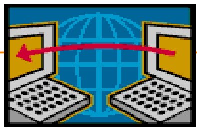


Forwarding (after a little more addressing)

EE122 Fall 2011

Scott Shenker

http://inst.eecs.berkeley.edu/~ee122/

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

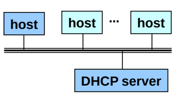
Follow-up from last time

- **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

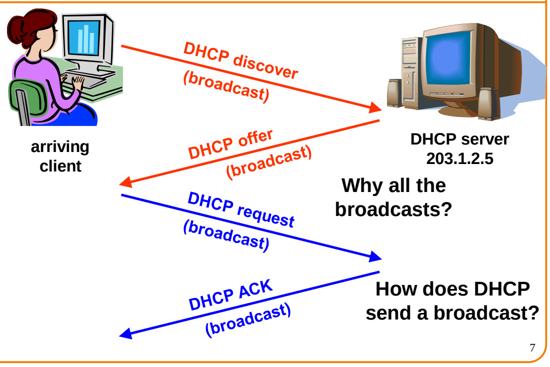
- Dynamic Host Configuration Protocol (DHCP)
  - Configures several aspects of hosts
  - Most important: assigns temporary address (lease)
  - Uses DHCP server to do allocation
  - Multiplexes block of addresses across users
- DHCP protocol:
  - Broadcast a server-discovery message (layer 2)
  - Server(s)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



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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?

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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

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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*

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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….

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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….

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How does a host handle packets?

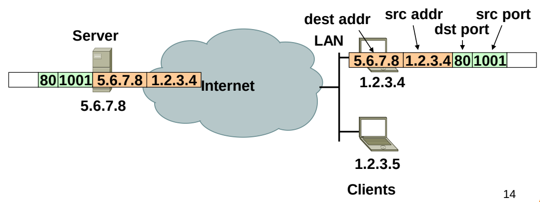
- Ethernet packet has EtherType field
  - Which protocol to hand payload to (e.g., IP)
- IP has Protocol field
  - Which protocol to hand payload to (e.g., UDP, TCP)
- Transport protocols have port numbers
  - **Which process to hand payload to**

Why?

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

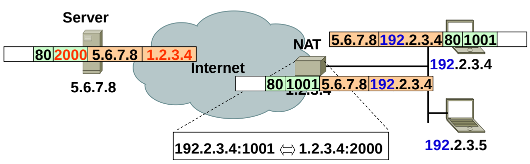
Network Address Translation (NAT)

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



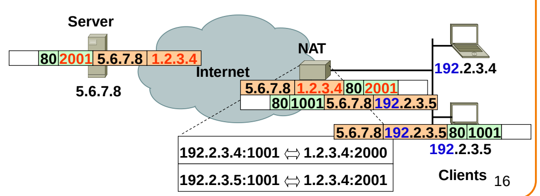
NAT (cont' d)

- 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:

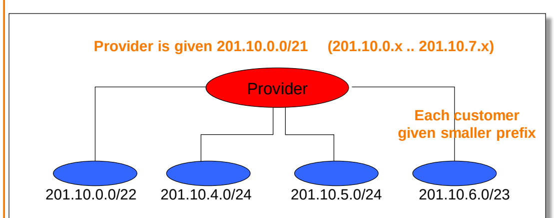
  ICANN ➔ ARIN ➔ AT&T ➔ Customer

  ICANN ➔ ARIN ➔ UCB ➔ Department

FAKE Example in More Detail

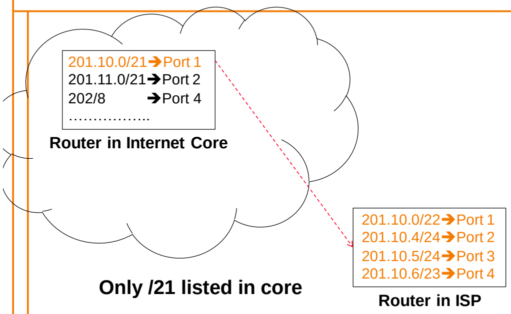
- ICANN gives ARIN several /8s, including **12.0/8**
  - **Network Prefix: 00001100**
- ARIN gives ACME Internet a /16, **12.197/16**
  - **Network Prefix: 0000110011000101**
- ACME give XYZ Hosting a /24, **12.197.45/24**
  - **Network Prefix: 000011001100010100101101**
- XYZ gives customer specific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

