Computer Networking : Principles, Protocols and Practice

Part 4 : Network Layer

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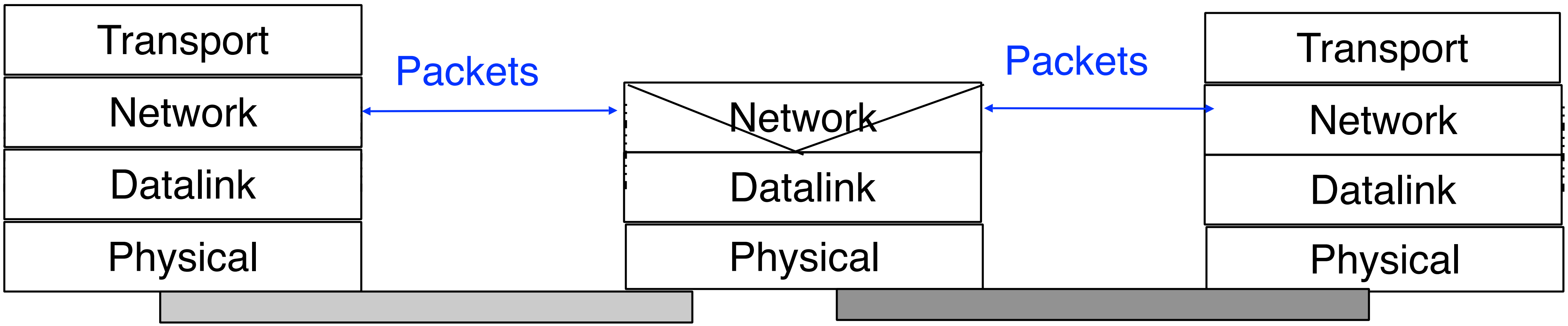
Network layer

- Basics
  - Datagram mode
  - Virtual circuits
- Routing
- IP : Internet Protocol
- Routing in IP networks

The network layer



Goal

Allow packets to be forwarded from any source to any destination through heterogeneous networks and routers

Services

Unreliable connectionless service
Reliable connection-oriented service

Two types of datalink layers

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- WAN type datalink layer
  - PPP, HDLC
    - Reliable exchange of frames between two hosts attached to the same “link”
    - Mainly used by wide area networks

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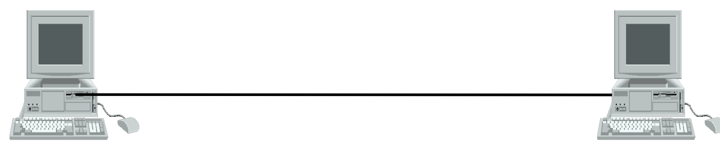

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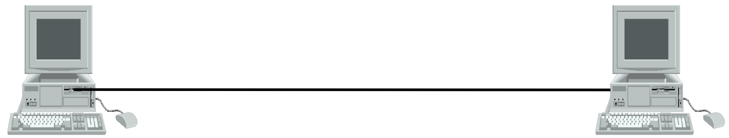
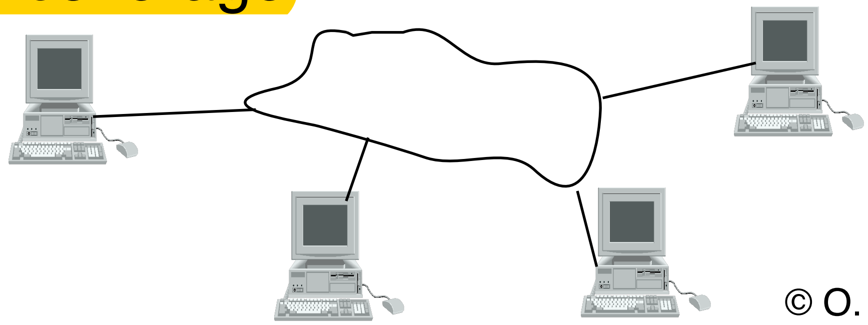
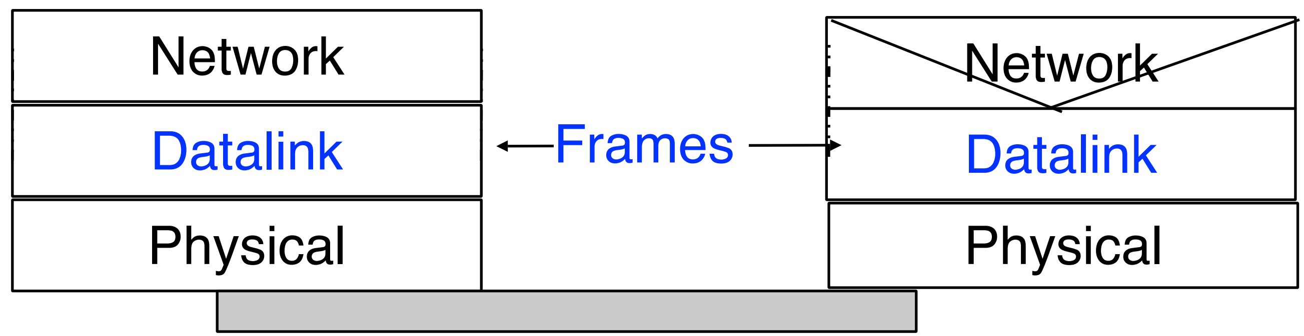


- LAN type datalink layer
  - Ethernet, Token Ring, FDDI, WiFi, Wimax,
    - Exchange of frames between hosts attached to the same LAN
    - limited geographical coverage

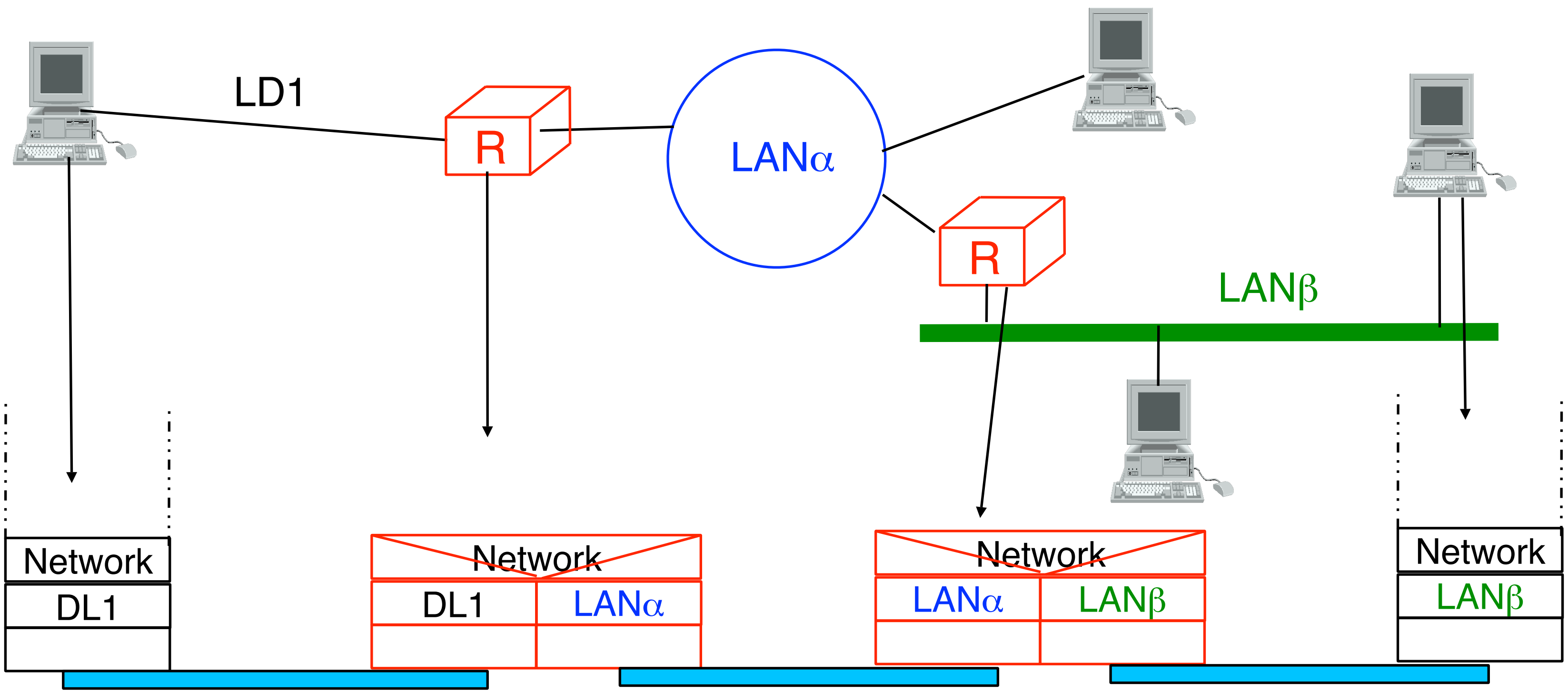


The datalink service



- Service of datalink layer
  - Unreliable connectionless service
    - Transmission of frames between hosts directly connected at the physical layer or directly attached to the same LAN
    - Unreliable transmission (frames can be lost but usually transmission errors are detected)
    - Most datalink layers have maximum frame length
  - Connection-oriented service, reliable or not
    - Transmission of frames between hosts directly connected at the physical layer or directly attached to the same LAN
    - Reliable or unreliable transmission

Routers



Router

Relay within the network layer

packet is unit of transmission

Network layer
Basic principles

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Network layer user should not need to know anything about the internal structure of the network layer to be able to send packets

Internal organisation of the network layer

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Two possible organisations

- datagrams
- virtual circuits

Internal organisation of the network layer

- Two possible organisations
  - datagrams
  - virtual circuits

- The internal organisation of the network is orthogonal to the service provided, but often
  - datagram mode is used to provide a connectionless service
  - virtual circuits are used to provide a connection-oriented service

Datagram transmission mode

Datagram transmission mode

- Basics
  - Each route/host is identified by an address
  - Information is divided in packets
  - Each packet contains
    - Source address
    - Destination address
    - Payload
  - Router behavior
    - Upon packet arrival look at destination address and routing table to decide where the packet should be forwarded
      - hop-by-hop forwarding, each routers takes a forwarding decision

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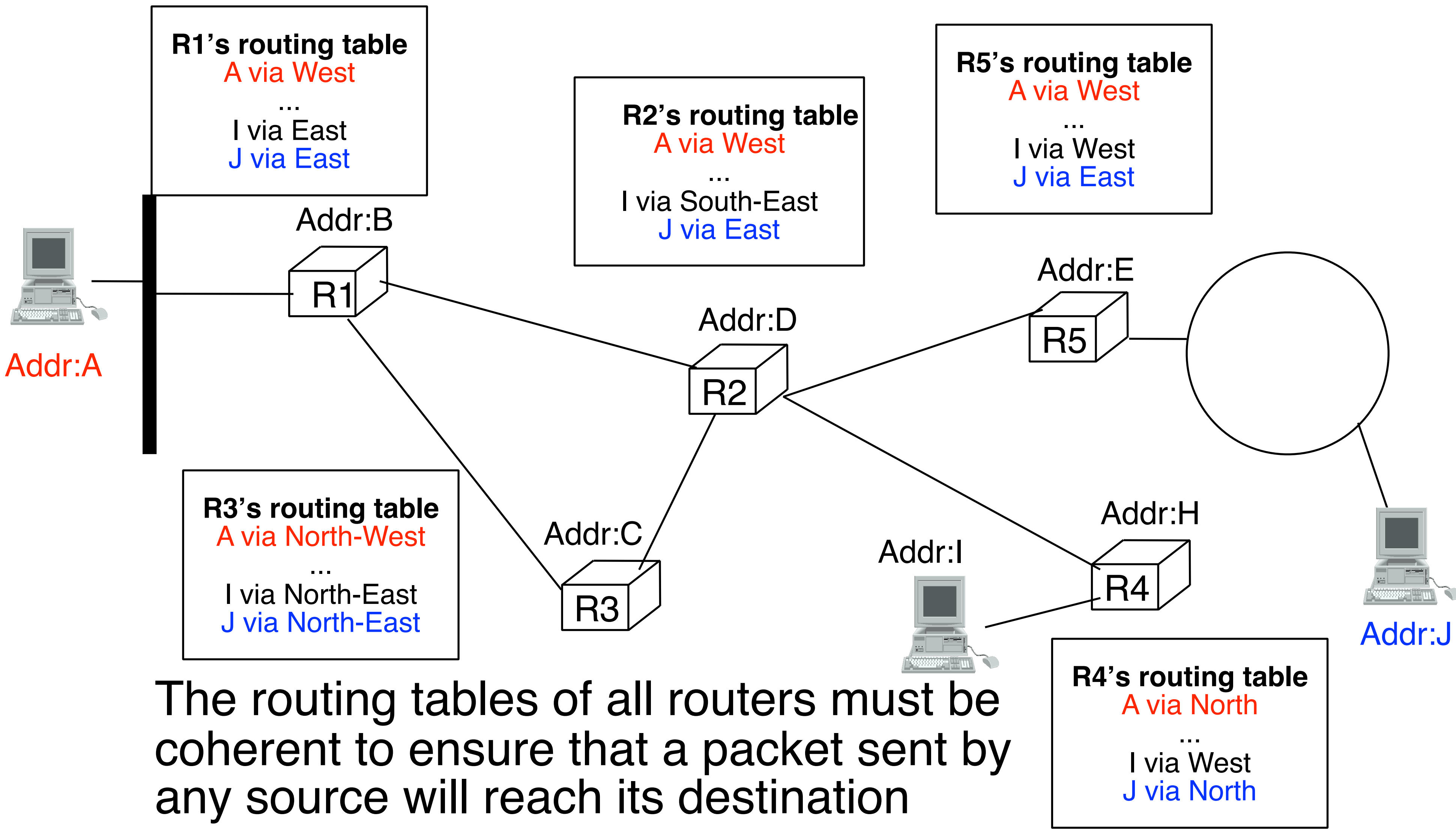
- Examples
  - IP (IPv4 and IPv6)
  - CLNP
  - IPX

Datagram transmission mode (2)



The routing tables of all routers must be coherent to ensure that a packet sent by any source will reach its destination

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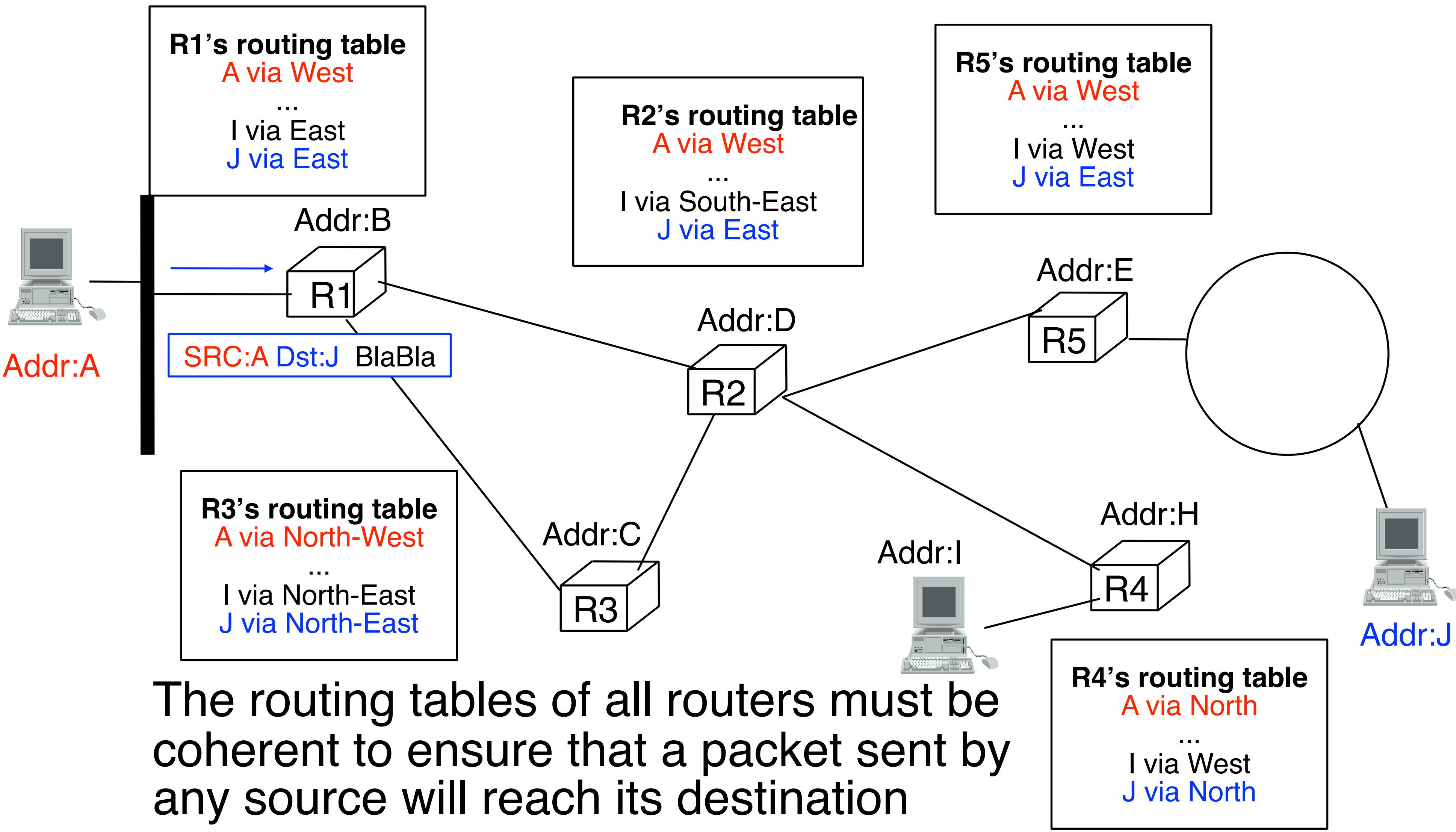

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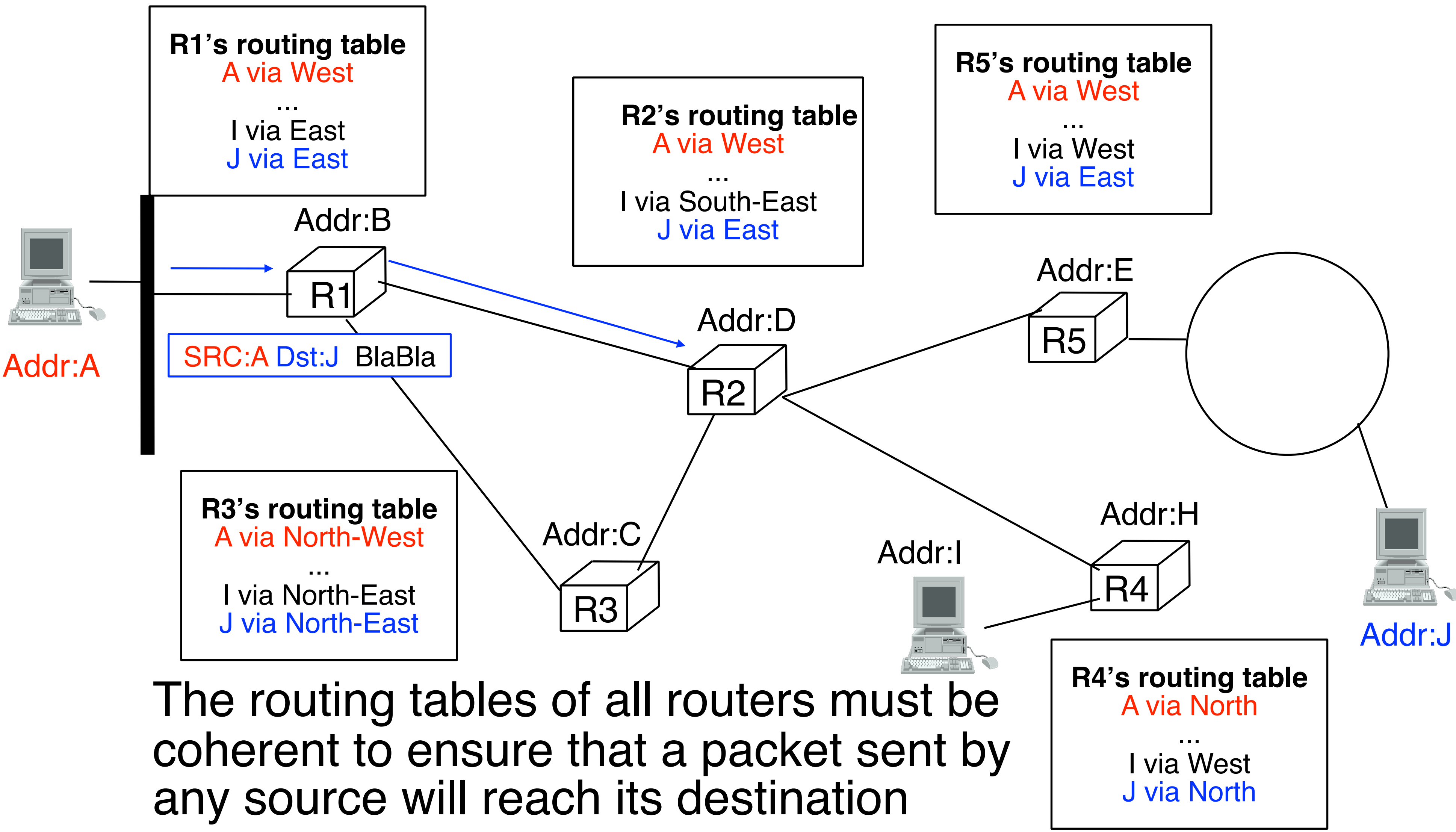

