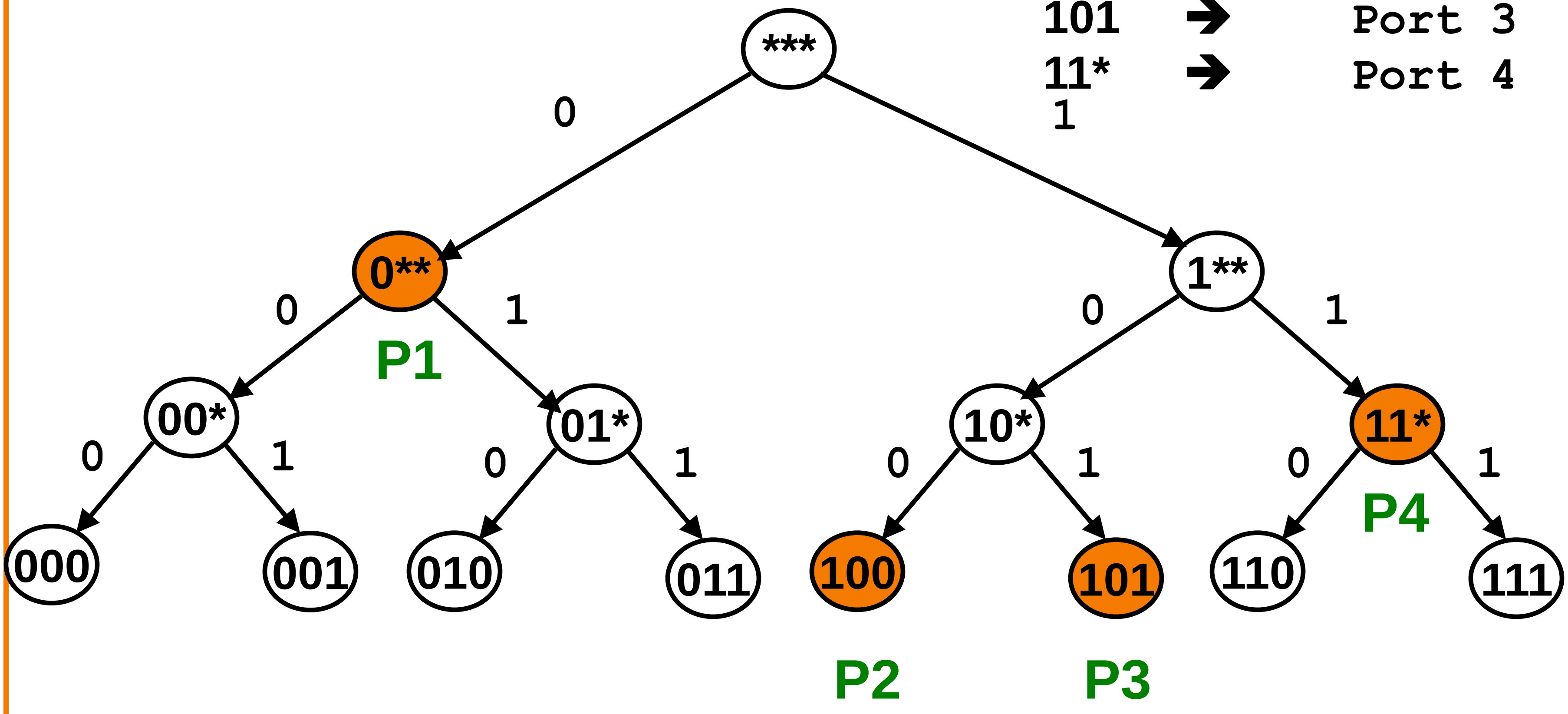
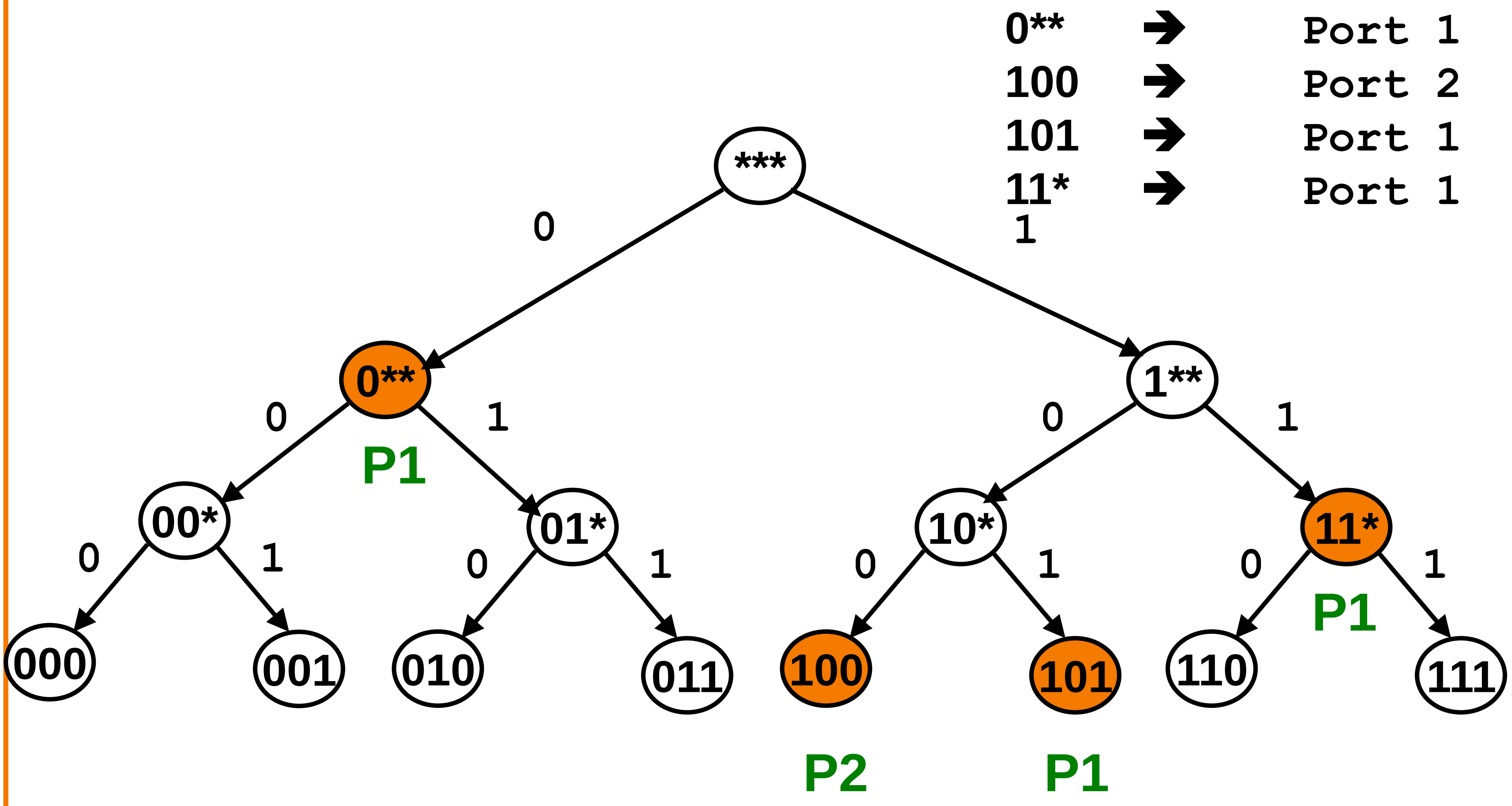


