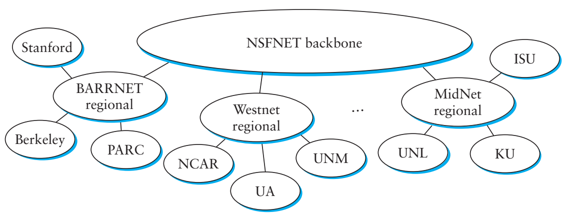
Lecture 6: Intra-Domain Routing

Overview

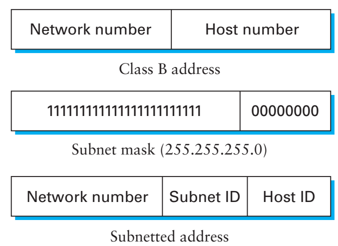
- Internet structure, ASes
- Forwarding vs. Routing
- Distance vector and link state
- Example distance vector: RIP
- Example link state: OSPF

The Internet, 1990



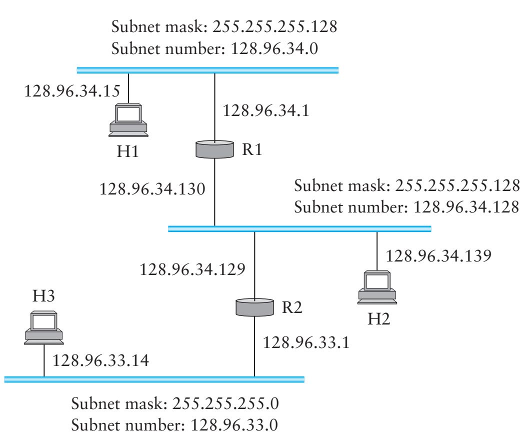
- **Hierarchical structure w. single backbone**

Address allocation, 1990

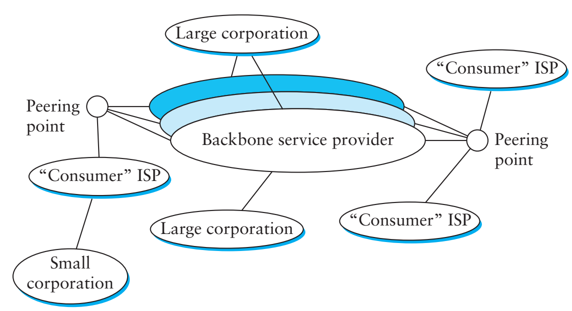


- **Hierarchical IP addresses**
  - Class A (8-bit prefix), B (16-bit), C (24-bit)
- ***Subnetting* adds another level within organizations**
  - Subnet masks define variable partition of host part
  - Subnets visible only within site

Example



The Internet, today



- **Multiple "backbones"**

Address allocation, today

- **Class system makes inefficient use of addresses**
  - class C with 2 hosts (2/255 = 0.78% efficient)
  - class B with 256 hosts (256/65535 = 0.39% efficient)
  - Causes shortage of IP addresses (esp. class B)
  - Makes address authorities reluctant to give out class Bs
- **Still Too Many Networks**
  - routing tables do not scale
  - route propagation protocols do not scale

Supernetting

- **Assign block of contiguous network numbers to nearby networks**
- **Called CIDR: Classless Inter-Domain Routing**
- **Represent blocks with a single pair**
  $(\textit{first network address}, \textit{count})$
- **Restrict block sizes to powers of 2**
  - Represent length of network in bits w. slash
  - E.g.: 128.96.34.0/25 means netmask has 25 1 bits, followed by 7 0 bits, or 0xffffff80 = 255.255.255.128
  - E.g.: 128.96.33.0/24 means netmask 255.255.255.0
- **All routers must understand CIDR addressing**

IP Connectivity

- **For each destination address, must either:**
  1. Have prefix mapped to next hop in forwarding table, or
  2. know "smarter router"—default for unknown prefixes
- **Route using longest prefix match, default is prefix 0.0.0.0/0**
- **Core routers know everything—no default**
- **Manage using notion of *Autonomous System* (AS)**
- **Two-level route propagation hierarchy**
  - interior gateway protocol (each AS selects its own)
  - exterior gateway protocol (Internet-wide standard)

