IP Addressing

Lecture 6, Spring 2026

IP Addressing

- Hierarchical Addressing
- Assigning Addresses
- Writing Addresses
- Aggregating Routes
- IPv6 Changes

Hierarchical Addressing

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Scaling Routing

Can we really scale routing and forwarding to every host on the Internet?

- Distance-vector: How many routing calculations does each router do?
- Link-state: Can we really store the entire network graph in every router?
- How long does it take to re-converge?

The secret to scaling routing is how we do addressing.

The trick: Use more informative names than A, B, C, D for destinations.

R3's Table	
Destination	Port
A	0
B	1
C	1
D	2
...	...

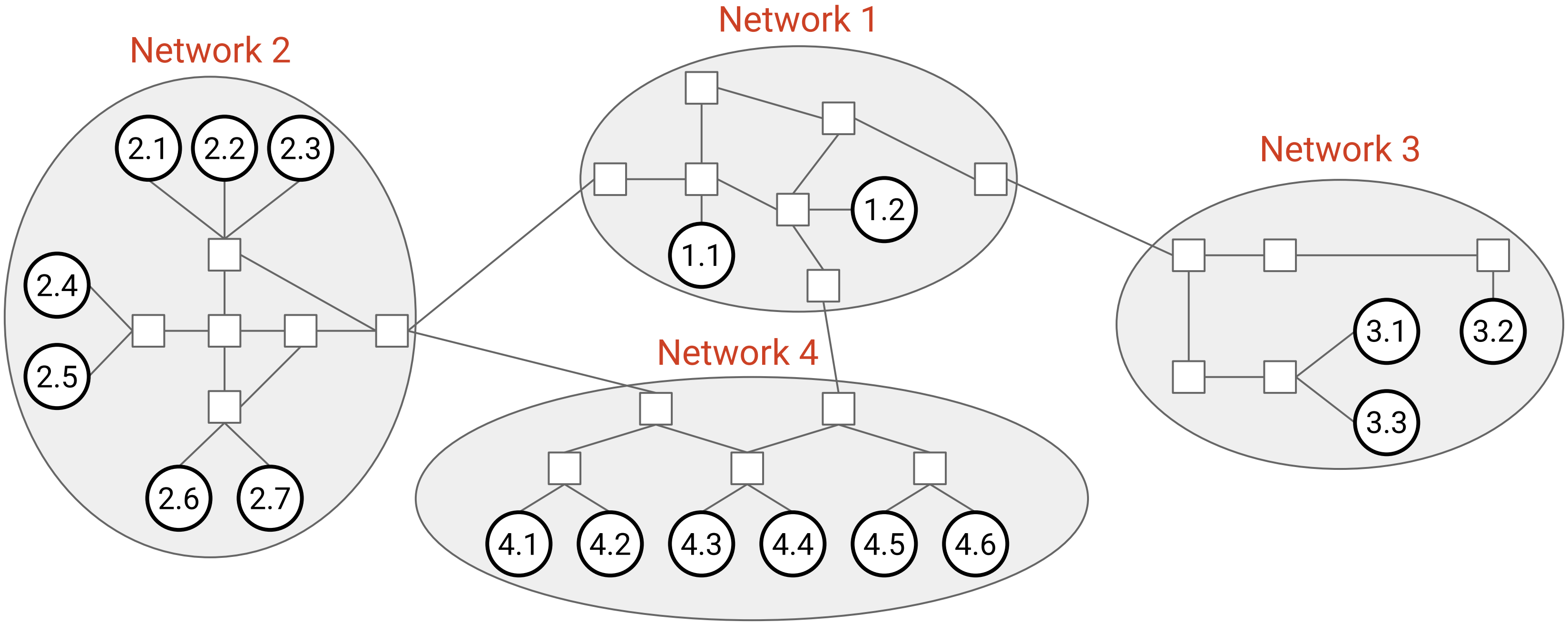
One entry for every possible destination.

Disclaimer: Today is about IP (Layer 3) addresses.
Other layers use different addressing systems.

Hierarchical Addressing – Conceptual

Recall: The Internet is a network of networks.

- Leads naturally to a hierarchy of addresses.
- Each network gets a number. Then, each host gets a number inside the network.

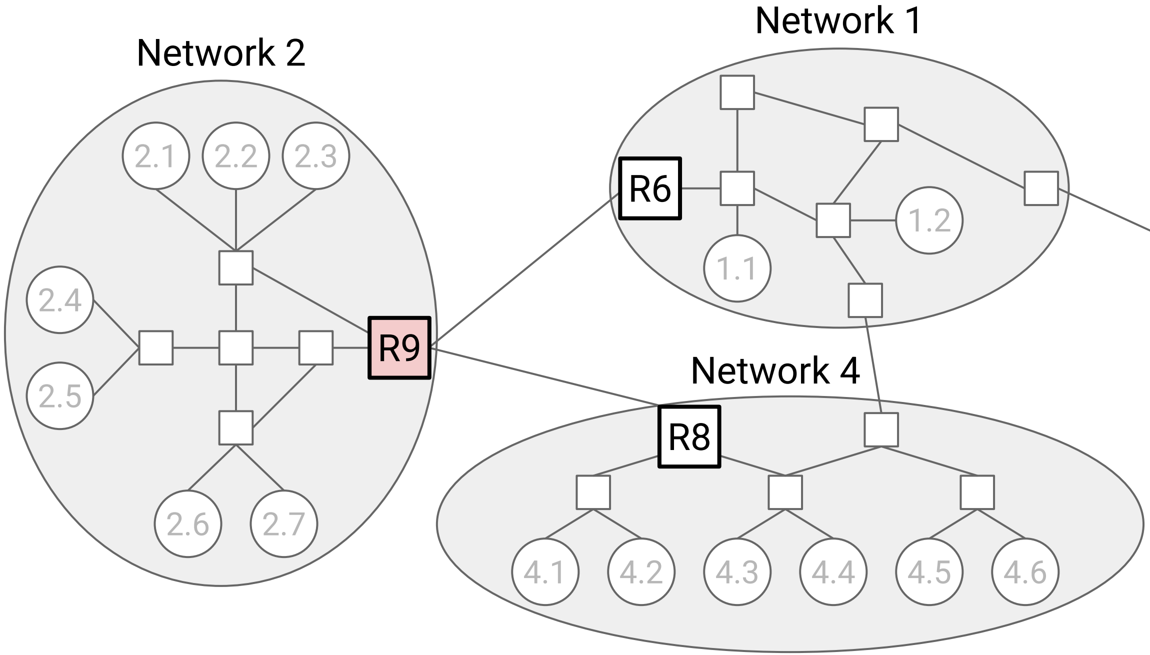


Hierarchical Addressing – Conceptual

R9 can summarize all hosts in another network with a single table entry.