Slightly Different Example

- Several of the unique prefixes go to same port

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

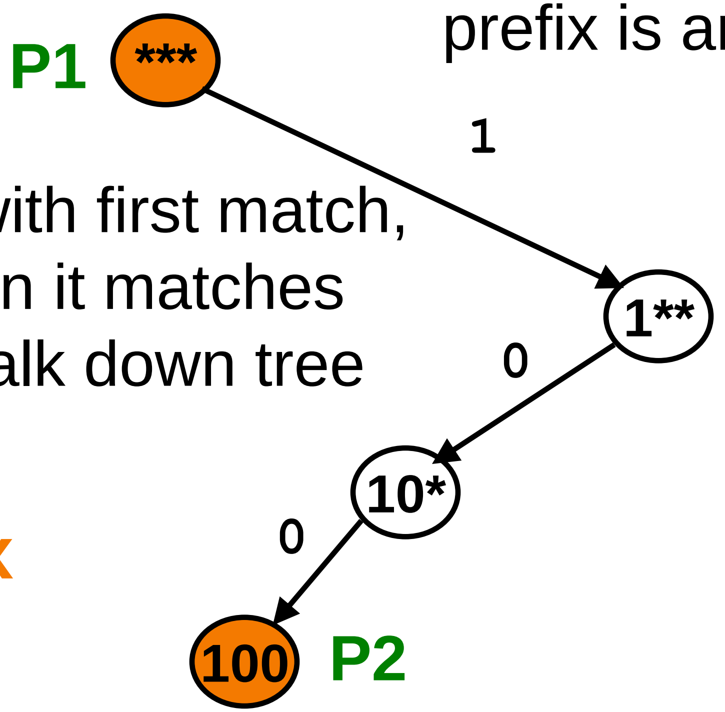
Prefix Tree



0** ➔ Port 1
100 ➔ Port 2
101 ➔ Port 1
11* ➔ Port 1
***
0
1
0**
1**
0
1
0
1
P1
00*
01*
10*
11*
0
1
0
1
0
1
0
1
P1
000
001
010
011
100
101
110
111
P2
P1

