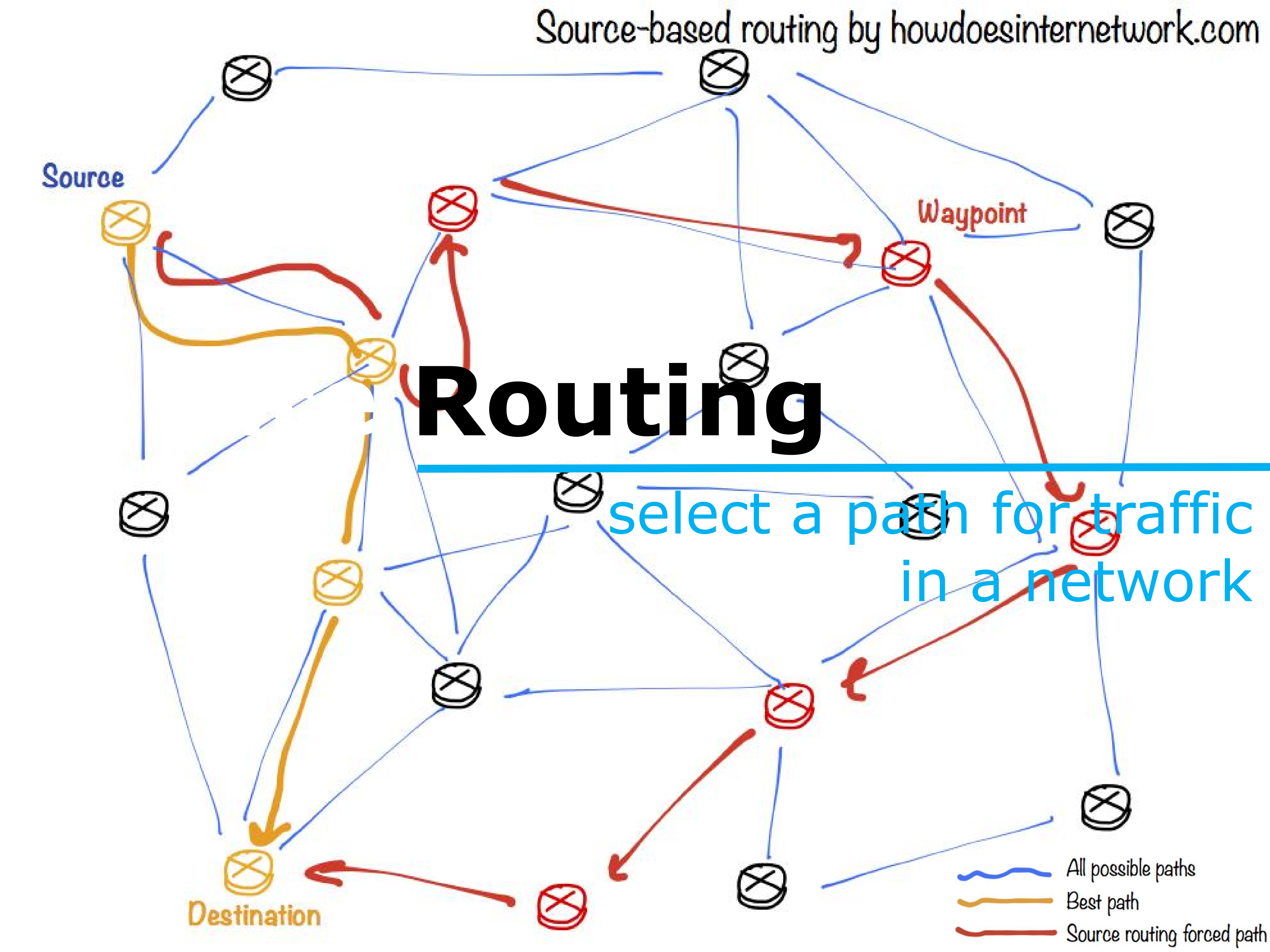
Secure Routing

Kai Bu
kaibu@zju.edu.cn
http://list.zju.edu.cn/kaibu/netsec2022

Routing

select a path for traffic in a network



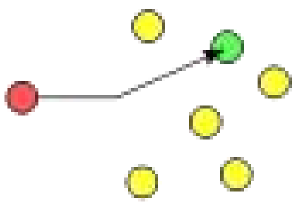
Secure Routing

How does routing work?

How is routing attacked?

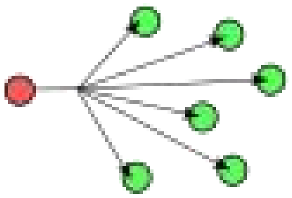
How is routing secured?

Delivery Scheme



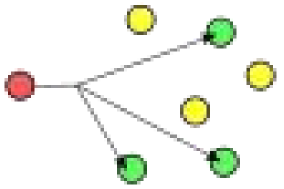
unicast

deliver msg to a single node



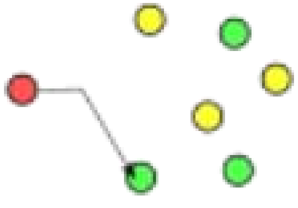
broadcast

deliver msg to all nodes in network



multicast

deliver msg to a group of nodes



anycast

deliver msg to any one of a group

Delivery Scheme

unicast

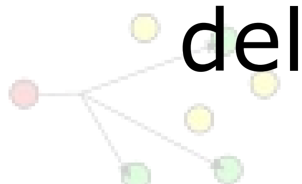
deliver msg to a single node

broadcast

deliver msg to all nodes in network

geocast

deliver a message to a group of nodes based on geographic location

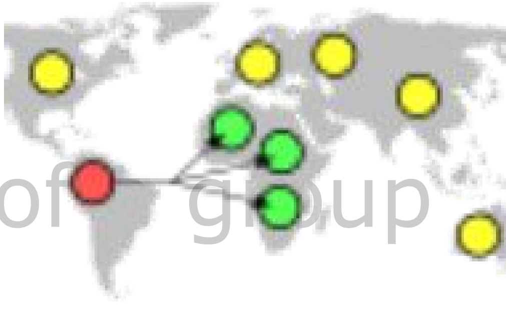


multicast

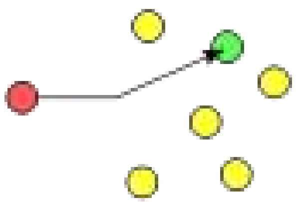
deliver msg to a group of nodes

anycast

deliver msg to any one of group



Delivery Scheme

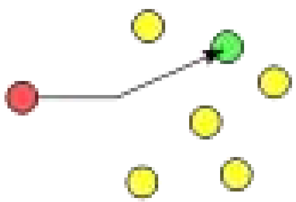


unicast

deliver msg to a single node

dominant form of msg delivery on inet

Routing Scheme



unicast

deliver msg to a single node

how to find a feasible path?

Routing Scheme

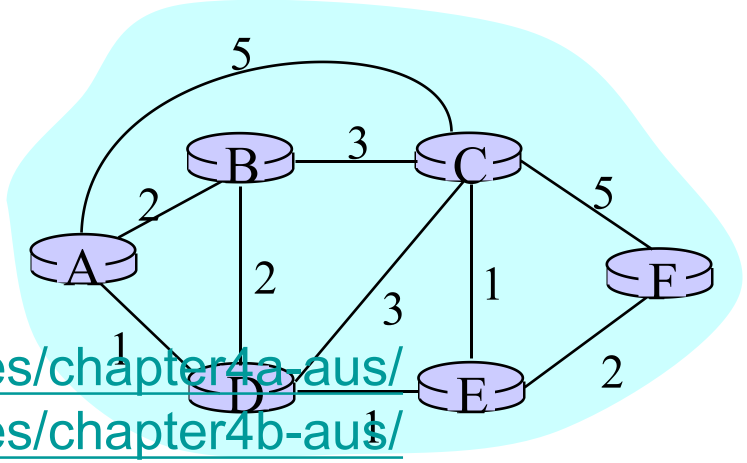
- Intra-domain routing

  inside an autonomous system
- Inter-domain routing

  between autonomous systems

Routing Scheme

- Intra-domain routing
  consider A-F as routers
- Inter-domain routing
  consider A-F as autonomous systems



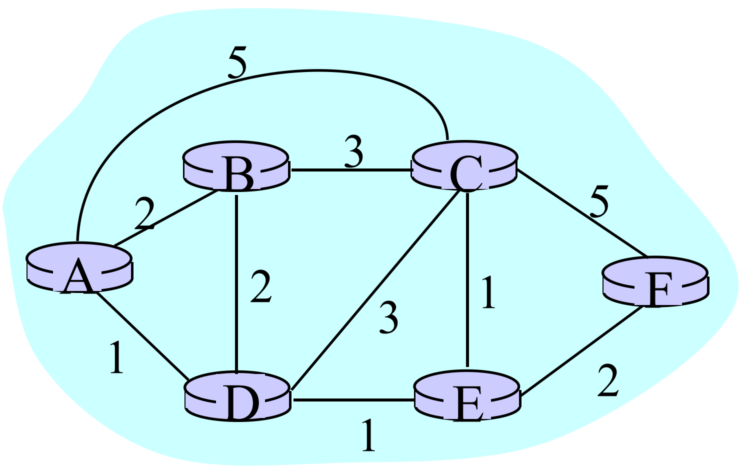
examples from
https://www.cs.umd.edu/~shankar/417-F01/Slides/chapter4a-aus/
https://www.cs.umd.edu/~shankar/417-F01/Slides/chapter4b-aus/

Route Computation

- Link-state algorithms

  each router knows complete topology & link cost information;

  independently run routing algorithm to calculate shortest path to each destination;



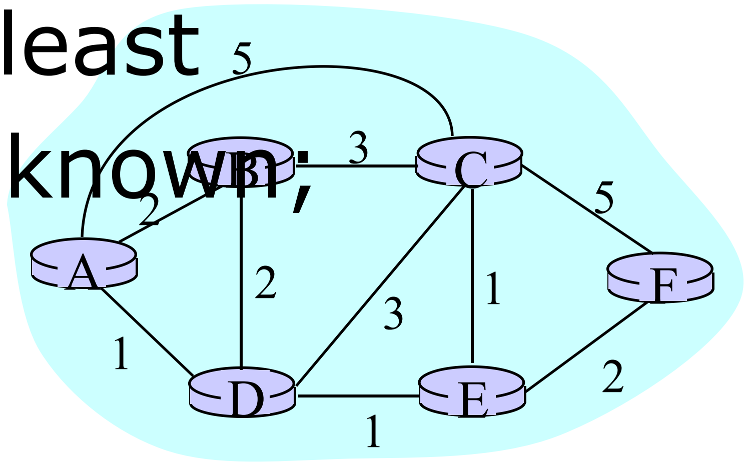
Dijkstra

c(i,j) link cost from i to j (∞ if unknown)

D(v) current value of cost of path from source to destination v;

p(v) predecessor node along path from source to v;

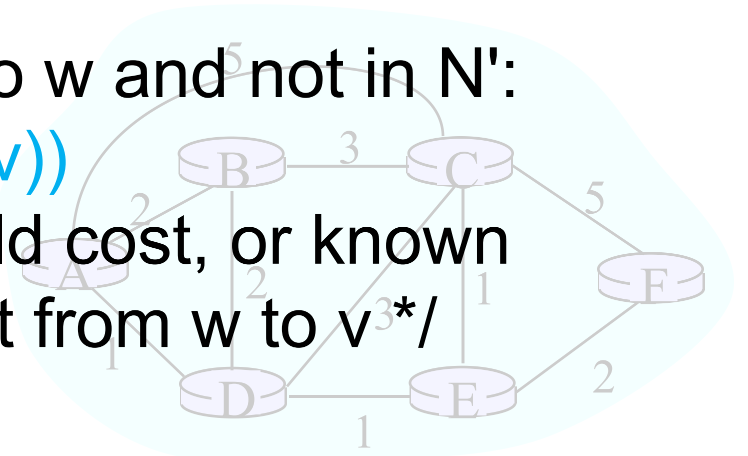
N’ set of nodes whose least cost path is already known;