Huge scaling improvement! Tables are smaller now.

R9's Table	
Destination	Next Hop
1.*	R6
3.*	R6
4.*	R8
...	...



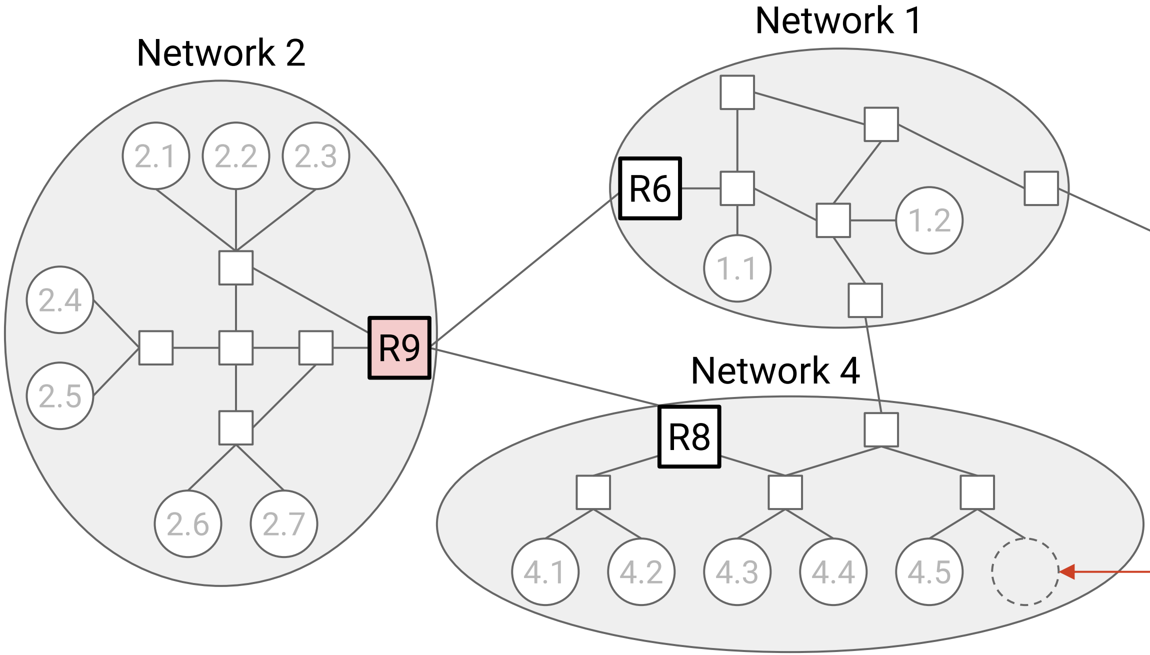
Hierarchical Addressing – Conceptual

Hierarchical addressing limits *table churn*.

Changes inside a network don't affect tables in other networks.

R9's Table	
Destination	Next Hop
1.*	R6
3.*	R6
4.*	R8
...	...

No change in table entry!

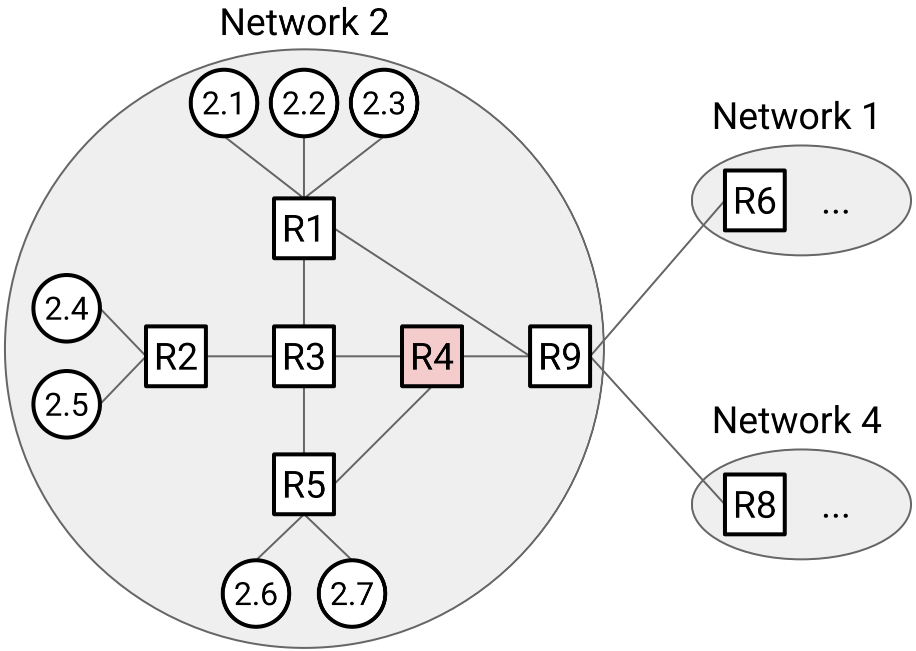


4.6 left the network!

Hierarchical Addressing – Conceptual

Size of the forwarding table scales with number of hosts in the current network, plus number of other networks.

- Big scaling improvement! Much better than listing every single host.



R4's Table	
Destination	Next Hop
2.1	R3
2.2	R3
2.3	R3
2.4	R3
2.5	R3
2.6	R5
2.7	R5
1.*	R9
3.*	R9
4.*	R9

Internal destinations.

External destinations.

Implications of Hierarchical Addressing

Inter-domain routing computes routes between networks.

- No need to think about churn inside networks.
- Just think about network 1, network 2, etc.

Intra-domain routing computes routes inside a network.

- No need to think about other networks.
- Just think about 2.1, 2.2, etc.

