Chapter 5
Network Layer: The Control Plane

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Chapter 5: network layer control plane

chapter goals: understand principles behind network control plane

- traditional routing algorithms
- SDN controllers
- Internet Control Message Protocol
- Simple Network Management Protocol

graph

routing

mangement

and their instantiation, implementation in the Internet:

- OSPF, BGP, OpenFlow, ODL and ONOS controllers, ICMP, SNMP

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Network-layer functions

Recall: two network-layer functions:

- *forwarding:* move packets from router's input to appropriate router output

data plane

- *routing:* determine route taken by packets from source to destination

control plane

Two approaches to structuring network control plane:

- per-router control (traditional)
- logically centralized control (software defined networking)

Per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables

Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables

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Routing protocols

Routing protocol goal: determine "good" paths (equivalently, routes), from sending hosts to receiving host, through network of routers

- path: sequence of routers packets will traverse in going from given initial source host to given final destination host
- "good": least "cost", "fastest", "least congested"
- routing: a "top-10" networking challenge!

Graph abstraction of the network

graph: G = (N,E)

node N = set of routers = { u, v, w, x, y, z }

edge E = set of links ={ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

aside: graph abstraction is useful in other network contexts, e.g., P2P, where *N* is set of peers and *E* is set of TCP connections

Graph abstraction: costs

c(x,x') = cost of link (x,x')
e.g., c(w,z) = 5

cost could always be 1, or inversely related to bandwidth, or inversely related to congestion

cost of path $(x_1, x_2, x_3, \ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

key question: what is the least-cost path between u and z ?
routing algorithm: algorithm that finds that least cost path

Routing algorithm classification

Q: global or decentralized information?

global:

- all routers have complete topology, link cost info
- "link state" algorithms

local:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Q: static or dynamic?

static:

- routes change slowly over time

dynamic:

- routes change more quickly
  - periodic update
  - in response to link cost changes

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A link-state routing algorithm

Dijkstra's algorithm

- net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have same info

global

- computes least cost paths from one node ('source') to all other nodes
  - gives *forwarding table* for that node
- iterative: after k iterations, knows least cost path to k dest.'s

notation:

- c(a,b): link cost from node a to b; = ∞ if not direct neighbors
- D(d): current value of cost of path from source to dest. d path cost
- p(d): predecessor node along path from source to d
- N': set of nodes whose least cost path definitively known

Dijsktra's algorithm

```
Initialization:
  N' = {a}                                  a = src
  for all nodes b
    if b adjacent to a
        then D(b) = c(a,b)
    else D(b) = ∞

Loop
  find i not in N' such that D(i) is a minimum
  add i to N'
  update D(j) for all j adjacent to i and not in N' :
      D(j) = min( D(j), D(i) + c(i,j) )
  /* new cost to j is either old cost to j or known
   shortest path cost to i plus cost from i to j */
until all nodes in N'
```

Dijkstra's algorithm: example

Step	N'	D(v) p(v)	D(w) p(w)	D(x) p(x)	D(y) p(y)	D(z) p(z)
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					

trace back

```
Initialization:
  N' = {a}
  for all nodes b
    if b adjacent to a
        then D(b) = c(a,b)
             p(b) = a
    else D(b) = ∞
```

notes:

- construct shortest path tree by tracing predecessor nodes
- ties can exist (can be broken arbitrarily)

shortest path tree

Quiz Time

Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u					

```
Initialization:
  N' = {a}
  for all nodes b
    if b adjacent to a
        then D(b) = c(a,b)
                p(b) = a
    else D(b) = ∞
```

Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2, u	5, u	1, u	∞	∞
1	ux	2, u	4, x		2, x	∞

```
Initialization:
  N' = {a}
  for all nodes b
    if b adjacent to a
        then D(b) = c(a,b)
                  p(b) = a
    else D(b) = ∞
```

Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞

8 ***Loop***
9 find i not in N' such that D(i) is a minimum add i to N'

11 update D(j) for all j adjacent to i and not in N' :
D(j) = min(D(j), D(i) + c(i,j))
p(j) = i, if D(i) + c(I,j) smaller

15 ***until all nodes in N'***

Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux					

8 ***Loop***

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0	u	2,u	5,u	1,u	∞	∞
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0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy					

```
Loop
  find i not in N' such that D(i) is a
  minimum add i to N'

  update D(j) for all j adjacent to i
  and not in N' :
      D(j) = min( D(j), D(i) + c(i,j) )
      p(j) = i, if D(i) + c(I,j) smaller

until all nodes in N'
```

Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y

8 ***Loop***
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1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv					

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0	u	2,u	5,u	1,u	∞	∞
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3	uxyv		3,y			4,y

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0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					

8 ***Loop***

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15 ***until all nodes in N'***

Dijkstra's algorithm: another example

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0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y

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0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

8 ***Loop***

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D(j) = min(D(j), D(i) + c(i,j))

p(j) = i, if D(i) + c(I,j) smaller

15 ***until all nodes in N'***

Dijkstra's algorithm: example (2)

resulting shortest-path tree from u:

resulting forwarding table in u:

destination	link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
z	(u,x)

Dijkstra's algorithm, discussion

algorithm complexity: n nodes

$n-1, n-2, n-3, \ldots, 1$

- each iteration: need to check all nodes, j, not in N'
- n(n-1)/2 comparisons: $O(n^2)$
- more efficient implementations possible: O(nlogn)

$\frac{(n-1+1)(n-1)}{2}$

oscillations possible:

- e.g., support link cost equals amount of carried traffic:

initially

given these costs, find new routing…. resulting in new costs

given these costs, find new routing…. resulting in new costs

given these costs, find new routing…. resulting in new costs

LS Routing Summary

- net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have the entire topology info
- computes least cost paths from one node ('source') to all other nodes
  - gives forwarding table for that node

LS Reports → Net Topo

- Node u sending a LS report
  - Node u: (v,5), (w,3), (x,7)

- Suppose node u received these LS reports
  - Node v: (u,5)
  - Node w: (u,3), (x,2)
  - Node x: (u,7), (w,2)

LS Routing Summary

- net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have the entire topology info
- computes least cost paths from one node ('source') to all other nodes
  - gives forwarding table for that node

- Do you see any problems?

  LS broadcast: consumes bandwidth n^2

  Topology info: occupies memory space n^2

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5.2 routing protocols

- link state global
- distance vector local

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Can you do without knowing the Topology?

Yes, I tell my neighbors.
You tell yours

For best route, check all neighbors

1. Cost to the neighbor $x(i)$
2. Neighbor's cost to the destination $y(i)$

$x(i)+y(i)$

Quiz Time!

How does a router know a route without the network topology?

Track how neighbors know about the destination

For best route, check all neighbors

1. Cost to the neighbor
2. Neighbor's cost to the destination

Distance vector algorithm

Bellman-Ford equation (dynamic programming)

let

$d_x(y)$:= cost of least-cost path from x to y

then

$$d_x(y) = \min_v \{c(x,v) + d_v(y)\}$$

cost from neighbor v to destination y

link cost to neighbor v

min taken over all neighbors v of x

Bellman-Ford example

clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

B-F equation says:

$$
\begin{aligned}
d_u(z) &= \min \{ c(u,v) + d_v(z), \\
&\qquad c(u,x) + d_x(z), \\
&\qquad c(u,w) + d_w(z) \} \\
&= \min \{2 + 5, \\
&\qquad 1 + 3, \\
&\qquad 5 + 3\} \ = 4
\end{aligned}
$$

node achieving minimum is next hop in shortest path, used in forwarding table

Distance vector algorithm

- $d_x(y)$ = estimate of least cost from x to y
  - x maintains distance vector $\mathbf{D}_x = [d_x(y): y \in N]$

    a set of nodes
- node x:
  - knows cost to each neighbor v: $c(x,v)$
  - maintains its neighbors' distance vectors. For each neighbor v, x maintains $\mathbf{D}_v = [d_v(y): y \in N]$

$d_i(z) = \min\{c(i,j) + d_j(z)\}$

Distance vector algorithm

key idea:

- from time-to-time, each node sends its own distance vector estimate to neighbors
- when x receives new $\mathbf{D}_v$ estimate from neighbor v, it updates its own $\mathbf{D}_x$ using B-F equation:

$$d_x(y) \leftarrow \min_v\{c(x,v) + d_v(y)\} \quad \text{for each node } y \in N$$

- under minor, natural conditions, the estimate $d_x(y)$ *converge to the actual least cost*

Distance vector algorithm

iterative, asynchronous: each local iteration caused by:

- local link cost change
- DV update message from neighbor

distributed:

- each node notifies neighbors when its DV changes
  - neighbors then notify their neighbors if necessary

each node:

wait for (change in local link cost or msg from neighbor)

recompute estimates

find better path

if DV to any dest has changed, *notify* neighbors

Distance vector algorithm

each node:

wait for (change in local link cost or msg from neighbor)

recompute estimates

if DV to any dest has changed, *notify* neighbors

$$d_x(y) = \min\{c(x,y) + d_y(y),\ c(x,z) + d_z(y)\}$$
$$= \min\{2+0\ ,\ 7+1\} = 2$$

$$d_x(z) = \min\{c(x,y) + d_y(z),\ c(x,z) + d_z(z)\}$$
$$= \min\{2+1\ ,\ 7+\boxed{0}\} = 3$$

init

1st

node x table

from	cost to x	cost to y	cost to z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

own D

neighor D

Null

from	cost to x	cost to y	cost to z
x	0	2	3
y	2	0	1
z	7	1	0

$d_x(y)$

D_x

node y table

from	cost to x	cost to y	cost to z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

D_y

node z table

from	cost to x	cost to y	cost to z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

D_z

	x	y	z
x	0	2	7
y	2	0	1
z	.		0

time

$d_z(x) = \min\{c(z,x) + d_x(x),\ c(z,y) + d_y(x)\}$

Quiz Time!

$$D_x(y) = \min\{c(x,y) + D_y(y),\ c(x,z) + D_z(y)\}$$
$$= \min\{2+0\ ,\ 7+1\} = 2$$

$$D_x(z) = \min\{c(x,y) + D_y(z),\ c(x,z) + D_z(z)\}$$
$$= \min\{2+1\ ,\ 7+0\} = 3$$

node x table

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node y table

from \ cost to	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

didn't change

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node z table

from \ cost to	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

time

converge into shortest path

Distance vector: link cost changes

link cost changes:

- node detects local link cost change
- updates routing info, recalculates distance vector
- if DV changes, notify neighbors

"good news travels fast"

t_0 : *y* detects link-cost change, updates its DV, informs its neighbors.

t_1 : *z* receives update from *y*, updates its table, computes new least cost to *x* , sends its neighbors its DV.

t_2 : *y* receives *z*'s update, updates its distance table. *y*'s least costs do *not* change, so *y* does *not* send a message to *z*.

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

Distance vector: link cost changes

link cost changes:

- node detects local link cost change
- *bad news travels slow* - "count to infinity" problem!
- 44 iterations before algorithm stabilizes: **Quiz!**

poisoned reverse:

- If Z routes through Y to get to X :
  - Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)
- will this completely solve count to infinity problem?

Comparison of LS and DV algorithms

message complexity

- ***LS:*** with n nodes, E links, O(nE) msgs sent
- ***DV:*** exchange between neighbors only

speed of convergence

- ***LS:*** $O(n^2)$ algorithm
  - may have oscillations
- ***DV:*** convergence time varies
  - may be routing loops
  - count-to-infinity problem

robustness: what happens if router malfunctions?

LS:

- node can advertise incorrect *link* cost
- each node computes its *own* table independently

DV:

- DV node can advertise incorrect *path* cost
- each node's table used by others
  - error propagate thru network

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local

5.4 routing among the ISPs: BGP

path vector

backbone

5.5 The SDN control plane

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Making routing scalable

our routing study thus far - idealized

- all routers identical
- network "flat"

… *not* true in practice

scale: with billions of destinations: 2^{32} 2^{128}

- can't store all destinations in routing tables! $2 \times 2^{32} = 8GB$
- routing table exchange would swamp links!

administrative autonomy

- internet = network of networks
- each network admin may want to control routing in its own network

Internet approach to scalable routing

aggregate routers into regions known as "autonomous systems" (AS) (a.k.a. "domains")

intra-AS routing

- routing among hosts, routers in same AS ("network")
- all routers in AS must run *same* intra-domain protocol
- routers in *different* AS can run *different* intra-domain routing protocol
- gateway router: at "edge" of its own AS, has link(s) to router(s) in other AS'es

inter-AS routing

- routing among AS'es
- gateways perform inter-domain routing (as well as intra-domain routing)

Interconnected ASes

- forwarding table configured by both intra- and inter-AS routing algorithm
  - intra-AS routing determine entries for destinations within AS
  - inter-AS & intra-AS determine entries for external destinations

Inter-AS tasks

- suppose router in AS1 receives datagram destined outside of AS1:
  - router should forward packet to gateway router, but which one?

AS1 must:

1. learn which dests are reachable through AS2, which through AS3
2. propagate this reachability info to all routers in AS1

job of inter-AS routing!