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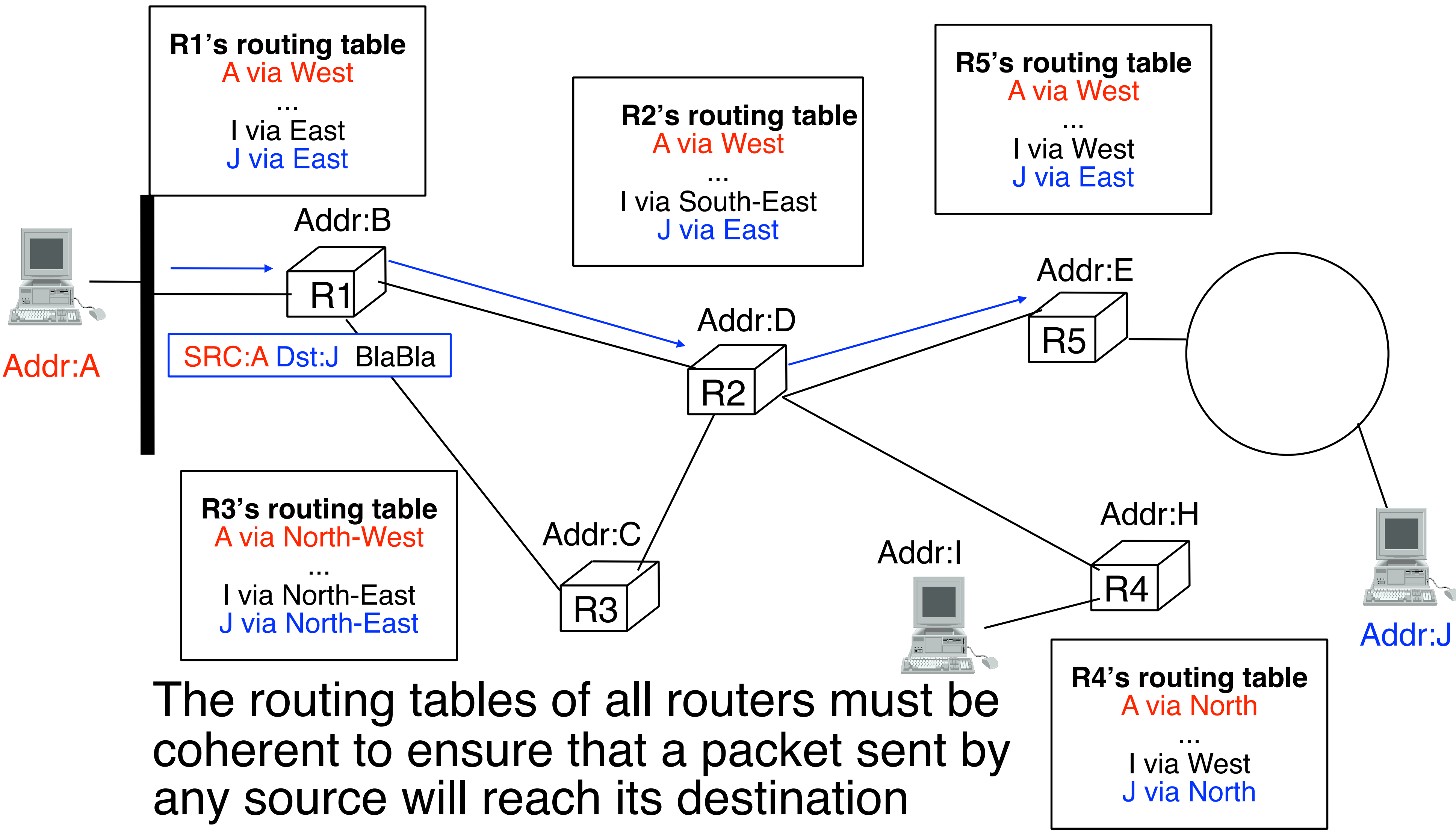

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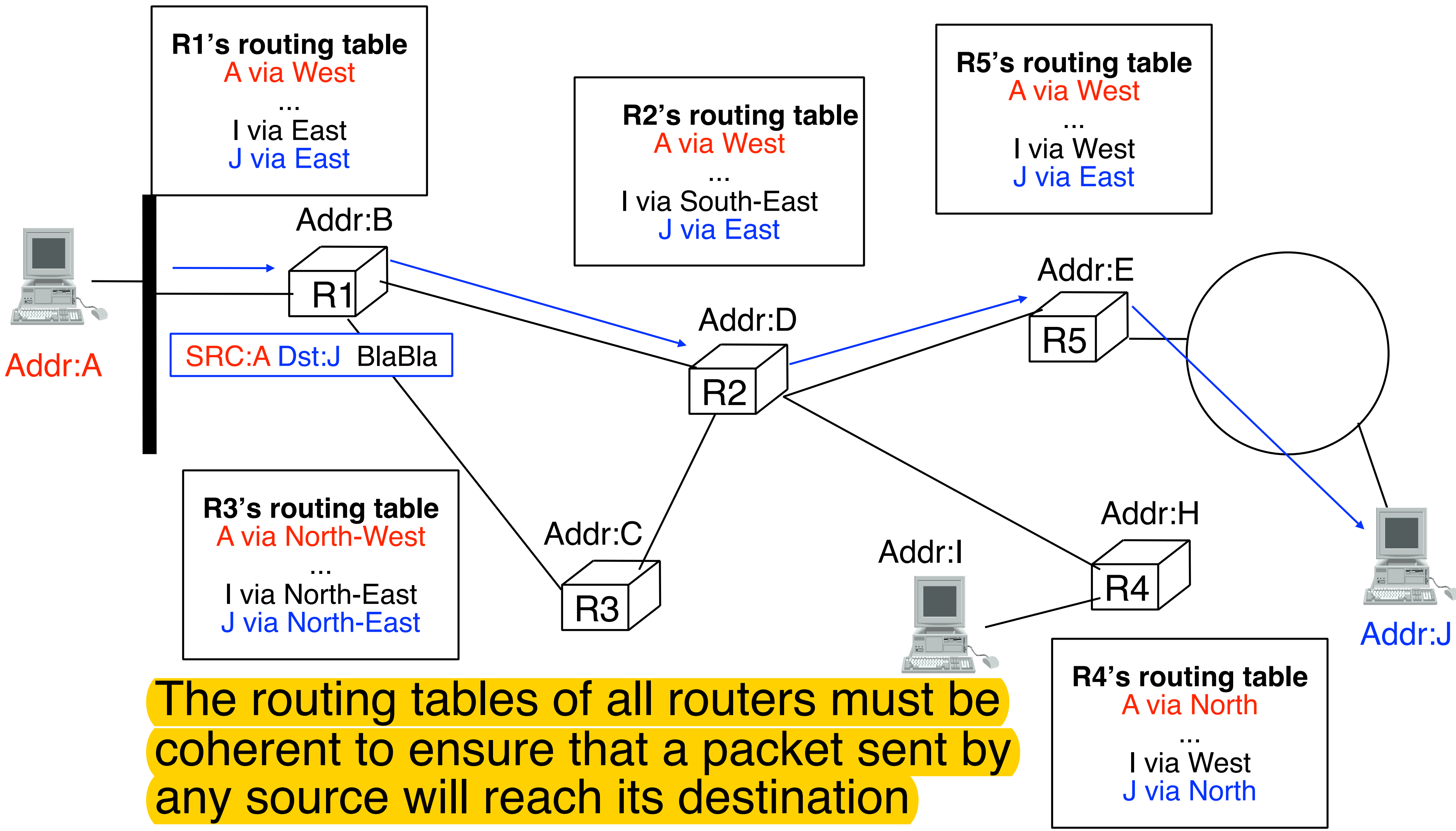

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Virtual circuit organisation

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- Goals
  - Keep forwarding on the routers as simple as possible
    - consulting a routing table for each packet is costly from a performance viewpoint

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  - Before transmitting packets containing data, create a virtual circuit that links source and destination through the network
    - During the virtual circuit establishment, efficient datastructures are updated on each transit router to simplify forwarding
  - Use the virtual circuits to forward the packets
    - All packets will follow the same path

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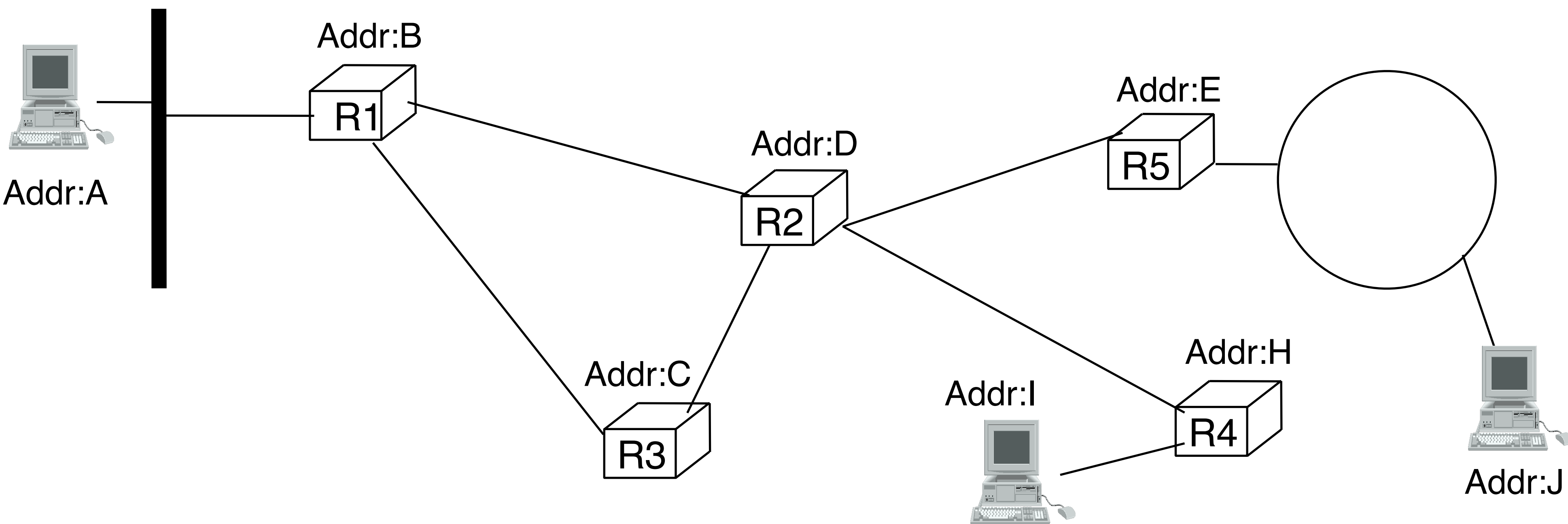
- Example
  - ATM, X.25, Frame Relay, MPLS, gMPLS

Establishment of a virtual circuit



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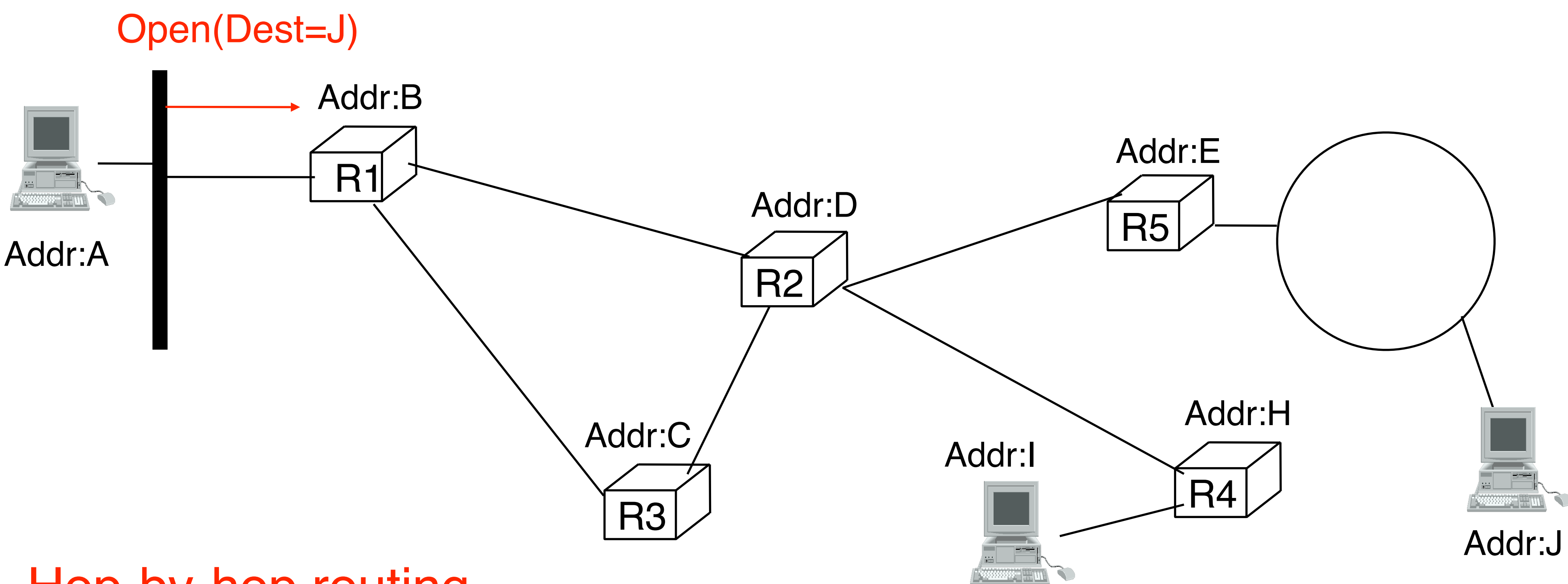

Hop-by-hop routing

Each router consults its routing table to forward vc establishment

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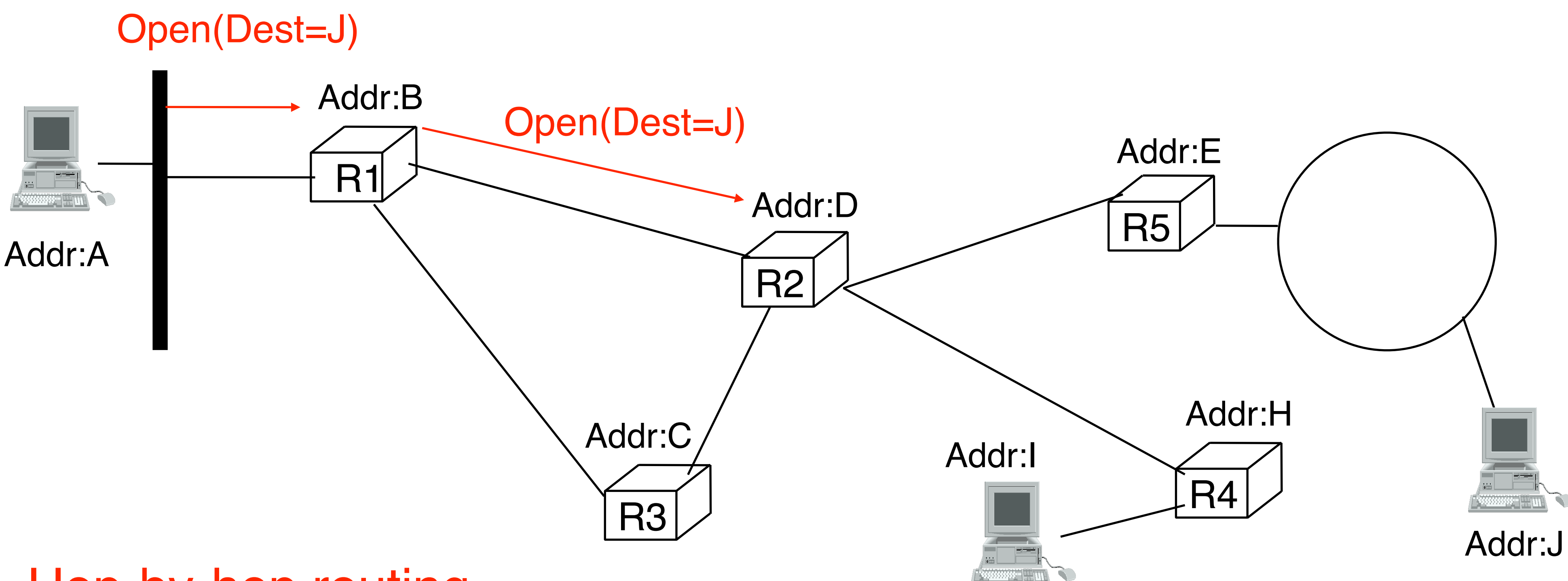

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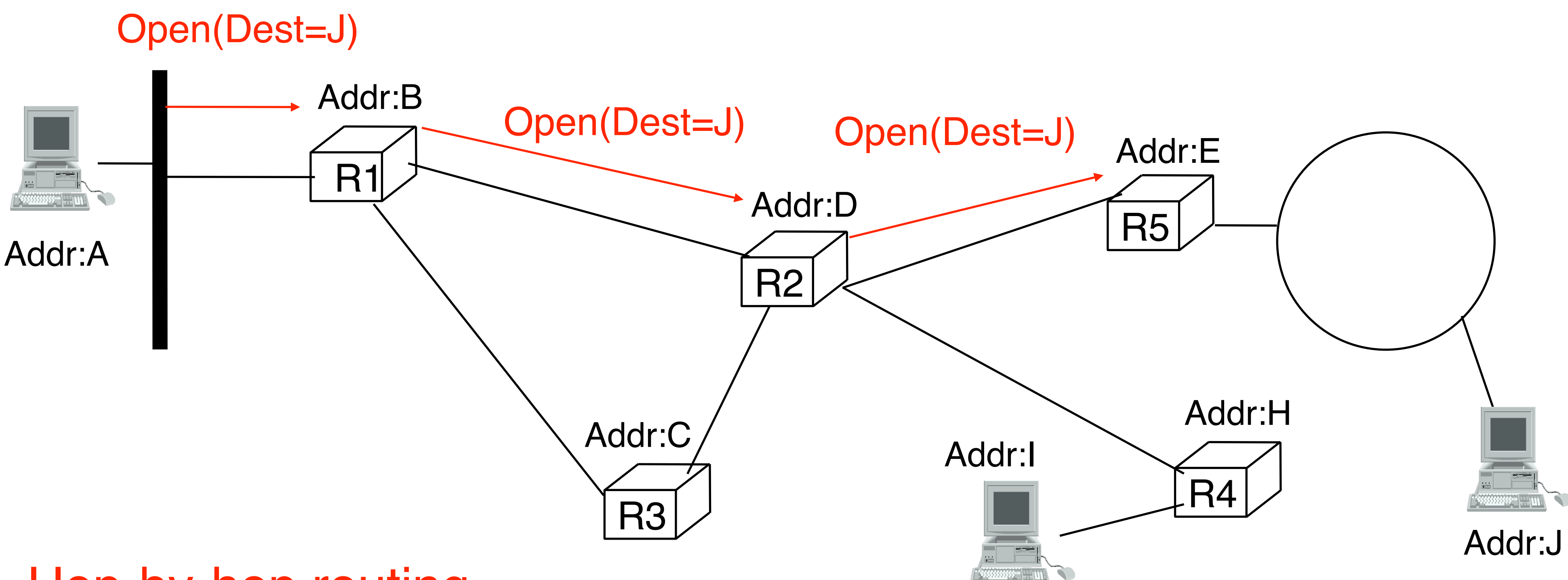

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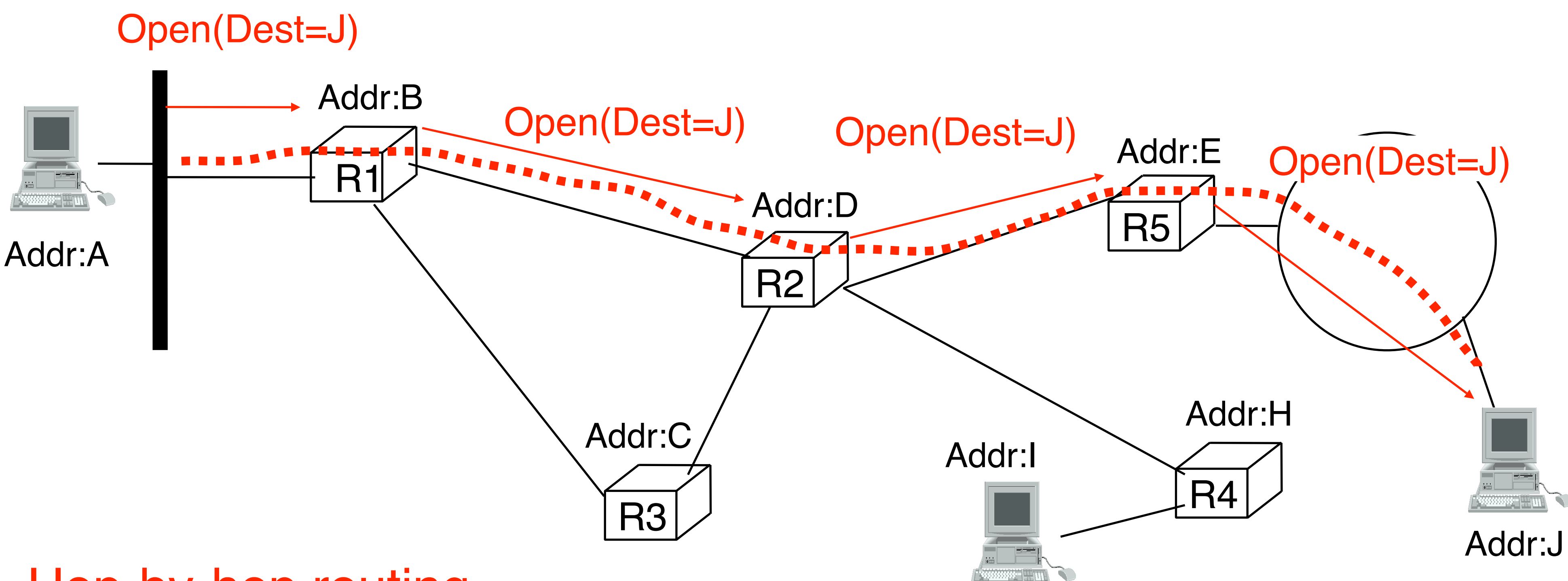

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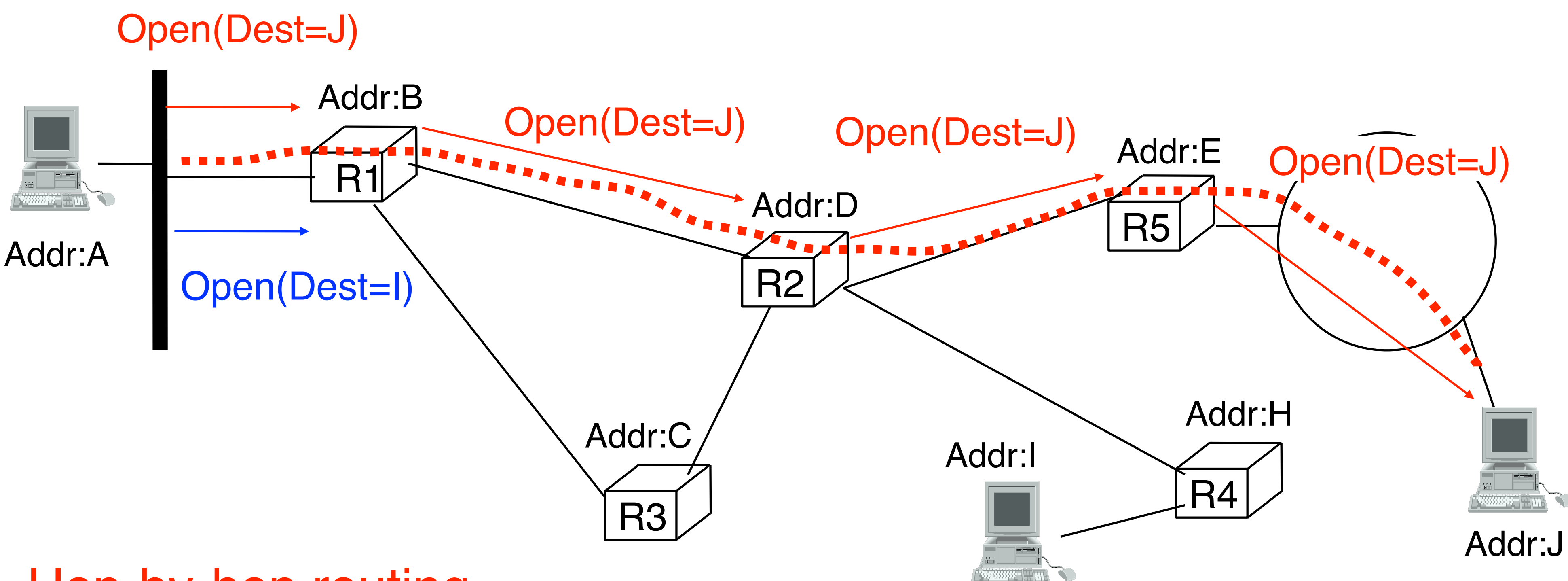

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Source (or first hop router) indicates in vc establishment packet the path to be followed