R4's Table	
Destination	Next Hop
2.1	R3
2.2	R3
2.3	R3
2.4	R3
2.5	R3
2.6	R5
2.7	R5
1.*	R9
3.*	R9
4.*	R9

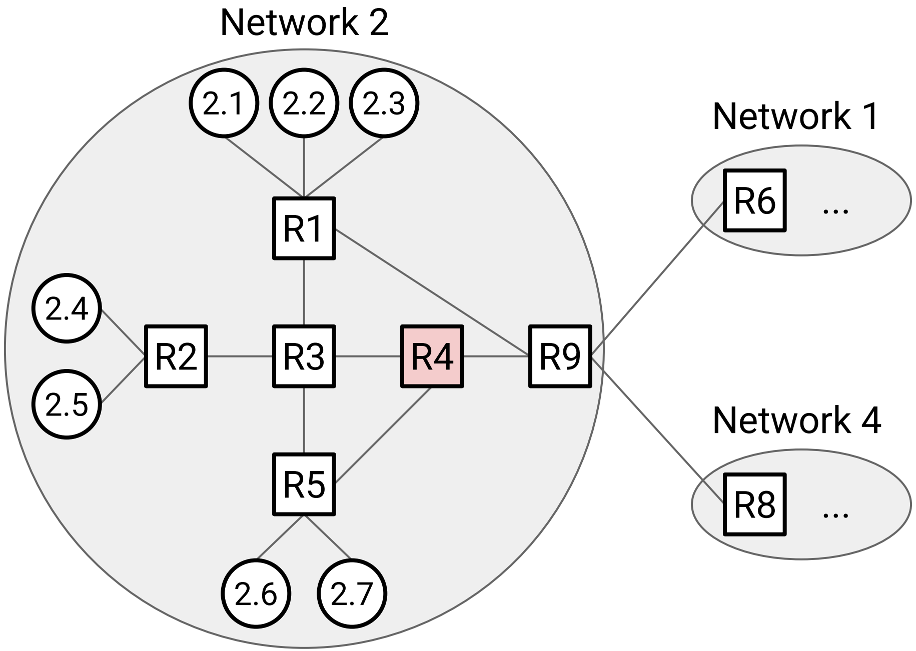
Internal destinations.

External destinations.

Aggregation – Conceptual

Sometimes, we can *aggregate* several rows into a single row.

- From R4, any packet to an external network has a next-hop of R9.
- *.* wildcard says: For any destination not in the table, forward to R9.



R4's Table

Destination	Next Hop
2.1	R3
2.2	R3
2.3	R3
2.4	R3
2.5	R3
2.6	R5
2.7	R5
1.*	R9
3.*	R9
4.*	R9

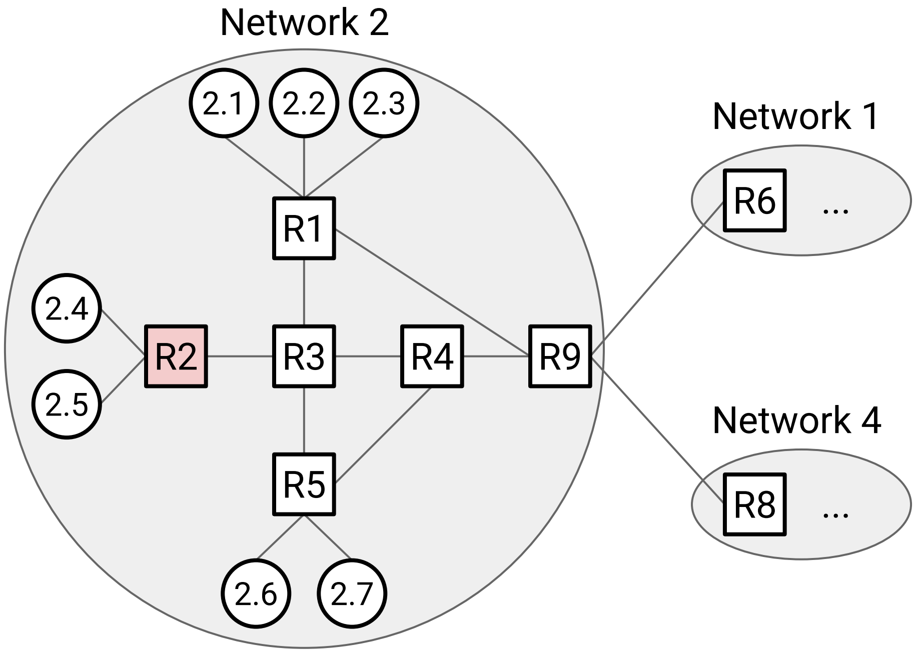
R4's Table

Destination	Next Hop
2.1	R3
2.2	R3
2.3	R3
2.4	R3
2.5	R3
2.6	R5
2.7	R5
.	R9

Aggregation – Conceptual

From R2, everything is reached through R3, so we can aggregate entries.

- The *.* wildcard (everything not in the table) is the **default route**.
- Most hosts only have the default route!



R2's Table

Destination	Next Hop
2.4	Direct
2.5	Direct
2.1	R3
2.2	R3
2.3	R3
2.6	R3
2.7	R3
1.*	R3
3.*	R3
4.*	R3

R2's Table

Destination	Next Hop
2.4	Direct
2.5	Direct
.	R3

Assigning Addresses

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Assigning Addresses

Hierarchical addressing makes routing scalable.

- Hosts that are "close to each other" (in some sense) share part of their address.
- Analogy: All third-floor room numbers start with the digit 3.

When a host joins the network, it's assigned an IP address based on its location in the network.

- Analogy: When you move to a new house, your address changes.
- How do we assign addresses to hosts?

Assigning Addresses, Attempt 1/3 – Early Internet

Addresses are 32 bits long.

- Top 8 bits = network ID.
- Bottom 24 bits = host ID.

Each organization gets a unique network ID.

- AT&T = ID 12.
- Apple = ID 17.
- Ford = ID 19.
- US Department of Defense = IDs 6, 7, 11, 21, 22, 26, 28, 29, 30, 33, 55, 214, 215.

Bob's address: `11010110 10000100 00111010 01101110`

Joe's address: `11010110 10010001 00000000 01001101`

Network ID ← Host ID →

Same network ID, so they must be in the same network.

Assigning Addresses, Attempt 1/3 – Early Internet

Addresses are 32 bits long.

- Top 8 bits = network ID.
- Bottom 24 bits = host ID.