Intra-AS Routing

- also known as *interior gateway protocols (IGP)*
- most common intra-AS routing protocols:
  - RIP: Routing Information Protocol DV
    open source
  - OSPF: Open Shortest Path First (IS-IS protocol essentially same as OSPF) LS
  - IGRP: Interior Gateway Routing Protocol (Cisco proprietary for decades, until 2016)

OSPF (Open Shortest Path First)

- "open": publicly available
- uses link-state algorithm
  - link state packet dissemination
  - topology map at each node
  - route computation using Dijkstra's algorithm
- router floods OSPF link-state advertisements to all other routers in *entire* AS
  - carried in OSPF messages directly over IP (rather than TCP or UDP
  - link state: for each attached link
- *IS-IS routing* protocol: nearly identical to OSPF

OSPF "advanced" features

- *security:* all OSPF messages authenticated (to prevent malicious intrusion)
- multiple same-cost paths allowed (only one path in RIP)
- for each link, multiple cost metrics for different ToS (e.g., satellite link cost set low for best effort ToS; high for real-time ToS)
- integrated uni- and multi-cast support:
  - Multicast OSPF (MOSPF) uses same topology data base as OSPF
- hierarchical OSPF in large domains.

Hierarchical OSPF

Hierarchical OSPF

- *two-level hierarchy:* local area, backbone.
  - link-state advertisements only in area
  - each nodes has detailed area topology
  - only know direction (shortest path) to nets in other areas.
- *area border routers:* "summarize" distances to nets in own area, advertise to other Area Border routers.
- *backbone routers:* run OSPF routing limited to backbone.
- *boundary routers:* connect to other AS' es.

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

path vector

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Internet inter-AS routing: BGP

事实上

- BGP (Border Gateway Protocol): *the* de facto inter-domain routing protocol only one protocol
  - "glue that holds the Internet together"
- BGP provides each AS a means to:
  - 1 eBGP: obtain subnet reachability information from neighboring ASes dest. AS path vector
  - 2. iBGP: propagate reachability information to all AS-internal routers.
  - determine "good" routes to other networks based on reachability information and *policy* (security
  - allows subnet to advertise its existence to rest of Internet: *"I am here"*

eBGP, iBGP connections

gateway routers run both eBGP and iBGP protools

BGP basics

layer 3

- BGP session: two BGP routers ("peers") exchange BGP messages over semi-permanent TCP connection: layer 4
  - advertising *paths* to different destination network prefixes (BGP is a "path vector" protocol)
- when AS3 gateway router 3a advertises path AS3,X to AS2 gateway router 2c:
  - AS3 *promises* to AS2 it will forward datagrams towards X

Path attributes and BGP routes

- advertised prefix includes BGP attributes
  - prefix + attributes = "route"
- two important attributes:
  - AS-PATH: list of ASes through which prefix advertisement has passed

    $\boxed{AS_2, AS_3, x}$ $\boxed{AS3, x}$ AS_3
  - NEXT-HOP: indicates specific internal-AS router to next-hop AS IP of the gateway router
- *Policy-based routing:*
  - gateway receiving route advertisement uses *import policy* to accept/decline path (e.g., never route through AS Y).
  - AS policy also determines whether to *advertise* path to other neighboring ASes

BGP path advertisement

- AS2 router 2c receives path advertisement AS3,X (via eBGP) from AS3 router 3a
- Based on AS2 policy, AS2 router 2c accepts path AS3,X, propagates (via iBGP) to all AS2 routers
- Based on AS2 policy, AS2 router 2a advertises (via eBGP) path AS2, AS3, X to AS1 router 1c

BGP path advertisement

gateway router may learn about multiple paths to destination:

- AS1 gateway router 1c learns path *AS2,AS3,X* from 2a
- AS1 gateway router 1c learns path *AS3,X* from 3a
- Based on policy, AS1 gateway router 1c chooses path *AS3,X, and advertises path within AS1 via iBGP*

BGP, OSPF, forwarding table entries

Q: how does router set forwarding table entry to distant prefix?

- recall: 1a, 1b, 1d learn about dest X via iBGP from 1c: "path to X goes through 1c"
- 1d: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 1

BGP, OSPF, forwarding table entries

Q: how does router set forwarding table entry to distant prefix?

- recall: 1a, 1b, 1c learn about dest X via iBGP from 1c: "path to X goes through 1c"
- 1d: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 1
- 1a: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 2

BGP route selection

- router may learn about more than one route to destination AS, selects route based on:
  1. local preference value attribute: policy decision
  2. shortest AS-PATH
  3. closest NEXT-HOP router: hot potato routing
  4. additional criteria

Hot Potato Routing

- 2d learns (via iBGP) it can route to X via 2a or 2c
- *hot potato routing:* choose local gateway that has least intra-domain cost (e.g., 2d chooses 2a, even though more AS hops to X): don't worry about inter-domain cost!