Dijkstra

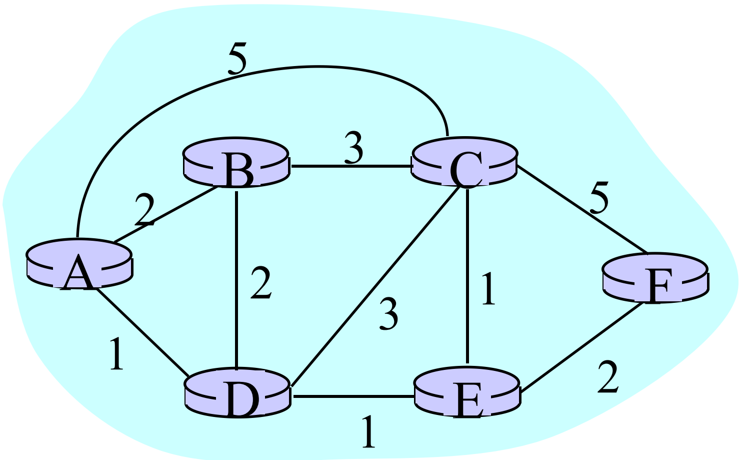
```
Initialization:
 N' = {A}
 for all nodes v
   if v adjacent to A
     then D(v) = c(A,v)
     else D(v) = ∞

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



Dijkstra

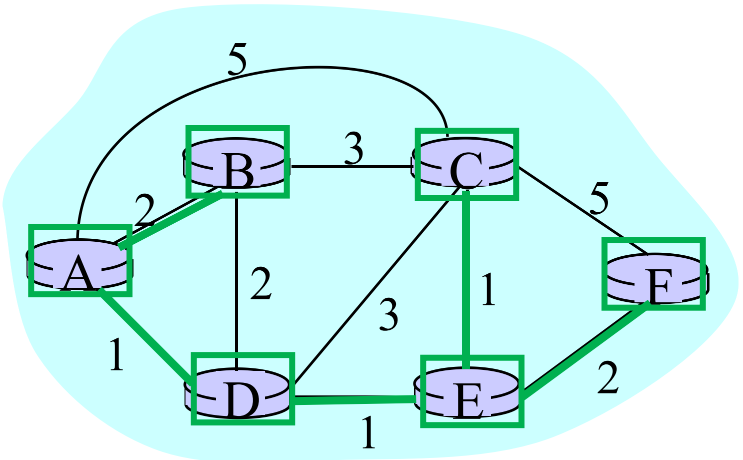
Step	start N'	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					



Dijkstra

Step	start N'	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					

resulting shortest-path tree for A:

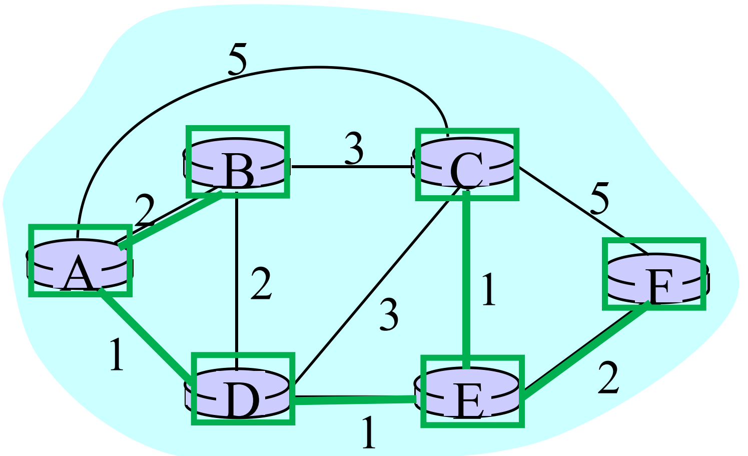


Dijkstra

Step	start N'	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					

resulting shortest-path tree for A:

destination	link
B	(A, B)
D	(A, D)
E	(A, D)
C	(A, D)
F	(A, D)



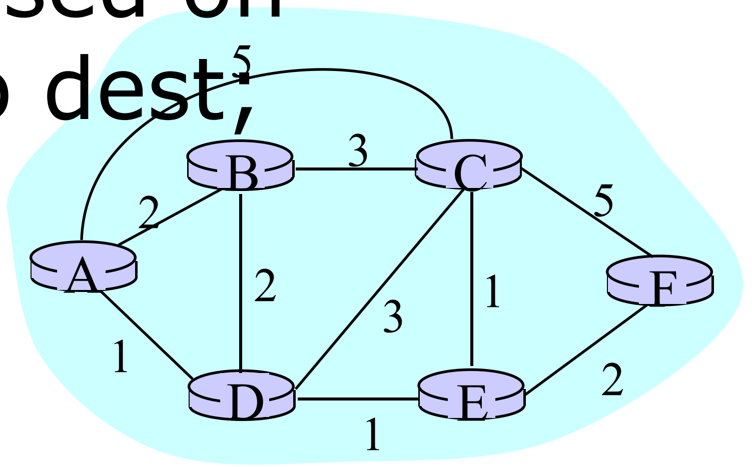
what if no global view?

Route Computation

- Distance-vector algorithms

  each router knows direct neighbors & link costs to neighbors;

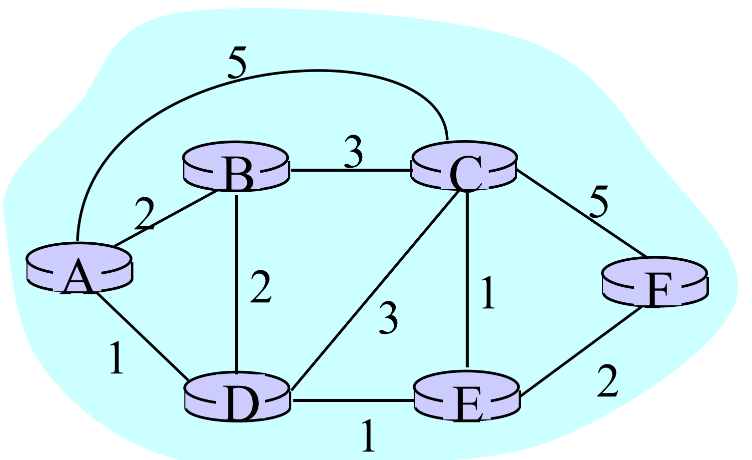
  independently calculate shortest path to each destination through an iterative process based on neighbors' distances to dest;



Bellman-Ford

$D_x(y)$ cost of least-cost path from x to y

$D_x(y) = \min\{c(x,v) + D_v(y)\}$
for all neighbors v of x



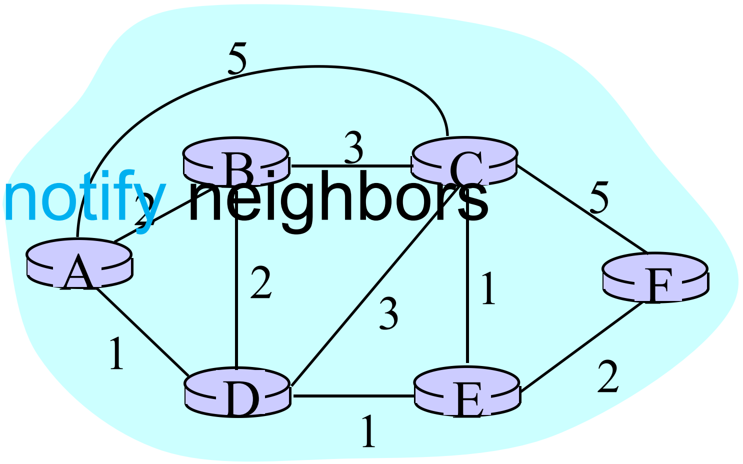
Bellman-Ford

$D_x(y)$ cost of least-cost path from x to y

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

recompute estimates

if DV to any dest has changed, notify neighbors



Bellman-Ford