Autonomous systems

- **Correspond to an administrative domain**
  - Internet is not a single network
  - ASes reflect organization of the Internet
  - E.g., Stanford, large company, etc.
- **Goals:**
  - ASes want to choose their own local routing algorithm
  - ASes want to set policies about non-local routing
- **Each AS assigned unique 16-bit number**

Types of traffic & AS

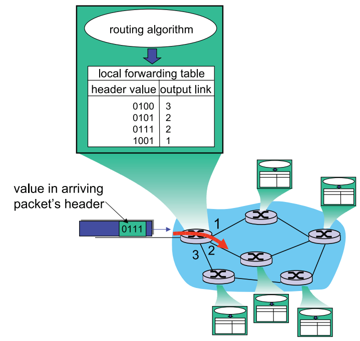
- ***Local traffic* – packets with src or dst in local AS**
- ***Transit traffic* – passes through an AS**
- ***Stub* AS**
  - Connects to only a single other AS
- ***Multihomed* AS**
  - Connects to multiple ASes
  - Carries no transit traffic
- ***Transit* AS**
  - Connects to multiple ASes and carries transit traffic

Intra-domain routing

- **Intra-domain routing: within an AS**
- **Single administrative control: optimality is important**
  - Contrast with inter-AS routing, where policy dominates
  - Next lecture will cover inter-domain routing (BGP)

Forwarding vs. Routing

What is routing?



- ***forwarding*** **– moving packets between ports**
  - Look up destination address in forwarding table
  - Find *out-port* or ⟨*out-port*, *MAC addr*⟩ pair
- ***Routing*** **is process of populating forwarding table**
  - Routers exchange messages about nets they can reach
  - Goal: Find optimal route for every destination
  - …or maybe good route, or just any route (depending on scale)

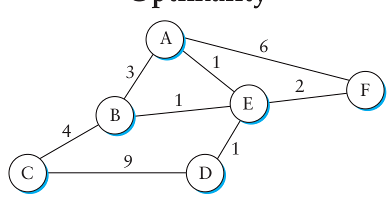
Stability

- **Stable routes are often preferred over rapidly changing ones**
- **Reason 1: management**
  - Hard to debug a problem if it's transient
- **Reason 2: higher layer optimizations**
  - E.g., TCP RTT estimation
  - Imagine alternating over 500ms and 50ms routes
- **Tension between optimality and stability**

Routing algorithm properties

- **Global vs. decentralized**
  - Global: All routers have complete topology
  - Decentralized: Only know neighbors & what they tell you
- ***Intra*-domain vs. *Inter*-domain routing**
  - Intra-: All routers under same administrative control
  - Intra-: Scale to ∼100 networks (e.g., campus like Stanford)
  - Inter-: Decentralized, scale to Internet
- **We'll cover basic algorithms for intra-domain routing and two protocols: RIP and OSPF**

Optimality



- **View network as a graph**
- **Assign *cost* to each edge**
  - Can be based on latency, b/w, utilization, queue length, …
- **Problem: Find lowest cost path between two nodes**
  - Each node individually computes the cost (some recent research argues against doing this, more on this later)

Scaling issues

- **Every router must be able to forward based on *any* destination IP address**
  - Given address, it needs to know "next hop" (table)
  - Naïve: Have an entry for each address
  - There would be 10^8 entries!
- **Solution: Entry covers range of addresses**
  - Can't do this if addresses are assigned randomly! (e.g., Ethernet addresses)
  - This is why *address aggregation* is important
  - Addresses allocation should be based on network structure
- **What is structure of the Internet?**

Distance Vector and Link State

Basic Algorithms

- **Two classes of intra-domain routing algorithms**
- **Link state**
  - Have a global view of the network
  - Simpler to debug
  - Require global state
- **Distance vector**
  - Require only local state (less overhead, smaller footprint)
  - Harder to debug
  - Can suffer from loops