BGP messages

- BGP messages exchanged between peers over TCP connection
- BGP messages:
  - OPEN: opens TCP connection to remote BGP peer and authenticates sending BGP peer
  - UPDATE: advertises new path (or withdraws old)
  - KEEPALIVE: keeps connection alive in absence of UPDATES; also ACKs OPEN request
  - NOTIFICATION: reports errors in previous msg; also used to close connection

Quiz Time!

BGP: achieving policy via advertisements

Suppose an ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs)

- A advertises path Aw to B and to C
- B *chooses not to advertise* BAw to C:
  - B gets no "revenue" for routing CBAw, since none of C, A, w are B's customers
  - C does not learn about CBAw path
- C will route CAw (not using B) to get to w

BGP: achieving policy via advertisements

Suppose an ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs)

- A,B,C are *provider networks*
- X,W,Y are customer (of provider networks)
- X is *dual-homed:* attached to two networks
- *policy to enforce:* X does not want to route from C to B via X
  - .. so X will not advertise to C a route to B

no $

Triple Quiz Time!

Why different Intra-, Inter-AS routing ?

policy:

- inter-AS: admin wants control over how its traffic routed, who routes through its net.
- intra-AS: single admin, so no policy decisions needed

scale:

- hierarchical routing saves table size, reduced update traffic

performance:

- intra-AS: can focus on performance
- inter-AS: policy may dominate over performance

Chapter 5: outline

5.1 introduction

5.2 routing protocols

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- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Recall: per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables

Recall: logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables

Software defined networking (SDN)

Why a *logically centralized* control plane?

- easier network management:
  - avoid router misconfigurations
  - greater flexibility of traffic flows

Difficult to manipulate where traffic flows in a traditional network!

Case 1: enforcing a policy?

Q: what if network operator wants u-to-z traffic to flow along *uvwz*?

A: need to define link costs so traffic routing algorithm computes routes accordingly (or need a new routing algorithm)!

Link costs are the only control "knobs": not good!

Case 2: speeding up Tx?

Q: what if network operator wants to split u-to-z traffic along uvwz *and* uxyz (load balancing)?

A: can't do it (or need a new routing algorithm)

OSPF might be able to do this to some degree!

Case 3: avoiding congestion?

Q: what if w wants to route blue and red traffic differently?

A: can't do it (with destination based forwarding, and LS, DV routing)

Software defined networking (SDN)

Why a *logically centralized* control plane?

- easier network management:
  - avoid router misconfigurations
  - greater flexibility of traffic flows
- Empowering general table-based forwarding
  - Traditional control plane: compute tables as result of distributed algorithm ← Hard to manipulate
  - Centralized control plane: compute/configure tables centrally and distribute ← Higher flexibility
- open (non-proprietary) implementation of control plane
  - Easier to contribute code for route computation

Traditional Router Architecture

- Internet network layer: historically has been implemented via distributed, per-router approach
- *Specialized* router contains switching hardware, runs proprietary implementation of Internet standard protocols (IP, RIP, IS-IS, OSPF, BGP) in proprietary router OS (e.g., Cisco IOS)
  - can't add functions as user demand rises. Therefore different "middleboxes" for different network layer functions: firewalls, load balancers, NAT boxes, ..
- ~2005: renewed interest in rethinking network control plane

Analogy: mainframe to PC evolution*

Vertically integrated
Closed proprietary
Slow innovation
Small industry

Horizontal separation
Open interfaces
Rapid innovation
Huge industry

* Slide courtesy: N. McKeown

Software defined networking (SDN)

SDN perspective: data plane switches

Data plane switches

- fast, simple, commodity switches
- implementing generalized data-plane forwarding (Section 4.4) in hardware
- flow table installed by controller

Open Flow

- API for table-based switch control
  - defines what is controllable and what is not
- protocol for communicating with controller

Network Layer: Control Plane 5-88

SDN perspective: SDN controller

SDN controller (network OS):

- maintain network state information
- interacts with network control applications "above" via northbound API
- interacts with network switches "below" via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness

Network Layer: Control Plane 5-89

SDN perspective: control applications

network-control apps:

- "brains" of control: implement control functions using lower-level services, API provided by SND controller
- *unbundled:* can be provided by 3rd party: distinct from routing vendor, or SDN controller