$D_x(y)$ cost of least-cost path from x to y

$$D_x(y) = \min\{c(x,v) + D_v(y)\}$$

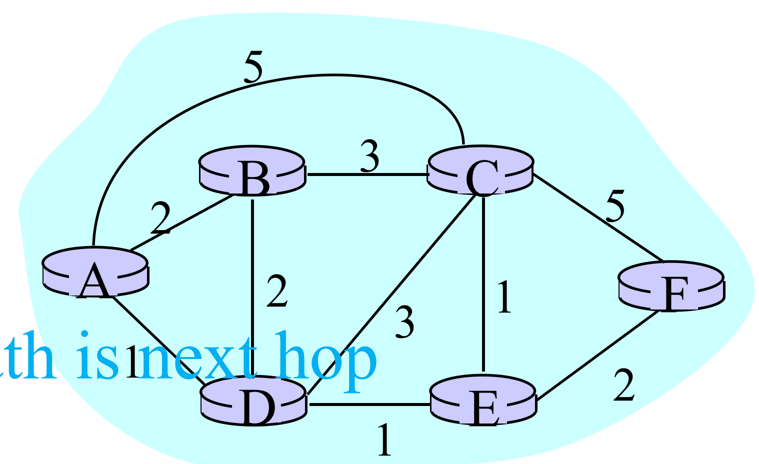
for all neighbors v of x

$$\begin{aligned} D_A(F) = \min \{&c(A,B) + D_B(F), \\ &c(A,D) + D_D(F), \\ &c(A,C) + D_C(F)\ \} \end{aligned}$$

$$\begin{aligned} = \min \{&2 + 5, \\ &1 + 3, \\ &5 + 3\} \quad = 4 \end{aligned}$$

node leading to shortest path is next hop

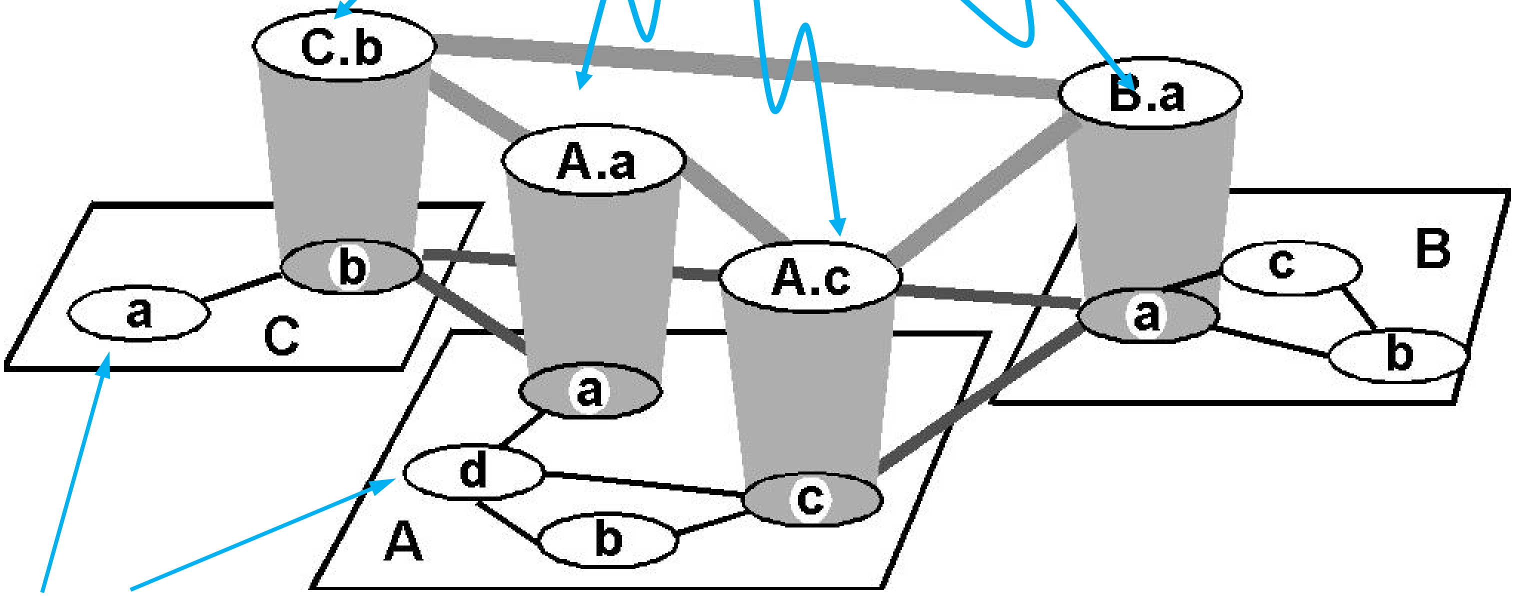
→ forwarding table



intra-domain vs inter-domain

Hierarchical Routing

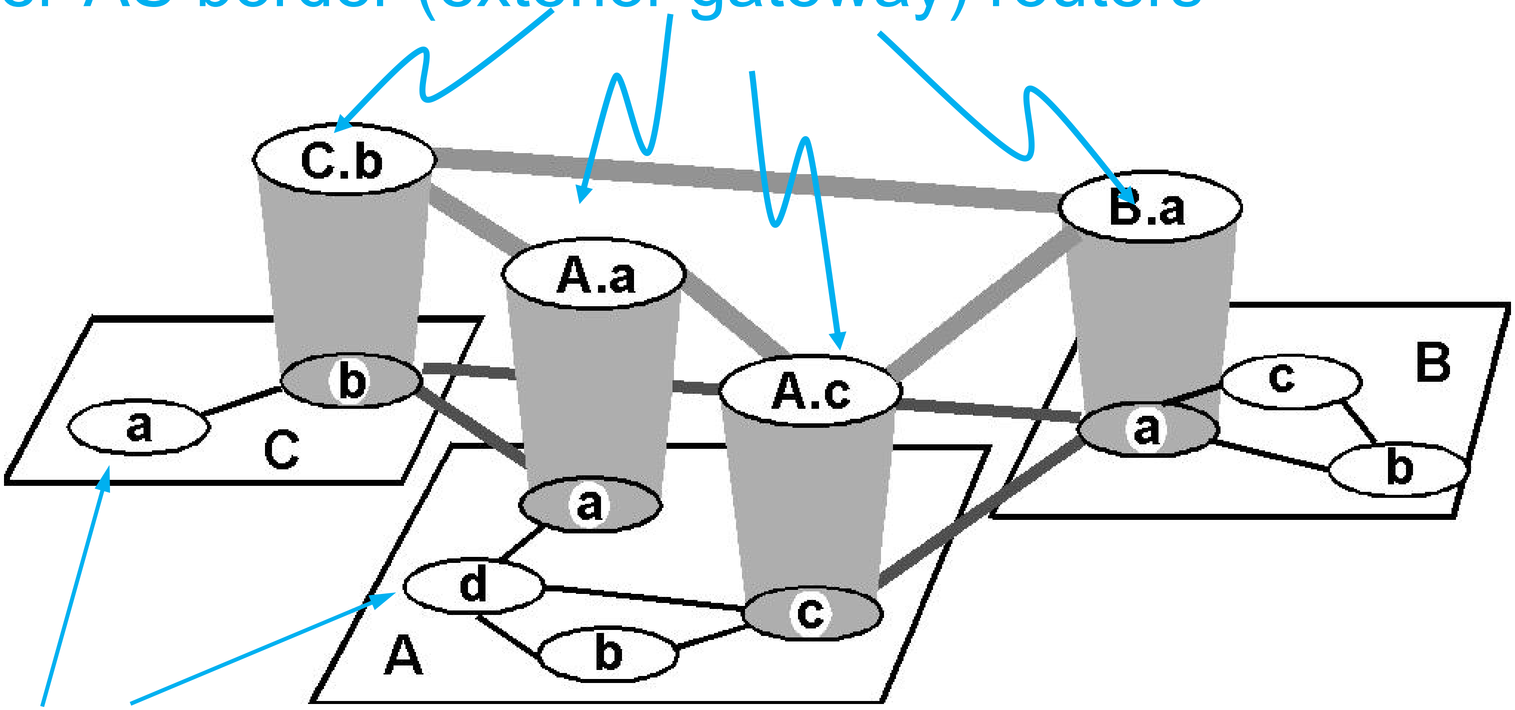
inter-AS border (exterior gateway) routers



intra-AS (interior gateway) routers

Hierarchical Routing

inter-AS border (exterior gateway) routers



intra-AS (interior gateway) routers

AS: autonomous system

each AS uses its own IGP internal routing protocol;

border routers run BGP as well;

IGP: Interior Gateway Prot

- RIP

  routing information protocol
- OSPF

  open shortest path first

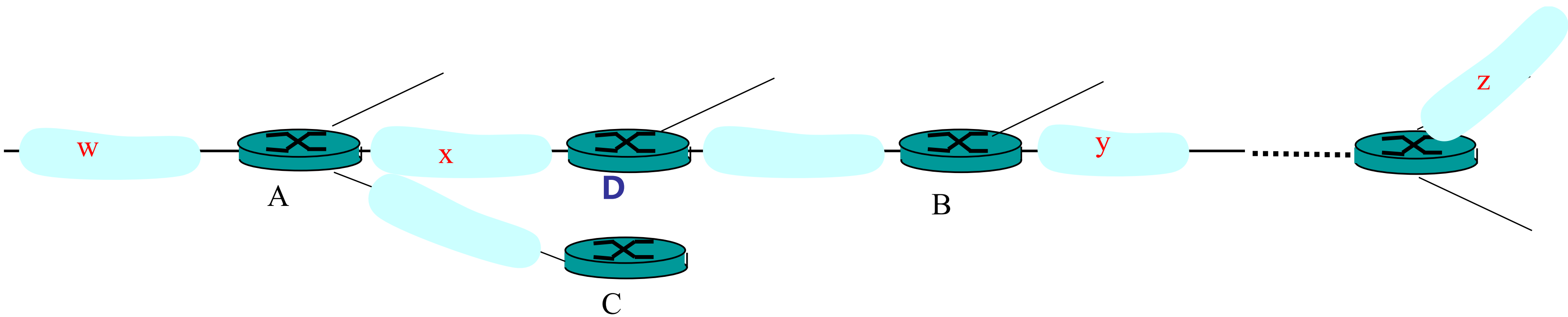
RIP

- Distance-vector algorithm

  distance metric: # of hops (max=15)
- Neighbor routers exchange routing advertisement every 30 seconds
- Failure and recovery

  if no update from neighbor N after 180s invalidate routes via N, notify neighbors

RIP



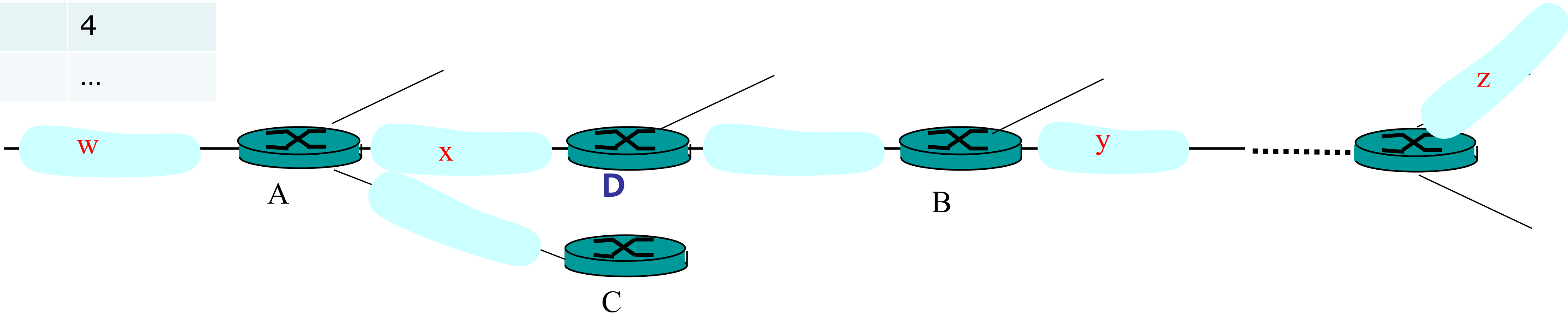
D: routing table

destination network	next router	# of hops to destination
w	A	2
y	B	2
z	B	7
x	--	1
…	…	…

RIP

dest	hops
w	1