More Compact Representation

If you ever leave path, you are done, last matched prefix is answer



Record port associated with first match, and only over-ride when it matches another prefix during walk down tree

This is longest prefix match (LPM)

Longest Prefix Match Representation

- *** → Port 1
- 100 → Port 2

- If address matches both, then take longest match

Longest Prefix Match Representation

- 201.143.0.0/21 → Port 1
- 201.143.4.0/24 → Port 2

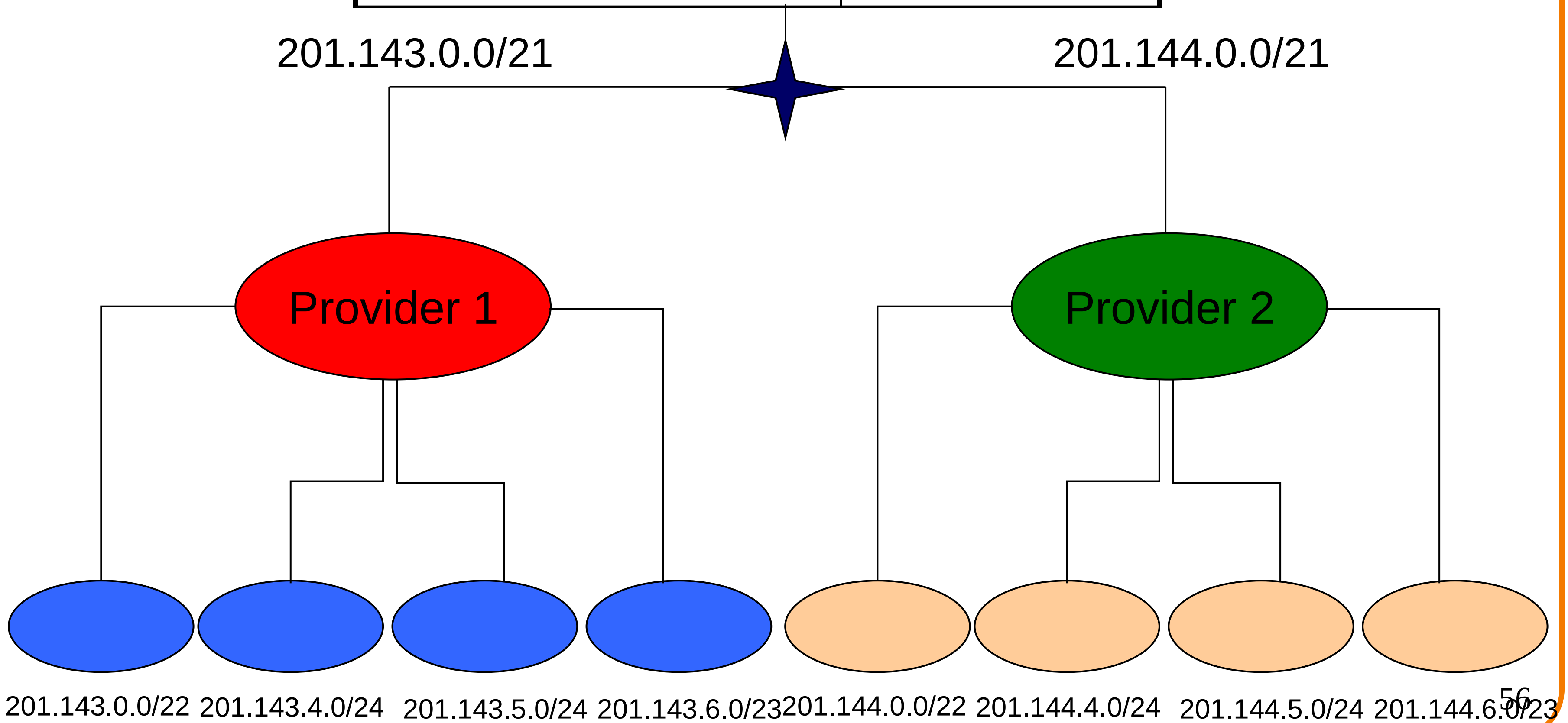
- If address matches both, then take longest match

We Use LPM Every Day…..