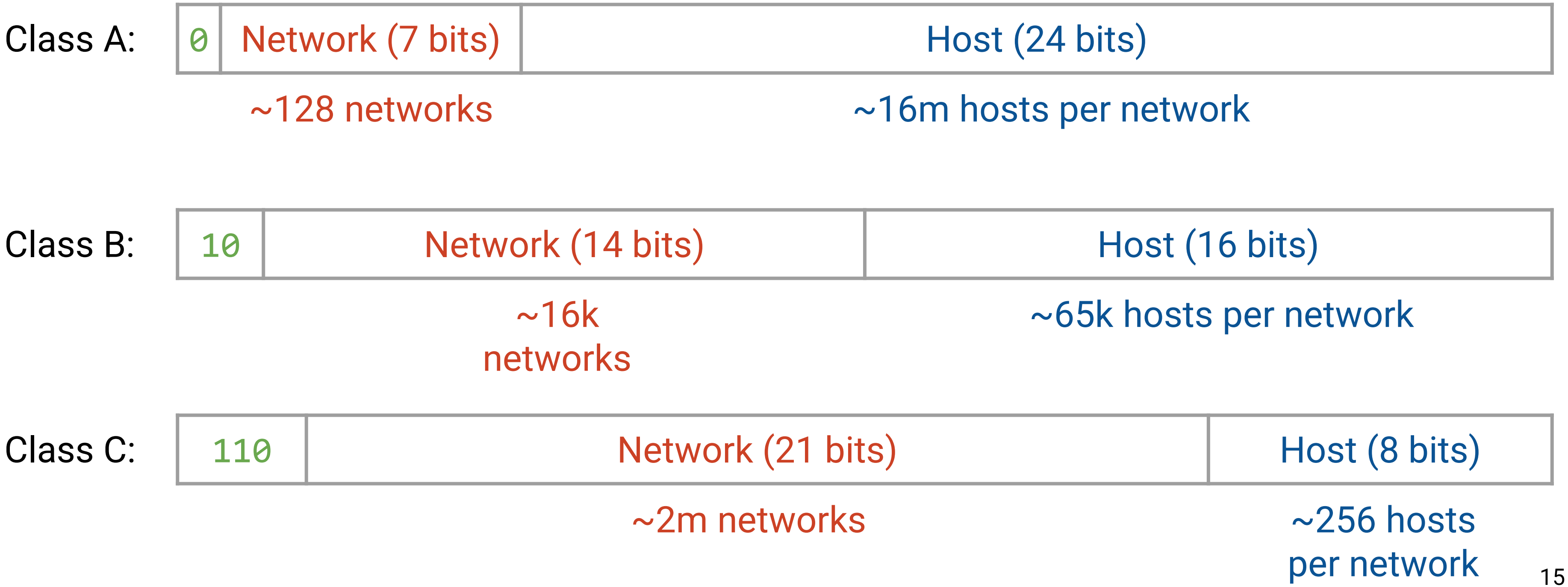
Problems:

- Only 2^8 = 256 different network IDs.
  - And we already gave the US Department of Defense 13 of them.
- Imagine a tiny network (Joe's Tire Shop) with 10 hosts.
  - If we give them an ID, we're giving them 2^{24} = 16,777,216 addresses!
- We're going to run out!

Assigning Addresses, Attempt 2/3 – Classful Addressing

Idea: Allocate different network sizes based on need.

- The top bits (`0`, `10`, or `110`) tell us how to split up the rest of the bits.



Class A: `0` | Network (7 bits) | Host (24 bits)

~128 networks

~16m hosts per network

Class B: `10` | Network (14 bits) | Host (16 bits)

~16k networks

~65k hosts per network

Class C: `110` | Network (21 bits) | Host (8 bits)

~2m networks

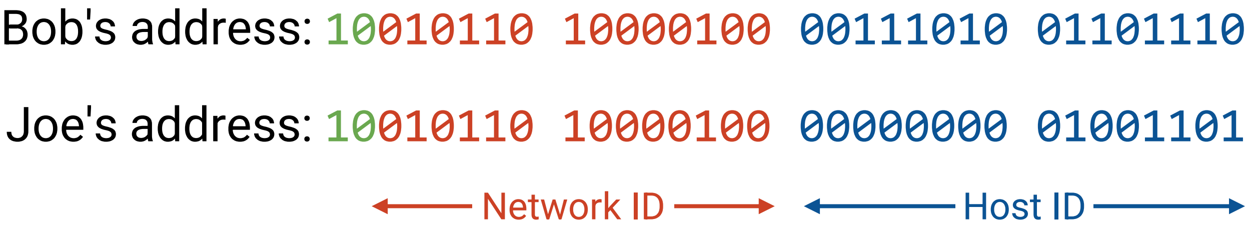
~256 hosts per network

Assigning Addresses, Attempt 2/3 – Classful Addressing

The top bits indicate this is Class B...

...so read the next 14 bits as the network ID...

...and read the last 16 bits as the host ID.



Bob's address: 10010110 10000100 00111010 01101110

Joe's address: 10010110 10000100 00000000 01001101

Class A:	0	Network (7 bits)	Host (24 bits)
Class B:	10	Network (14 bits)	Host (16 bits)
Class C:	110	Network (21 bits)	Host (8 bits)

Assigning Addresses, Attempt 2/3 – Classful Addressing

Class A:	~128 networks.	~16m hosts per network.
Class B:	~16k networks.	~65k hosts per network.
Class C:	~2m networks.	~256 hosts per network.

Problems:

- Class A is way too big for most organizations.
- Class C is way too small for most organizations.
- Class B is the best option for many.
  - ~65k hosts is still too big for most organizations.
  - ~16k is still not enough networks. We're running out again!

Assigning Addresses, Attempt 3/3 – CIDR

With classful addressing, we tried to use convenient 8-bit boundaries.

- Class A: 8 bits for class/network. 24 bits for host.
- Class B: 16 bits for class/network. 16 bits for host.
- Class C: 24 bits for class/network. 8 bits for host.

What if we could assign network IDs of any length?

- Leads to **CIDR (Classless Inter-Domain Routing)**.
- This is what the Internet uses today.

Class A:	`0`	Network (7 bits)	Host (24 bits)
Class B:	`10`	Network (14 bits)	Host (16 bits)
Class C:	`110`	Network (21 bits)	Host (8 bits)

Assigning Addresses, Attempt 3/3 – CIDR

Suppose Joe's Tire Shop has 450 hosts.