x	1
z	4
…	…

advertisement from A to D



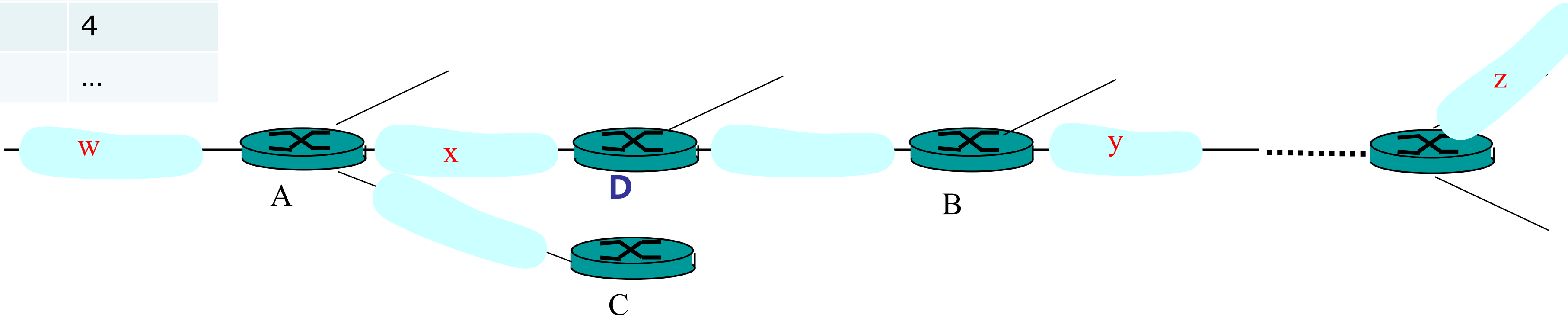
D: routing table

destination network	next router	# of hops to destination
w	A	2
y	B	2
z	B	7
x	--	1
…	…	…

RIP

dest	hops
w	1
x	1
z	4
…	…

advertisement from A to D



D: routing table

destination network	next router	# of hops to destination
w	A	2
y	B	2
z	B→A	7→5
x	--	1
…	…	…

OSPF

- Link-state algorithm

  each node knows its direct neighbors & the link distance to each(link-state);

  each node periodically broadcasts its link-state to the entire network;

OSPF

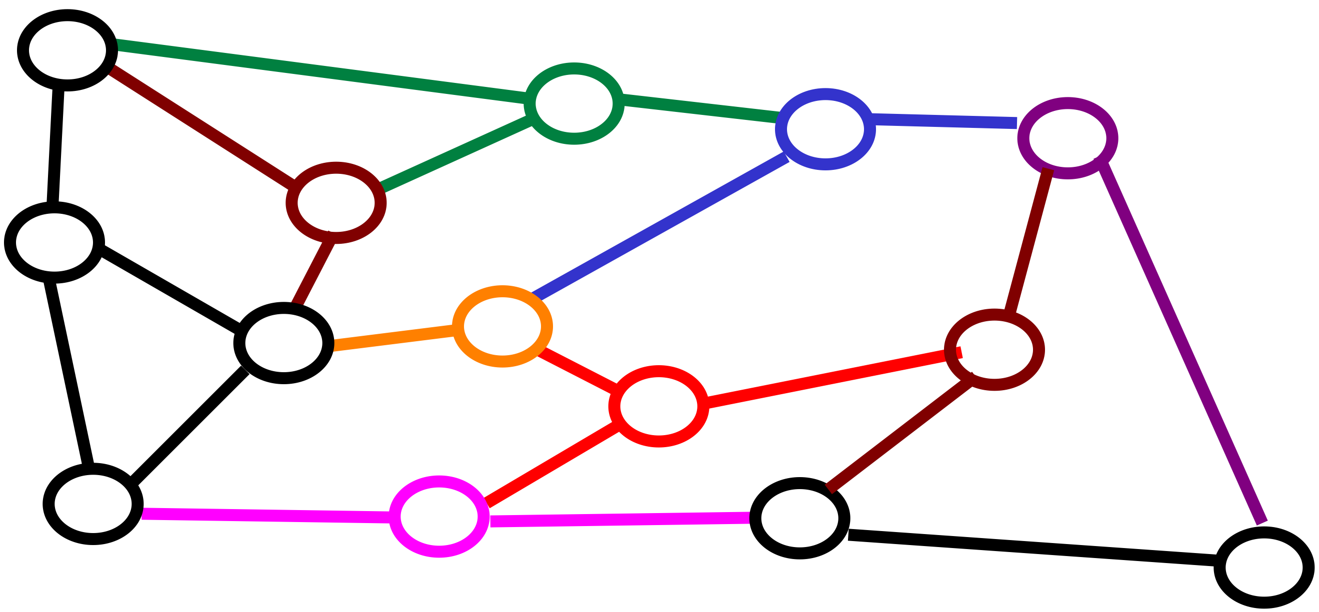
- LSP (Link-State Packet)
  one entry per neighbor router:
  ID of the node that created the LSP;
  a list of direct neighbors, with link cost;
  sequence number for this LSP (SEQ);
  time-to-live (TTL) for info in this LSP;

OSPF

- Build a complete map using link states

  everyone broadcasts a piece of topology

  put all pieces together → complete map



OSPF

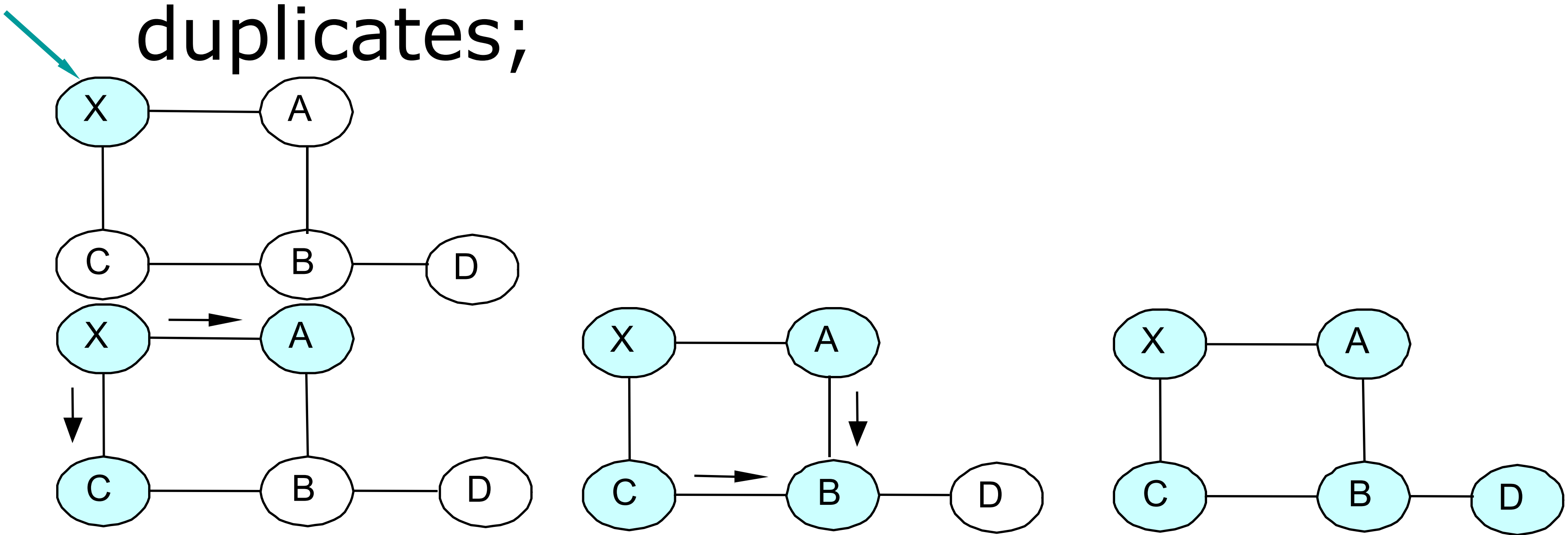
- Each node stores and forwards LSPs
- Decrement TTL of stored SLPs
- Discard info when TTL=0
- Compute routes using Dijkstra
- Generate LSPs periodically with increasing SEQ

OSPF

- Reliable flooding of LSP

  forward each received LSP to all neighbors but the one that sent it;

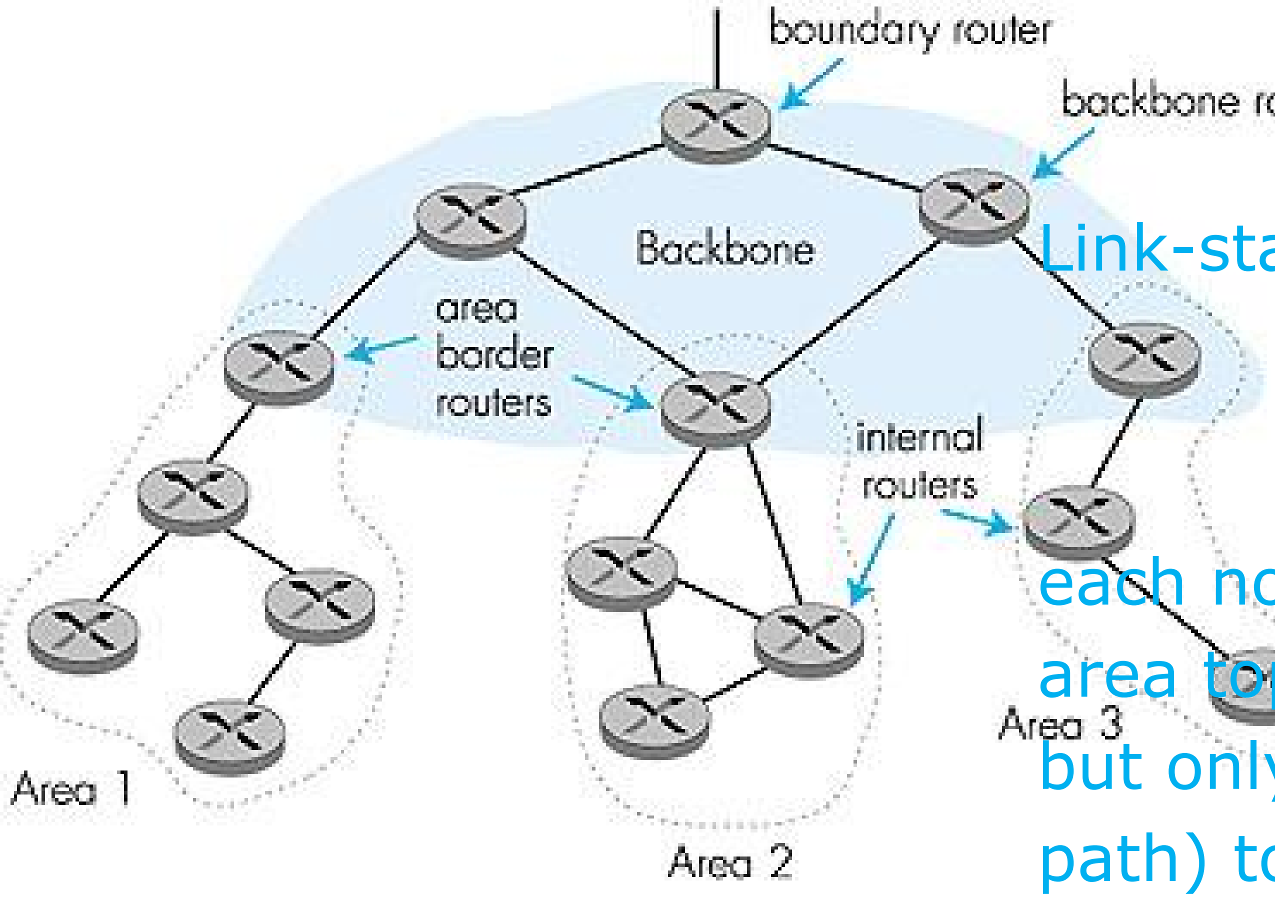
  use the source-ID and SEQ to detect duplicates;



OSPF

- All OSPF messages are authenticated