Link State

- **Strategy**
  - Send to all nodes (not just neighbors)
  - Send only information about directly connected links (not entire routing table)
- **Link State Packet (LSP)**
  - ID of the node that created the LSP
  - Cost of link to each directly connected neighbor
  - Sequence number (SEQNO)
  - Time-to-live (TTL) for this packet

Reliable flooding

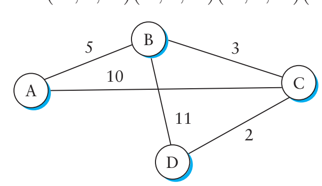
- **Store most recent LSP from each node**
- **Forward LSP to all nodes but one that sent it**
- **Generate new LSP periodically**
  - Increment SEQNO
- **Start SEQNO at 0 when reboot**
  - If you hear your own packet w. SEQNO$=n$, set your next SEQNO to $n+1$
- **Decrement TTL of each stored LSP**
  - discard when TTL$=0$

Calculating best path

- **Dijkstra's shortest path algorithm**
- **Let:**
  - N denote set of nodes in the graph
  - $l(i,j)$ denotes non-negative cost (weight) for edge (i,j)
  - s denotes yourself (node computing paths)
- **Initialize variables**
  - $M \leftarrow \{s\}$ (set of nodes "incorporated" so far)
  - $C_n \leftarrow l(s,n)$ (cost of the path from s to n)
  - $R_n \leftarrow \perp$ (next hop on path to n)

Dijkstra's algorithm

- **While** $N \neq M$
  - Let $w \in (N-M)$ be node with lowest C_w
  - $M \leftarrow M \cup \{w\}$
  - Foreach $n \in (N-M)$, if $C_w + l(w,n) < C_n$ then $C_n \leftarrow C_w + l(w,n)$, $R_n \leftarrow w$
- **Example: D** $(D,0,\perp)(C,2,C)(B,5,C)(A,10,C)$



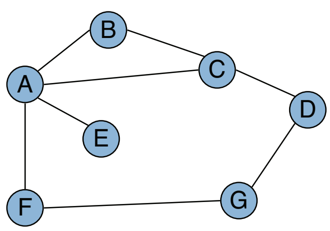
Distance Vector

- *Local* routing algorithm
- **Each node maintains a set of triples**
  - $(Destination, Cost, NextHop)$
- **Exchange updates with direct neighbors**
  - periodically (on the order of several seconds to minutes)
  - whenever table changes (called triggered update)
- **Each update is a list of pairs:**
  - $(Destination, Cost)$
- **Update local table if receive a "better" route**
  - smaller cost
  - from newly connected/available neighbor
- **Refresh existing routes; delete if they time out**

Calculating best path

- **Bellman-Ford equation**
- **Let:**
  - $D_a(b)$ denote the distance from a to b
  - $c(a, b)$ denote the cost of a link from a to b
- **Then** $D_x(y) = min_z(c(x, z) + D_z(y))$
- **Routing messages contain** D**; when does a node transmit a message?**

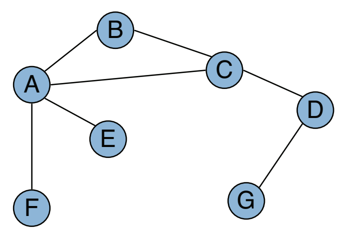
DV Example



- **B's routing table:**

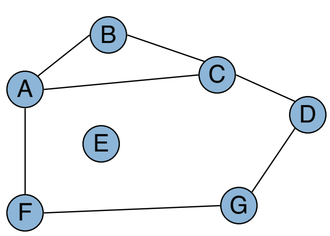
Destination	Cost	NextHop
A	1	A
C	1	C
D	2	C
E	2	A
F	2	A
G	3	A

Adapting to failures



- F detects that link to G has failed
- F sets distance to G to infinity and sends update to A
- A sets distance to G to infinity since it uses F to reach G
- A receives periodic update from C with 2-hop path to G
- A sets distance to G to 3 and sends update to F
- F decides it can reach G in 4 hops via A

Danger: Loops



- link from A to E fails
- A advertises distance of infinity to E
- B and C advertise a distance of 2 to E
- B decides it can reach E in 3 hops; advertises this to A
- A decides it can reach E in 4 hops; advertises this to C
- C decides that it can reach E in 5 hops…