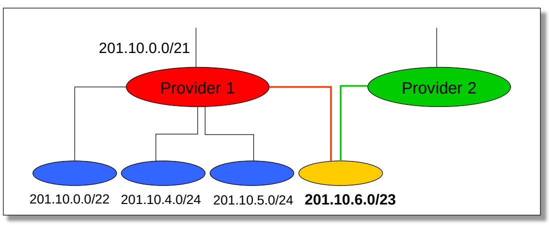
Original Prefix:

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

Subprefixes: (disjoint coverage of original prefix)

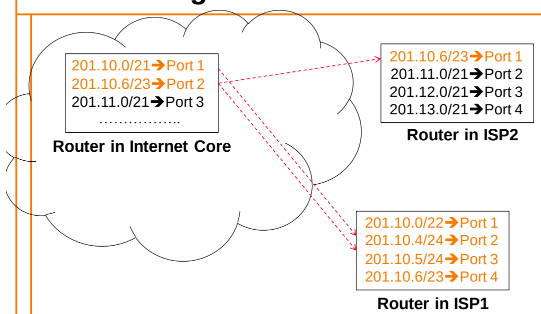
- 201.10.0/22=11001001|00001010|000000**|*******
- 201.10.4/24=11001001|00001010|00000100|*******
- 201.10.5/24=11001001|00001010|00000101|*******
- 201.10.6/23=11001001|00001010|0000011*|*******

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…..

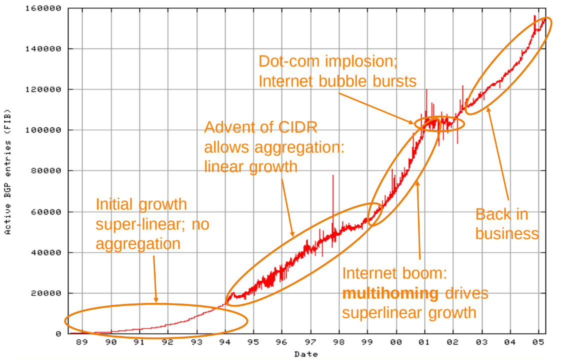
Addresses Advertised in Two Places?

- 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

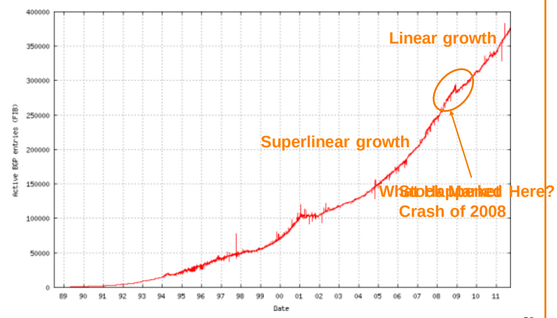
Two Countervailing Forces

- 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:

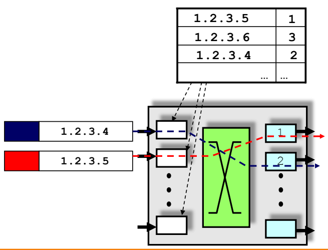
- Design better addressing scheme
- Take five minutes
- Work in groups
- Will take three proposals
- We will then vote on the winner….

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

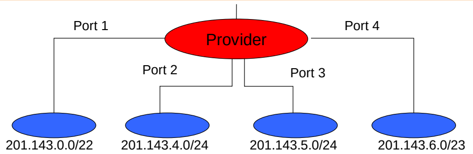
- With classful addressing, this is easy:
  - Early bits in address specify mask
    - Class A [0]: /8 Class B [10]: /16 Class C [110]: /24
  - Can find exact match in forwarding table
    - Use prefix as index into hash table
- Why won't this work for CIDR?
  - What's the network prefix in this address?