Network Layer: Control Plane 5-90

Components of SDN controller

Interface layer to network control apps: abstractions API

Network-wide state management layer: state of networks links, switches, services: a *distributed database*

communication layer: communicate between SDN controller and controlled switches

ONOS controller

- control apps separate from controller
- intent framework: high-level specification of service: what rather than how
- considerable emphasis on distributed core: service reliability, replication performance scaling

OpenDaylight (ODL) controller

- ODL Lithium controller
- network apps may be contained within, or be external to SDN controller
- Service Abstraction Layer: interconnects internal, external applications and services

OpenFlow protocol

- operates between controller, switch
- TCP used to exchange messages
  - optional encryption
- three classes of OpenFlow messages:
  - controller-to-switch
  - Switch-to-controller
  - symmetric (misc)

OpenFlow: controller-to-switch messages

Key controller-to-switch messages

- *features:* controller queries switch features, switch replies
- *configure:* controller queries/sets switch configuration parameters
- *modify-state:* add, delete, modify flow entries in the OpenFlow tables
- *packet-out:* controller can send packets out of a specific switch port

OpenFlow: switch-to-controller messages

Key switch-to-controller messages

- *packet-in:* transfer packet (and its control) to controller. See packet-out message from controller
- *flow-removed:* flow table entry deleted at switch
- *port status:* inform controller of a change on a port.

Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use higher-level abstraction at controller

SDN: control/data plane interaction example

① s1, experiencing link failure using OpenFlow port status message to notify controller

② SDN controller receives OpenFlow message, updates link status info

③ Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.

④ Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

SDN: control/data plane interaction example

⑤ link state routing app interacts with flow-table-computation component in SDN controller, which generates new flow tables needed

⑥ Controller uses OpenFlow to install new tables in switches that need updating

SDN: selected challenges

- hardening the control plane: reliable, secure distributed system
  - robustness to failures: leverage strong theory of reliable distributed system for control plane
  - reliability, security: "baked in" from day one?
- networks, protocols meeting mission-specific requirements
  - e.g., real-time, ultra-reliable, ultra-secure (TLS)
- Internet-scaling
  - BGP configuration using SDN

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

ICMP: internet control message protocol

- used by hosts & routers to communicate network-level information
  - error reporting: unreachable host, network, port, protocol
  - echo request/reply (used by ping)
- network-layer "above" IP:
  - ICMP msgs carried in IP datagrams
- ICMP message: type, code plus first 8 bytes of IP datagram causing error

Type	Code	description
0	0	echo reply (ping)
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	0	echo request (ping)
9	0	route advertisement
10	0	router discovery
11	0	TTL expired
12	0	bad IP header

Traceroute and ICMP

- source sends series of UDP segments to destination
  - first set has TTL =1
  - second set has TTL=2, etc.
- when datagram in *n*th set arrives to nth router:
  - router discards datagram and sends source ICMP message (type 11, code 0)
  - ICMP message include name of router & IP address
- when ICMP message arrives, source records RTTs

stopping criteria:

- UDP segment eventually arrives at destination host
- source stops

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

What is network management?

- autonomous systems (aka "network"): 1000s of interacting hardware/software components
- other complex systems requiring monitoring, control:
  - jet airplane
  - nuclear power plant
  - others?

"Network management includes the deployment, integration and coordination of the hardware, software, and human elements to monitor, test, poll, configure, analyze, evaluate, and control the network and element resources to meet the real-time, operational performance, and Quality of Service requirements at a reasonable cost."

Infrastructure for network management

definitions:

managed devices contain *managed objects* whose data is gathered into a *Management Information Base (MIB)*

SNMP protocol

Two ways to convey MIB info, commands:

request/response mode

trap mode

SNMP protocol: message types

Message type	Function
GetRequest GetNextRequest GetBulkRequest	manager-to-agent: "get me data" (data instance, next data in list, block of data)
InformRequest	manager-to-manager: here's MIB value
SetRequest	manager-to-agent: set MIB value
Response	Agent-to-manager: value, response to Request
Trap	Agent-to-manager: inform manager of exceptional event

Chapter 5: summary

we've learned a lot!

- approaches to network control plane
  - per-router control (traditional)
  - logically centralized control (software defined networking)
- traditional routing algorithms
  - implementation in Internet: OSPF, BGP
- SDN controllers
  - implementation in practice: ODL, ONOS
- Internet Control Message Protocol
- network management

next stop: link layer!