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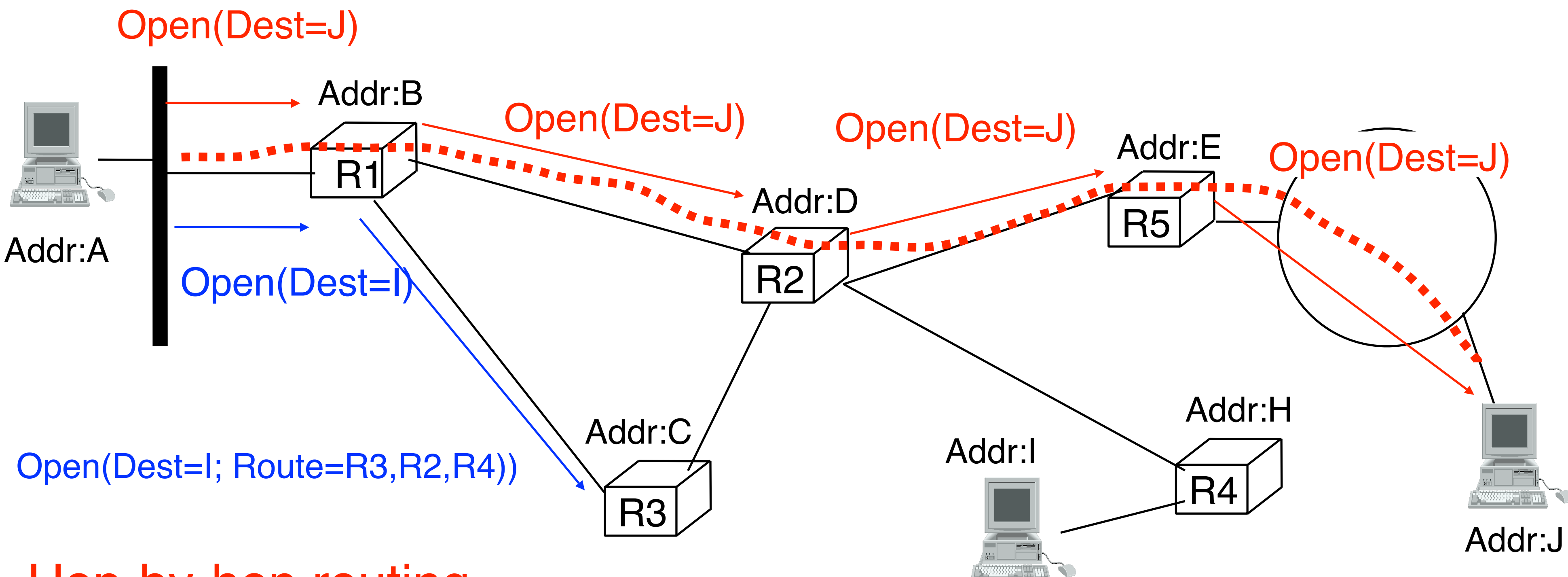

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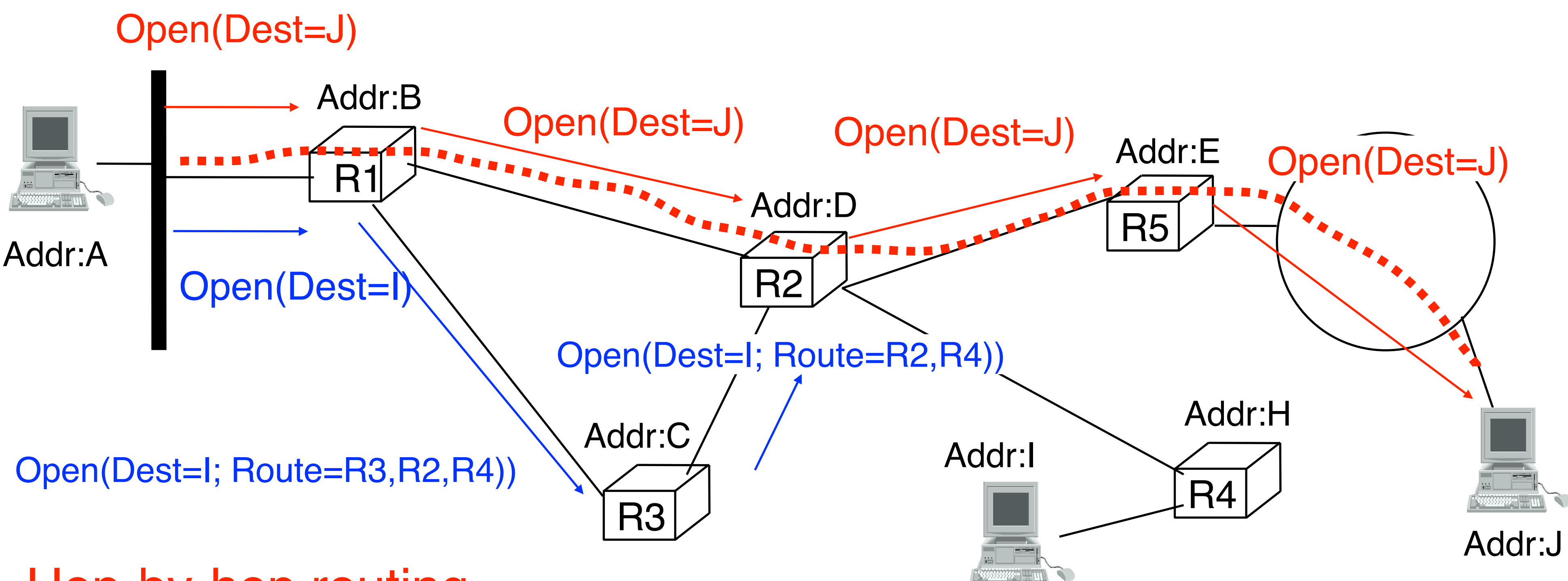

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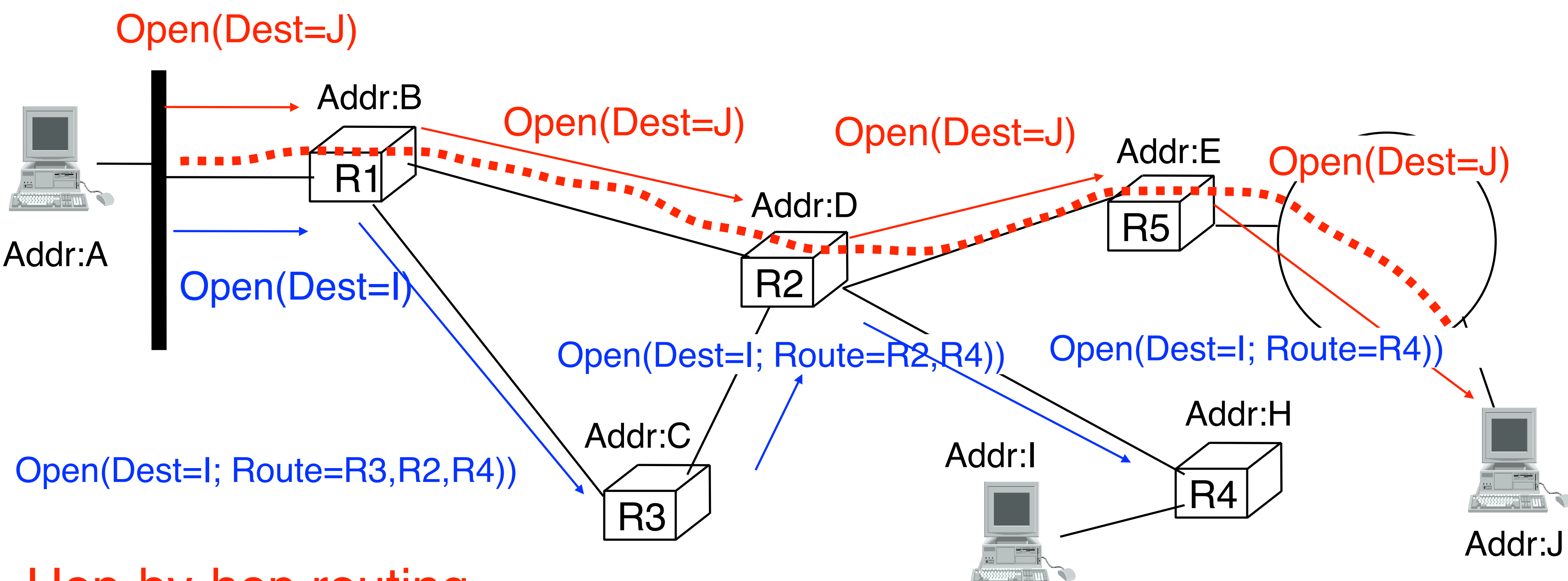

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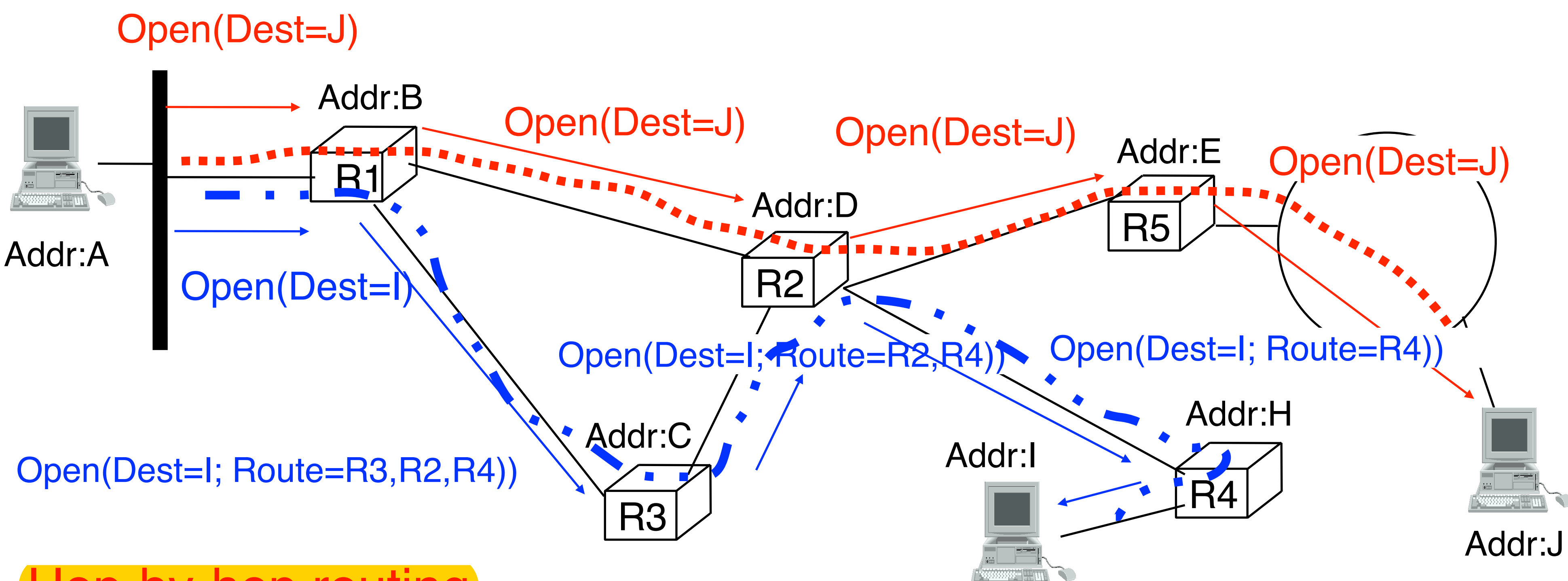

Hop-by-hop routing
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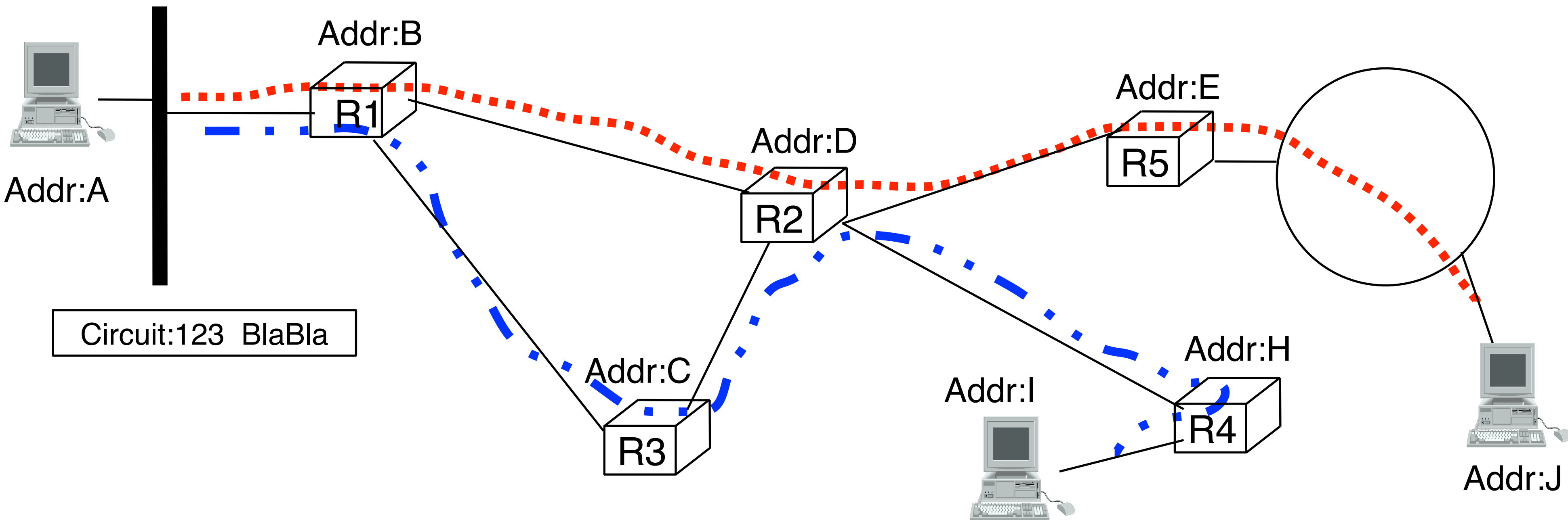
Packet transmission



- Packet contents
  - virtual circuit identifier
  - packet payload
- What kind of virtual circuit identifier
  - Naive solution
    - unique identifier for all virtual circuits inside network
      - How to coordinate allocation of vc identifiers ?

Packet transmission (2)

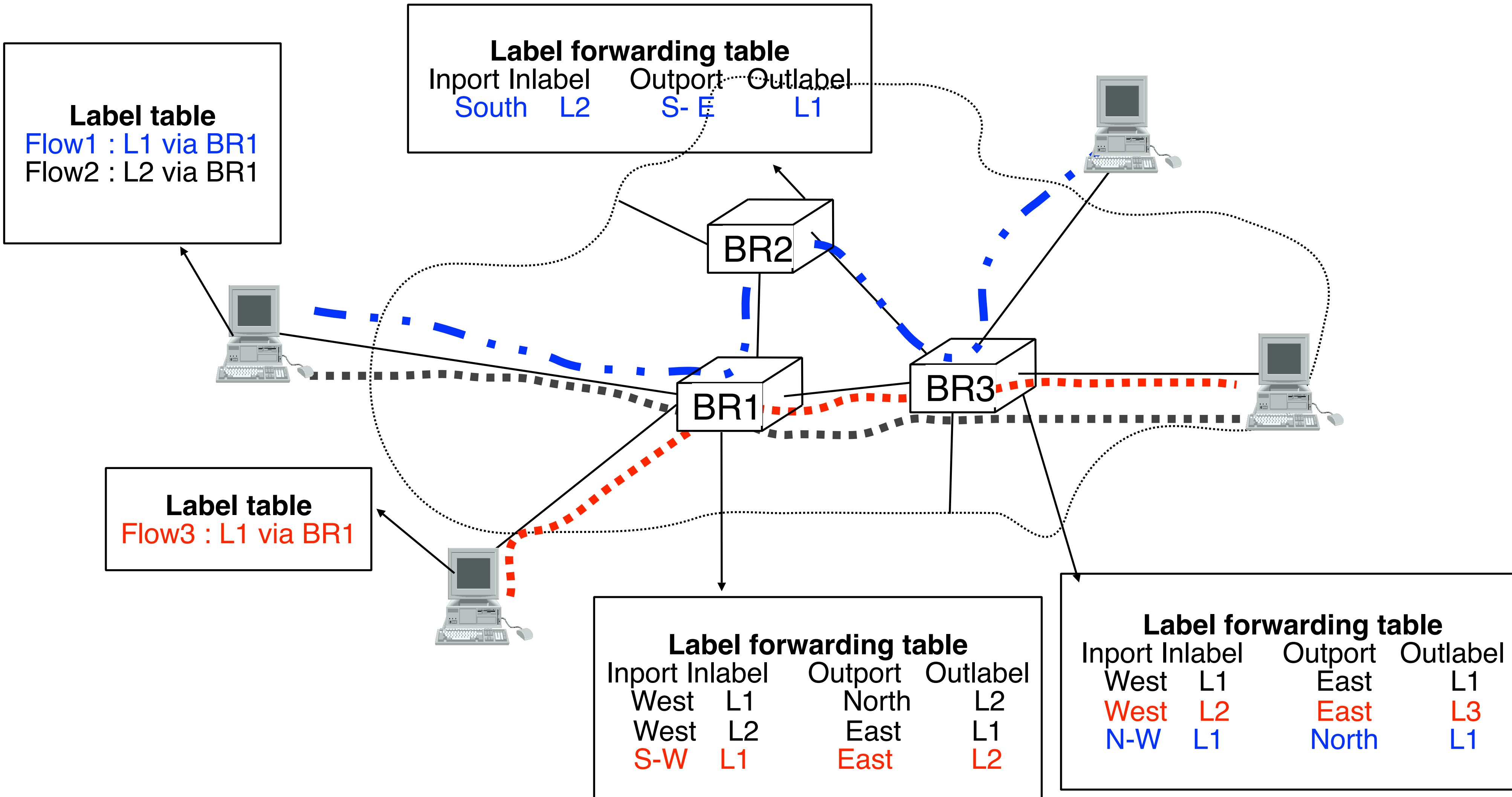
- How unique should virtual circuits identifiers be ?
  - globally unique
    - unrealistic
  - unique inside a given network
    - then coordination among routers is necessary
  - unique on a given link
    - easier to manage, no coordination required, but
    - virtual circuit identifier may need to be changed from link to link

- How to update the virtual circuit identifier of packets
  - All routers must contain a label forwarding table
    - this table is updated every time a virtual circuit is established

Label forwarding table

Inport	Inlabel	Outport	Outlabel
West	L1	East	L1
West	L2	East	L3
N-W	L1	North	L1

Virtual circuits : example



Network layer

Basics

Routing
- Static routing
- Distance vector routing
- Link state routing

IP : Internet Protocol

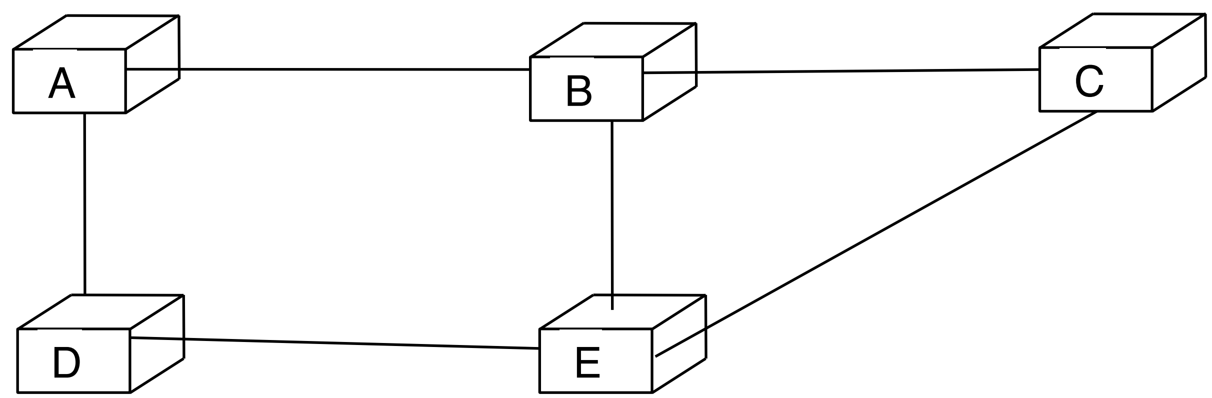
Routing in IP networks

Routing and Forwarding

- Main objective of network layer
  - transport packets form source to destination
- Two mechanisms are used in network layer
  - forwarding
    - algorithm use by each router to determine on which interface each packet should be sent to reach its destination or follow its virtual circuit
      - relies on the routing table maintained by each router
  - routing
    - algorithm (usually distributed) that distributes to all routers the information that allows them to build their routing tables

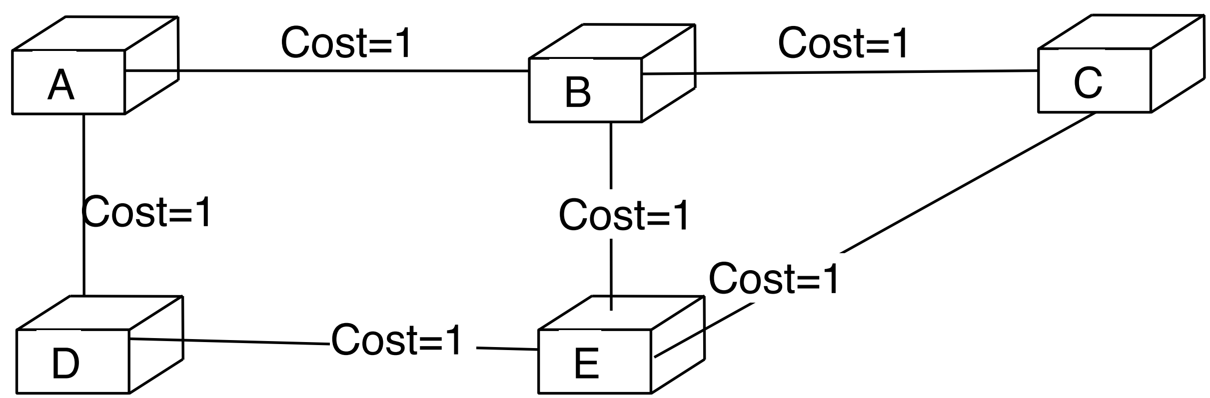
Routing (2)

How to build the routing tables of each router ?