Classful addressing:

- Class C gives us ~256 hosts. Not enough!
- Class B gives us ~65k hosts. Too many!
- We have to use Class B (and waste tons of addresses).

Classless (CIDR) addressing:

- 8 host bits = 256 bits. Not enough!
- 9 host bits = 512 bits.
- Still not exactly 450, so still some wasted addresses.
- But much less wasteful!

Network ID (23 bits)	Host ID (9 bits)

Granular Hierarchical Assignment with CIDR

CIDR enables multi-layered hierarchical assignment of addresses.

- ICANN. (*Internet Corporation for Names and Numbers*)
  - Top-level organization that owns all the IP addresses.
  - They allocate blocks to...
- RIRs. (*Regional Internet Registries*)
  - Representing Europe (*RIPE*), North America (*ARIN*), Asia/Pacific (*APNIC*), South America (*LACNIC*), and Africa (*AFRINIC*).
  - They give out portions to...
- Large organizations or ISPs.
  - Sometimes called Local Internet Registries (*especially in Europe*).
  - They give out portions to...
- Small organizations and individuals.
  - Examples: Hofstra University, Joe's Tire Shop.

Granular Hierarchical Assignment with CIDR

ICANN owns all addresses: ....

ARIN (North America) owns: 1101............................

4 bits fixed, 2^{28} ≈ 268m addresses.

AT&T (large ISP) owns: 110111001.......................

9 bits fixed, 2^{23} ≈ 8m addresses.

Hofstra owns: 110111001110100010..............

18 bits fixed, 2^{14} ≈ 16k addresses.

SIC owns: 110111001110100010011010........

24 bits fixed, 2^{8} ≈ 256 addresses.

Prof. Gu owns: 11011100111010001001101001011101

All bits fixed, 1 address.

Writing Addresses

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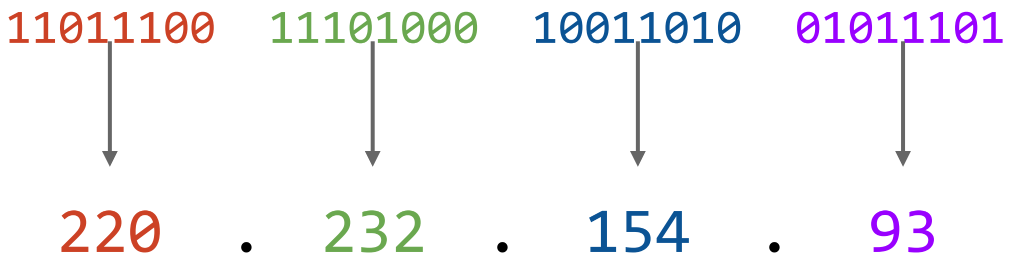
Writing IPv4 Addresses

We could write an IP address as a 32-bit number: `11011100111010001001101001011101`

- Nobody wants to read that.

Dotted quad notation:

- Split into groups of 8 bits.
- Write each 8-bit number in decimal, separated by dots.



```
11011100   11101000   10011010   01011101

  220    .   232    .   154    .   93
```

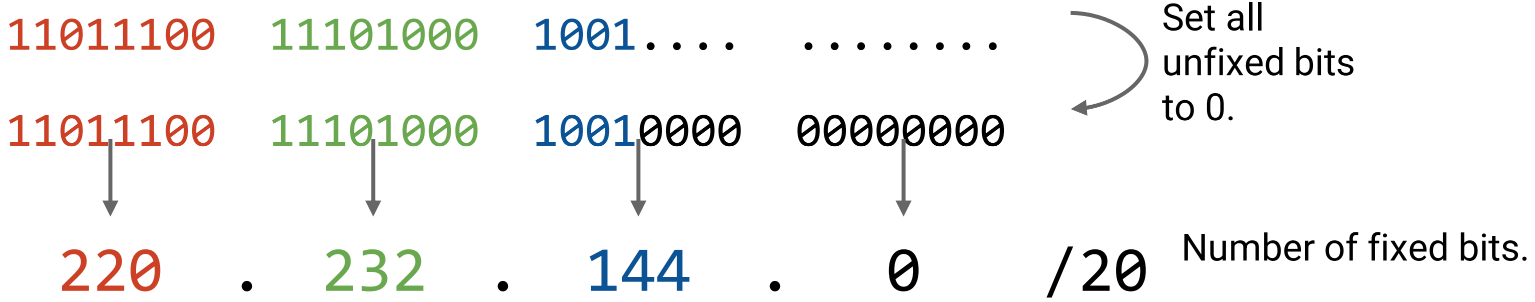
Writing IPv4 Address Ranges

Slash notation for writing ranges of addresses:

- Set all unfixed bits to 0. Write as a dotted quad. After the slash, write how many bits are fixed.

Examples:

- 192.168.1.0/24 means 24 bits are fixed. Range is 192.168.1.0 – 192.168.1.255. (8 bits address range)
- 192.168.1.0/29 means 29 bits are fixed. Range is 192.168.1.0 – 192.168.1.7. (3 bits address range)
- 192.168.1.1/32 means 32 bits are fixed. A single address.



```
11011100   11101000   1001....   ........

11011100   11101000   10010000   00000000

   220   .    232   .    144   .    0      /20
```

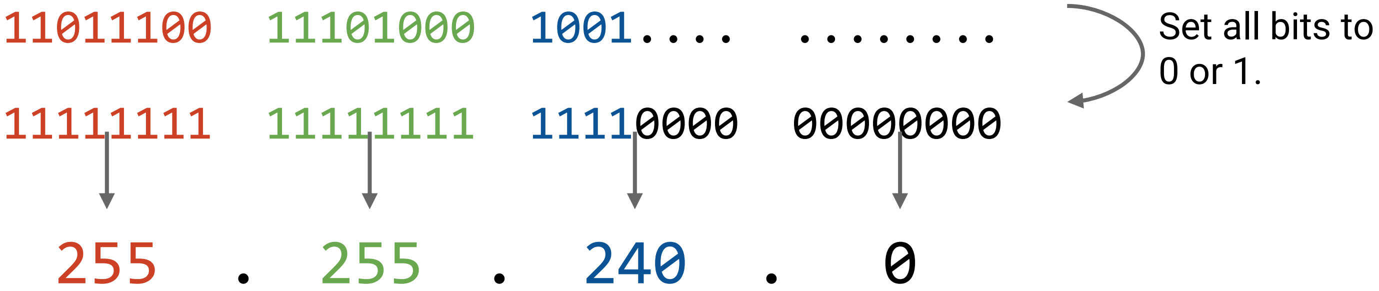
Set all unfixed bits to 0.