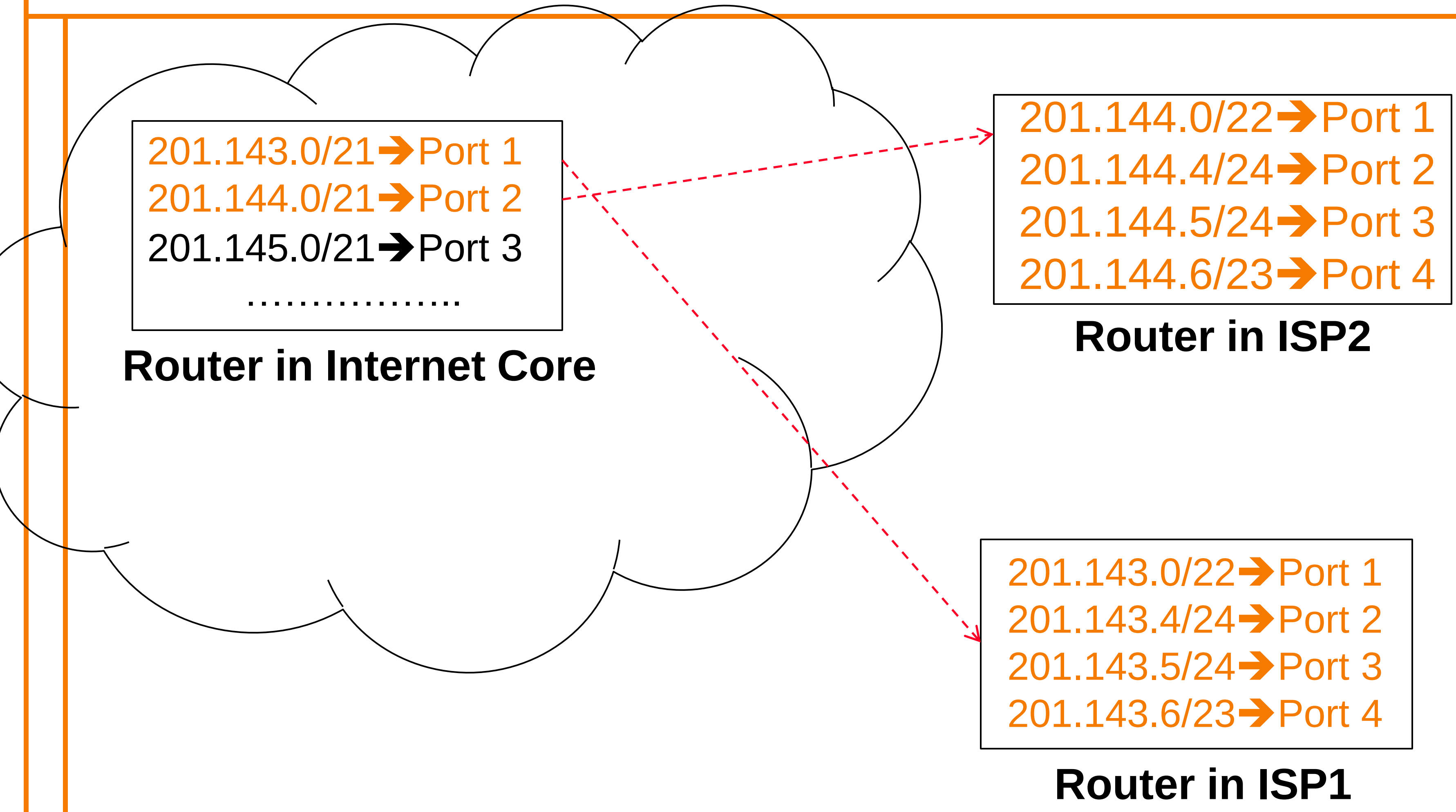
- “Everyone go outside to play….
- …except for John, who has to stay inside…”
- We routinely insert an “except” whenever we make a general statement and then a contradictory specific statement
- Point: we would never explicitly list the members of the class, but instead use the term for the aggregate and then specify the exceptions