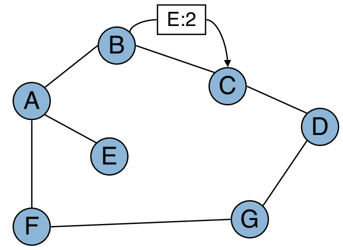
How to avoid loops

- **IP TTL field prevents a packet from living forever**
  - Does not break or repair a loop
- **Simple approach: consider small cost** n **(e.g., 16) to be infinity**
  - After n rounds will decide node is unavailable
  - But rounds can be long: this takes time
- **Distance vector based only on local information**

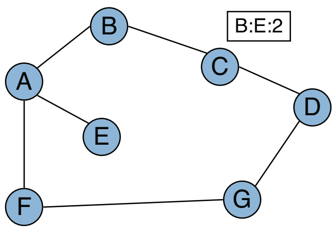
Better loop avoidance

- **Split horizon**
  - When sending updates to node A, don't include destinations you route to through A
  - Prevents B and C from sending cost 2 to A
- **Split horizon with poison reverse**
  - When sending updates to node A, explictly include very high cost ("poison") for destinations you route to through A
  - When does poison reverse help?

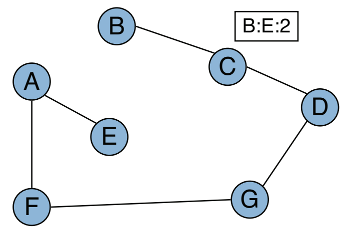
Poison Reverse example



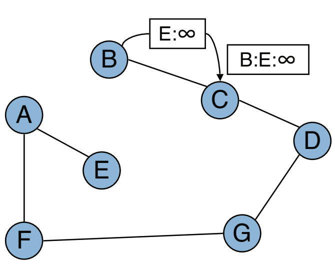
Poison Reverse example



Poison Reverse example



Poison Reverse example



Warning

- **Note: Split horizon/split horizon with poison reverse only help between two nodes**
  - Can still get loop with three nodes involved
  - Might need to delay advertising routes after changes, but will affect convergence time

Distance Vector vs. Link State

- **# of messages**
  - DV: convergence time varies, but $\Omega(d)$ where d is # of neighbors of node
  - LS: $O(n \cdot d)$ for n nodes in system
- **Computation**
  - DV: Could count all the way to ∞ if loop
  - LS: $O(n^2)$
- **Robustness – what happens with malfunctioning router?**
  - DV: Node can advertise incorrect *path* cost
  - DV: Costs used by others, errors propagate through net
  - LS: Node can advertise incorrect *link* cost

Metrics

- **Original ARPANET metric**
  - measures number of packets enqueued on each link
  - took neither latency nor bandwidth into consideration
- **New ARPANET metric**
  - stamp each incoming packet with its arrival time (AT)
  - record departure time (DT)
  - when link-level ACK arrives, compute $\mathit{Delay} = (DT - AT) + \mathit{Transmit} + \mathit{Latency}$
  - if timeout, reset DT to departure time for retransmission
  - link cost = average delay over some time period
- **Fine Tuning**
  - compressed dynamic range
  - replaced *Delay* with link utilization
- **Today: policy often trumps performance [more later]**

Intradomain routing protocols

- **RIP (routing information protocol)**
  - Fairly simple implementation of DV
  - RFC 2453 (38 pages)
- **OSPF (open shortest path first)**
  - More complex link-state protocol
  - Adds notion of *areas* for scalability
  - RFC 2328

2-minute stretch

Example Distance Vector: RIP

RIPv2 [RFC 2453]

- **Runs over UDP port 520**
- **Limits networks to 15 hops (16 = ∞)**
- **Depends on count to infinity for loops**
- **Supports split horizon, poison reverse**
- **RFC 1812 specifes what options routers should or must have**

RIPv2 packet format

```
0                   1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  command (1)  |  version (1)  |       must be zero (2)        |
+---------------+---------------+-------------------------------+
|                                                               |
~                         RIP Entry (20)                        ~
|                                                               |
+---------------+---------------+---------------+---------------+
```