Number of fixed bits.

Writing IPv4 Address Ranges

Netmask is an alternative to the number after the slash..

- Set all *fixed* bits to 1, and all *unfixed* bits to 0. Write as a dotted quad.
- Useful in code: To extract network ID, bitwise AND the address and netmask.
- Slash notation is more convenient for humans.



```
11011100   11101000   1001....   ........
11111111   11111111   11110000   00000000
  255    .   255    .   240    .    0
```

Set all bits to 0 or 1.

Slash notation: `220.232.144.0/20`

Netmask notation: `220.232.144.0` (netmask `255.255.240.0`)

Aggregating Routes

Lecture 6, Spring 2026

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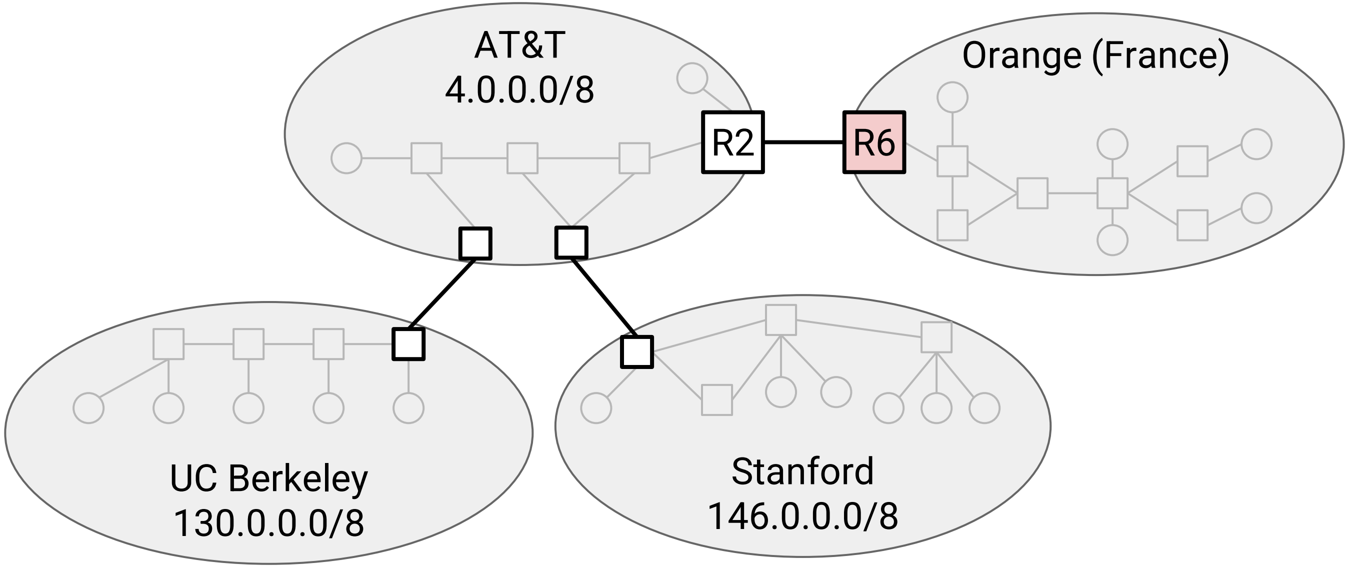
Inter-Domain Routing

In inter-domain routing, we're looking for routes to other networks.

- Each destination is a network, represented by an IP prefix.
- Already better than one entry per host...but we can do even better!



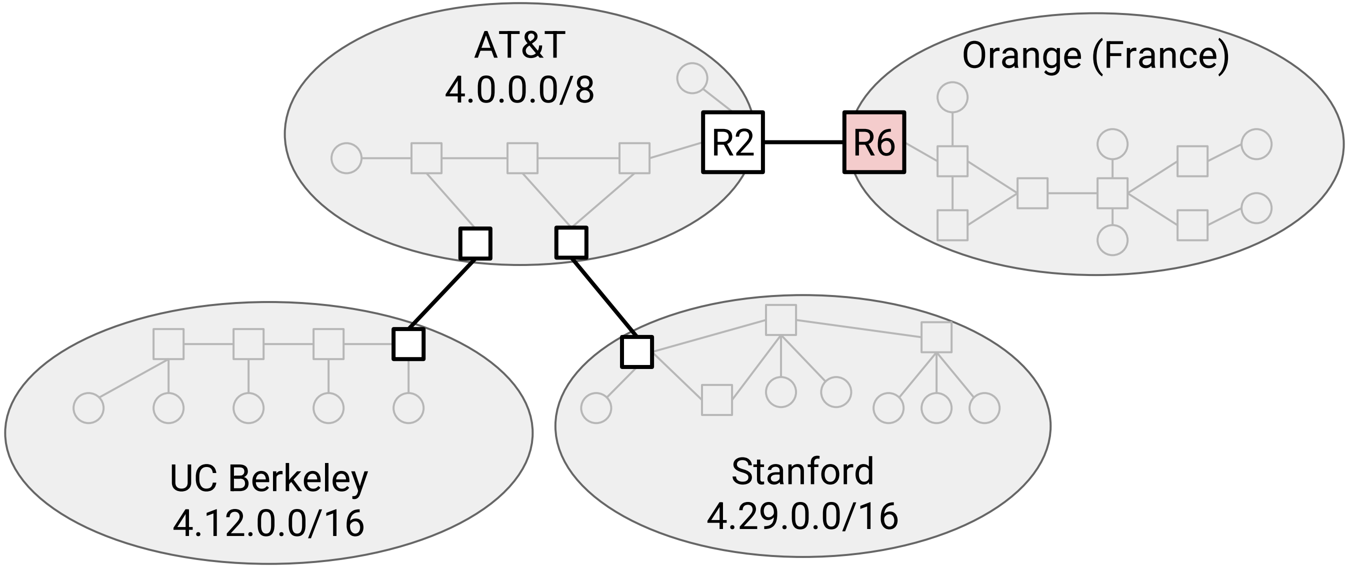
R6's Table

Destination	Next Hop
4.0.0.0/8	R2
130.0.0.0/8	R2
146.0.0.0/8	R2
...	...