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

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:

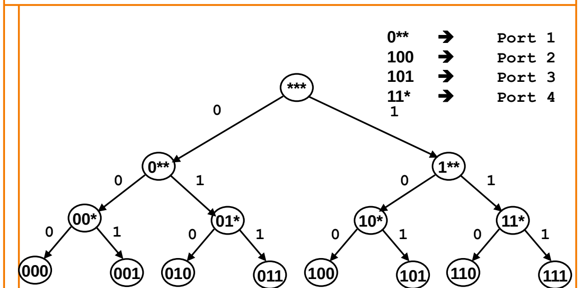
Prefix	Port
1100100110001111000000************	1
110010011000111100000100********	2
110010011000111100000101********	3
11001001100011110000011*********	4

Consider four three-bit prefixes

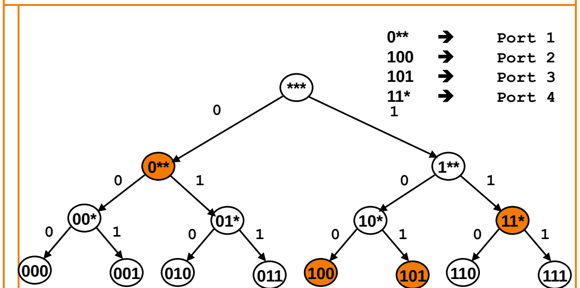
- Just focusing on the bits where all the action is….

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

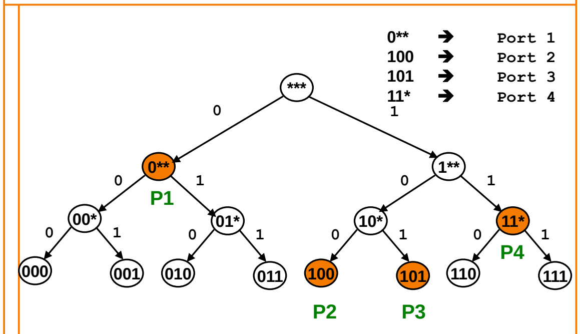
Tree Structure



Walk Tree: Stop at Prefix Entries



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

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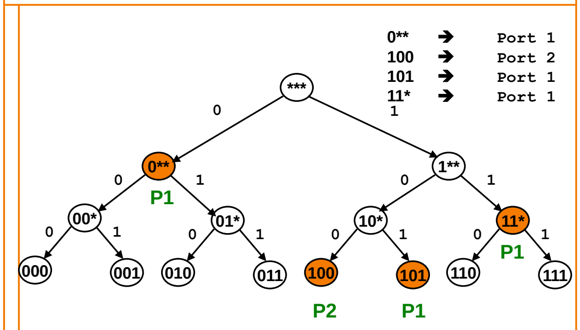
Prefix Tree



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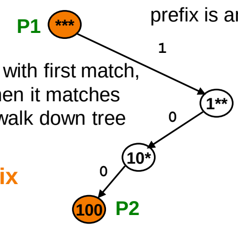
More Compact Representation

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)

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Longest Prefix Match Representation

- *** → Port 1
- 100 → Port 2

- If address matches both, then take longest match

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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

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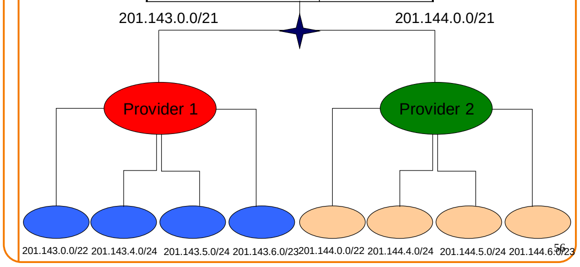
We Use LPM Every Day…..