- Multiple same-cost paths are allowed
- Hierarchical OSPF is used in large dom

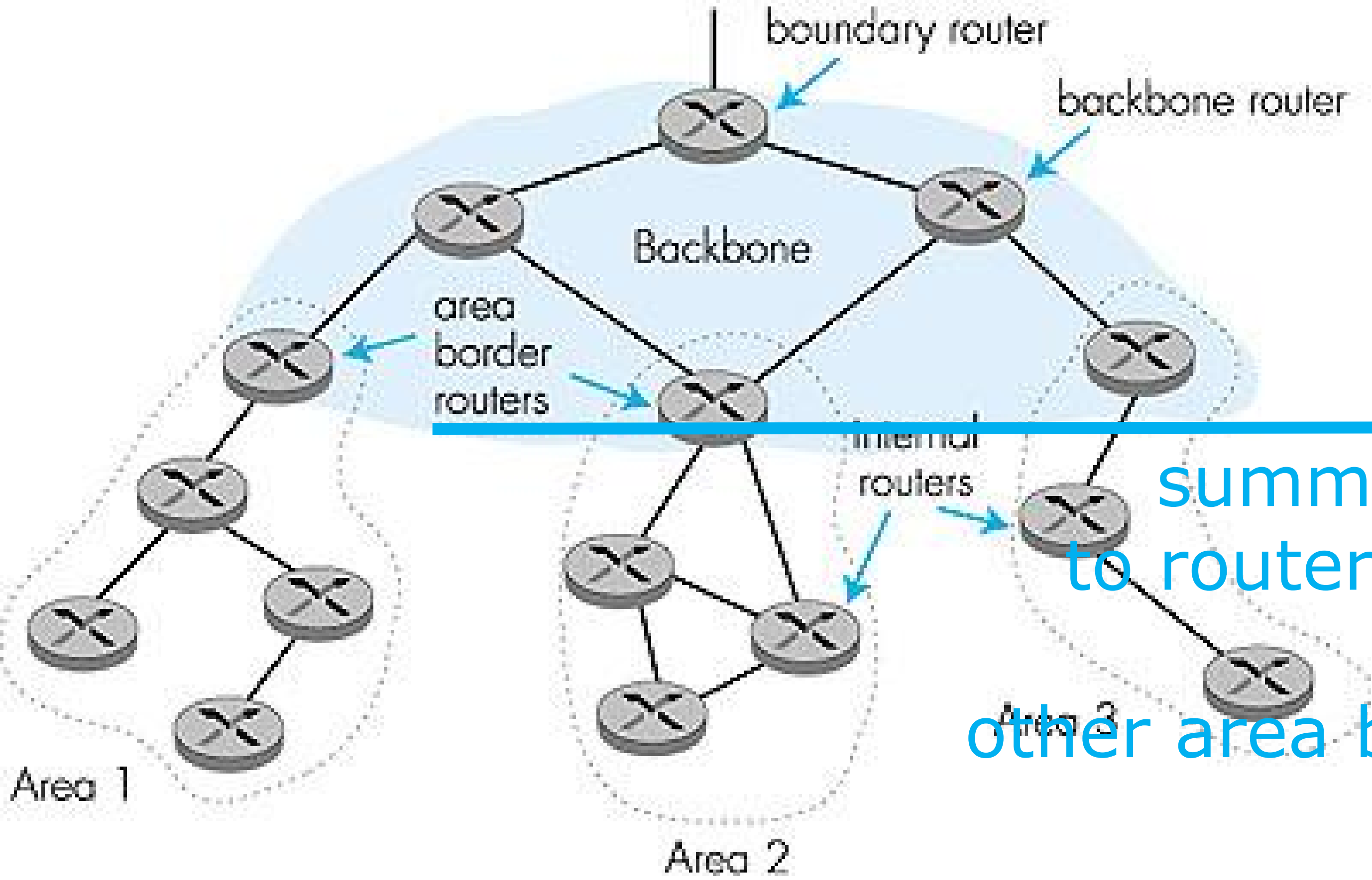
Hierarchical OSPF



Link-state ads only in area

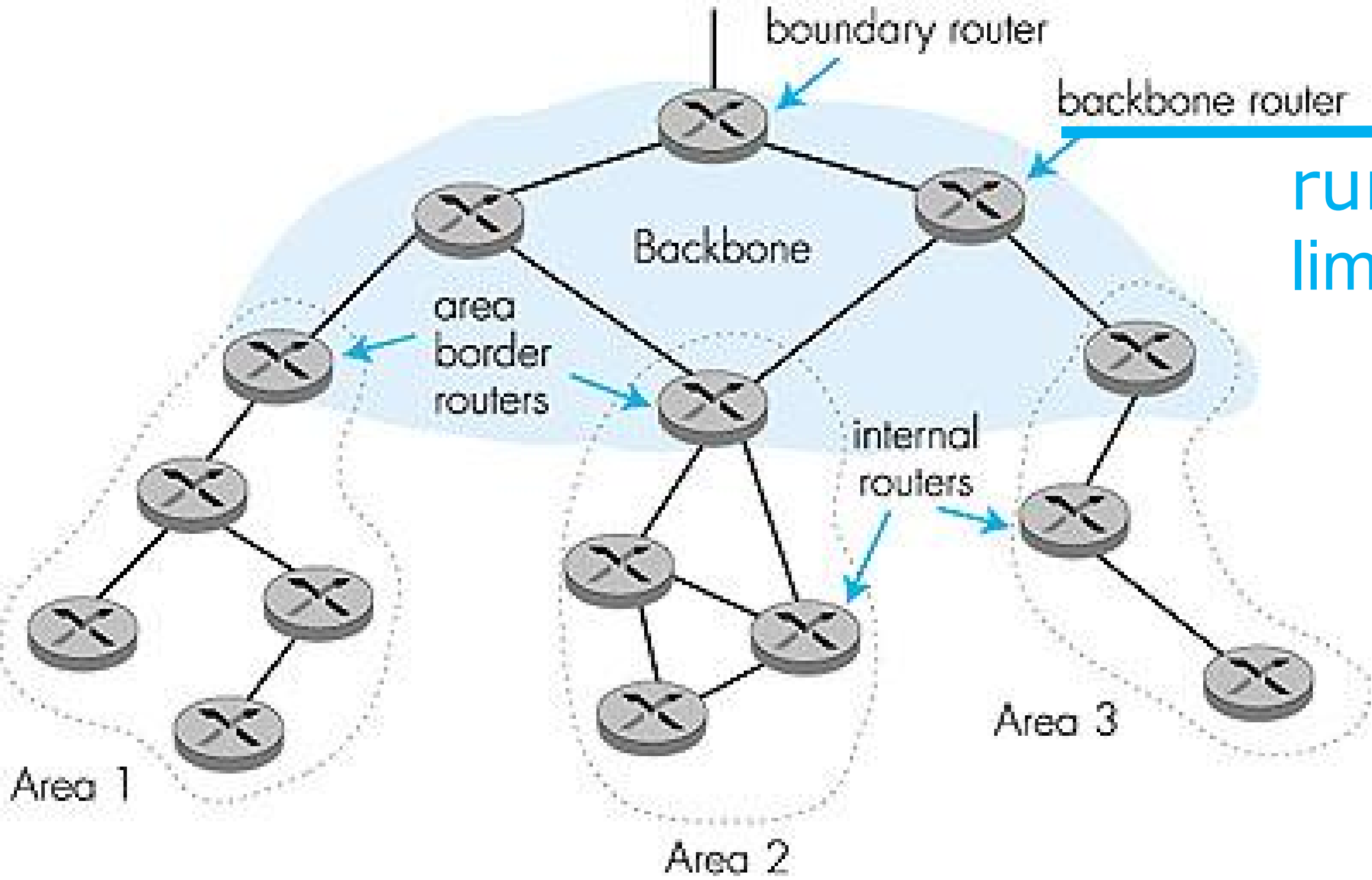
each node has detailed area topology,
but only direction (shortest path) to other areas;

Hierarchical OSPF



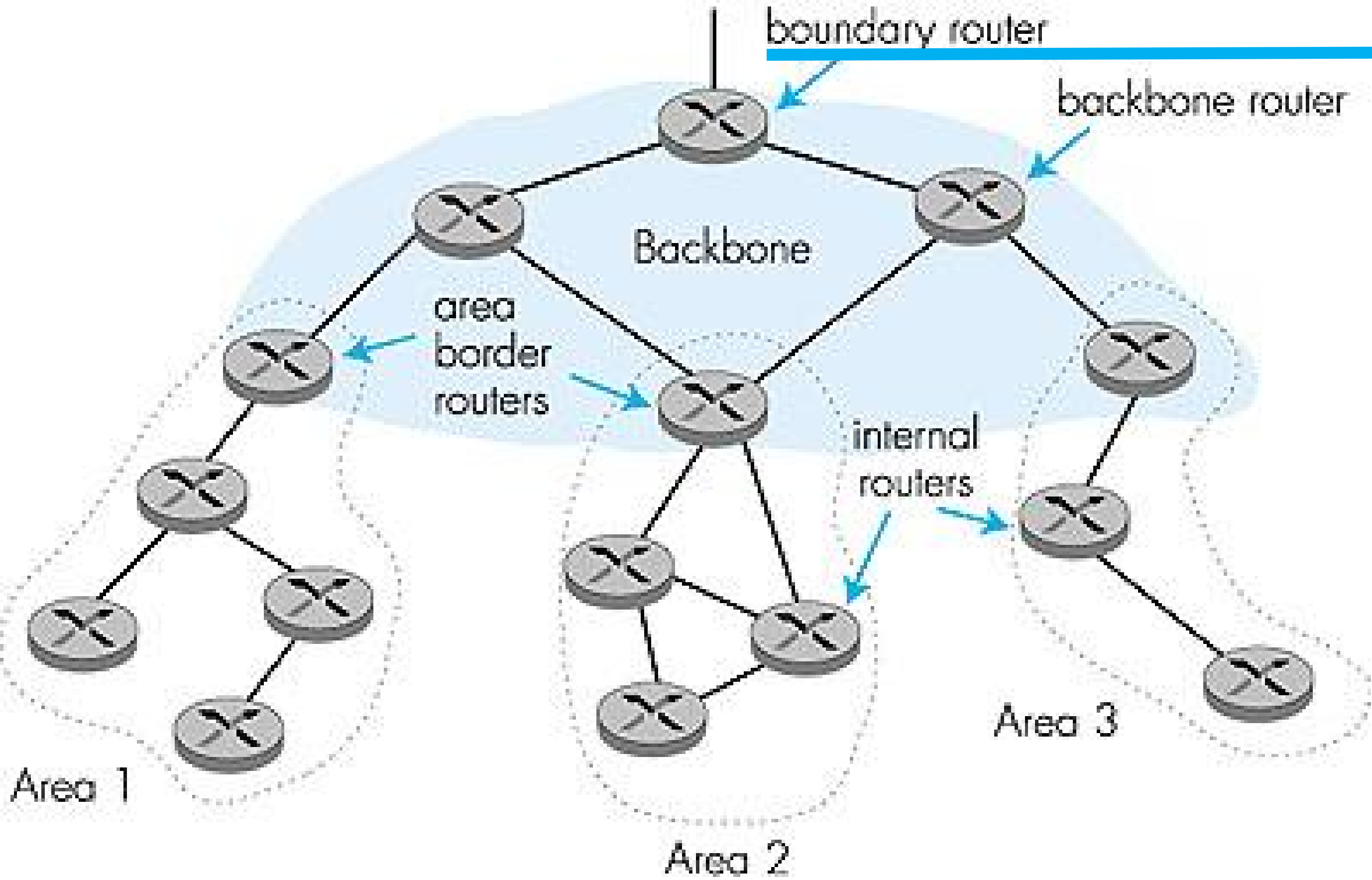
summarize distances to routers in local area; advertise to other area border routers;

Hierarchical OSPF



run OSPF routing limited to backbone

Hierarchical OSPF

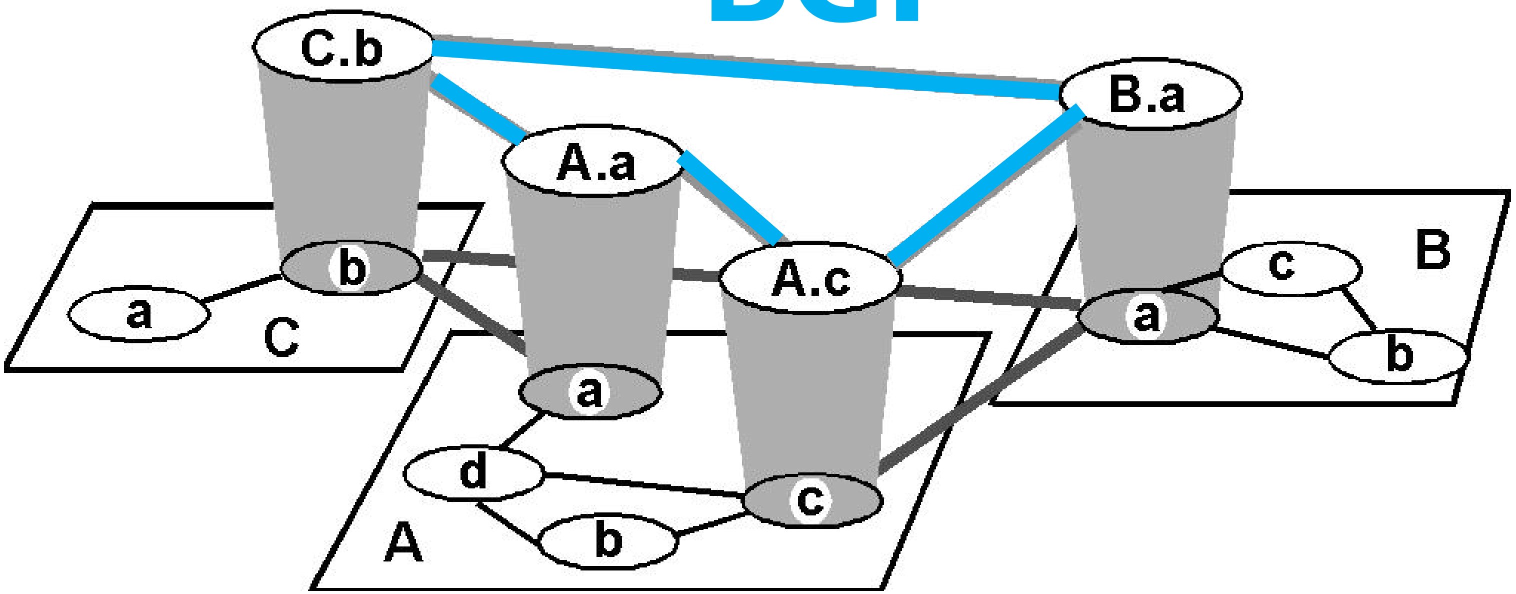


connect to other ASes

inter-domain routing

BGP: Border Gateway Protocol

BGP



- Path-vector protocol among border routers

  each border router broadcasts to neighbors entire path of AS sequence to destination:

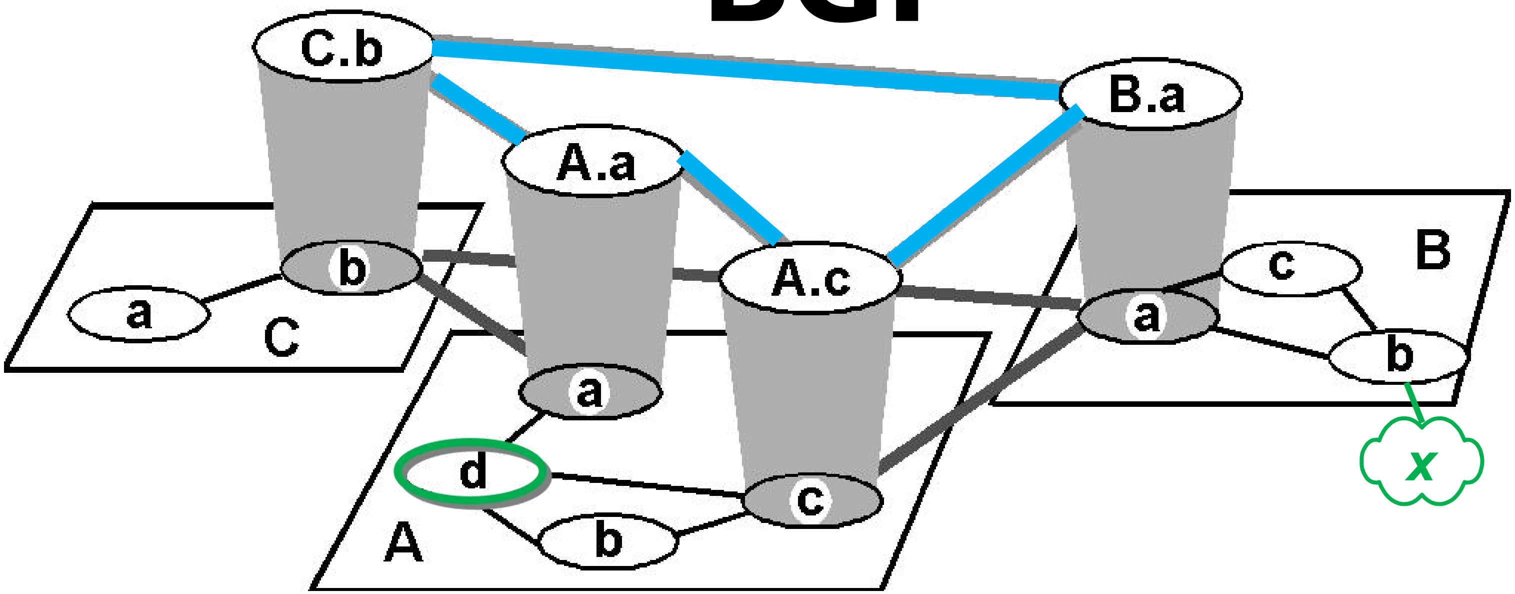
  e.g., Path(B,C) = B, A, C

BGP

For each AS:

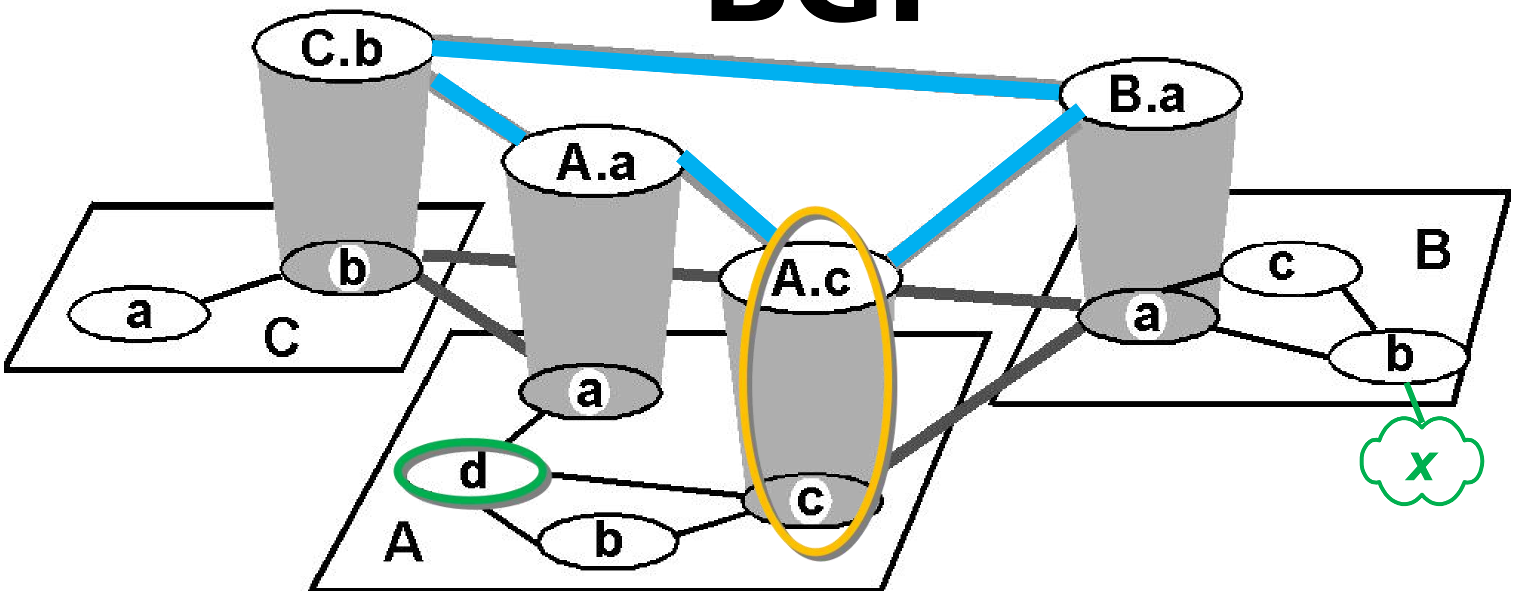
- Obtain subnet reachability information from neighbor ASes;
- Propagate the reachability information to all internal routers;
- Determine routes to subnets based on reachability information and policy

BGP



- Example: forwarding table entry for d→x

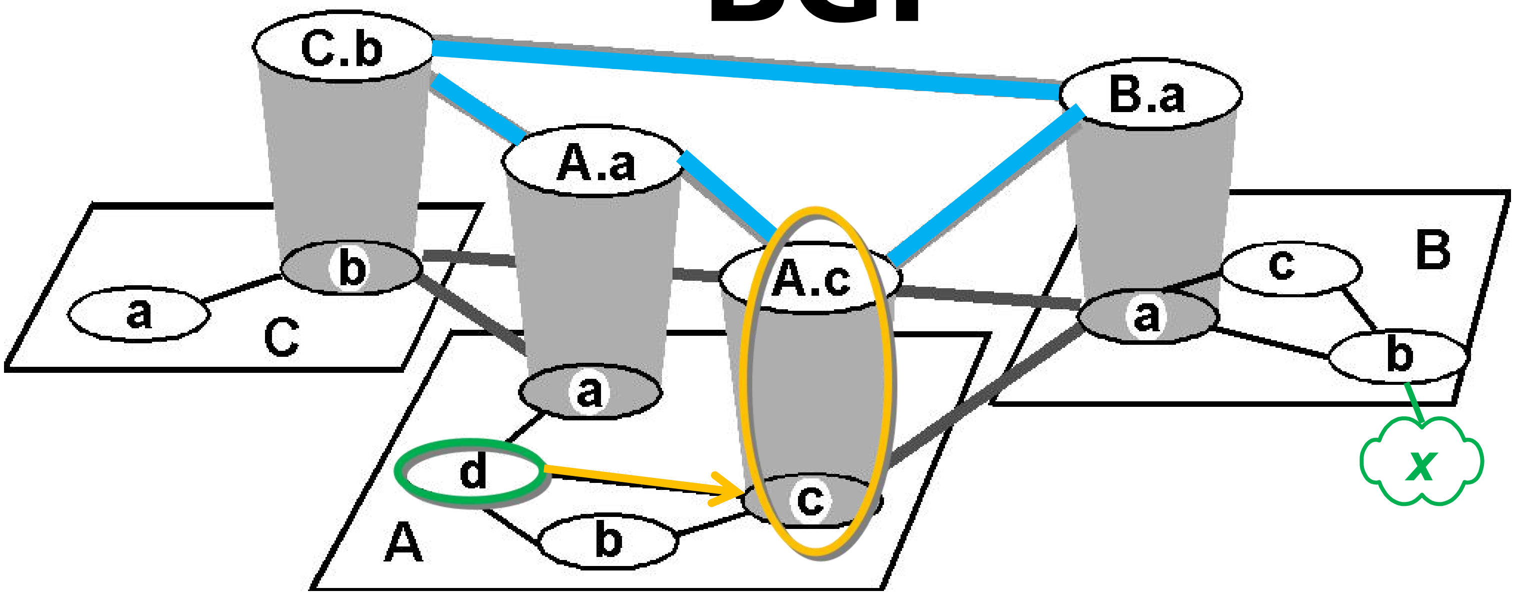
BGP



- Example: forwarding table entry for d→x

  AS A learns from BGP that subnet x is reachable from AS B via border router A.c;

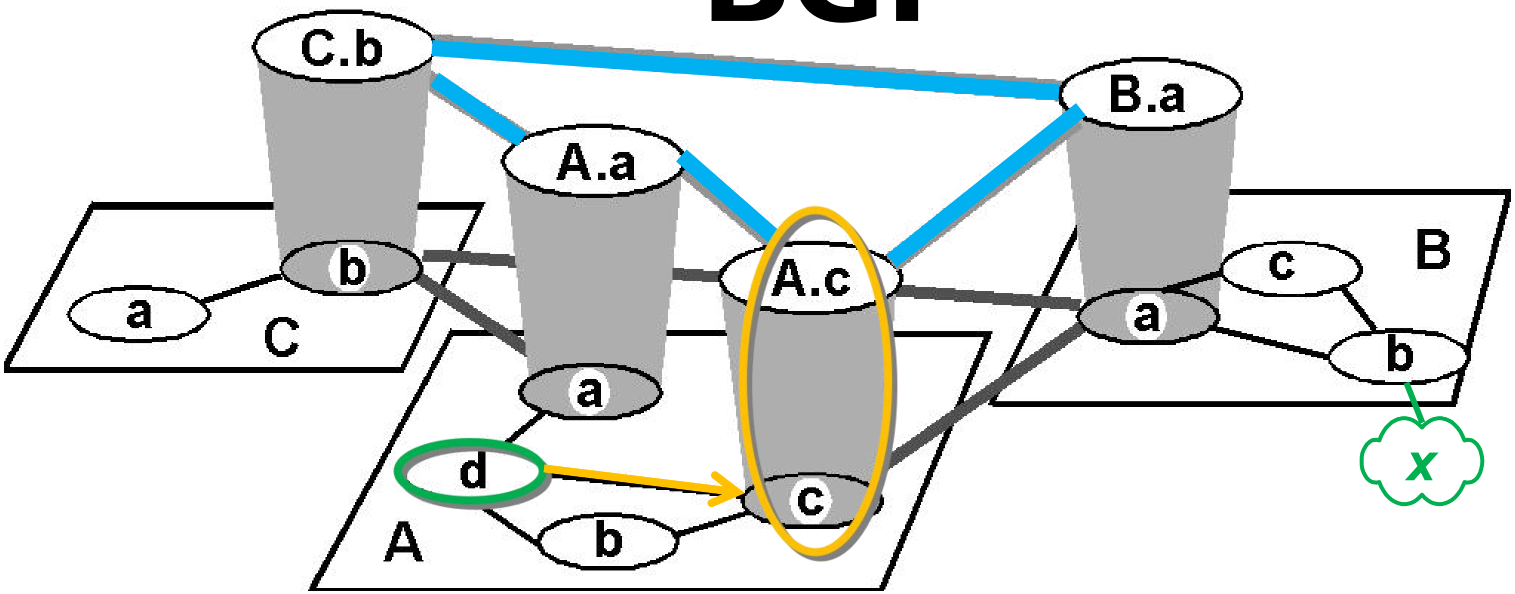
BGP