Inter-Domain Routing

With CIDR, AT&T allocates parts of its ranges to UC Berkeley and Stanford.

- We can aggregate many networks into a single entry!
- 4.0.0.0/8 represents AT&T, and all its subordinates.

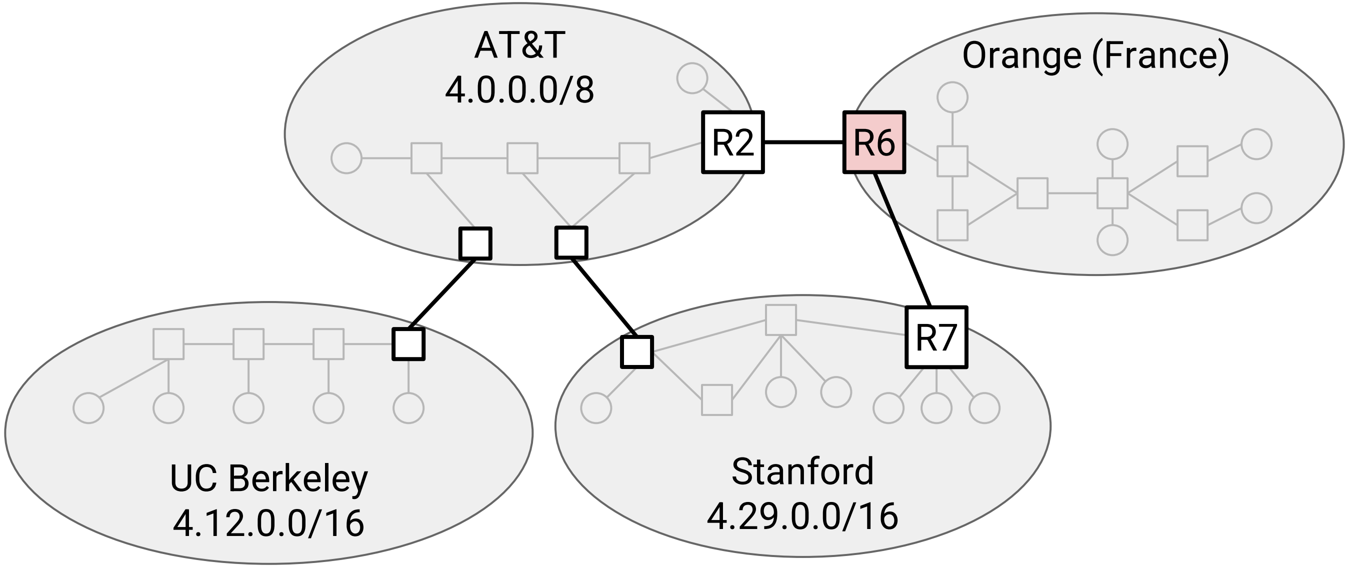


R6's Table	
Destination	Next Hop
4.0.0.0/8	R2
~~4.12.0.0/16~~	~~R2~~
~~4.29.0.0/16~~	~~R2~~
...	...

Inter-Domain Routing

Now, Stanford wants to connect to multiple networks. This is called **multi-homing**.

- We need an entry for both AT&T and Stanford (one of its subordinates).
- Multi-homing limits aggregation!

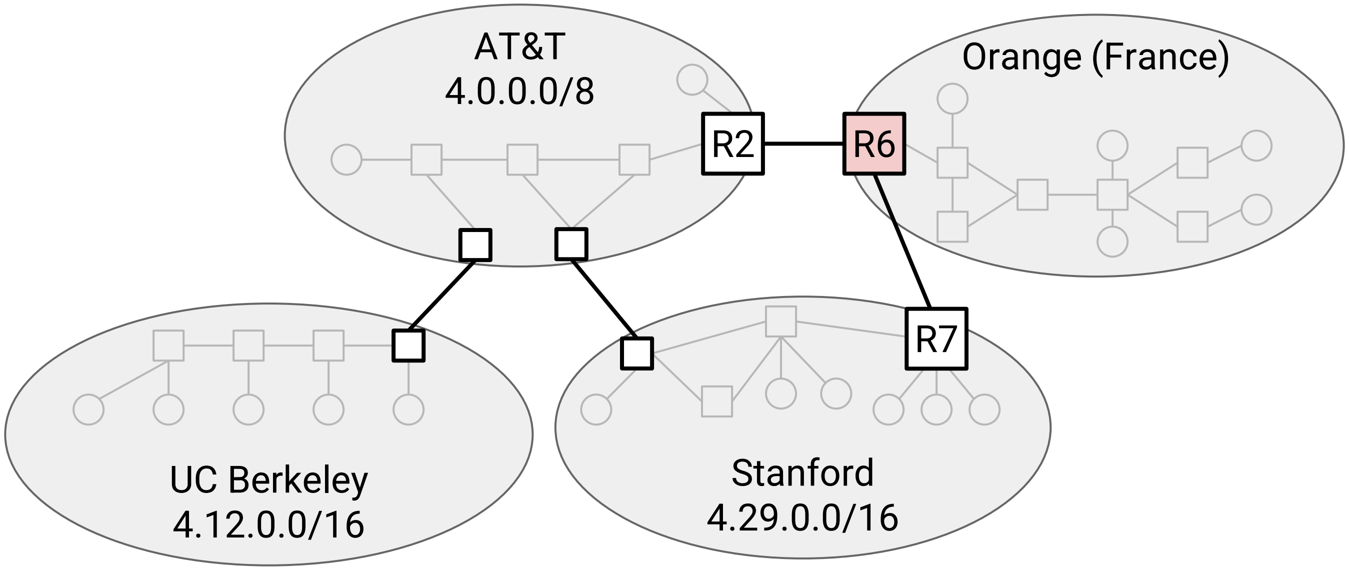


R6's Table	
Destination	Next Hop
4.0.0.0/8	R2
~~4.12.0.0/16~~	~~R2~~
4.29.0.0/16	R7
...	...

Inter-Domain Routing

Ranges in the table might overlap.

- **Longest prefix matching**: If a destination matches many ranges, pick the most specific range.
- Example: 4.29.1.2 matches both 4.0.0.0/8 and 4.29.0.0/16 (more specific).



R6's Table	
Destination	Next Hop
4.0.0.0/8	R2
~~4.12.0.0/16~~	~~R2~~
4.29.0.0/16	R7
...	...