- Principle
  - Include in the routing table of each router the path to allow it to reach each destination
    - Which path to be included in the routing table
      - From A to C ?
      - From D to B

Selection of the shortest paths



- Principle
  - Associate a weight/cost to each link
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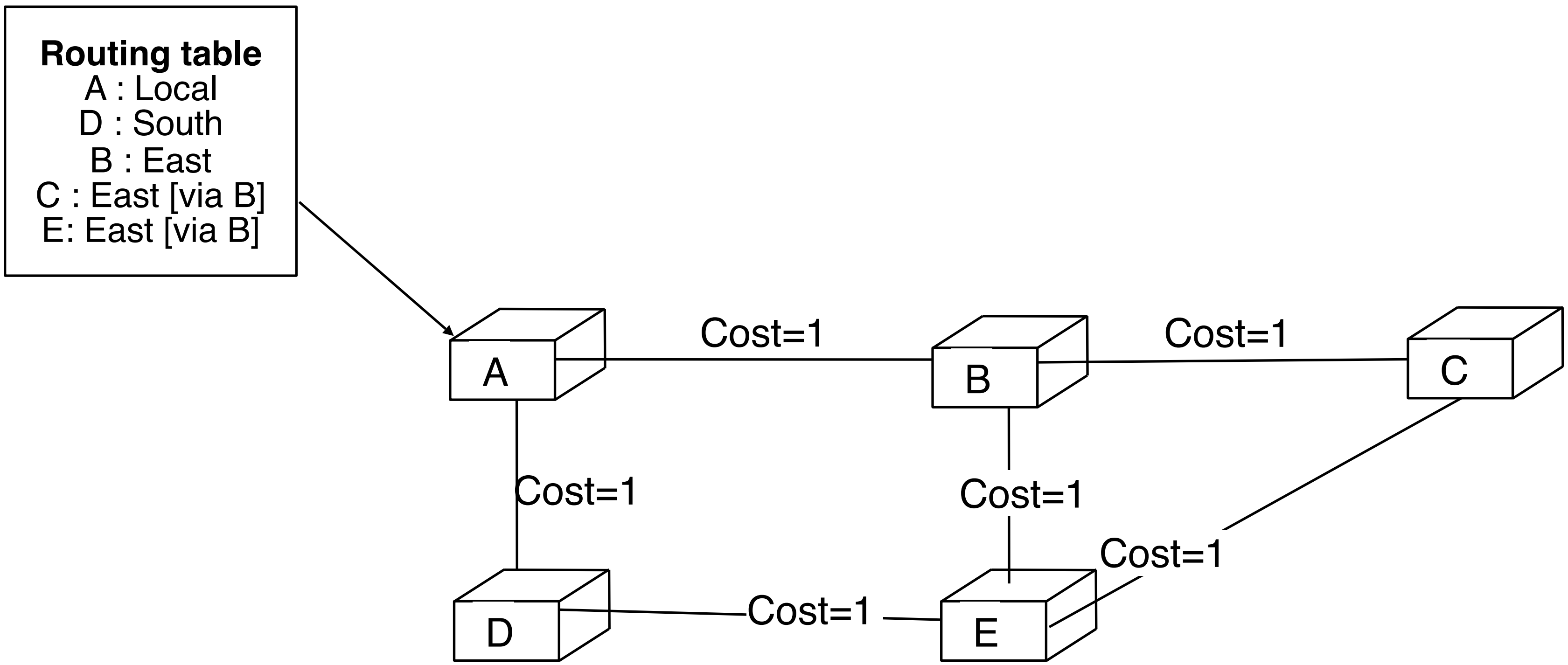

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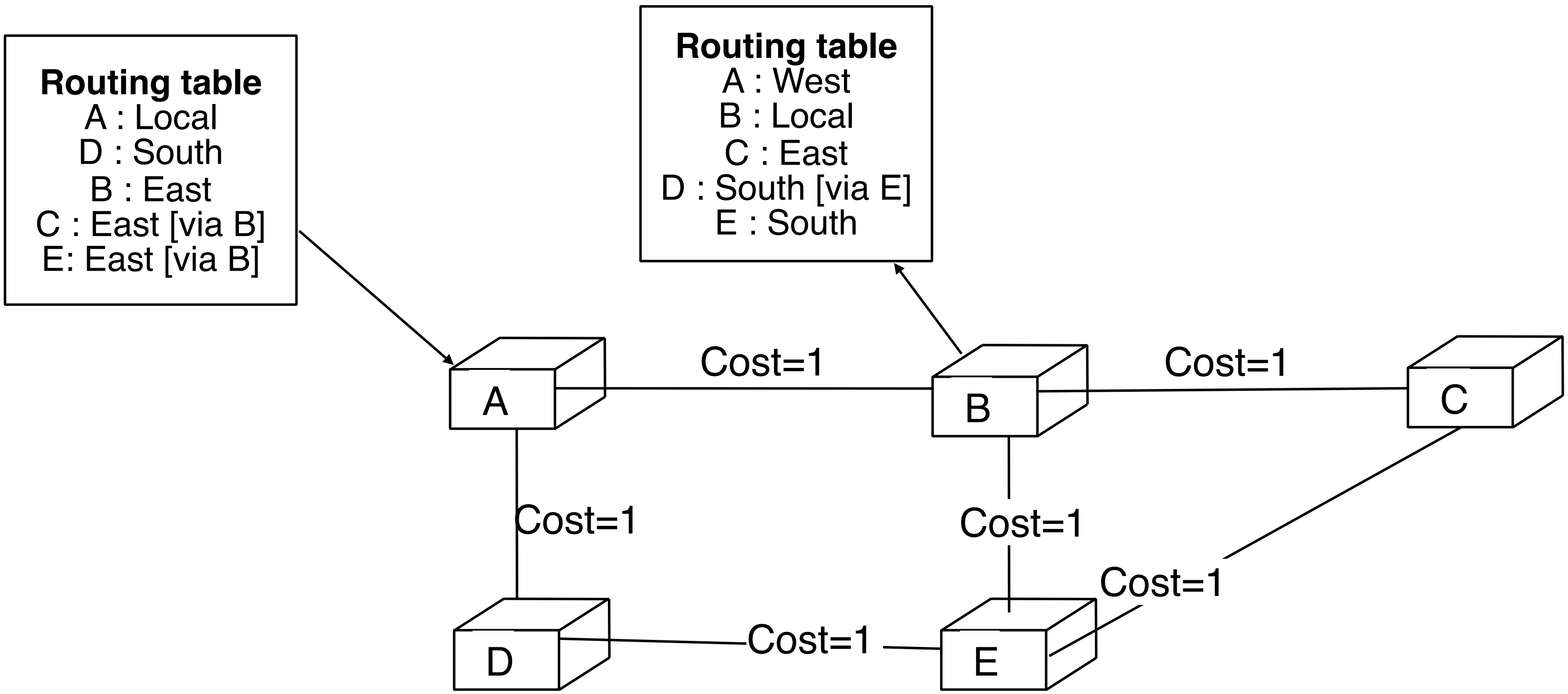

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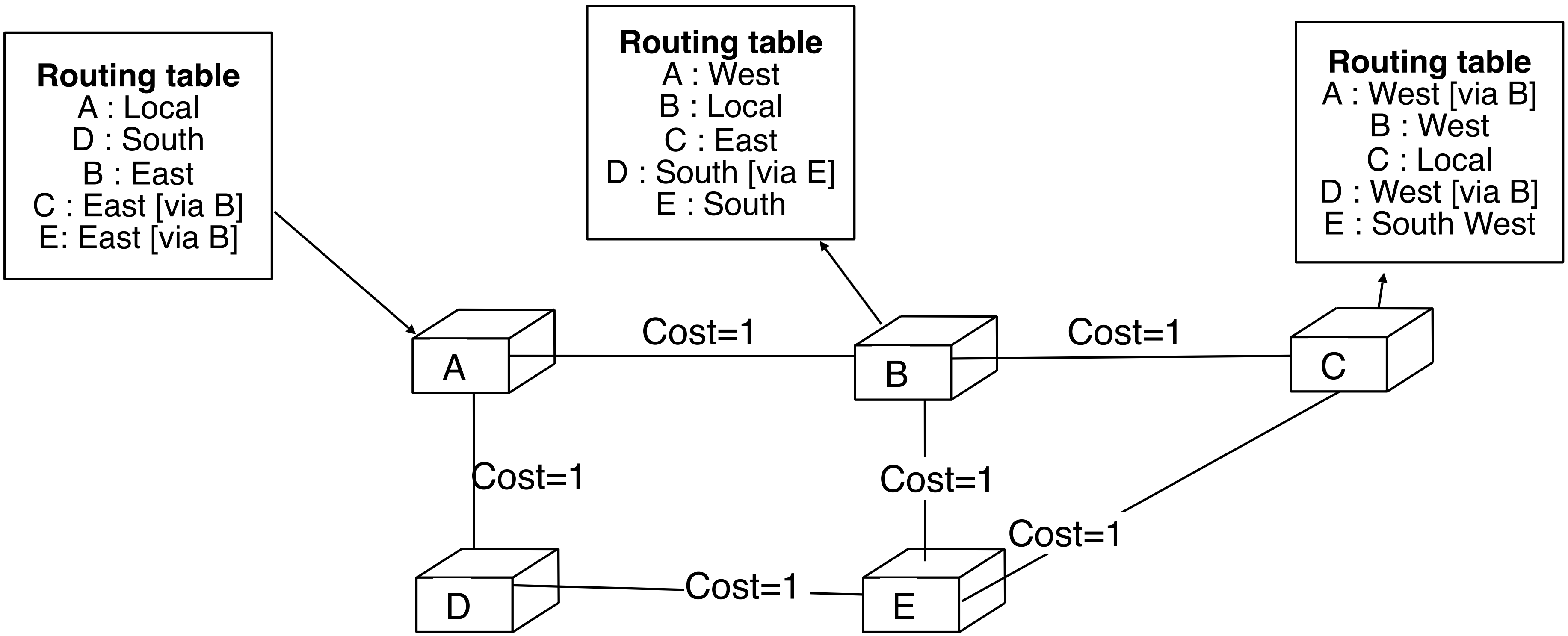

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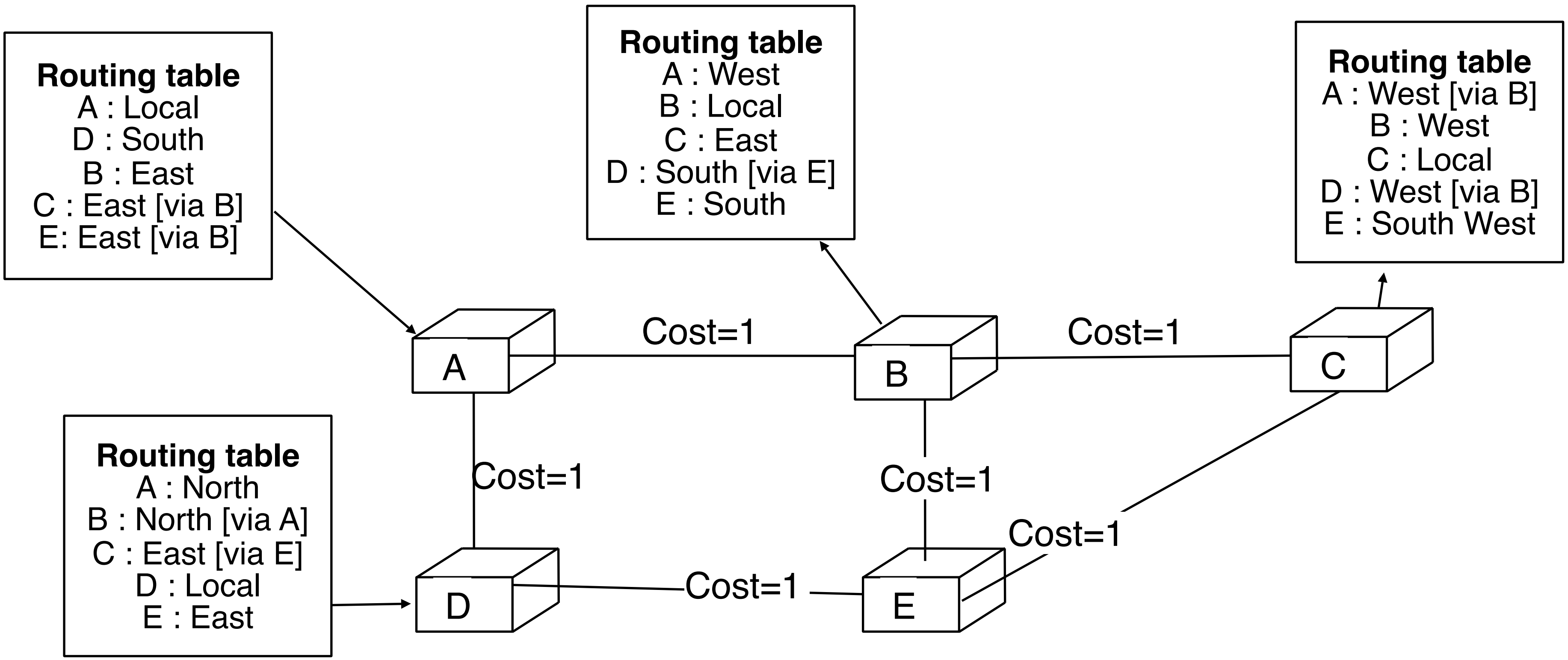

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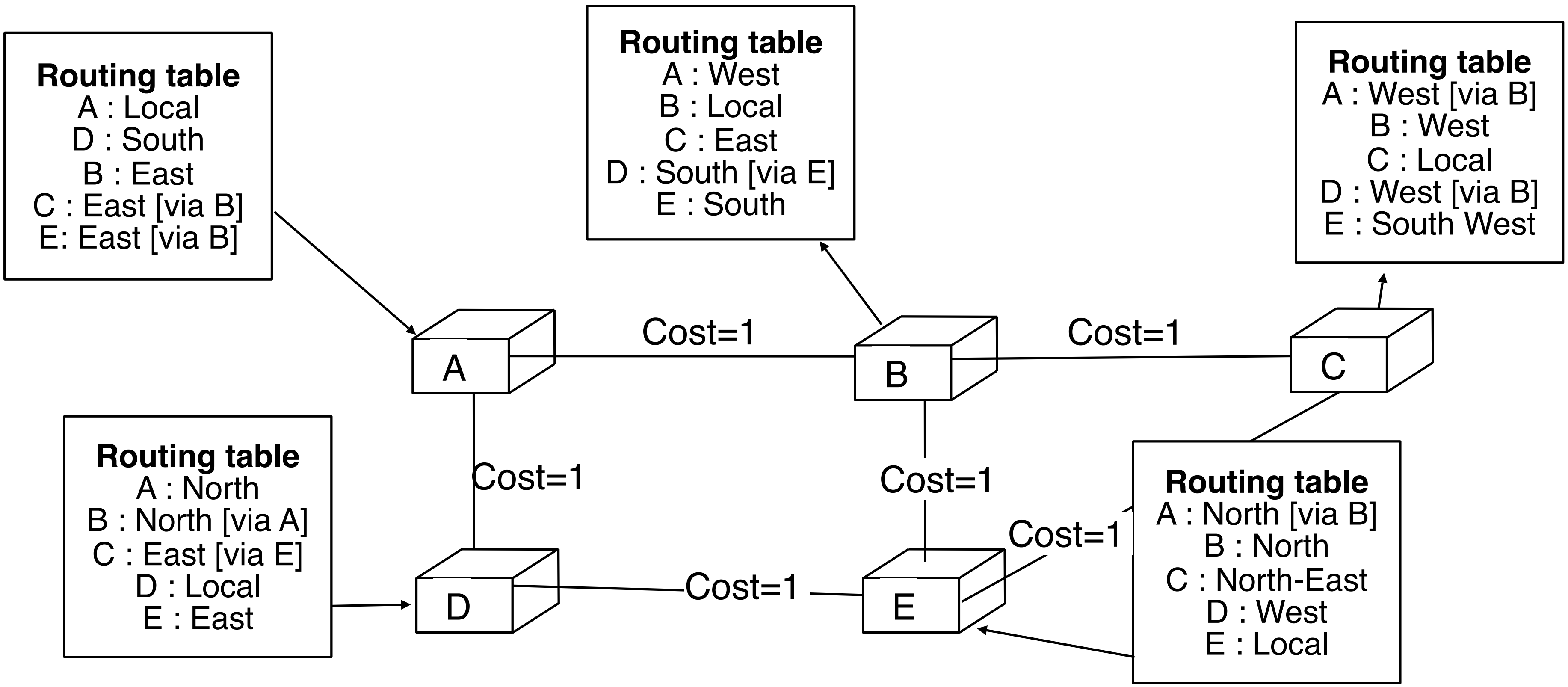

Principle
- Associate a weight/cost to each link
- Each router chooses the lowest cost path
  - How to ensure that the routing tables of all routers are coherent ?

Static Routing

- Principle
  - Network manager or network management station computes all routing tables and downloads them on all routers
  - How to compute routing tables ?
    - shortest path algorithms
    - more complex algorithms to provide load balancing or traffic engineering
- Advantages of static routing
  - Easy to use in a small network
  - routing tables can be optimised
- Drawbacks of static routing
  - does not adapt dynamically to network load
  - how to deal with link and router failures ?

Dynamic or distributed routing

- Principle
  - routers exchange messages and use a distributed algorithm to build their routing tables
  - used in almost all networks
- Advantages
  - can easily adapt routing tables to events
- Drawbacks
  - more complex to implement than static routing
- Most common distributed routing methods
  - Distance vector routing
  - Link state routing

Network layer

Basics

Routing

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- Distance vector routing
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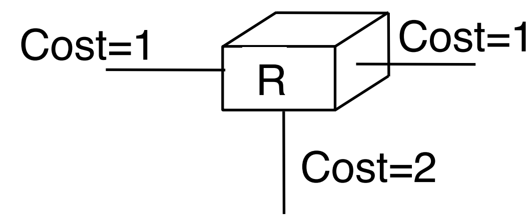
IP : Internet Protocol

Routing in IP networks

Distance vector routing

- Basic principles
  - Configuration of each router
    - Cost of each link



- When it boots, a router only knows itself
- Each router sends periodically to all its neighbours a vector that contains for each destination that it knows
  1. Destination address
  2. Distance between transmitting router and destination
     - distance vector is a summary of the router's routing table
- Each router will update its routing table based on the information received from its neighbours

Distance vector routing (2)

- Routing table *maintained by router*
  - For each destination d inside routing table
    - R[d].cost = total cost of shortest path to reach d
    - R[d].link = outgoing link used to reach d via shortest path
- Distance vector *sent to neighbours*
  - For each destination d
    - V[d].cost = total cost of shortest path to reach d

```
Every N seconds:
 Vector=null;
 for each destination=d in R[]
 {
  Vector=Vector+Pair(d,R[d].cost);
 }
 for each interface
 {
  Send(Vector);
 }
```

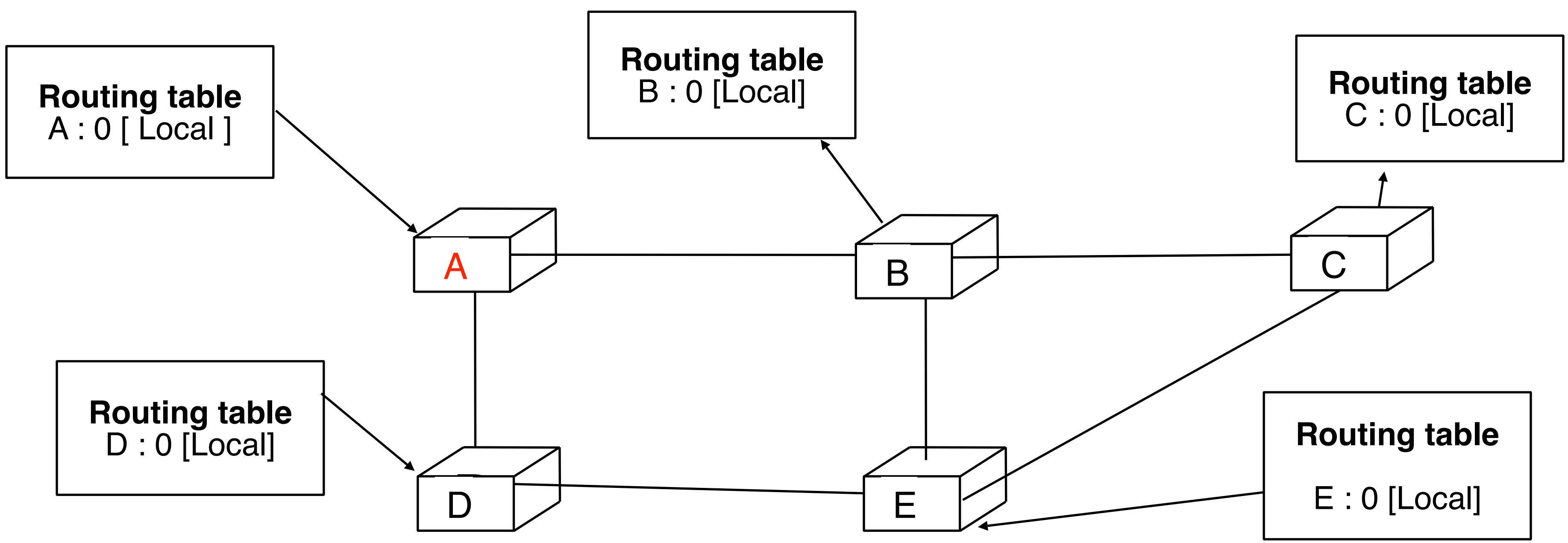
Distance vector routing (3)

Processing of received distance vectors

```
Received(Vector V[],link l)
{ /* received vector from link l */
for each destination=d in V[]
{
  if (d isin R[])
  { if ((V[d].cost+l.cost) < R[d].cost)
     { /* shorter path */
       R[d].cost=V[d].cost+l.cost;
       R[d].link=l;
     }
   }
   else
   { /* new route */
     R[d].cost=V[d].cost+l.cost;
     R[d].link=l;
   }
}
```