- Example: forwarding table entry for d→x

  router d determines from intra-domain routing info that its interface I is on the least cost path to c;

BGP



- Example: forwarding table entry for d→x

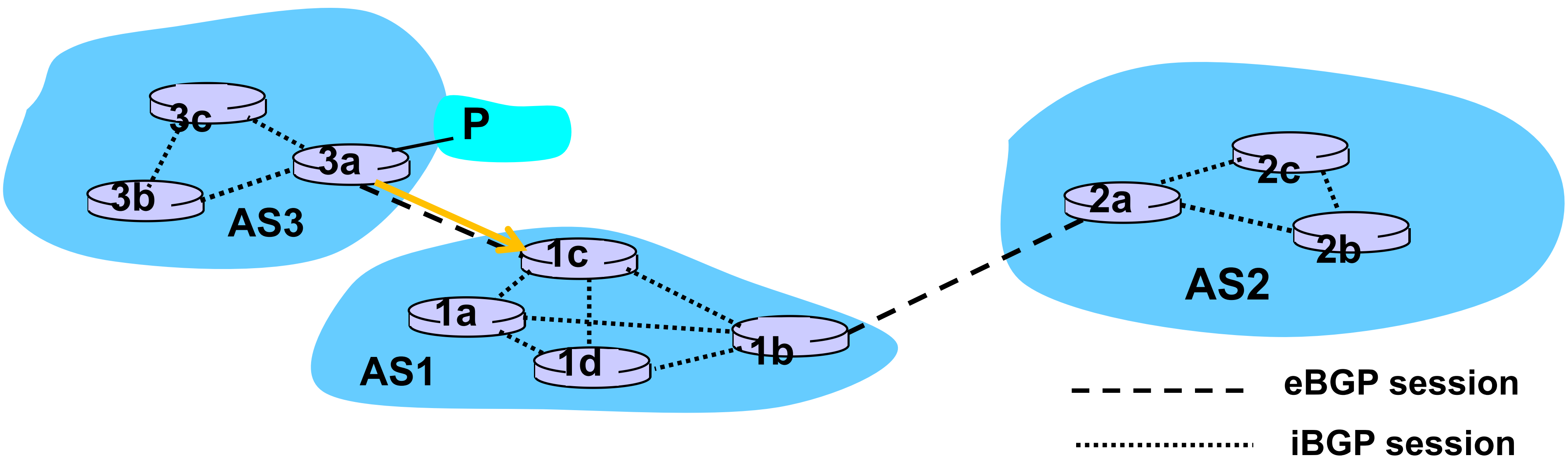
destination	next hop
x	I

BGP

Distribute reachability information:

- with eBGP session 3a-to-1c,

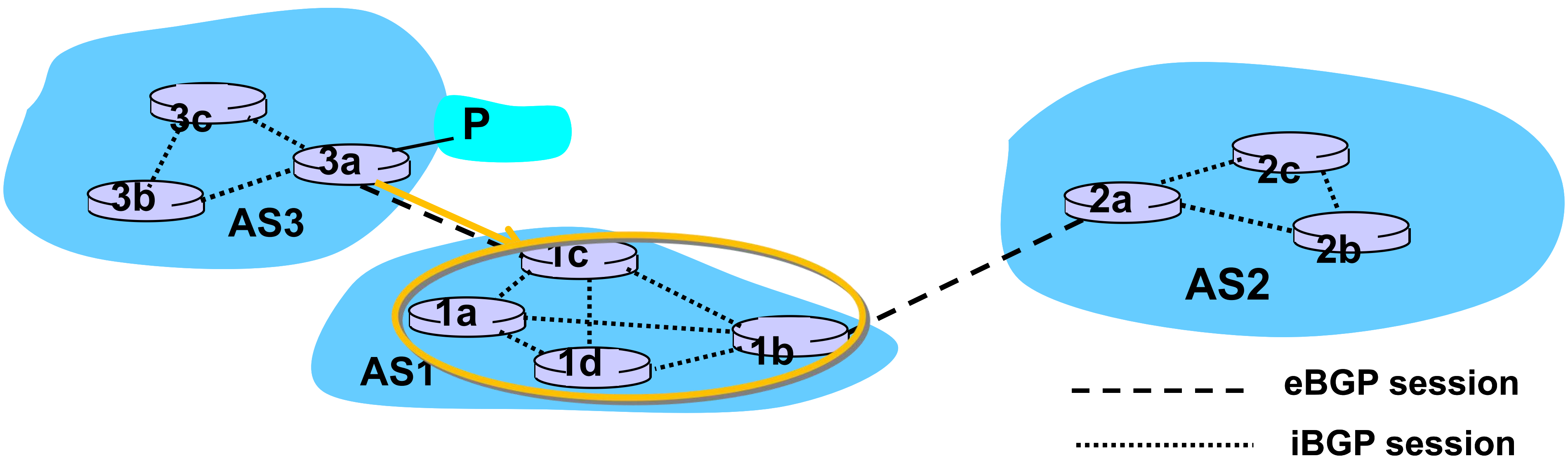
  AS3 sends prefix reachability info to AS1



BGP

Distribute reachability information:

- 1c uses iBGP sessions to distribute this new prefix reachability info to all routers in AS1;

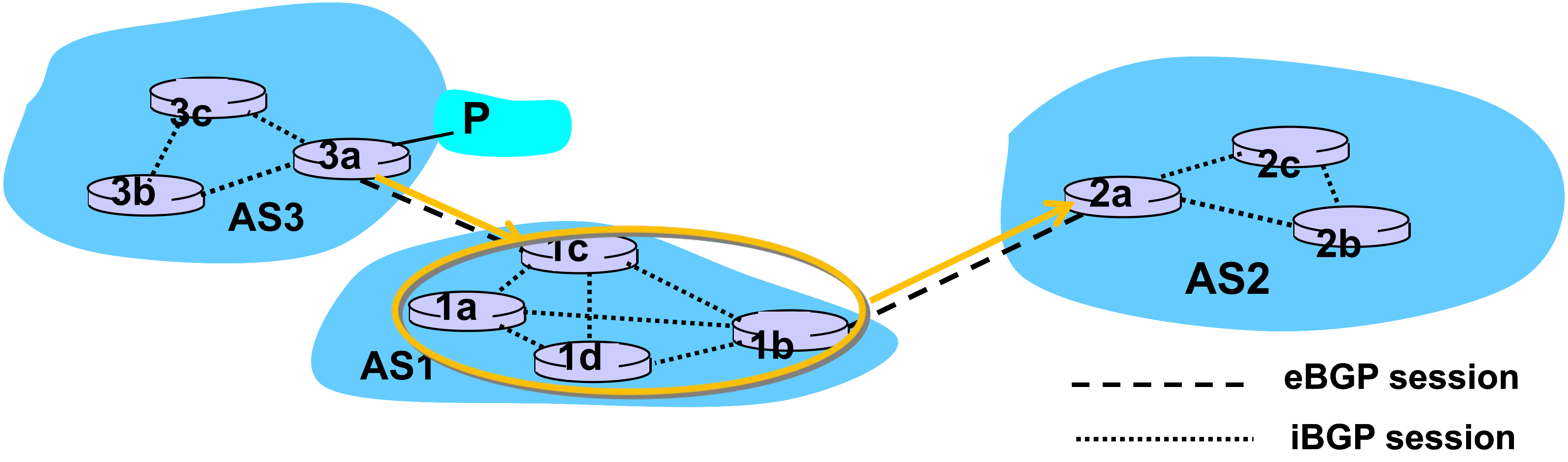


BGP

Distribute reachability information:

- 1b re-advertises the new reachability info to AS2

  over the 1b-to-2a eBGP session;



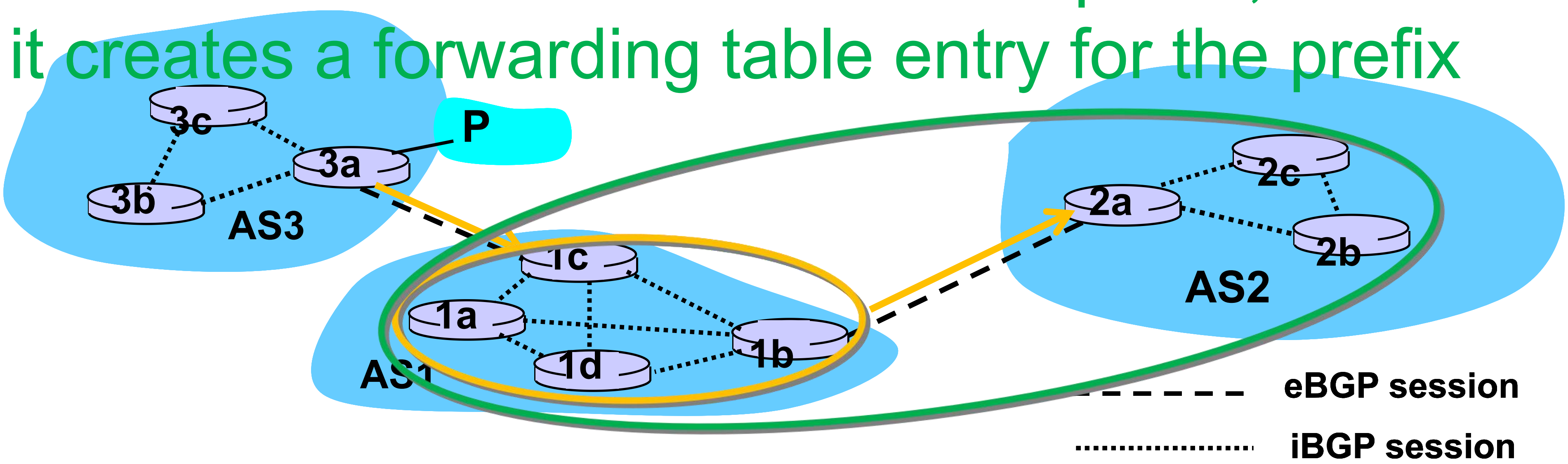
BGP

Distribute reachability information:

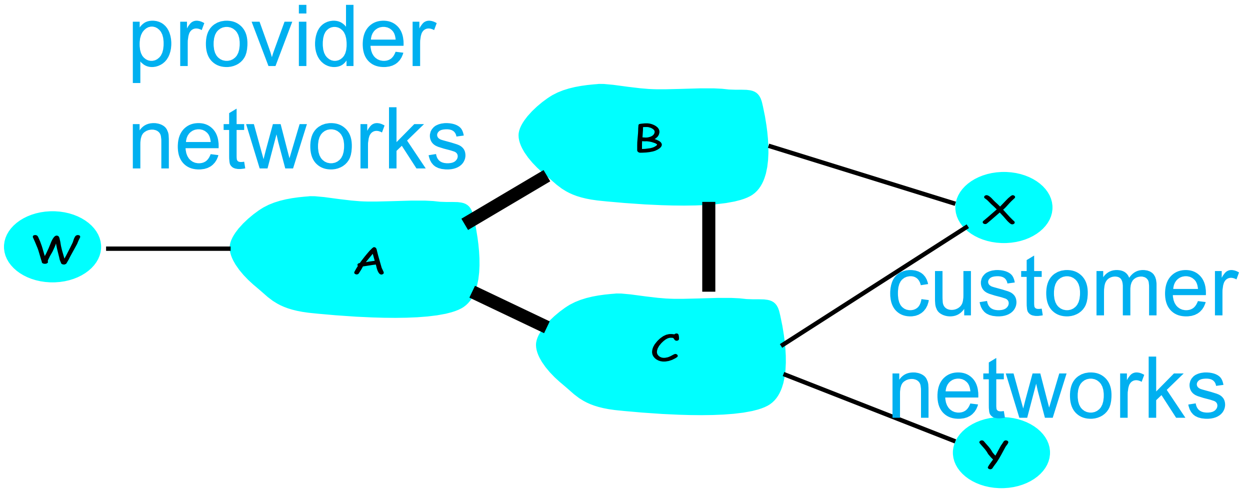
- 1b re-advertises the new reachability info to AS2

  over the 1b-to-2a eBGP session;

when a router learns about a new prefix,
it creates a forwarding table entry for the prefix



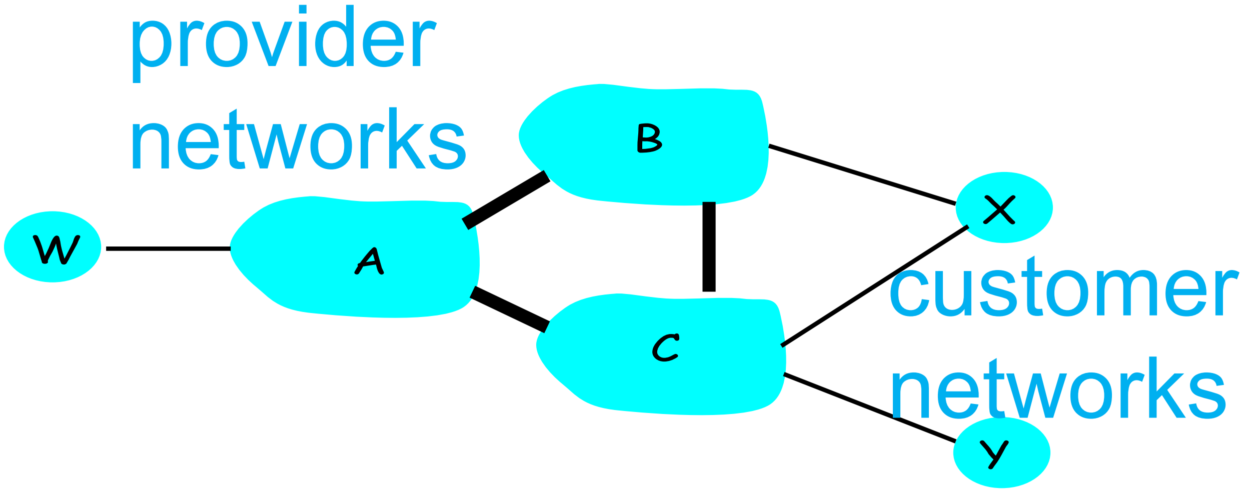
BGP



Routing policy:

- Provider networks: A, B, C
- Customer networks (of provider networks): X, Y, W

BGP

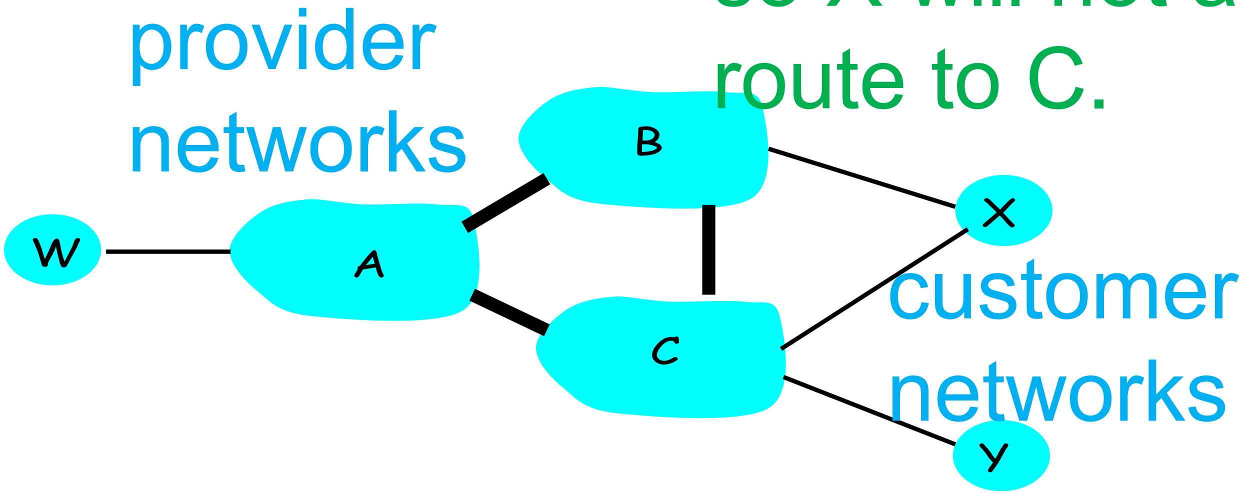


Routing policy:

- Provider networks: A, B, C
- Customer networks (of provider networks): X, Y, W
- X is dual-homed: attached to two networks

BGP

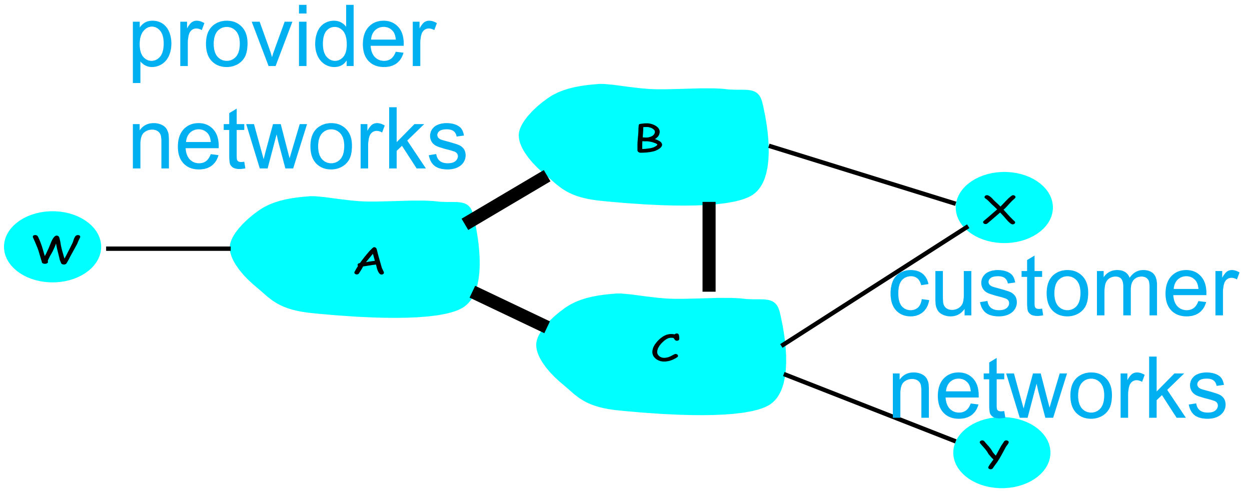