Example #2: Aggregating Customers

Prefix	Port
201.143.0/21	Provider 1
201.144.0/21	Provider 2

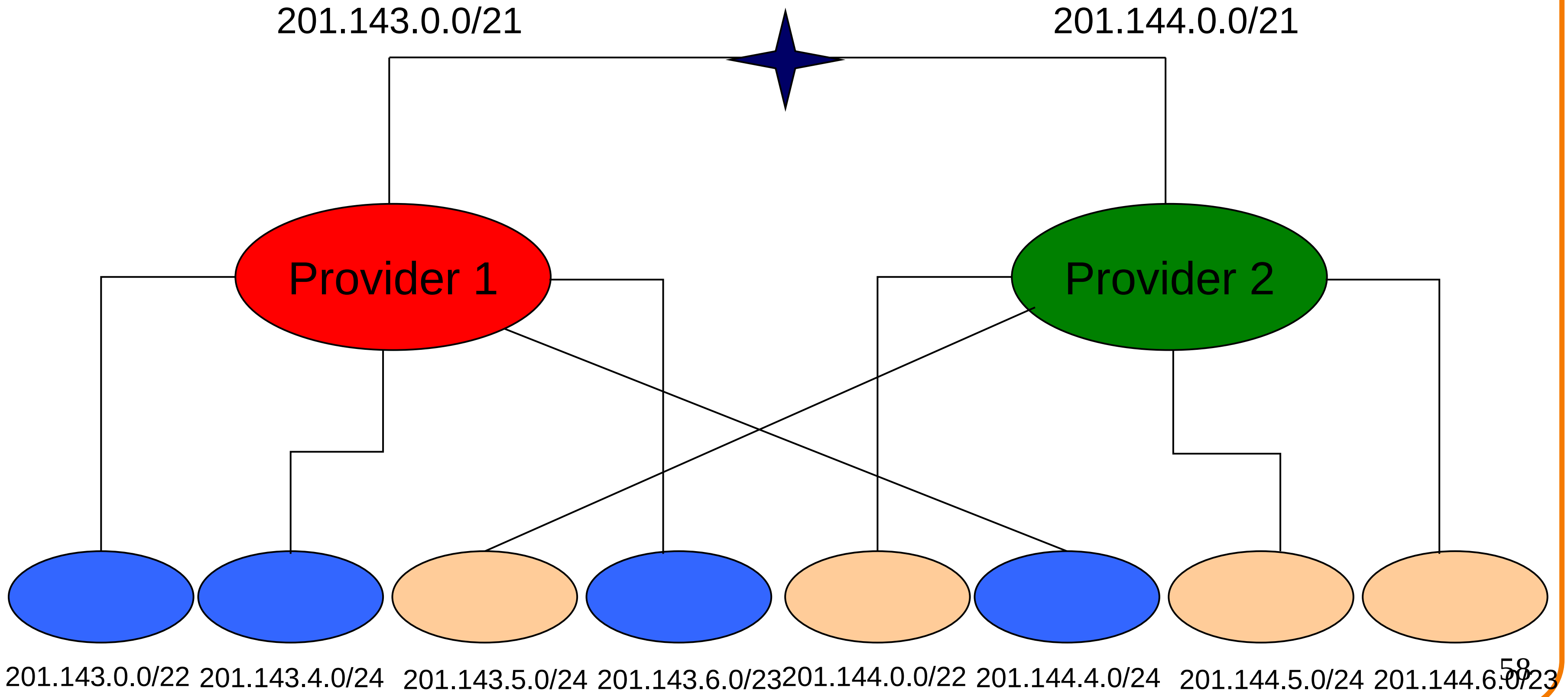


Global Picture



Example #3: Complications

Forwarding table more complicated when addressing is non-topological



Global Picture

201.143.0/22 →	Port 1
201.143.4/24 →	Port 1
201.144.4/24 →	Port 1
201.143.6/23 →	Port 1
201.144.0/22 →	Port 2
201.144.5/24 →	Port 2
201.143.5/24 →	Port 2
201.144.6/23 →	Port 2
………………	

Router in Internet Core

201.144.0/22 →	Port 1
201.144.5/24 →	Port 2
201.143.5/24 →	Port 3
201.144.6/23 →	Port 4

Router in ISP2

201.143.0/22 →	Port 1
201.143.4/24 →	Port 2
201.144.4/24 →	Port 3
201.143.6/23 →	Port 4