IPv6 Changes

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Introducing IPv6

IPv4 addresses are 32 bits long. $2^{32} \approx 4$ billion addresses. That is not enough.

IPv6 was introduced in 1998 to deal with IPv4 address exhaustion.

- Main difference: Addresses are now 128 bits, instead of 32.
- Fundamentally, same addressing structure as IPv4.

WIth 128-bit address

- $2^{128} \approx 3.4 \times 10^{38}$ possible addresses.
- We won't run out again.

IPv6 Addresses

IPv6 uses hexadecimal instead of decimal.

- `2001:0DB8:CAFE:BEEF:DEAD:1234:5678:9012`
- Colon between every 4 hex digits (16 bits).

Shorthand:

- Omit leading zeros per block:
  `2001:0DB8:0000:0000:0000:0000:0000:0001` → `2001:DB8:0:0:0:0:0:1`
- Omit a long string of zeros, once per address:
  `2001:DB8:0:0:0:0:0:1` → `2001:DB8::1`

Can still use slash notation for ranges.

- `2001:0DB8::/32` has 32 bits fixed, and 2^{96} addresses.

IPv6 Addresses

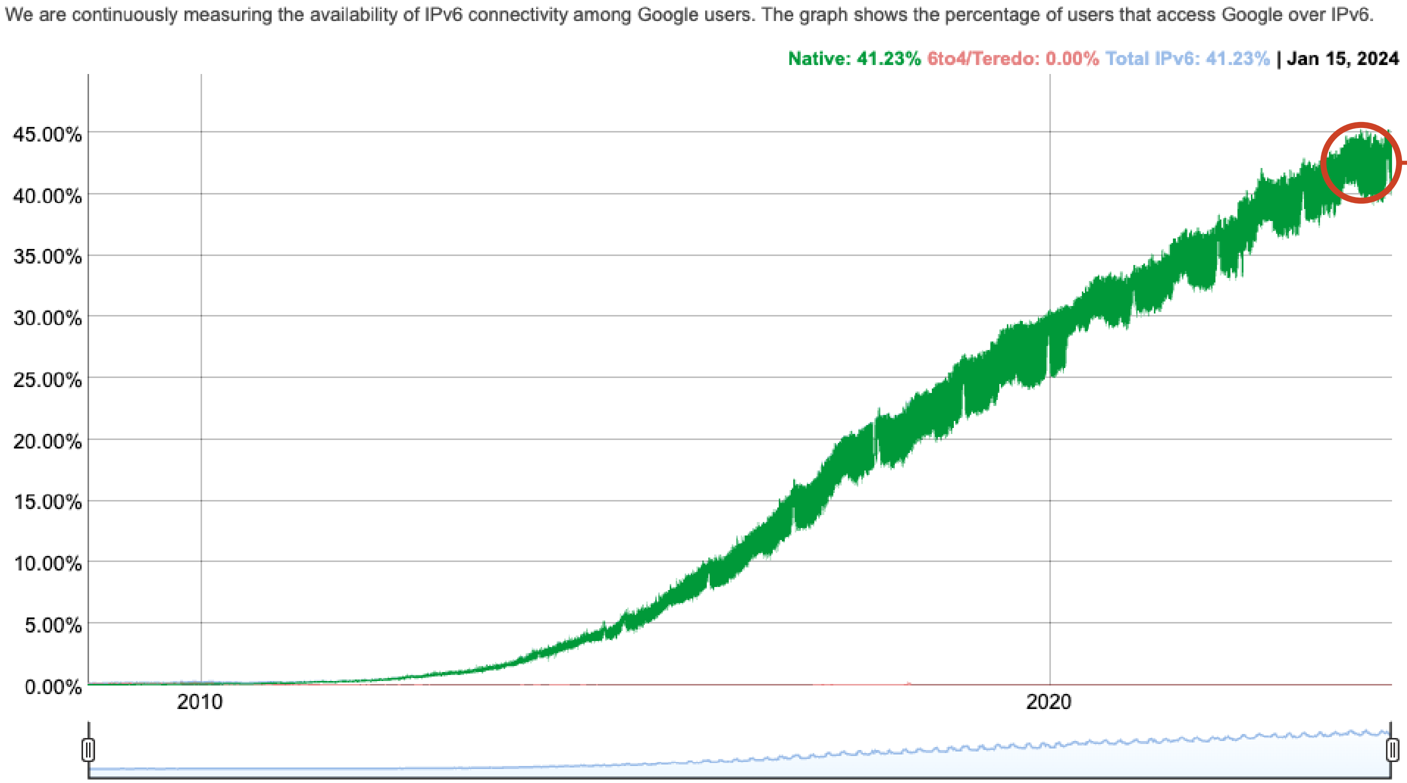
IPv6 uses the same hierarchical addressing approach as IPv4.

Some changes:

- Instead of someone (e.g. ICANN) giving you a prefix, you can pick your own prefix.
    - Uses a protocol called SLAAC *(Stateless Address Autoconfiguration)*.
    - Pick a random prefix. If someone else is using it, pick another one.
    - Works in IPv6 (not IPv4) because there are so many prefixes.
- In practice, prefixes usually fix at most 64 bits.
    - Even the smallest network has 2^{64} hosts.

IPv6 Adoption

IPv6 introduced in the 1990s, but wide adoption started in the 2010s.



We are continuously measuring the availability of IPv6 connectivity among Google users. The graph shows the percentage of users that access Google over IPv6.

Native: 41.23% 6to4/Teredo: 0.00% Total IPv6: 41.23% | Jan 15, 2024

Today, ~40% of hosts have adopted IPv6.

IPv6 Adoption – Challenges

Why is IPv6 adoption hard?

- Requires software and hardware upgrades, from both hosts and routers.
- IPv4 and IPv6 are not compatible with each other.
    - To support both, you need 2 forwarding tables.
    - No way to convert between IPv4 and IPv6.
- If I support both IPv4 and IPv6, which should I use?
    - IPv6 usually faster, but other factors could affect your choice.

Main driver for IPv6 adoption: We're running out of IPv4 addresses!

Summary: IP Addressing

- Hosts on the Internet have addresses (IPv4, IPv6, or both).
- These addresses are hierarchical.
    - They are assigned in groups to specific organizations.
- Wildcard matching can help forwarding and routing scale better.