X does not want to carry traffic from B to C, so X will not advertise to B a route to C.



Routing policy:

- Provider networks: A, B, C
- Customer networks (of provider networks): X, Y, W
- X is dual-homed: attached to two networks

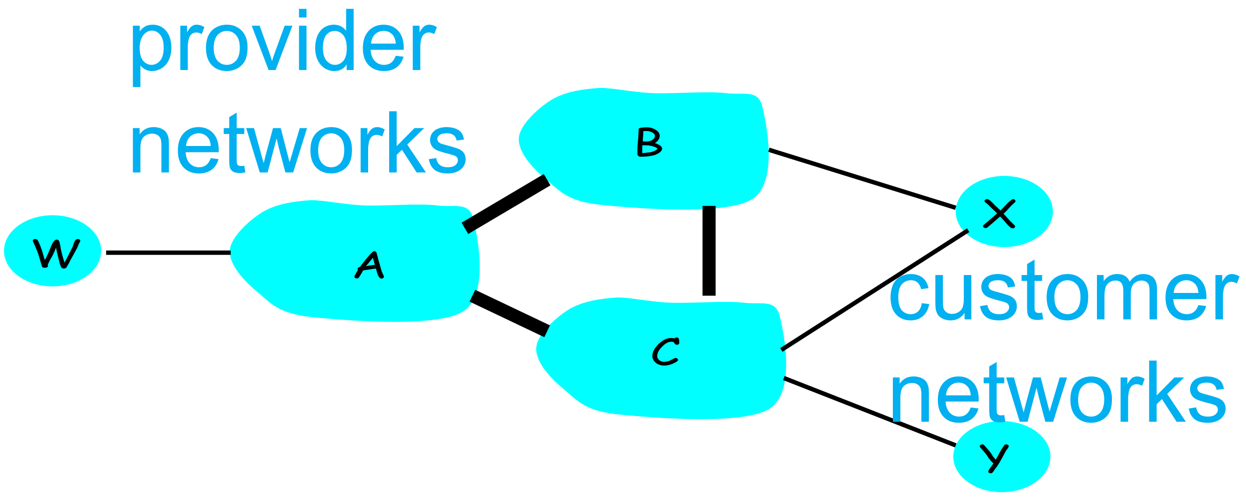
BGP



Routing policy:

- A advertises to B the path AW
- B advertises to X the path BAW

BGP



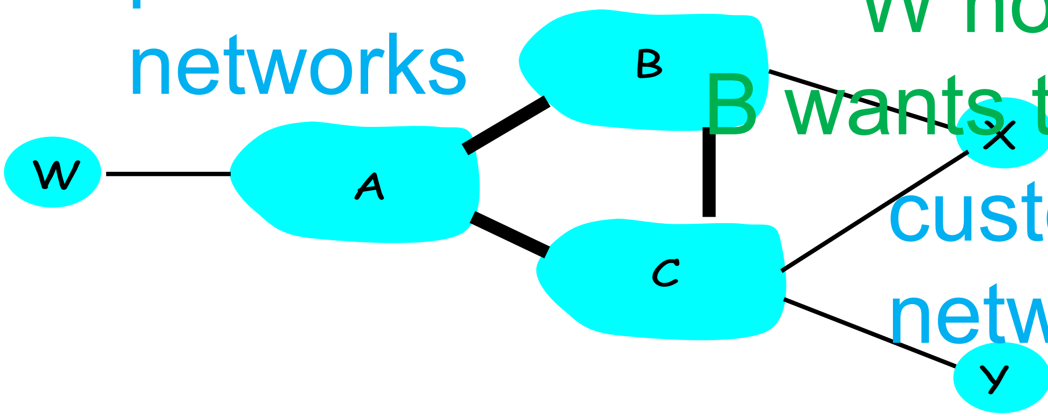
Routing policy:

- A advertises to B the path AW
- B advertises to X the path BAW
- Should B advertise to C the path BAW?

BGP

No way! B gets no revenue for routing CBAW as neither W nor C is B's customer.

B wants to route only to/from its customers.



Routing policy:

- A advertises to B the path AW
- B advertises to X the path BAW
- Should B advertise to C the path BAW?

routing attacks

distance-vector

link-state

BGP

routing attacks

distance-vector:

announce 0 distance to all other nodes

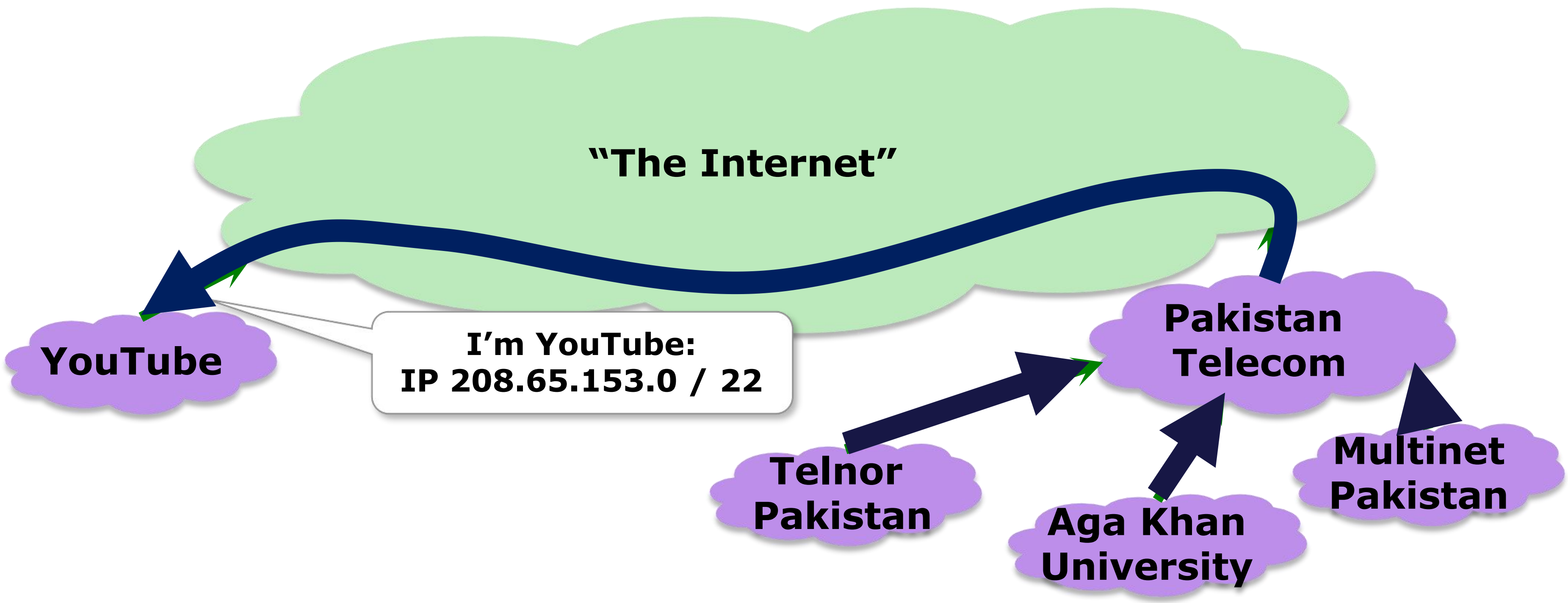
link-state:

drop links; claim direct link to other routers

BGP:

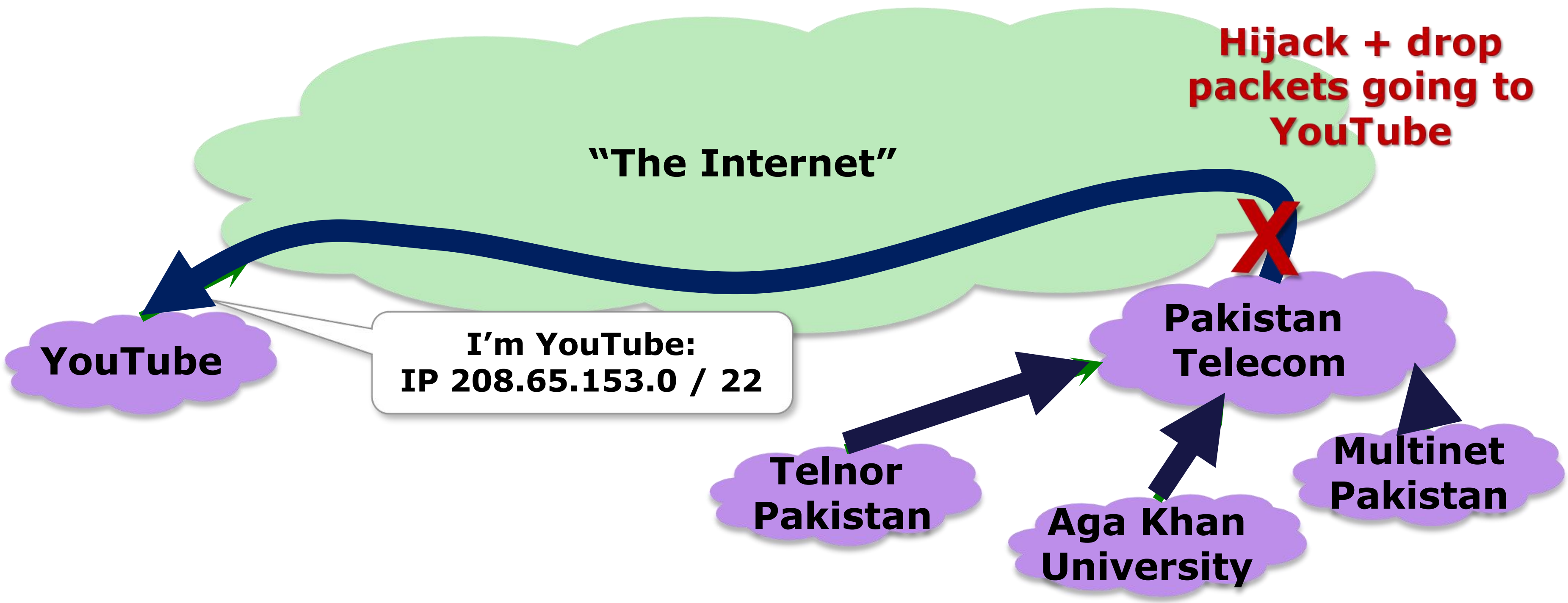
announce arbitrary prefix; alter paths

Prefix Hijacking: Case 1



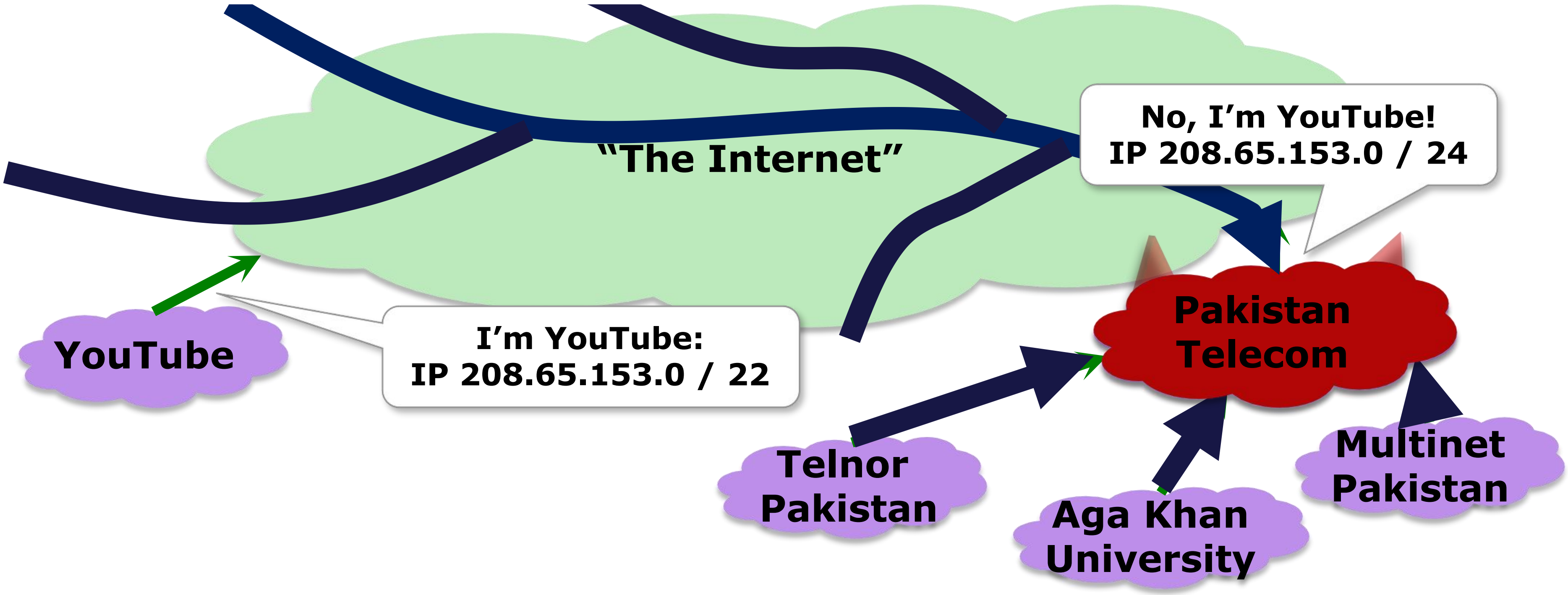
examples from https://people.cs.umass.edu/~phillipa/CSE390/RoutingSecurity.pptx

Here’s what should have happened….

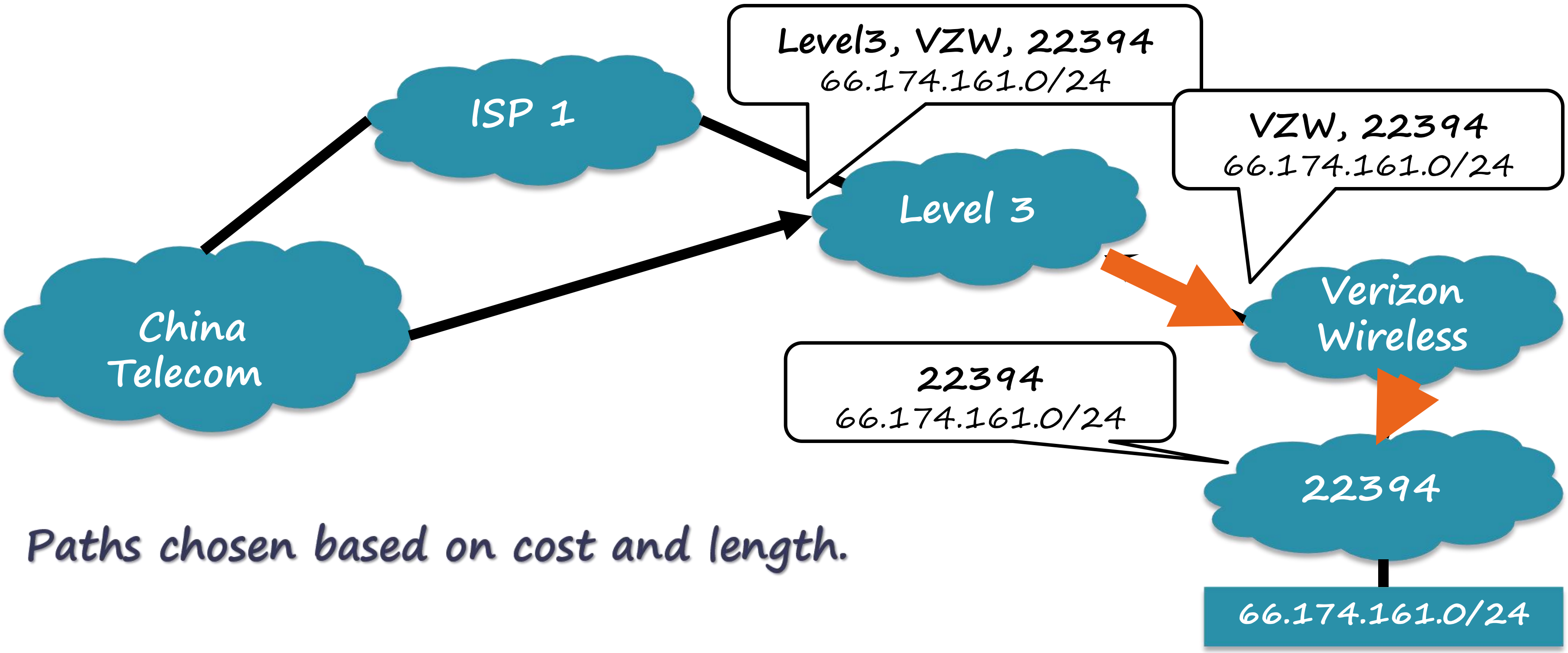


Block your own customers.

But here's what Pakistan ended up doing…