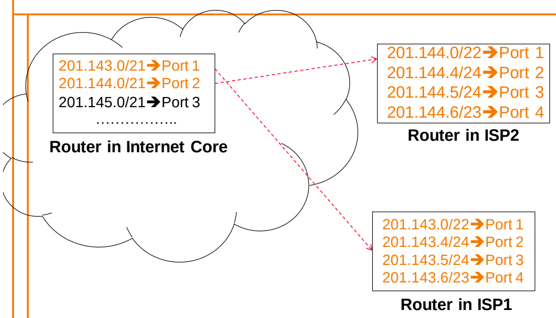
- "Everyone go outside to play….
- …except for John, who has to stay inside…"
- We routinely insert an "except" whenever we make a general statement and then a contradictory specific statement
- Point: we would never explicitly list the members of the class, but instead use the term for the aggregate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

Example #2: Aggregating Customers

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

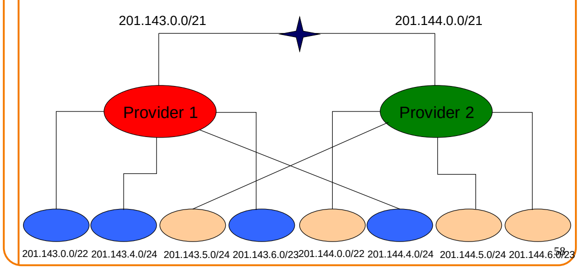


Global Picture

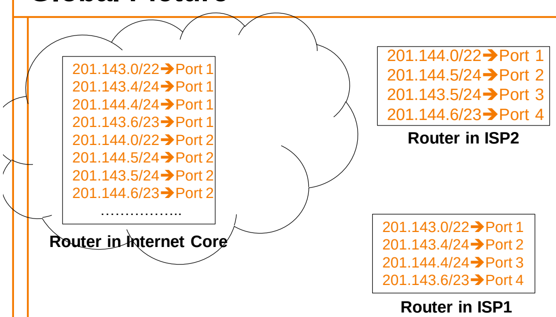


Example #3: Complications

Forwarding table more complicated when addressing is non-topological



Global Picture



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	--------

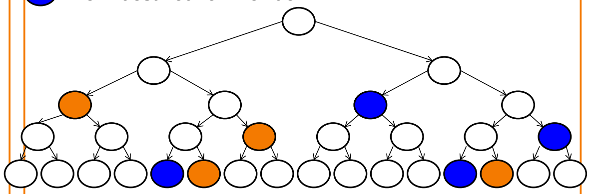
If match any of these prefixes, go to Provider 2

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

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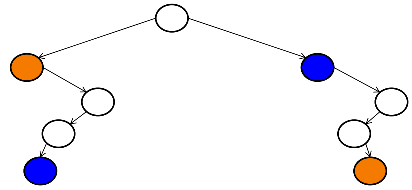
More Compact Representation

Prefix destined for Provider 1

Prefix destined for Provider 2



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Longest Prefix Match

New 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

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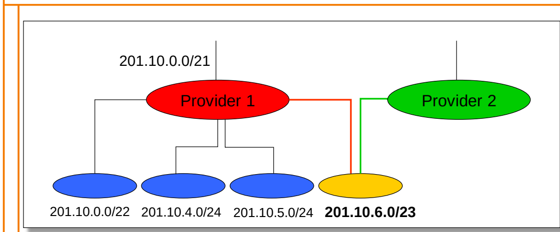
Return to multihoming example



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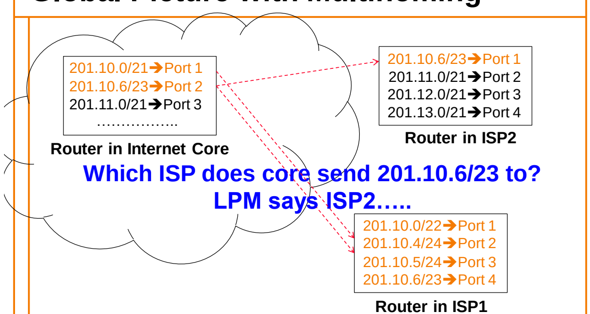
Global Picture with Multihoming



Need explicit decisions about prefix granularity
ISP1 might also advertise specific prefix

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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….

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