Distance vectors example

All links have a unit cost



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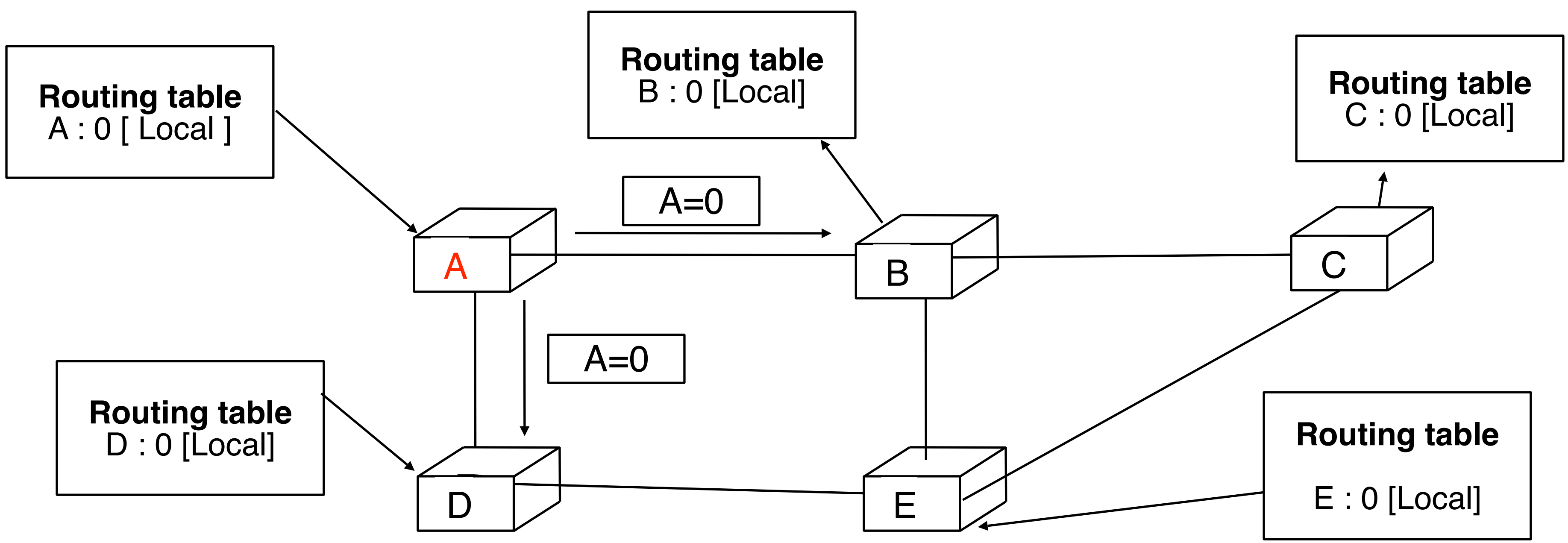
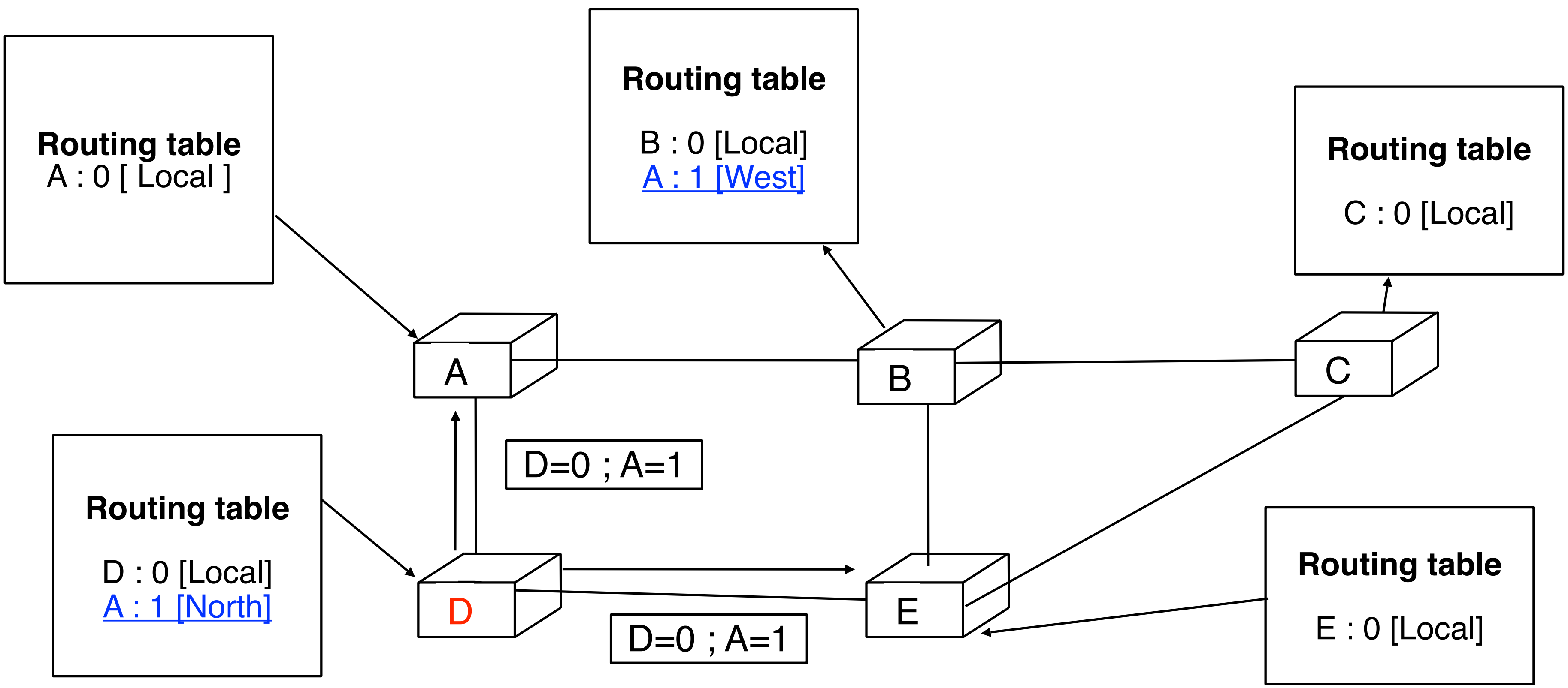


When a router boots, it only knows itself. Its distance vector thus contains only its address

Distance vectors example (2)



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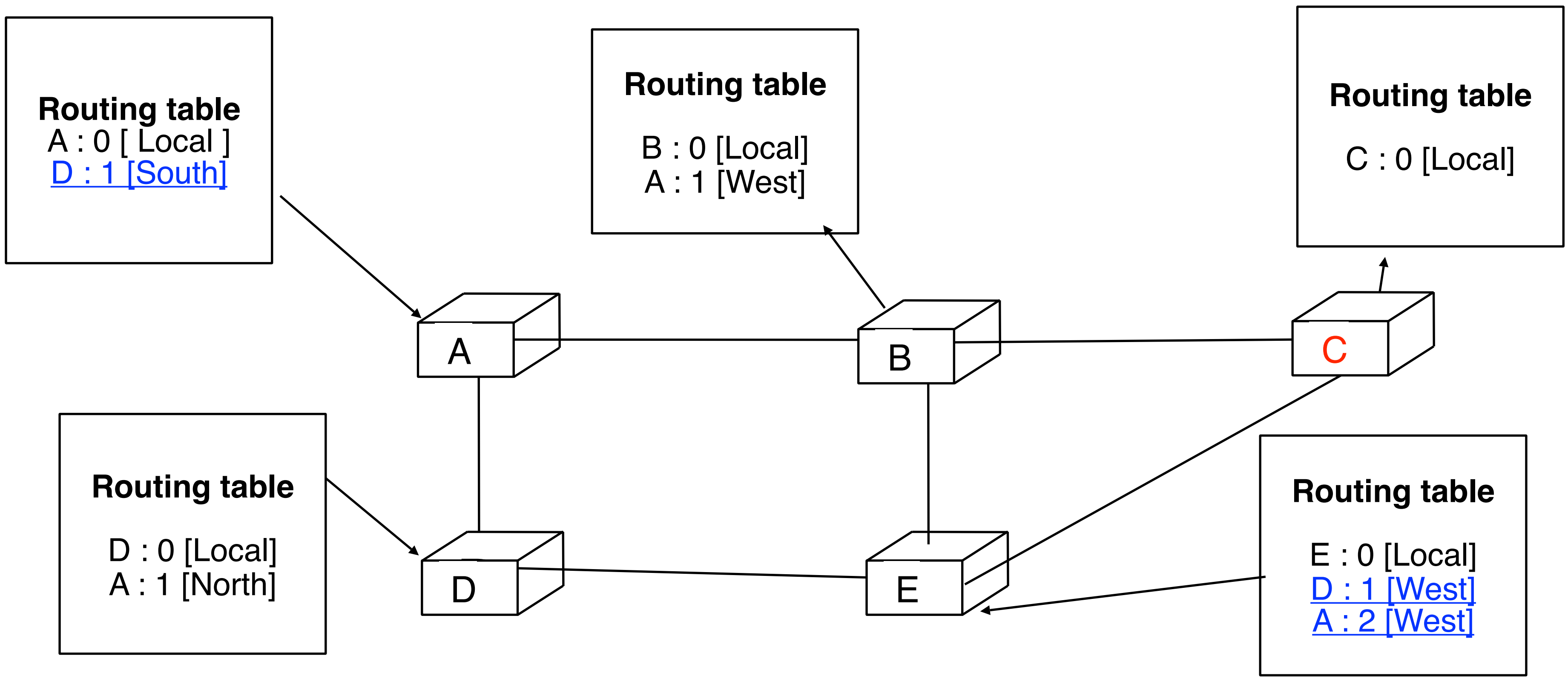

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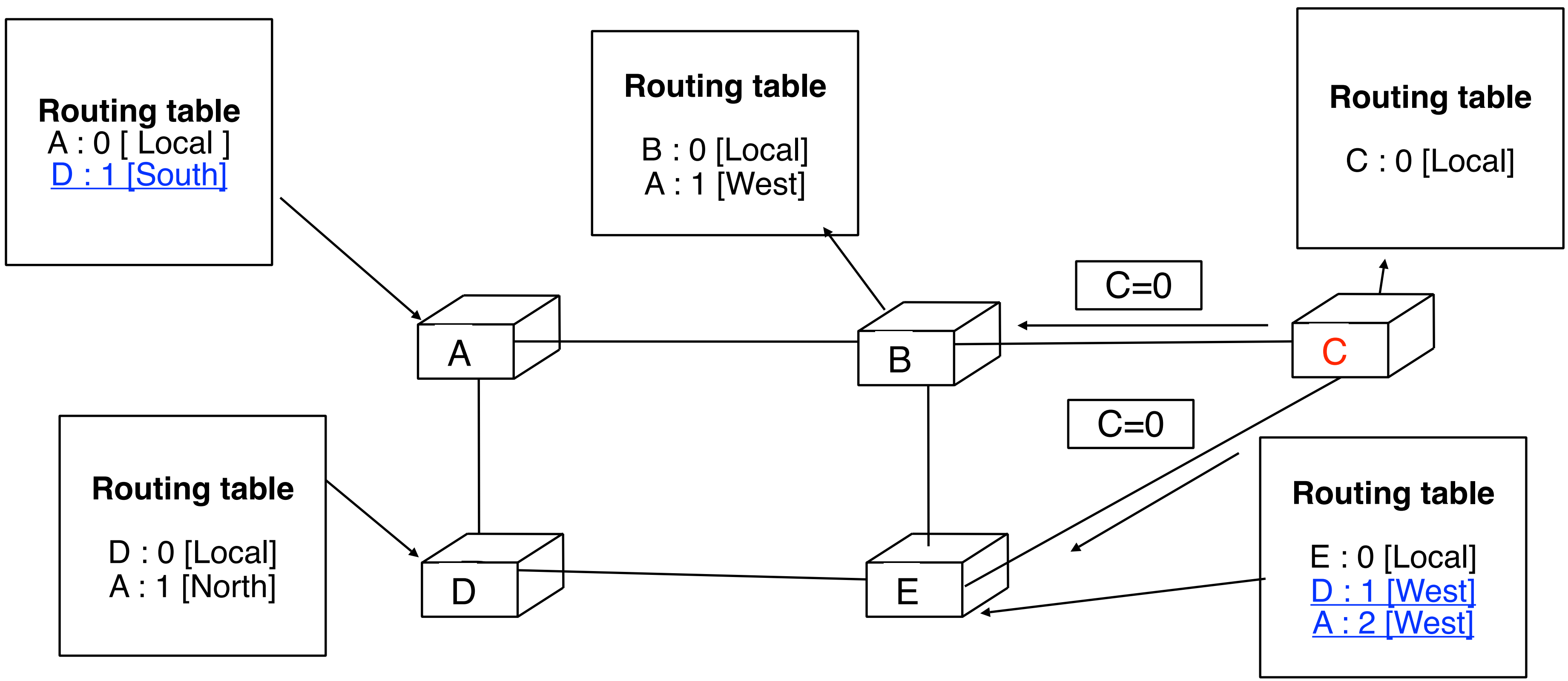
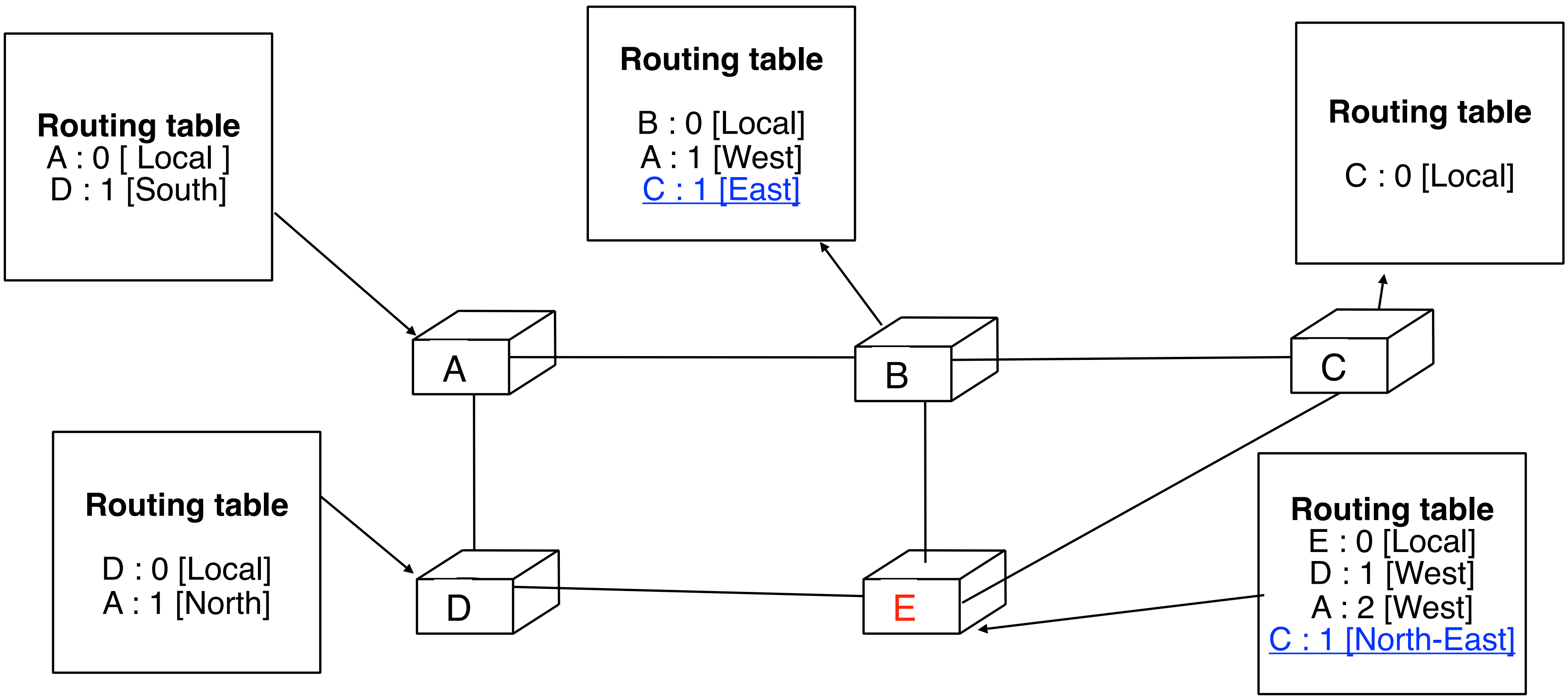


Distance vectors example (4)



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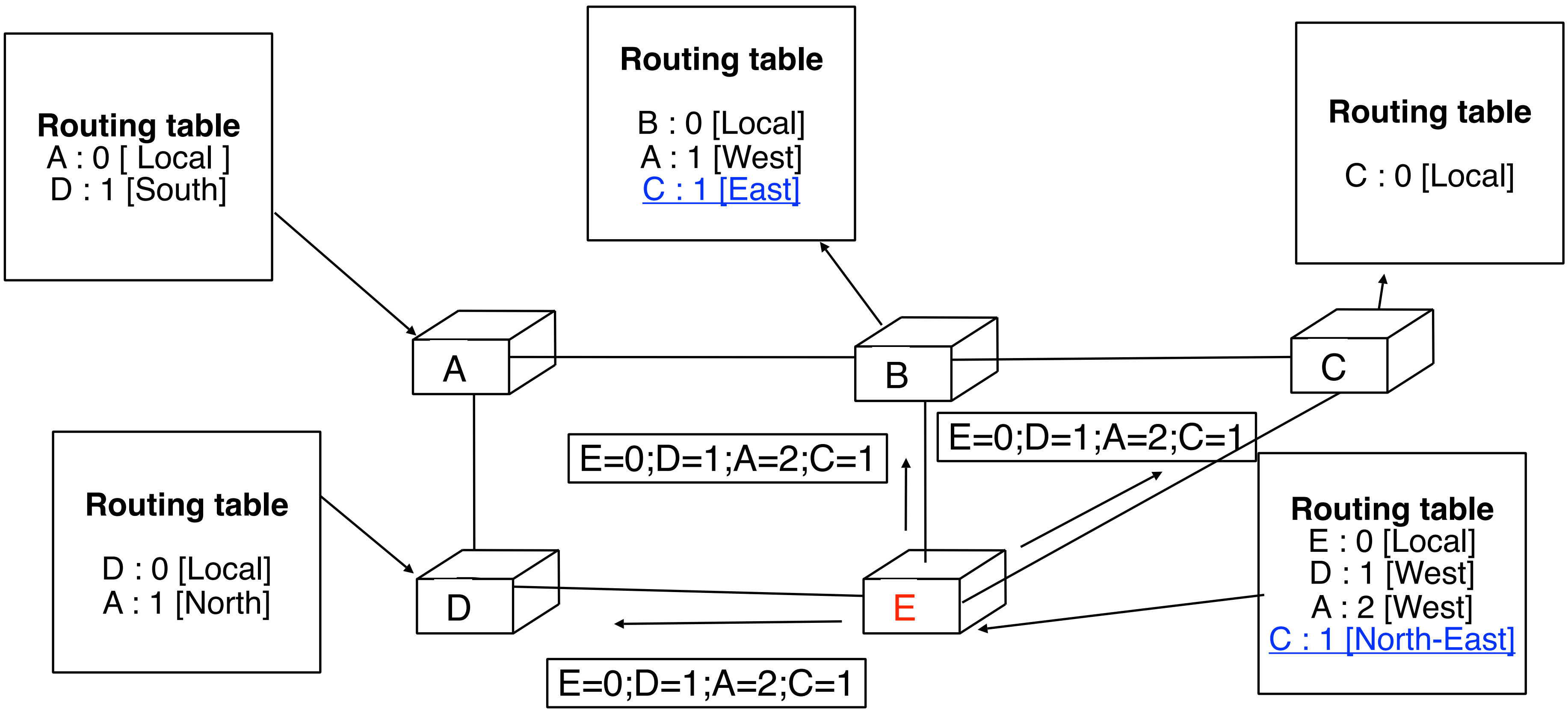

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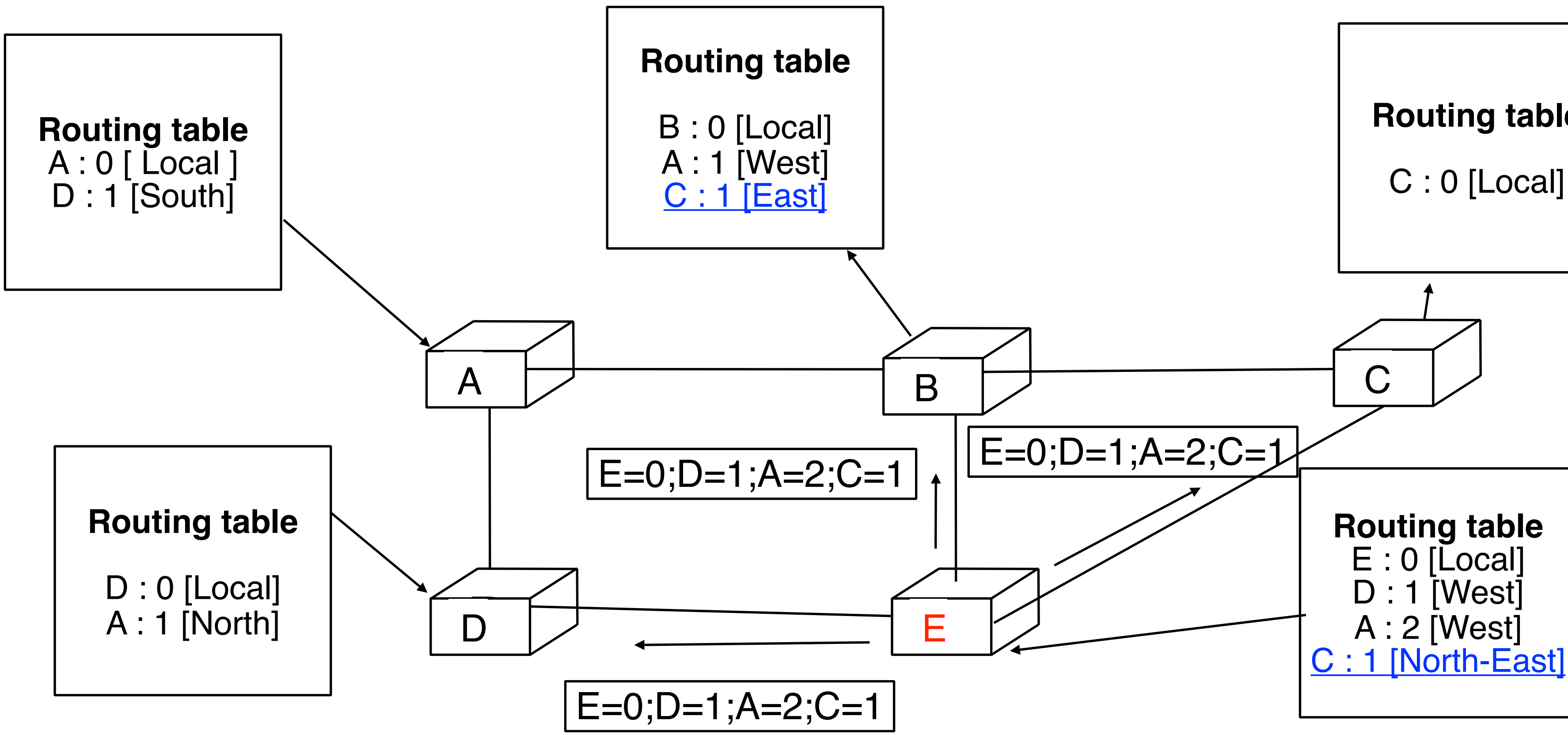
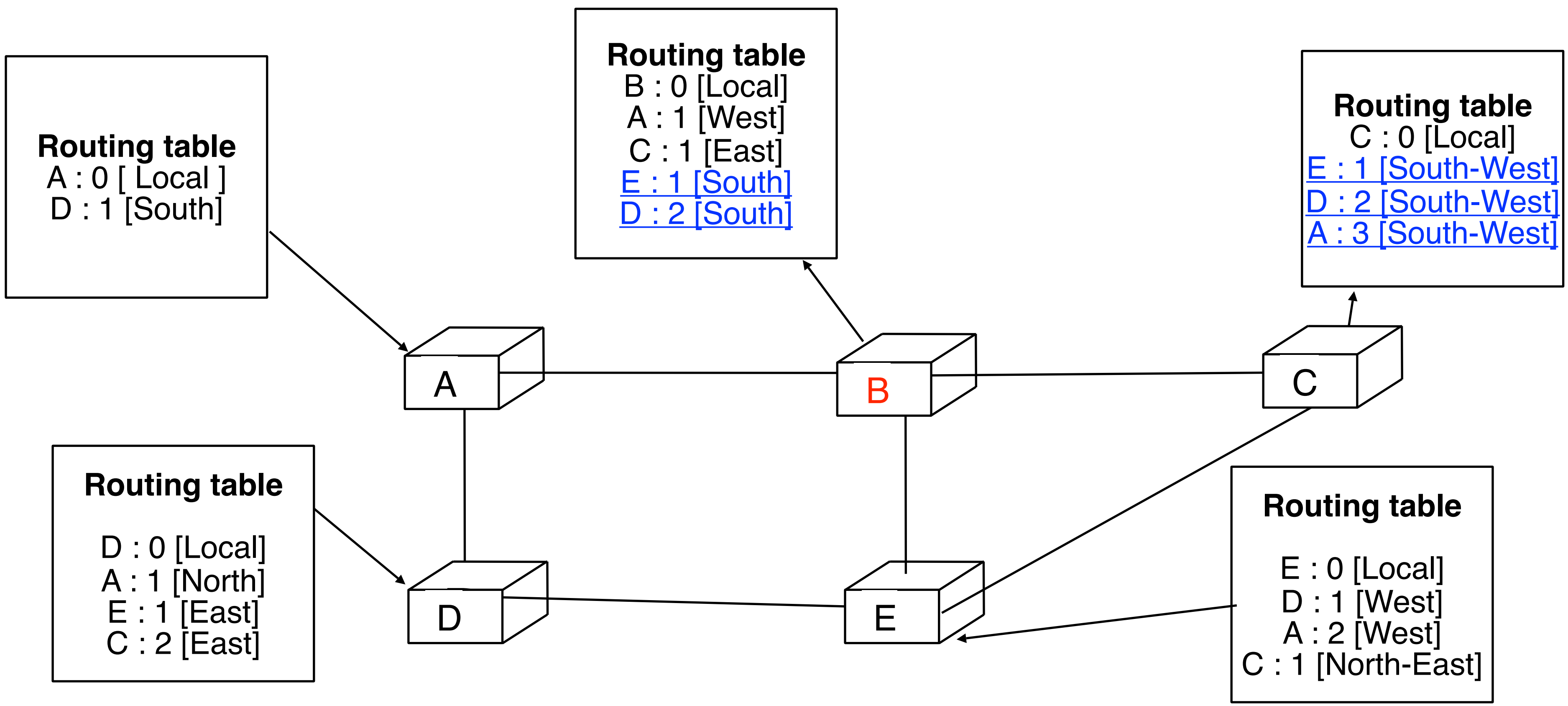