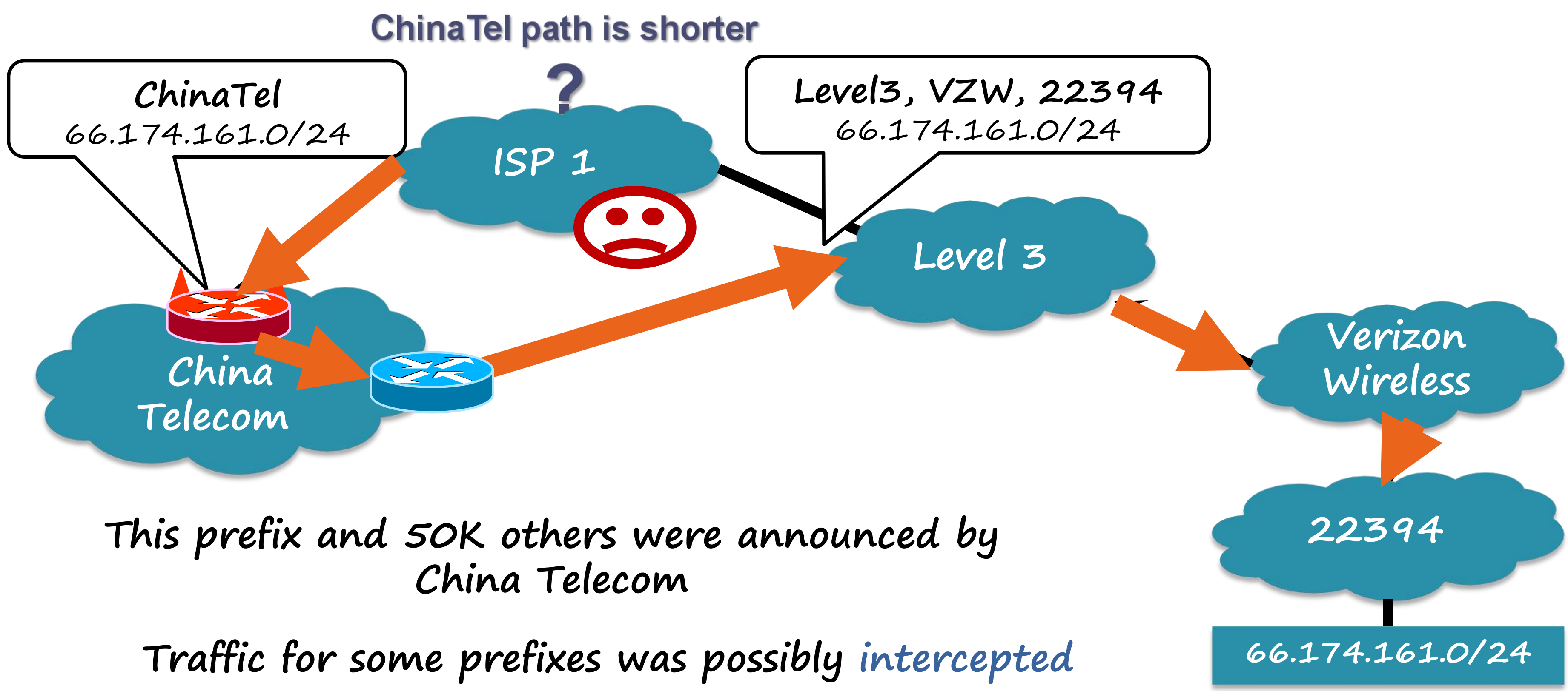


Prefix Hijacking: Case 2



Paths chosen based on cost and length.

April 2010 : China Telecom intercepts traffic



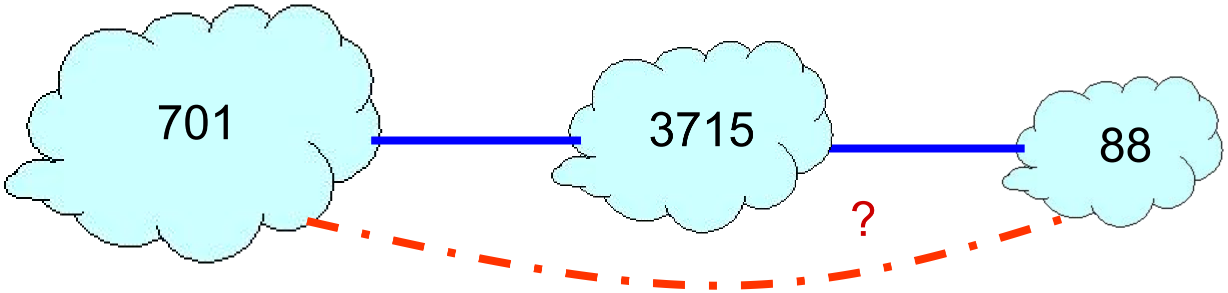
This prefix and 50K others were announced by China Telecom

Traffic for some prefixes was possibly *intercepted*

Path Tampering

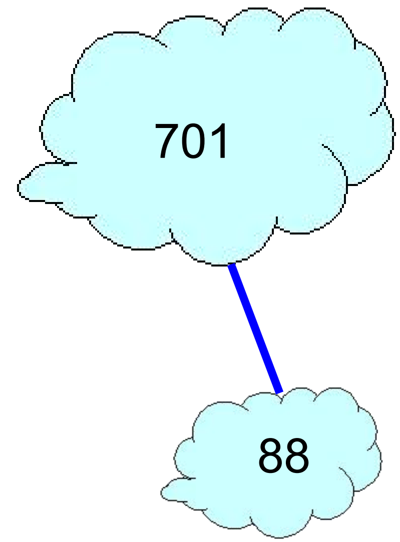
- Remove ASes from the AS path

701 ~~3715~~ 88



- Add ASes to the AS path

701 88 →
701 3715 88

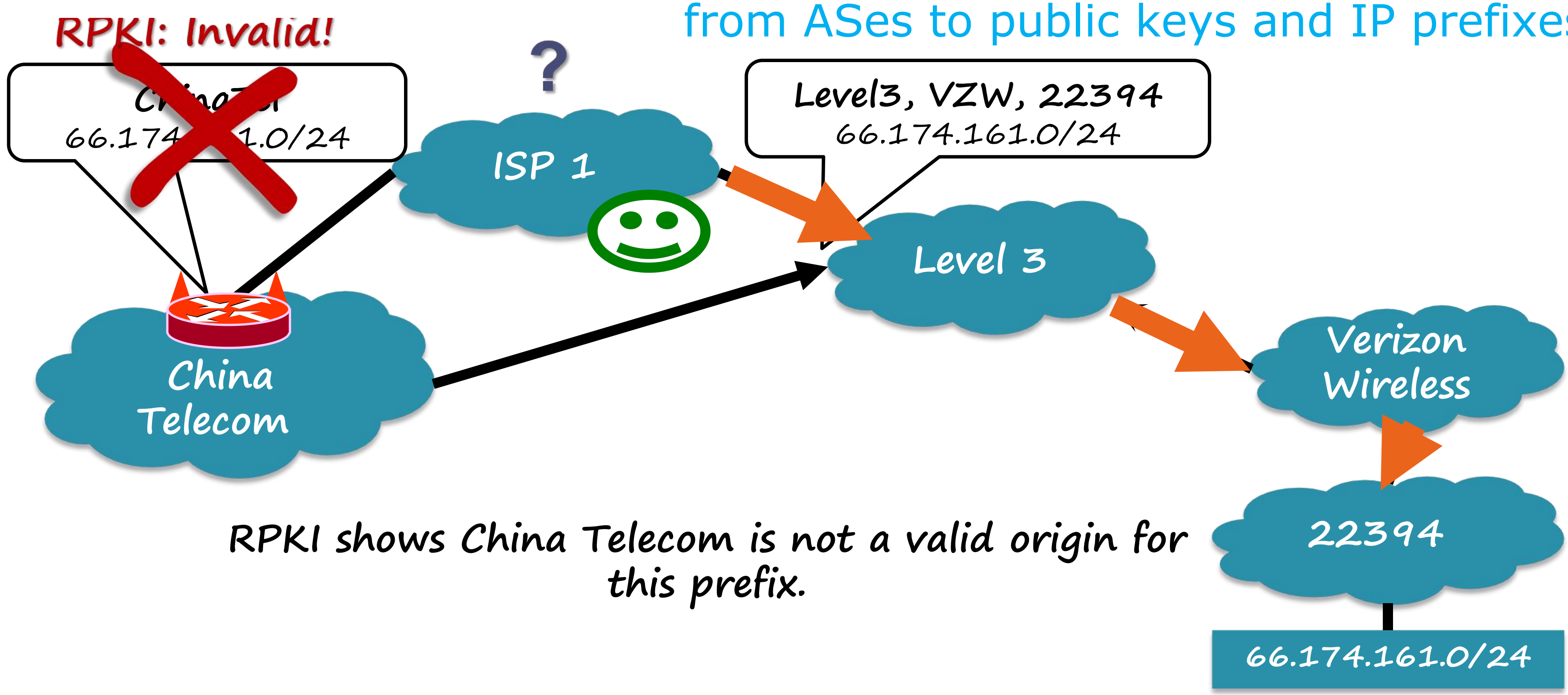


how to secure routing?

RPKI

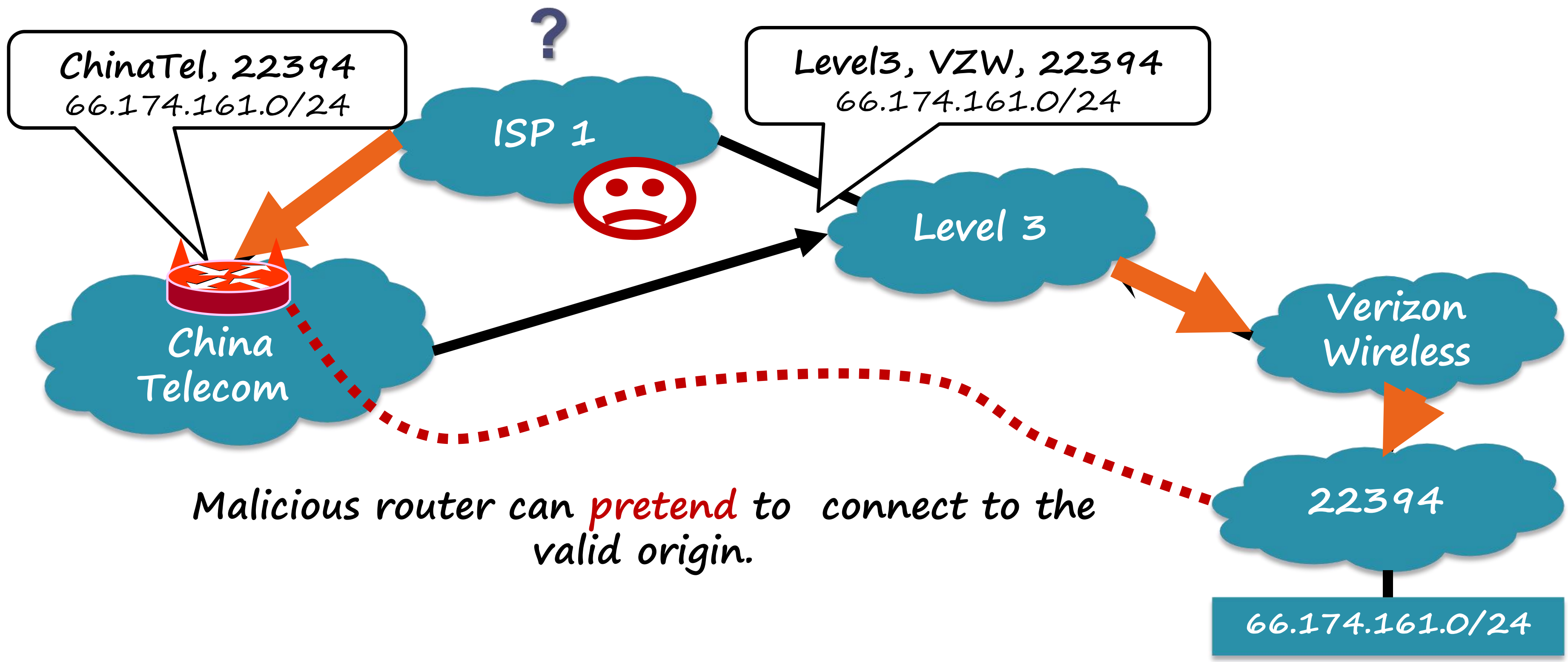
Resource Public Key Infrastructure

certified mapping
from ASes to public keys and IP prefixes



RPKI shows China Telecom is not a valid origin for this prefix.

RPKI
insufficient!



Malicious router can *pretend* to connect to the valid origin.

S-BGP

- Each AS on the path cryptographically signs its announcement
- Guarantees that each AS on the path made the announcement in the path:

  AS path indicates the order ASes were traversed;

  No intermediate ASes were added or removed;

S-BGP

Deployment challenges:

- Complete, accurate registries
- Public key infrastructure
- Cryptographic operations
- Need to perform operations quickly
- Difficulty of incremental deployment

?

Readings

- BGP Hijack Explained by Jorge Ribas
- Why Is It Taking So Long to Secure Internet Routing? by Sharon Goldberg

Thank You