Router in ISP1

Matching disjoint prefixes

If match any of these prefixes, go to Provider 1

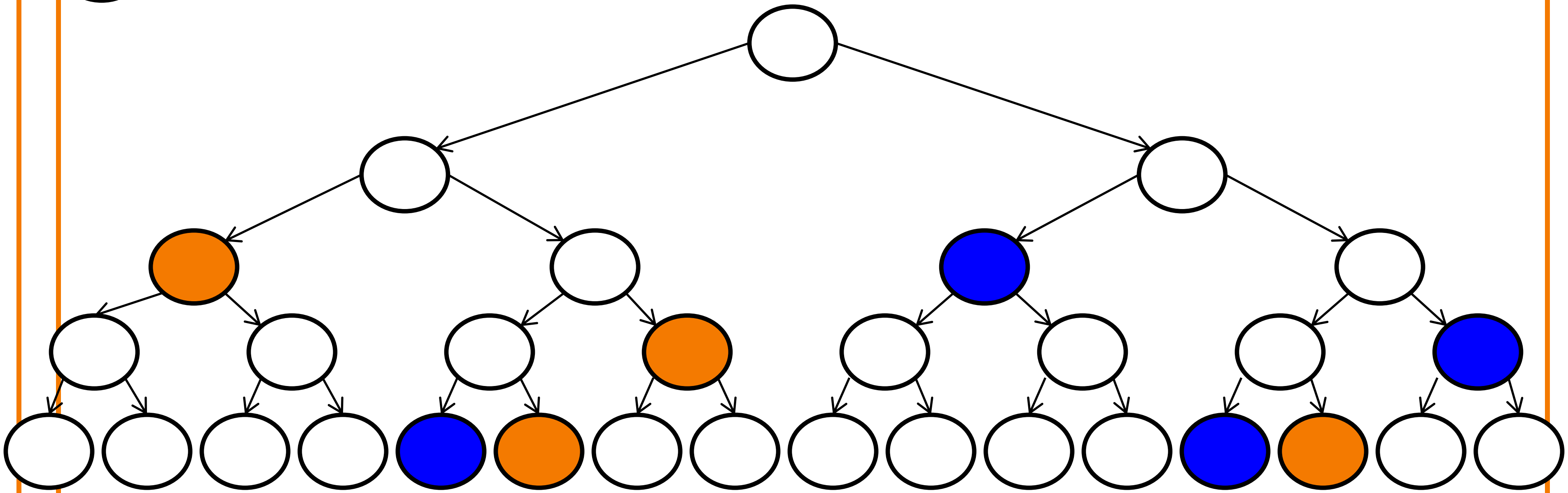
11001001	10001111	000000––	––––––––
11001001	10001111	00000100	––––––––
11001001	10001111	0000011–	––––––––
11001001	10010000	00000100	––––––––

If match any of these prefixes, go to Provider 2

11001001	10001111	00000101	––––––––
11001001	10010000	000000––	––––––––
11001001	10010000	00000101	––––––––
11001001	10010000	0000011–	––––––––