- Reception of distance vector on B
  - New route to reach E and D, longer route for A
- Reception of distance vector on C
  - New routes to reach D, A and E
- Reception of distance vector on D
  - New routes to reach E and C, longer route for A

Distance vectors example (5)

B is the first to send its vector



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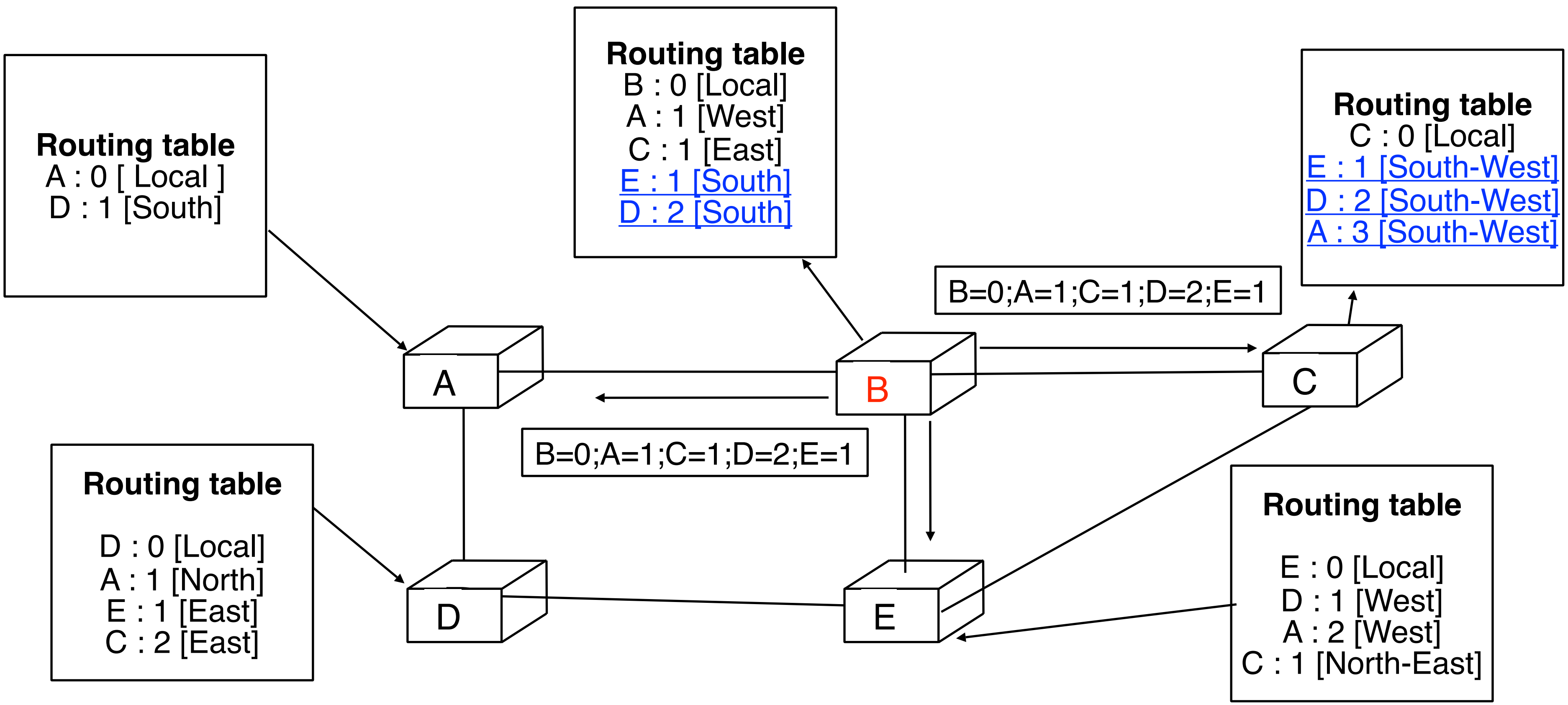

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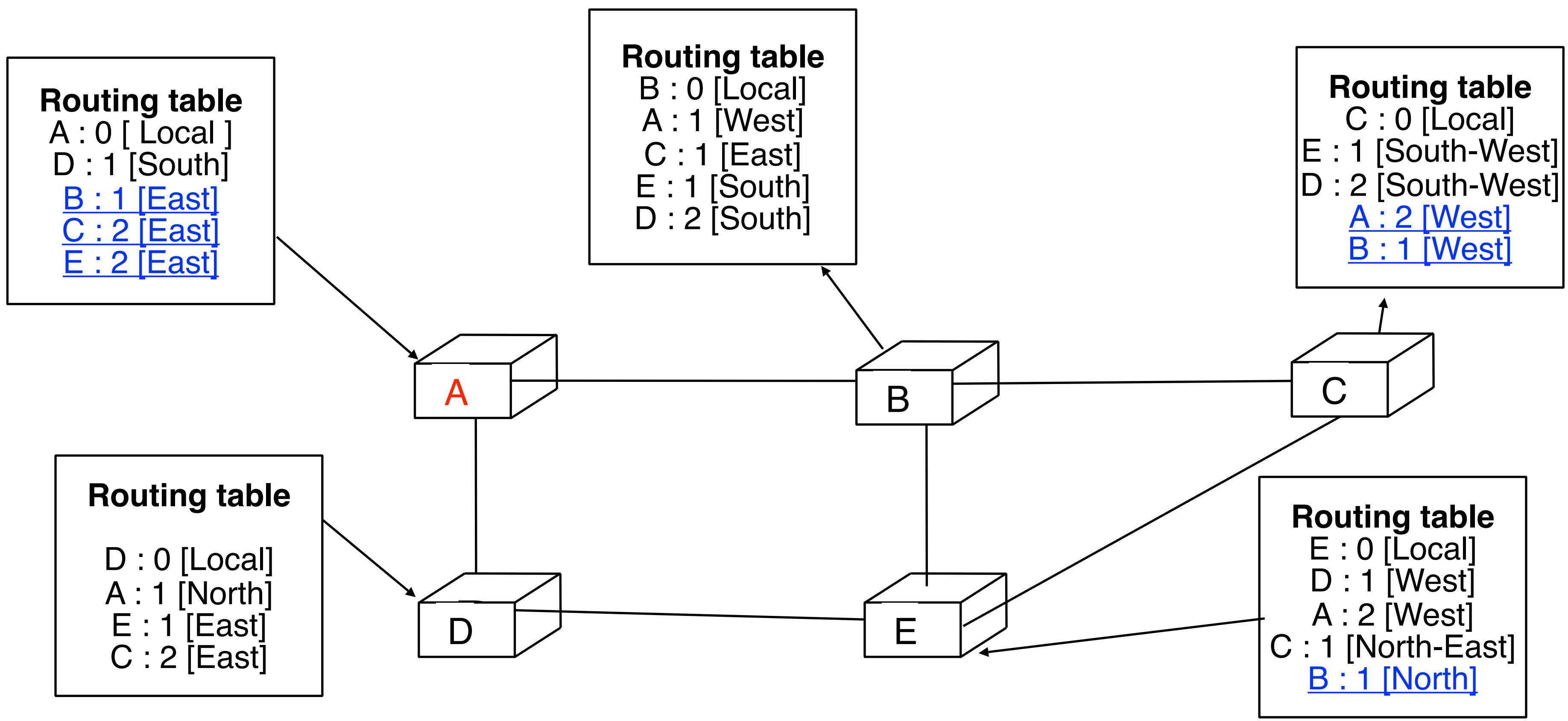
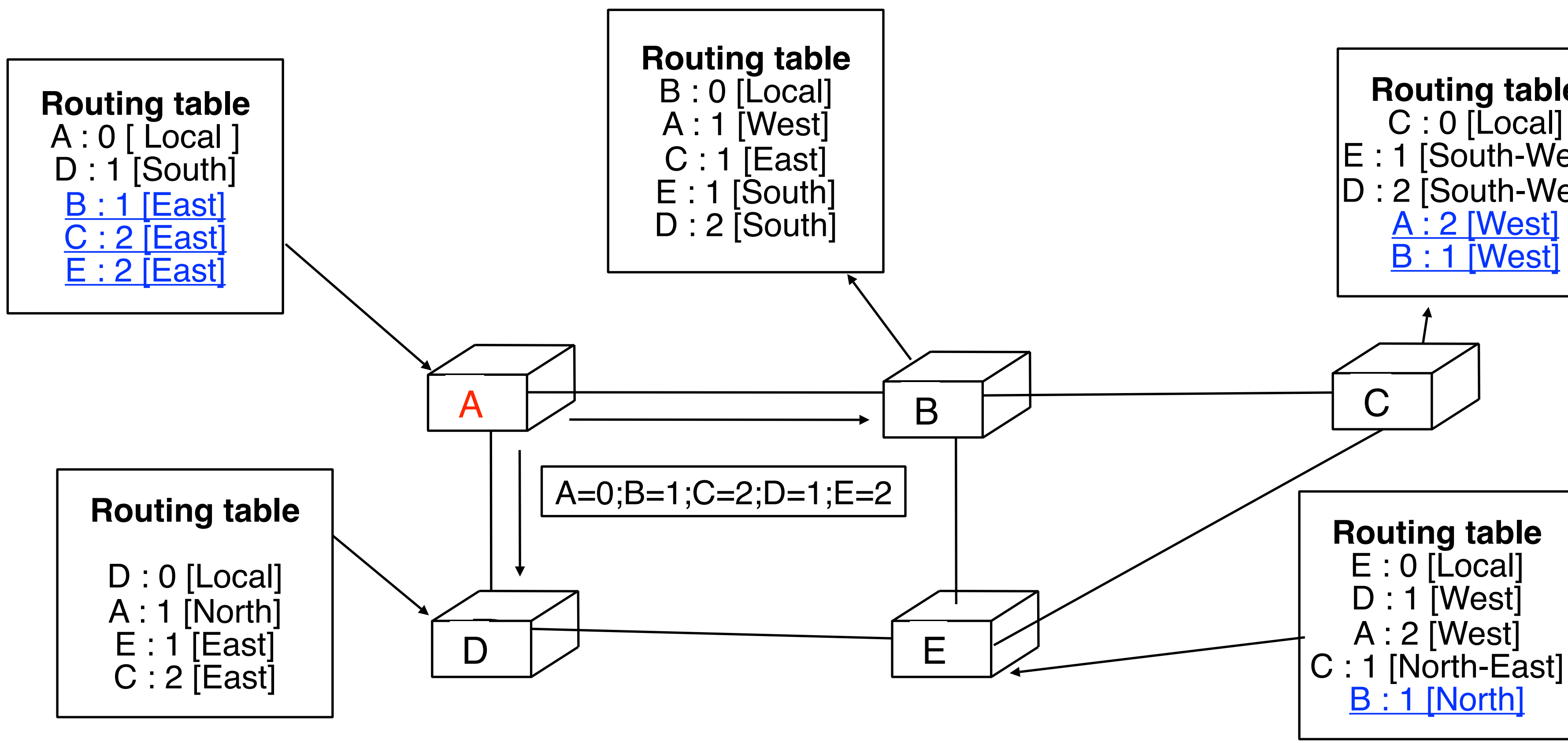
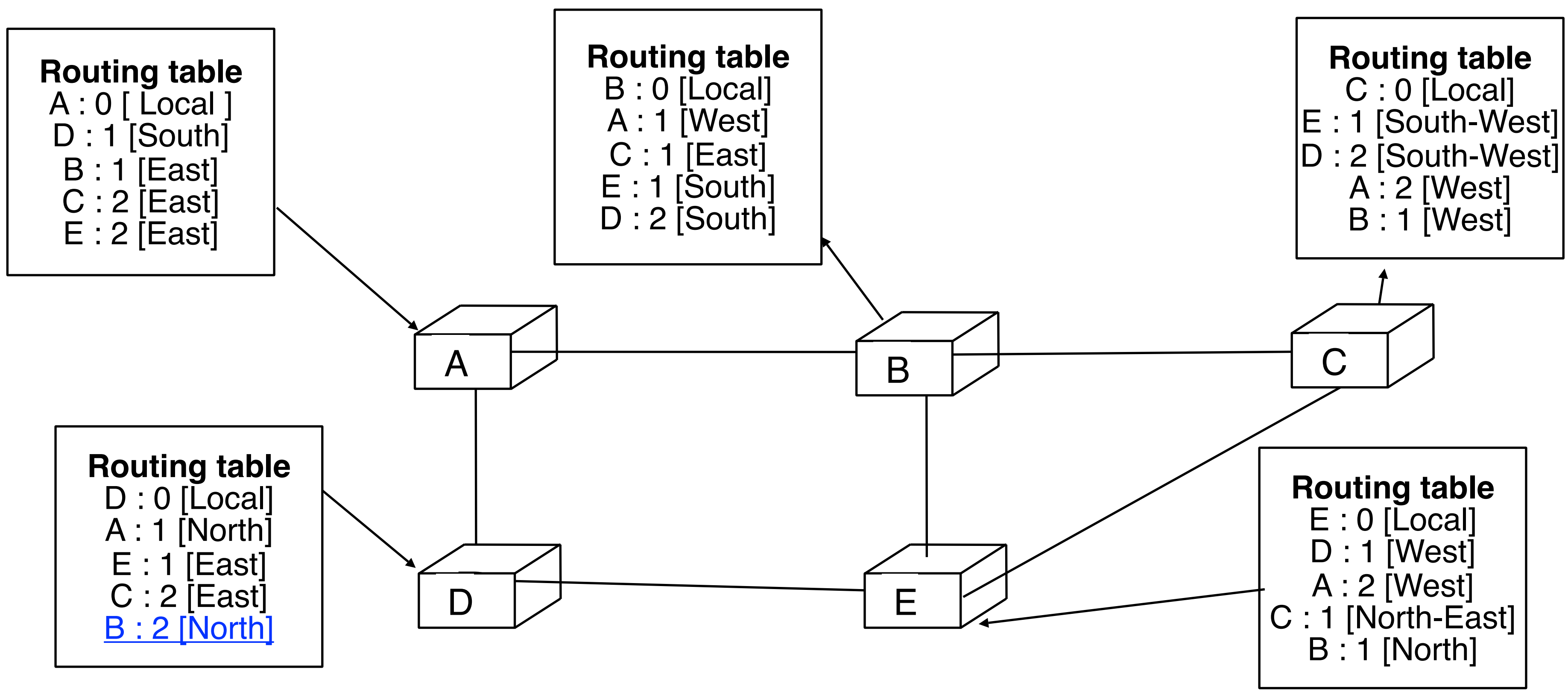


Distance vectors example (6)



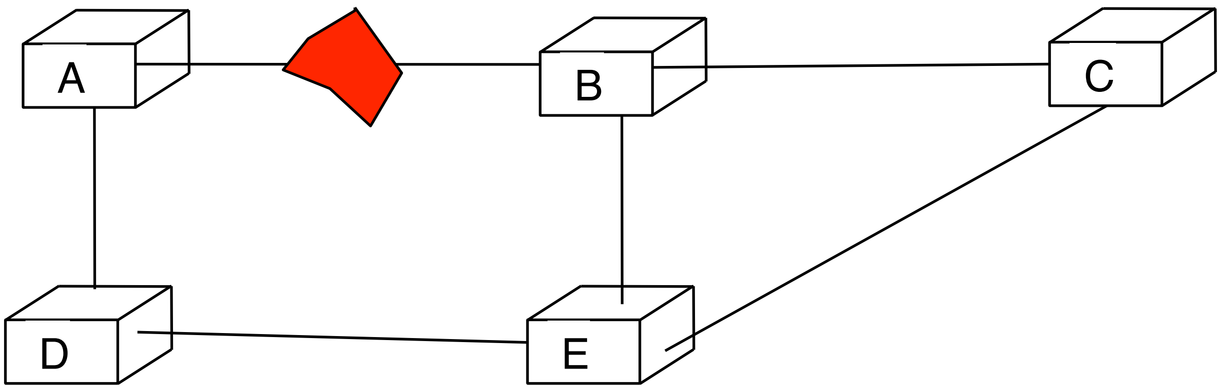
Distance vectors example (7)



- All routers know how to reach all other routers
- Routing tables are stable
  - If a distance vector is sent by one router, it will not cause any change to the routing table of other routers in the network

Distance vectors
Link failures

How to deal with link failures ?



Two problems must be solved for failures

How to detect that the link has failed ?

How to indicate to all routers that they should update their routing table since the paths that use link A-B do not work anymore ?

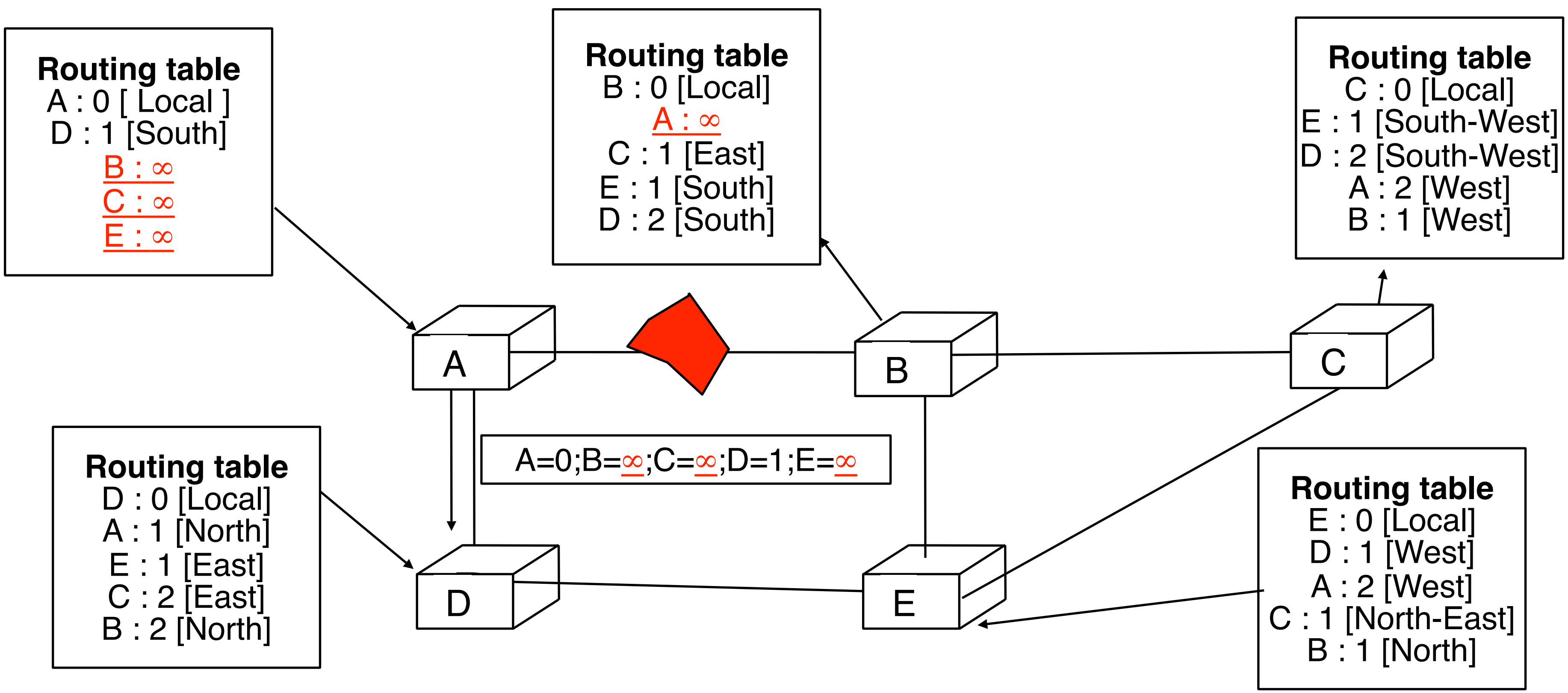
Detection of link failures

Two types of solutions

- rely on failure information from datalink or physical layer
  - fast and reliable
  - unfortunately not supported by all datalink/physical layers
- ask each router to regularly send its distance vector (e.g. every 30 seconds)
  - If a router does not receive a refresh for a route in a distance vector from one of its neighbours during some time (e.g. 90 seconds), it assumes that the route is not available anymore

How to update the routing table ?