RIPv2 Entry

```
0                   1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| address family identifier (2) |       Route Tag (2)           |
+-------------------------------+-------------------------------+
|                         IP address (4)                        |
+---------------------------------------------------------------+
|                         Subnet Mask (4)                       |
+---------------------------------------------------------------+
|                         Next Hop (4)                          |
+---------------------------------------------------------------+
|                         Metric (4)                            |
+---------------------------------------------------------------+
```

Route Tag Field

- Allows RIP nodes to distinguish internal and external routes
- Must persist across announcements
- E.g., encode AS

Next Hop Field

- Allows one router to advertise routes for multiple routers on same subnet
- Suppose only XR1 talks RIP2:

```
-----   -----   -----           -----   -----   -----
|IR1|   |IR2|   |IR3|           |XR1|   |XR2|   |XR3|
--+--   --+--   --+--           --+--   --+--   --+--
  |       |       |               |       |       |
--+-------+-------+---------------+-------+-------+--
  <-------------RIP-2------------->
```

Example Link State: OSPF

OSPFv2 [RFC 2328]

- Link state protocol
- RFC 2328 (244 pages)
- Runs directly over IP (protocol 89)
  - Has to provide its own reliability
- All exchanges are authenticated
- Adds notion of *areas* for scalability

OSPF Areas

- Area 0 is "backbone" area (includes all boundary routers)
- Traffic between two areas must always go through area 0
- Only need to know how to route exactly within area
- Else, just route to appropriate area
- (Virtual links can allow distant routers to be in area 0)

OSPF areas

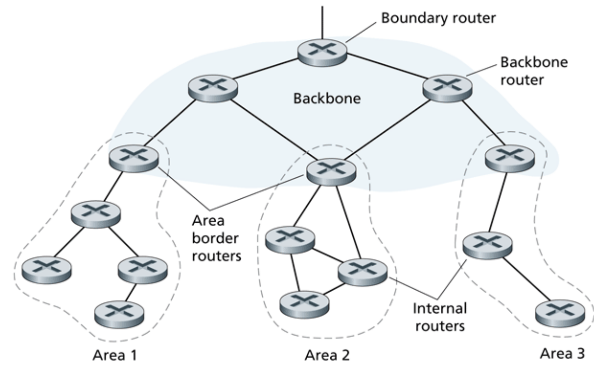


Figure 4.40 ♦ Hierarchically structured OSPF AS with four areas

OSPF Packet Header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Version #   |     Type      |         Packet length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Router ID                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Area ID                             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|           Checksum            |             AuType            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Authentication                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Authentication                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

OSPF Packet Types

- 1 - Hello packet
- 2 - Database Description
- 3 - Link State Request
- 4 - Link State Update
- 5 - Link State Acknowledgment