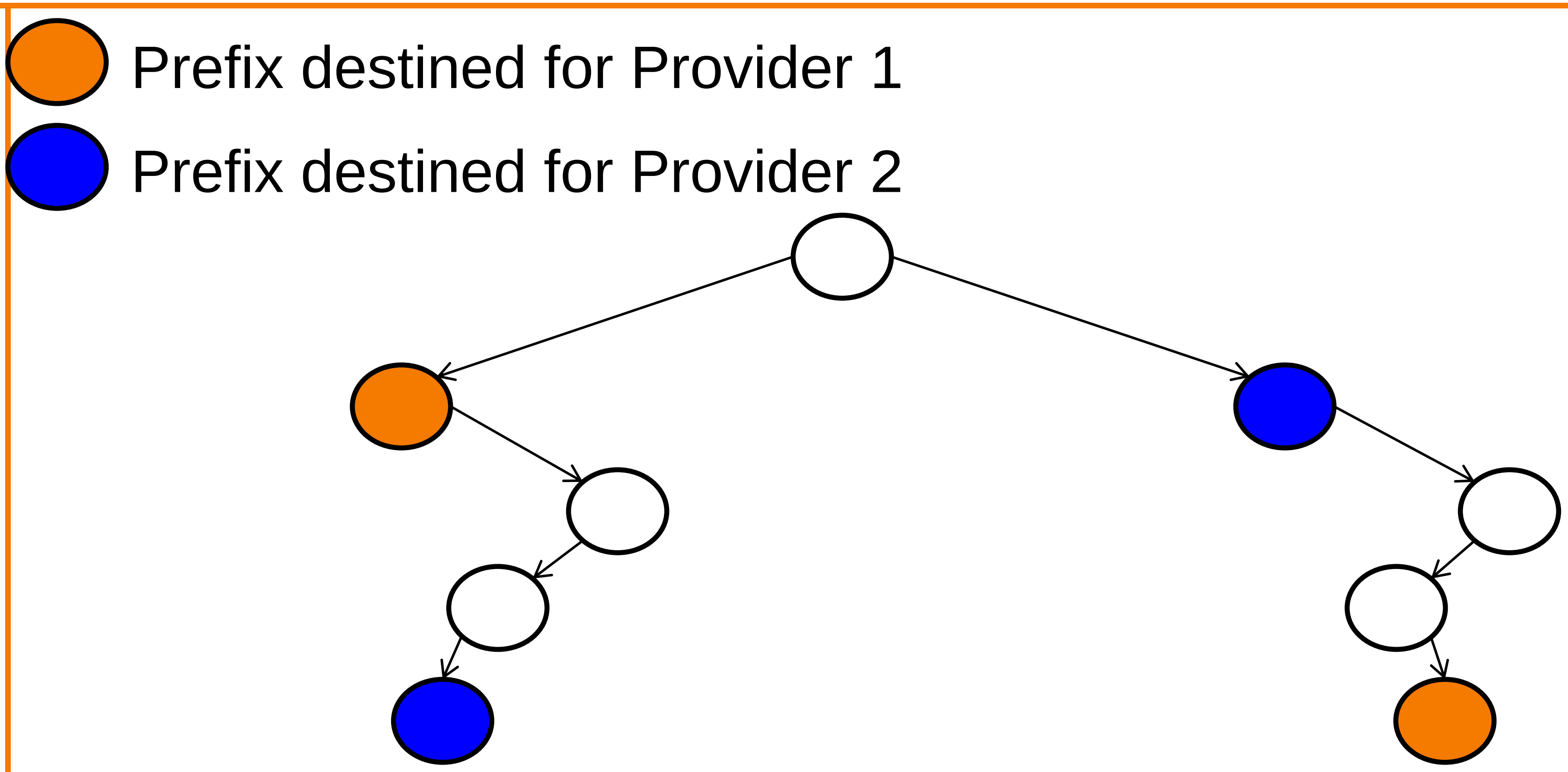
Focusing Only on Crucial Bits

- Prefix destined for Provider 1
- Prefix destined for Provider 2



No packet will match more than one prefix
All paths reach a unique prefix

More Compact Representation



Longest Prefix Match

New Arriving packet:
Arriving packet:

11001001 10010000 00000100 01101101

Provider 1

11001001	10001111	00000–––	–––––––––

201.143.0.0/21

11001001	10010000	00000100	–––––––––

201.144.4.0/24

Provider 2

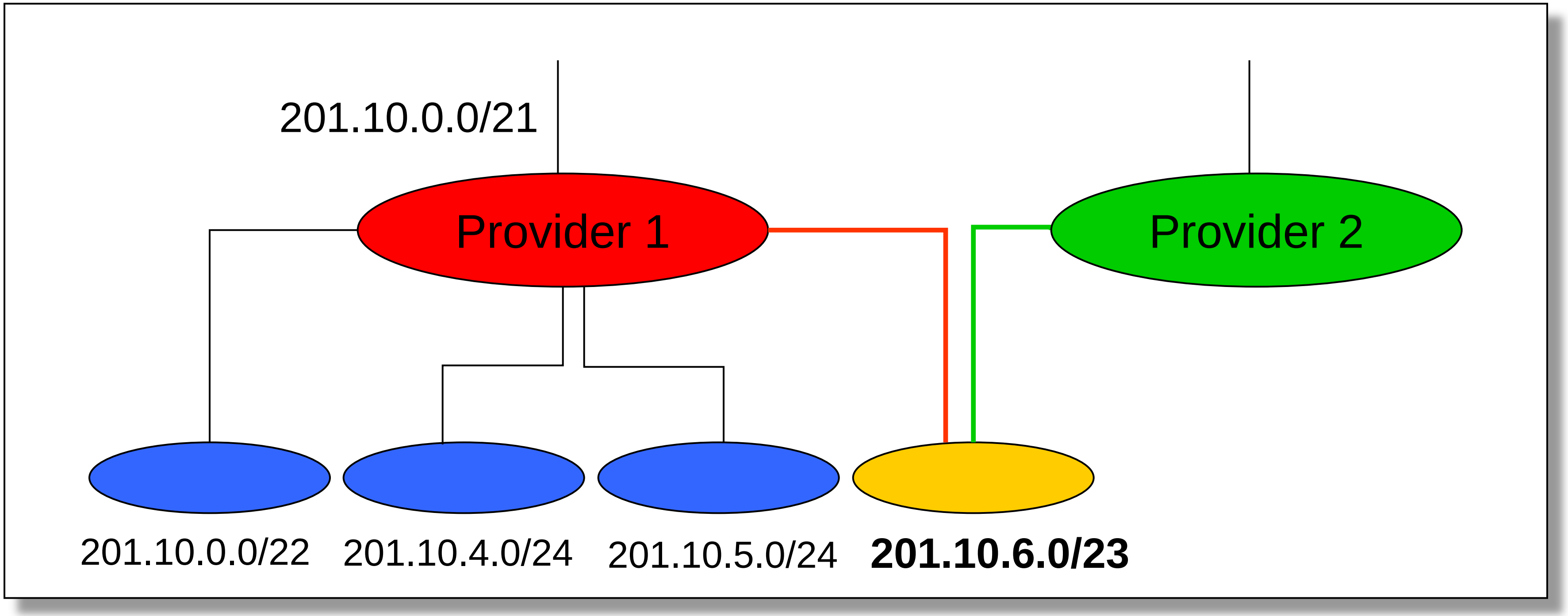
11001001	10010000	00000–––	–––––––––

201.144.0.0/21

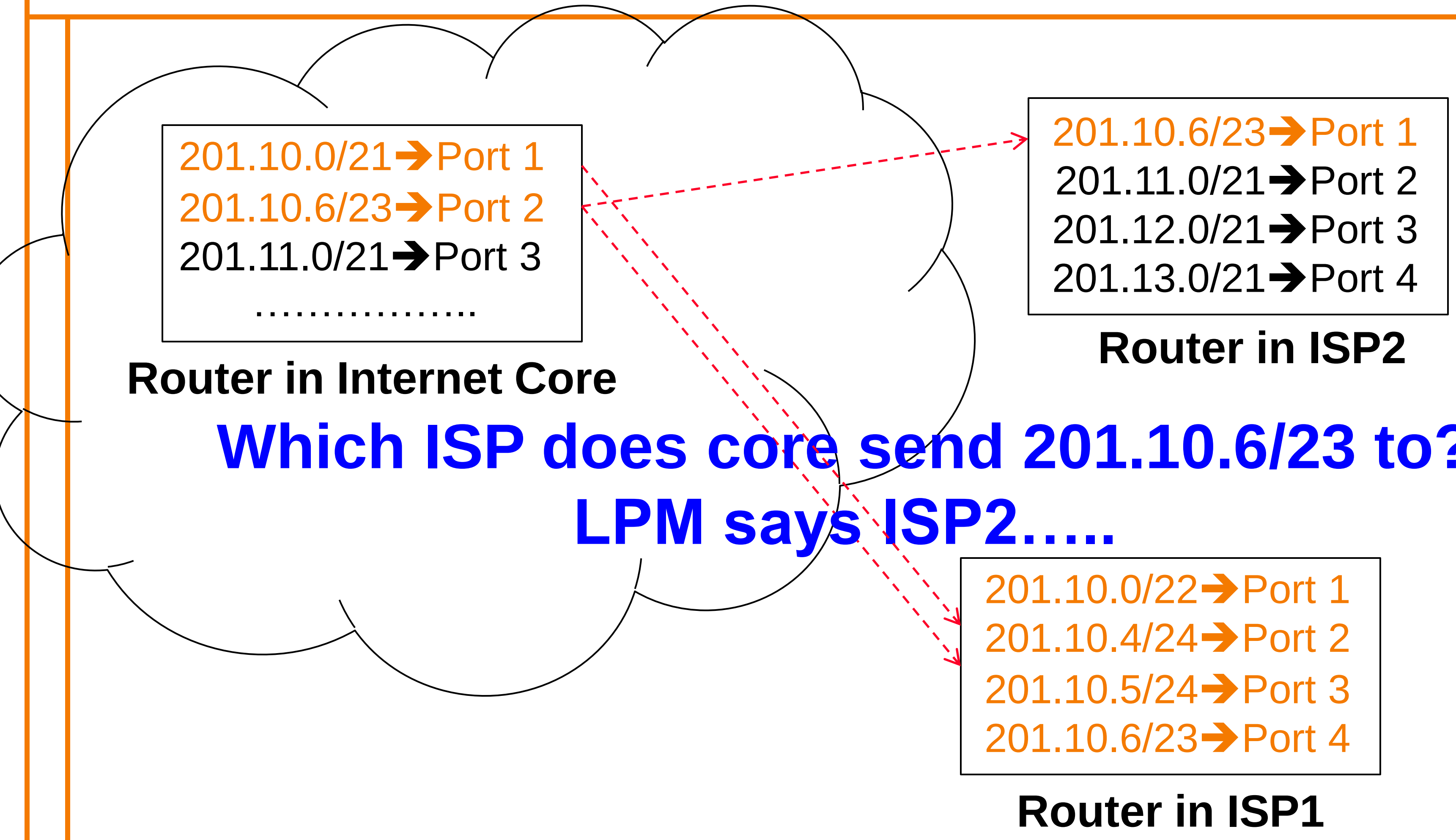
11001001	10001111	00000101	–––––––––

201.143.5.0/24

Return to multihoming example



Global Picture with Multihoming



Which ISP does core send 201.10.6/23 to?

LPM says ISP2…..

Need explicit decisions about prefix granularity

ISP1 might also advertise specific prefix

Forwarding Summary

- Nontrivial to find matches in CIDR
  - Because can't tell where network address ends
  - Must walk down bit-by-bit
- LPM decreases size of routing table
  - Reducing memory consumption
- Multihoming and LPM might have unintended consequences….