All routes that use a failed link are marked with an infinite cost

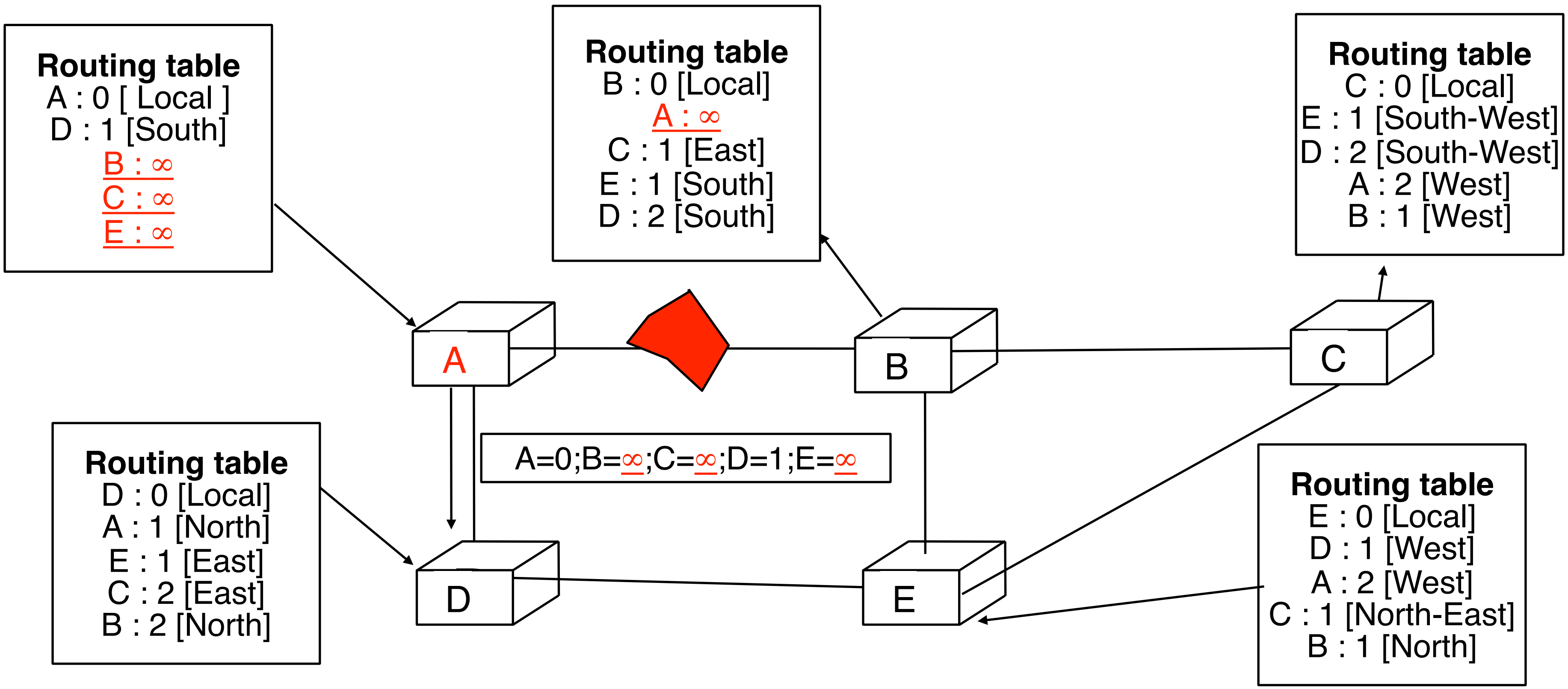


How to update the routing table ? (2)

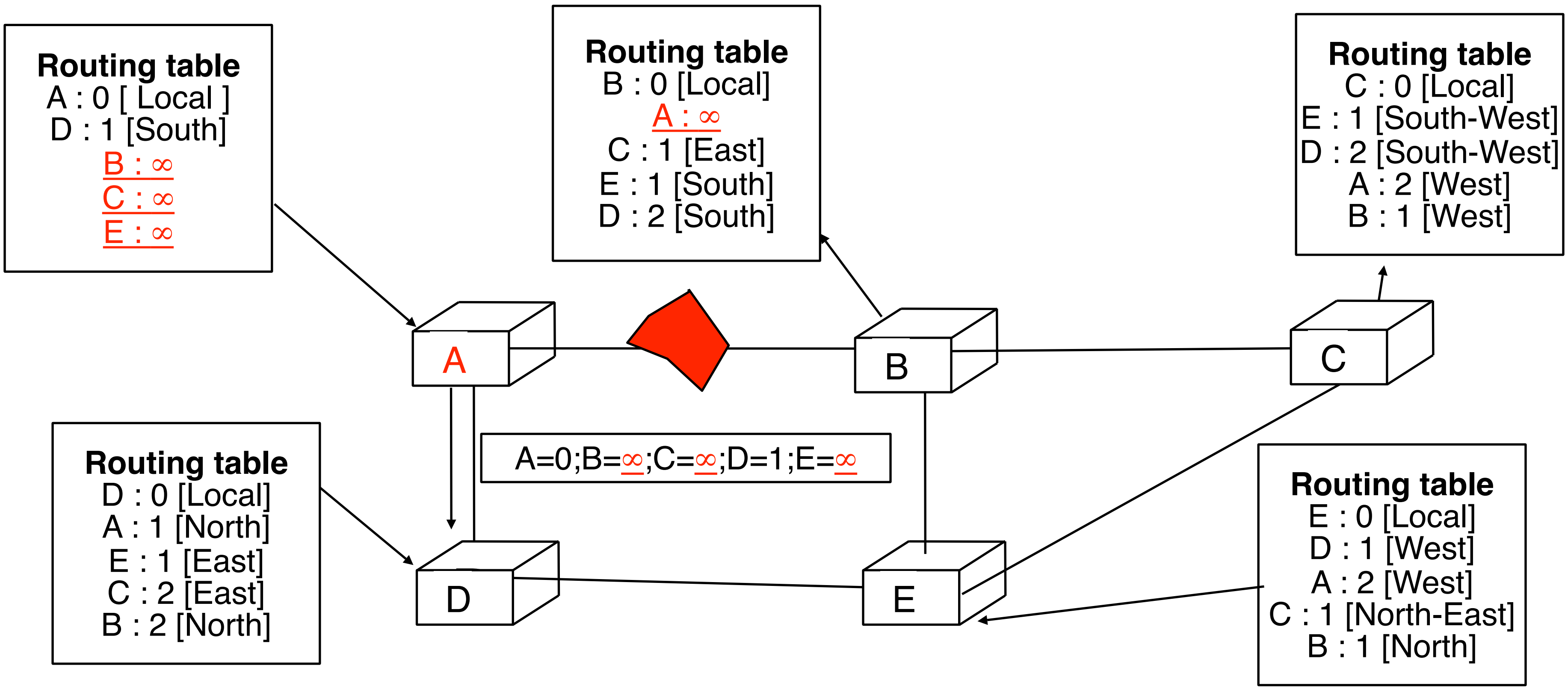
Reception of a distance vector

```
Received(Vector V[],link l)
{ /* received vector from link l */
for each destination=d in V[]
{
  if (d isin R[])
  { if ( ((V[d].cost+l.cost) < R[d].cost) OR
         ( R[d].link == l) )
      { /* better route or change to current route */
        R[d].cost=V[d].cost+l.cost;
        R[d].link=l;
      }
    }
    else
    { /* new route */
      R[d].cost=V[d].cost+l.cost;
      R[d].link=l;
    }
}
```

How to update the routing table ? (3)

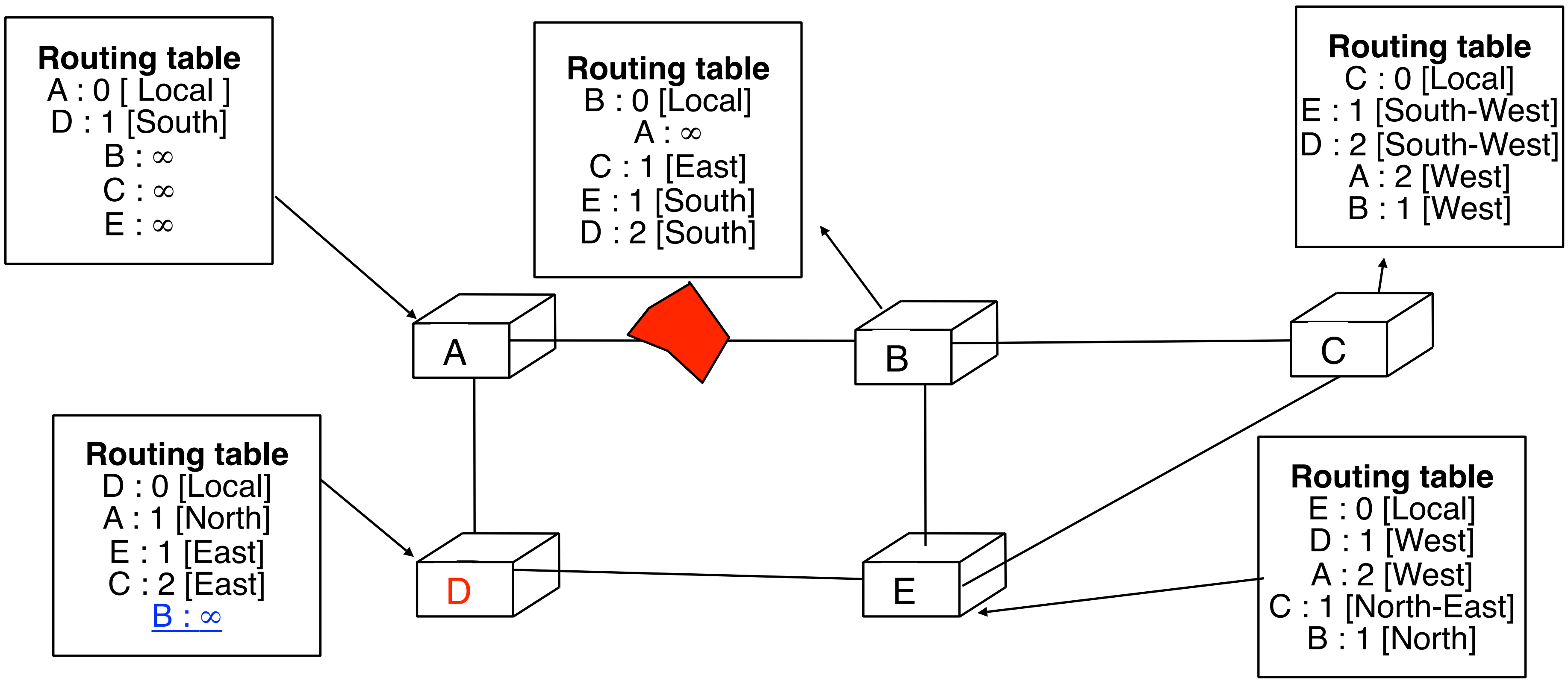


How to update the routing table ? (3)



D must remove from its routing tables all the routes that it learned from its North link and are announced now with an ∞ cost

How to update the routing table ? (4)



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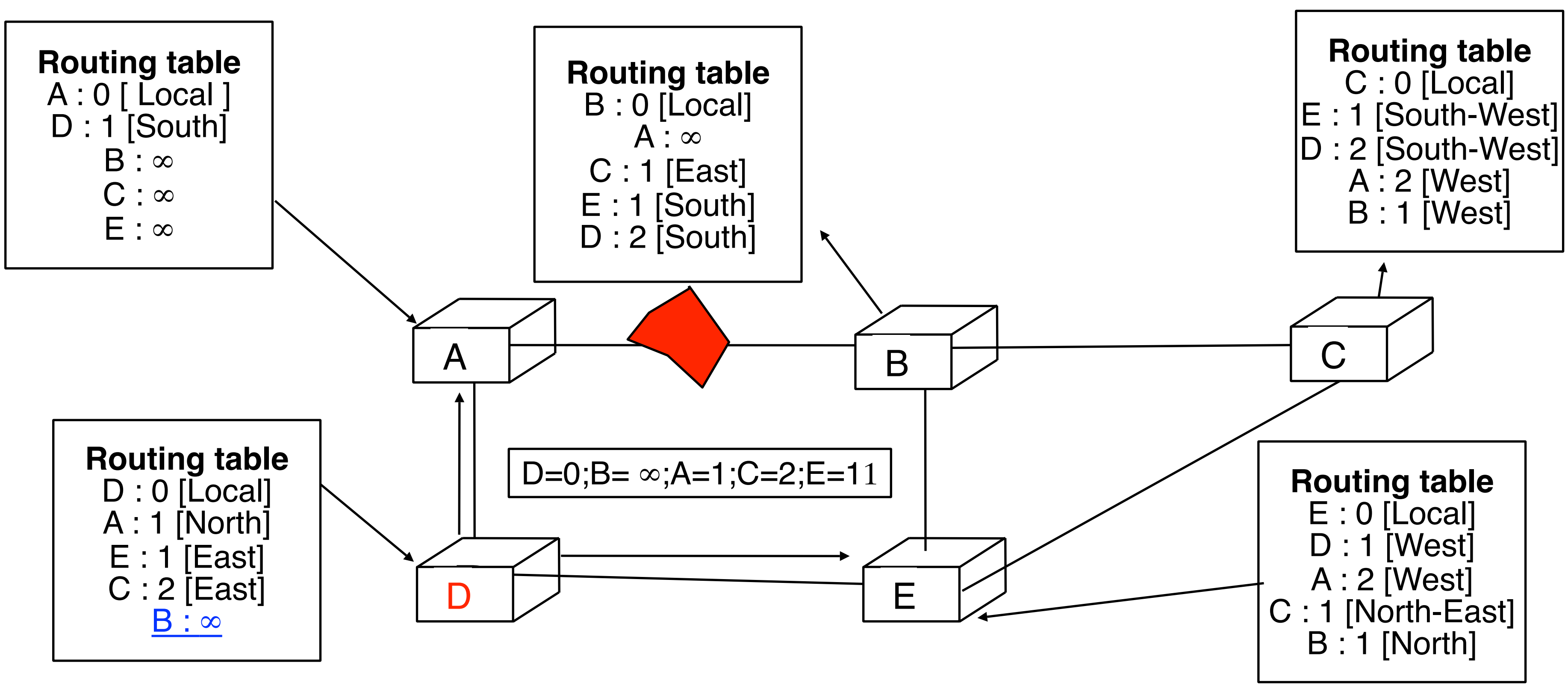
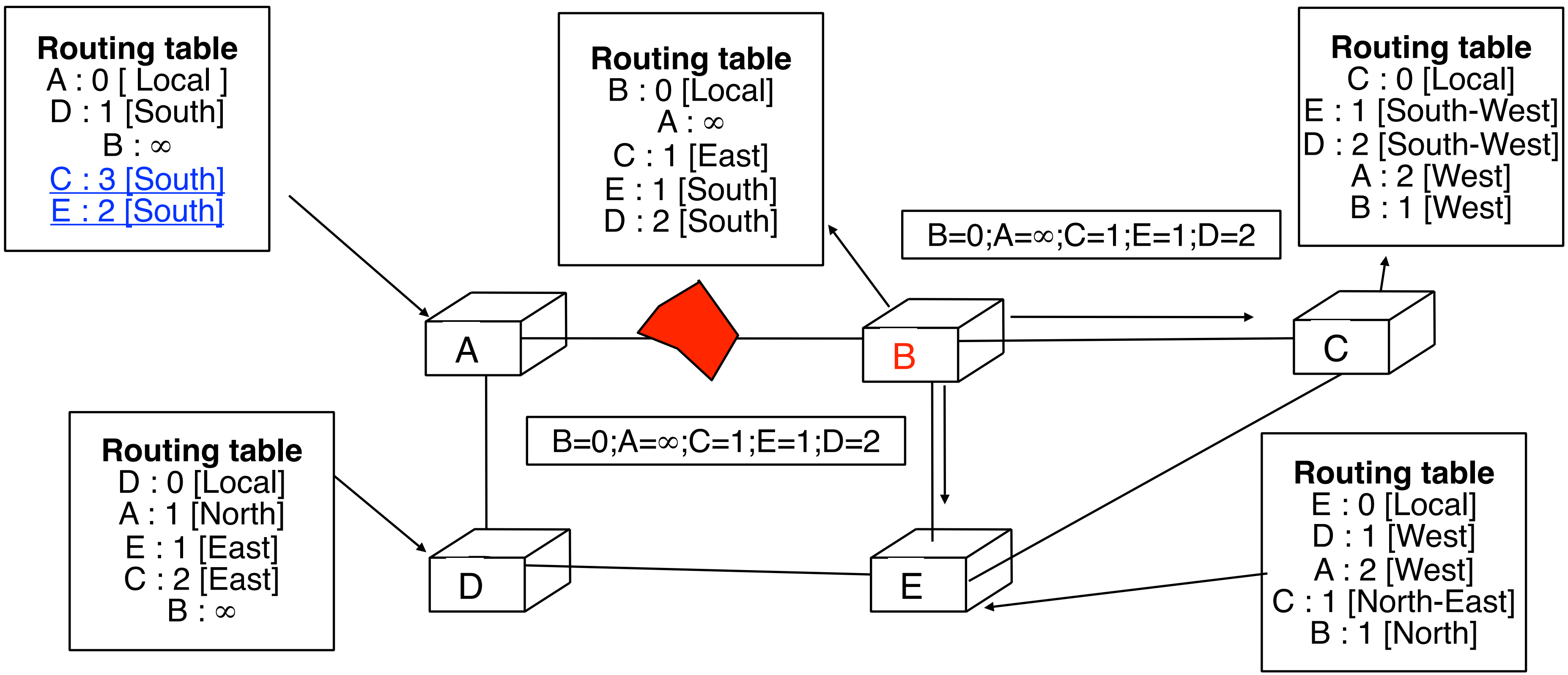
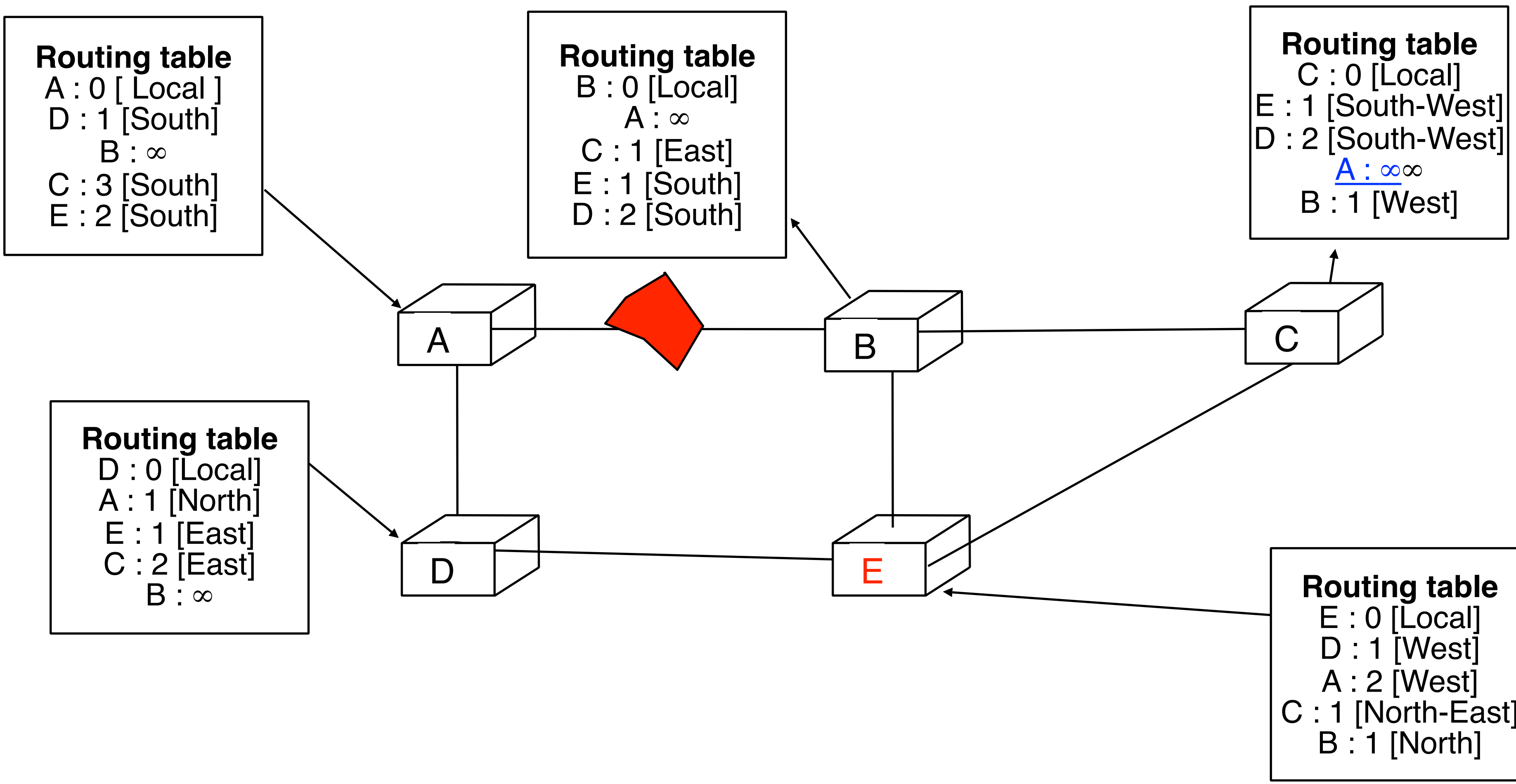


How to update the routing table ? (5)



How to update the routing table ? (6)



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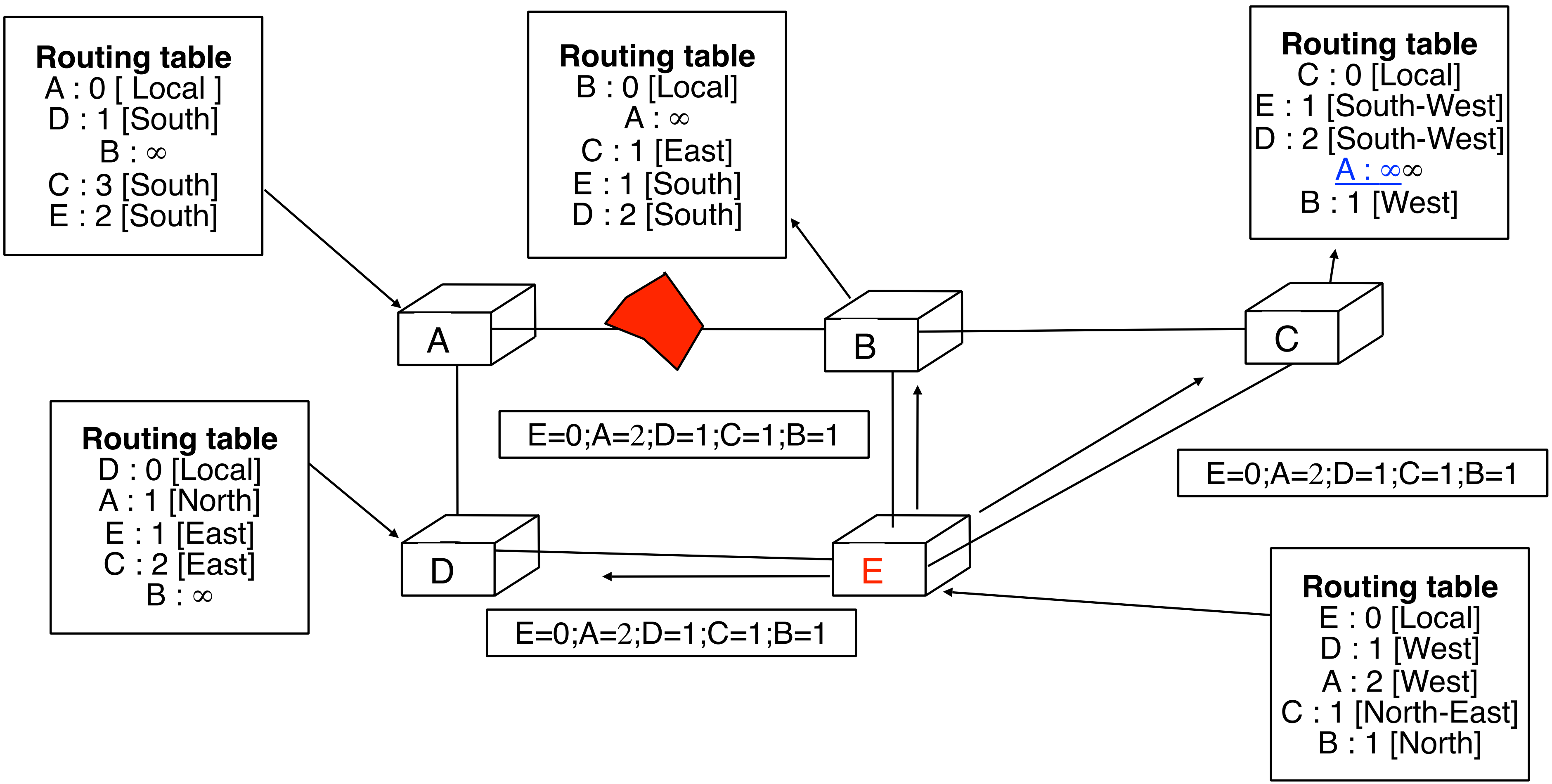
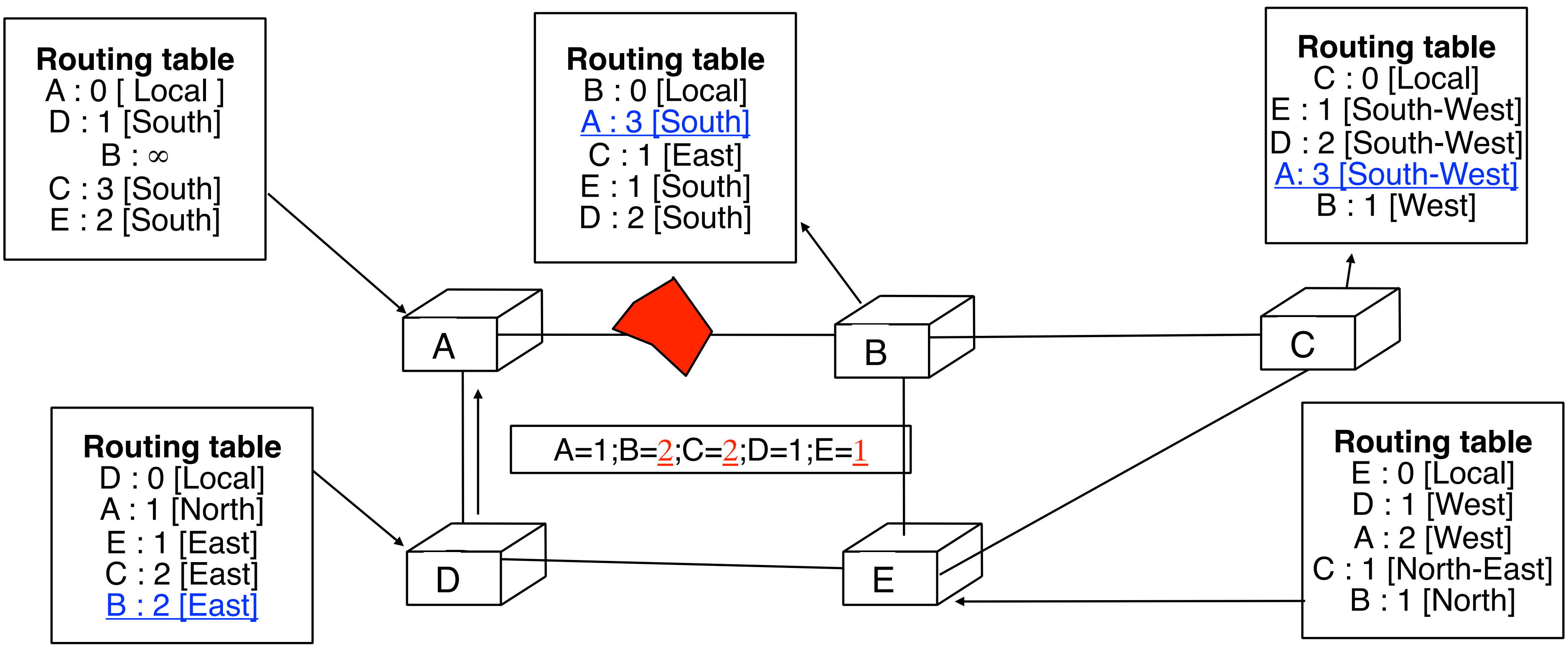