Database Description

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Interface MTU         |    Options    |0|0|0|0|0|I|M|MS
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     DD sequence number                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
~                     An LSA Header (20+bytes)                  ~
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                              ...                              |
```

Database Description Packet Fields

- Interface MTU
- Options (multicast, external LSAs, etc.)
- Init bit, More bit, Master/Slave bit
- Sequence number: distinguishes DD packets.
- Exchange
  - First packet in an exchange has the I bit sent, all but last have M bit set, sequence number increments on each packet

DD Packet Exchange

- Used to initialize routing state
- Node A sends an empty DD to node B with sequence number n, the I, M, and MS bits set
- Node B responds with a DD with the I and MS bits cleared, seq. no n
  - Can contain LSAs - if there are more, set the M bit
- Node A $n+1$, I bit cleared, MS bit set, M bit depends on whether there are more LSAs
- Continues until both send cleared M bit

OSPF areas

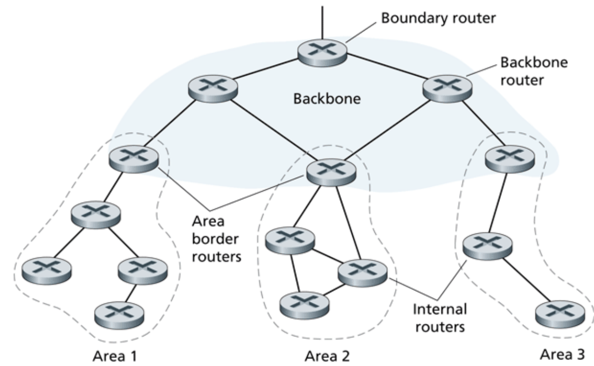


Figure 4.40 ♦ Hierarchically structured OSPF AS with four areas

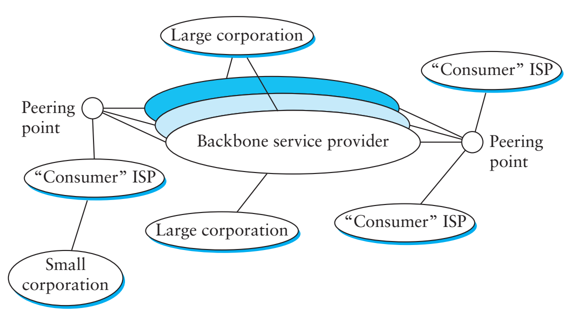
LSA Details

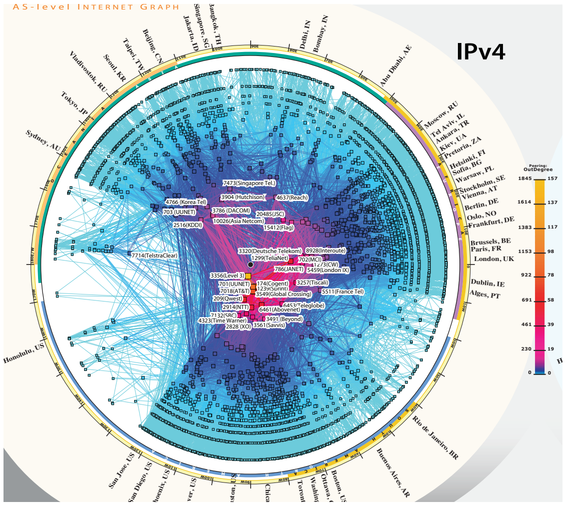
- Many different LSA formats
- Example 1: Router-LSAs, describe a router's links
- Example 2: Summary-LSAs, generated by area border routers
  - Describes an IP network within the area
  - Includes IP address, network mask, and cost metric
- Example 3: AS-external-LSAs
  - Describes an IP network in another AS
  - Includes IP address, netmask, cost, and forwarding address

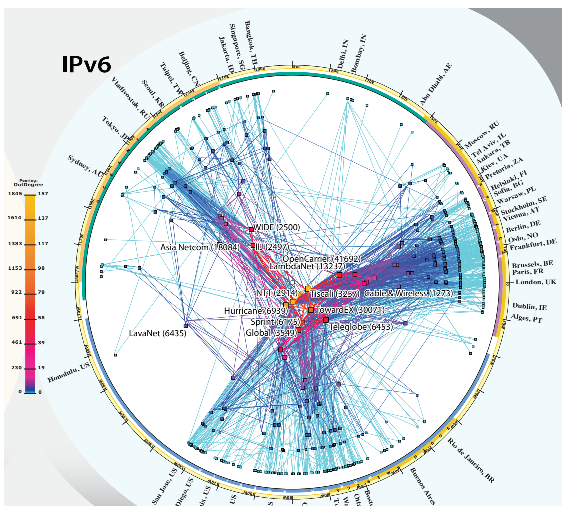
Basic Algorithms

- Two classes of intra-domain routing algorithms
- Link state (e.g., OSPF)
  - Have a global view of the network
  - Simpler to debug
  - Require global state (OSPF reduces this through areas)
- Distance vector (e.g. RIP)
  - Require only local state (less overhead, smaller footprint)
  - Harder to debug
  - Can suffer from loops

The Internet, today







Overview

- Internet structure, ASes
- Forwarding vs. Routing
- Distance vector and link state
- Example distance vector: RIP
- Example link state: OSPF
- Next lecture: BGP