How to update the routing table ? (7)



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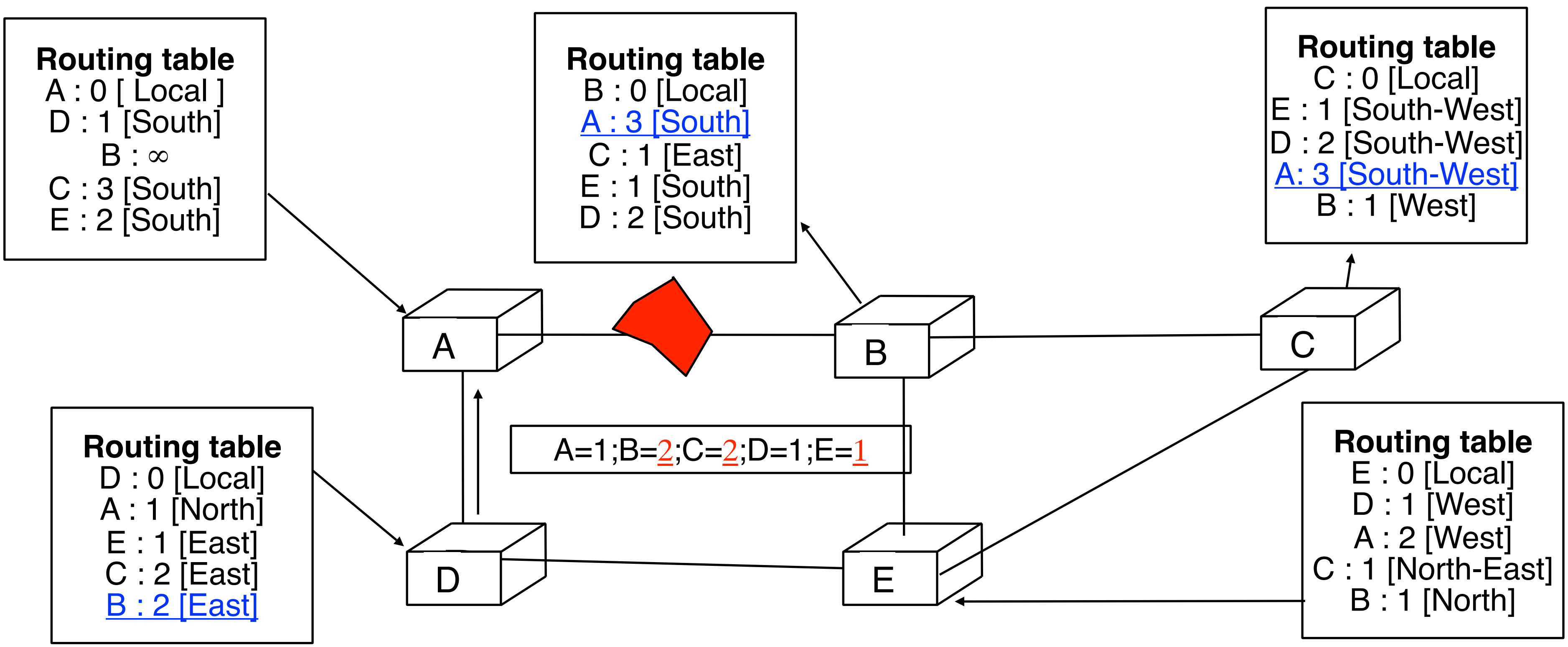
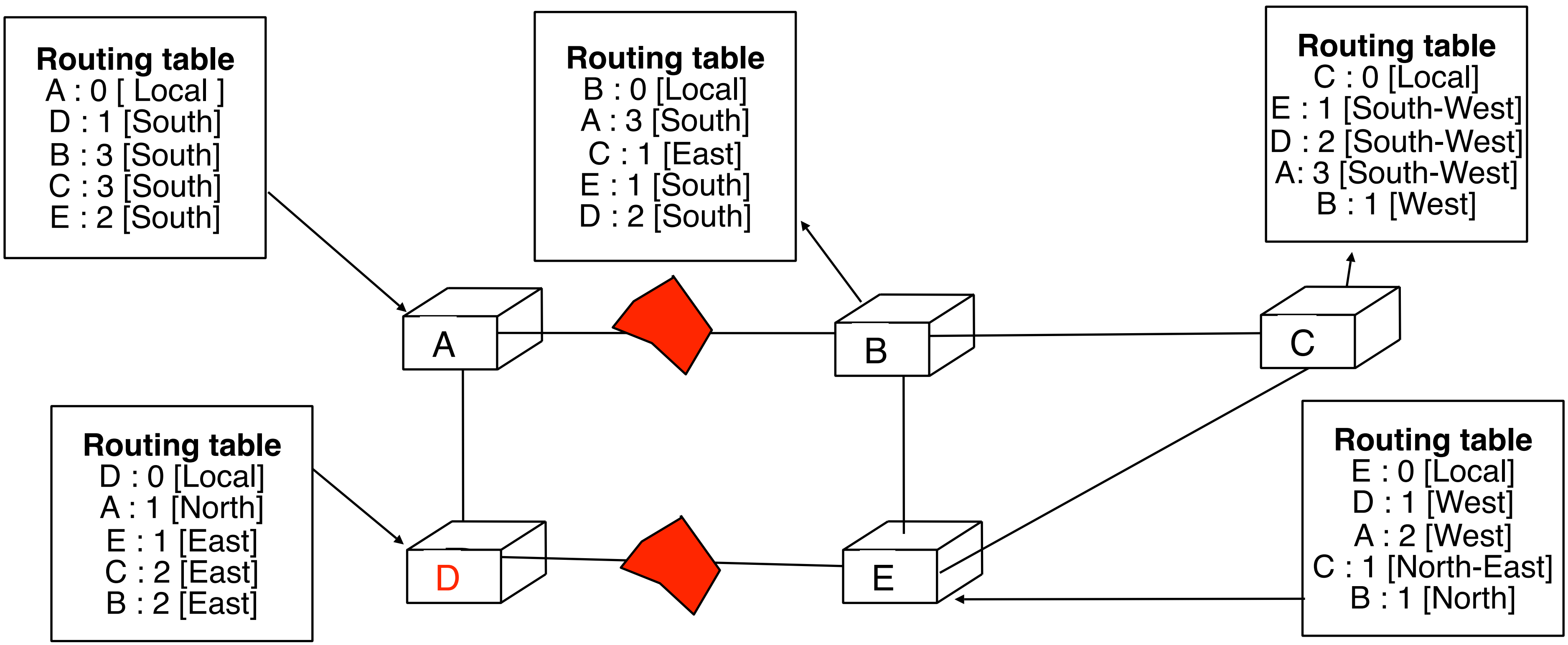


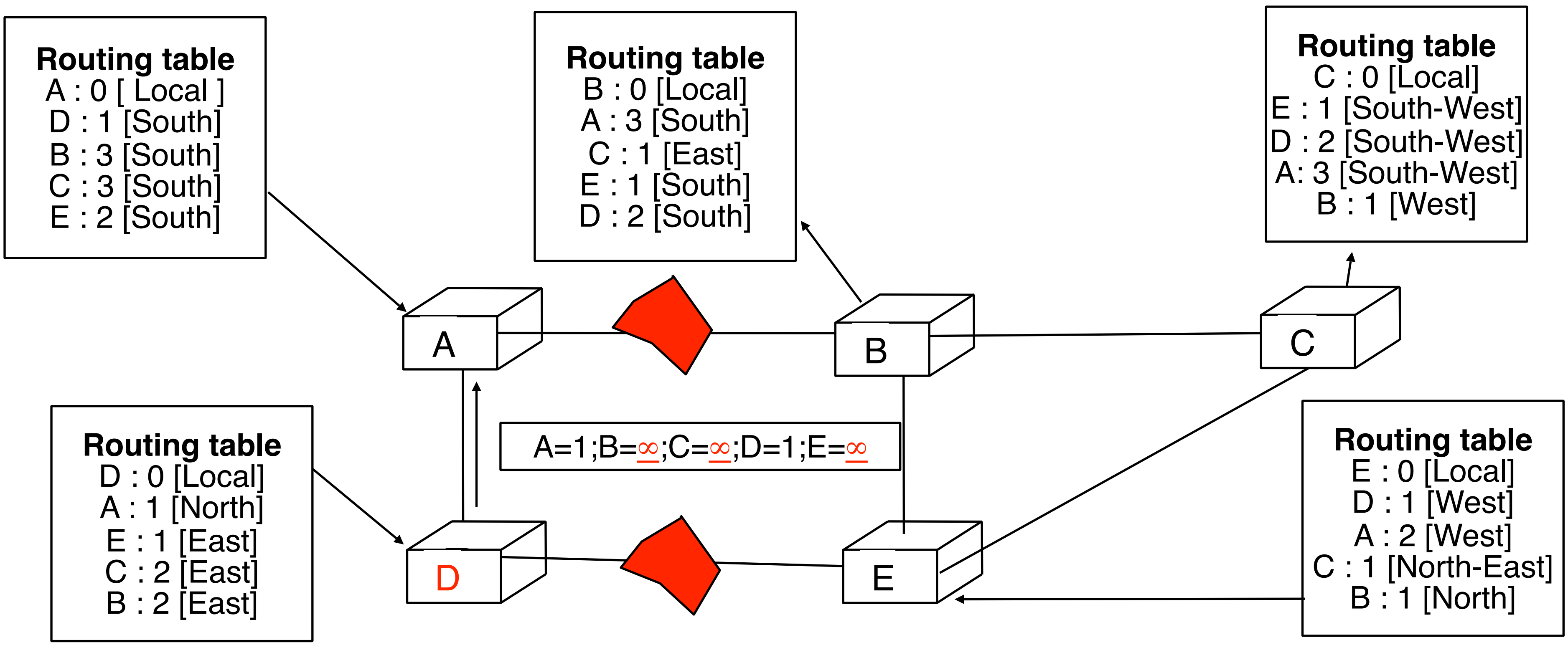
Failure has been recovered, all routers are now reachable again from any router

Second link failure



- D detects the failure
  - If it is the first to send its distance vector, failure is detected and router A updates its routing table

Second link failure



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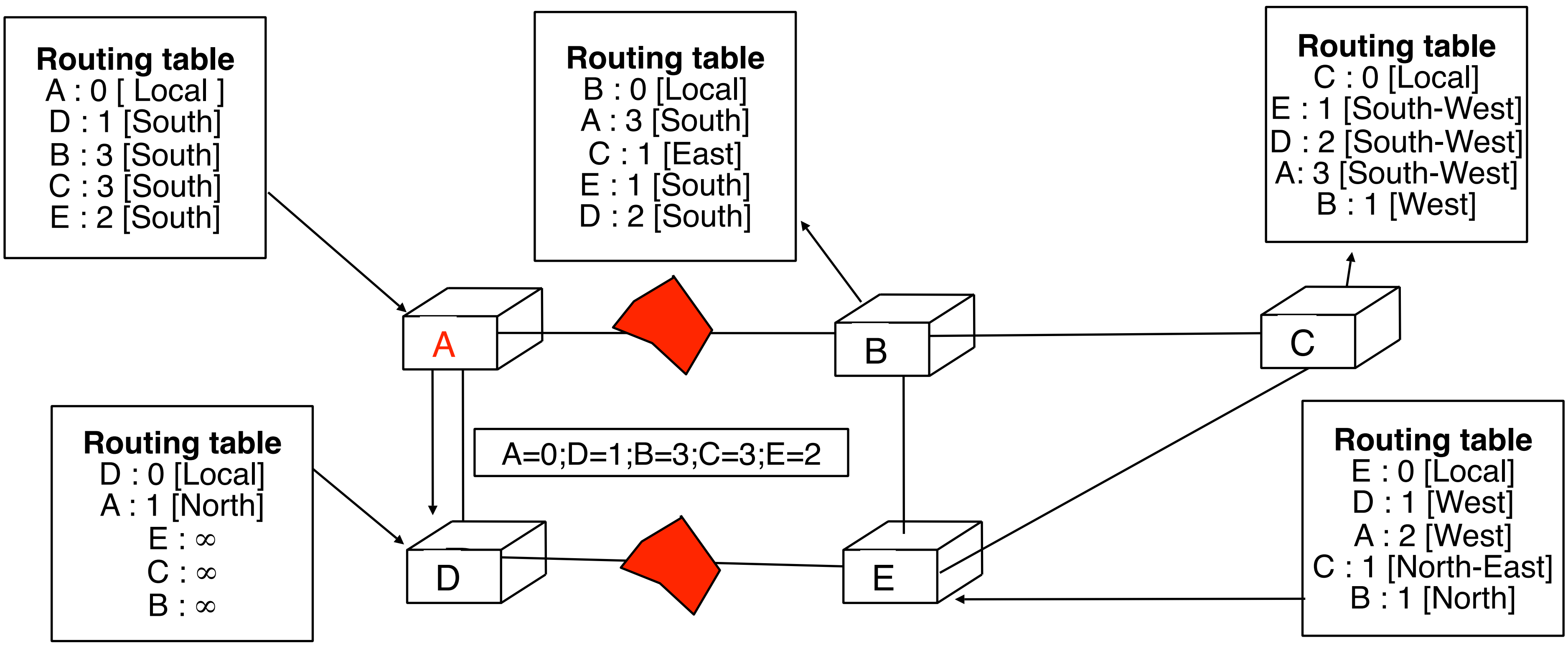
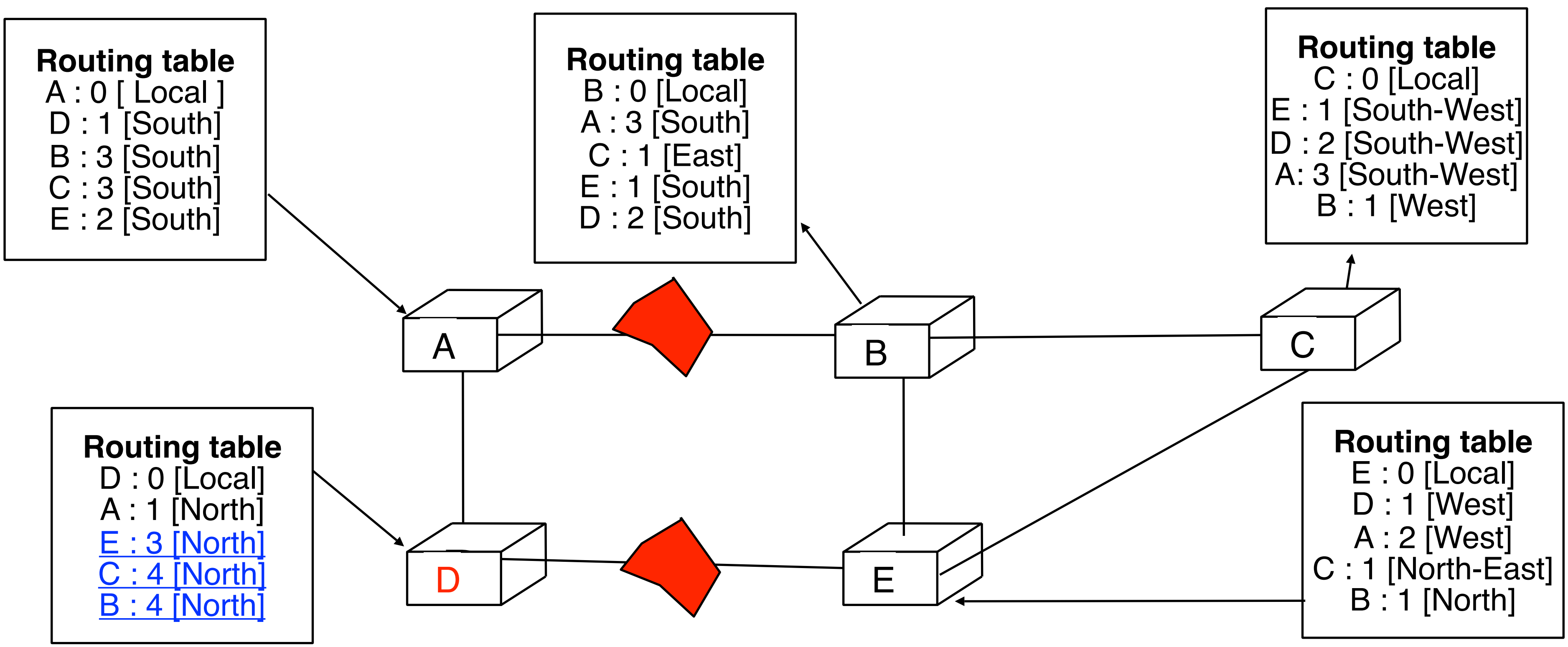
Second link failure (2)



But if A sends its distance vector before having received or processed D's updated distance vector ...

Second link failure (3)

Upon reception of A's vector, D updates its routing table



Second link failure (3)

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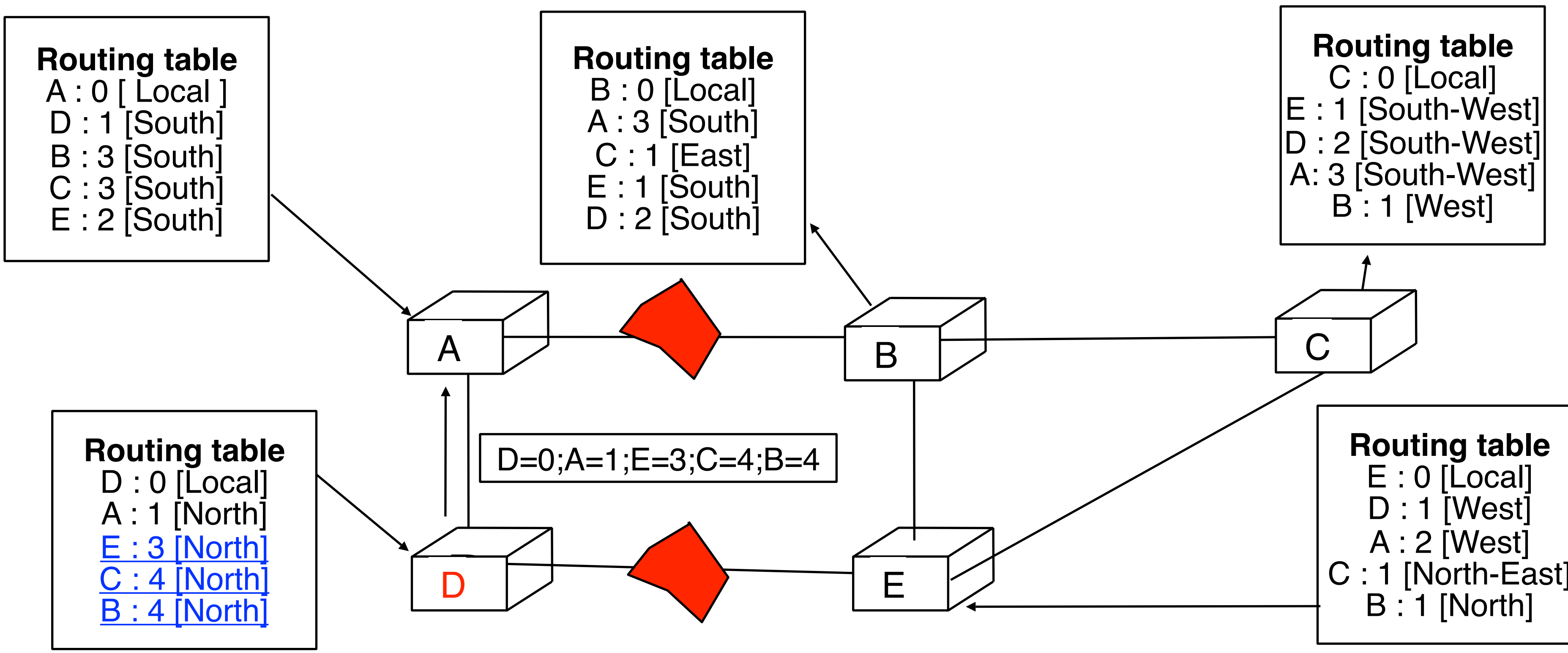
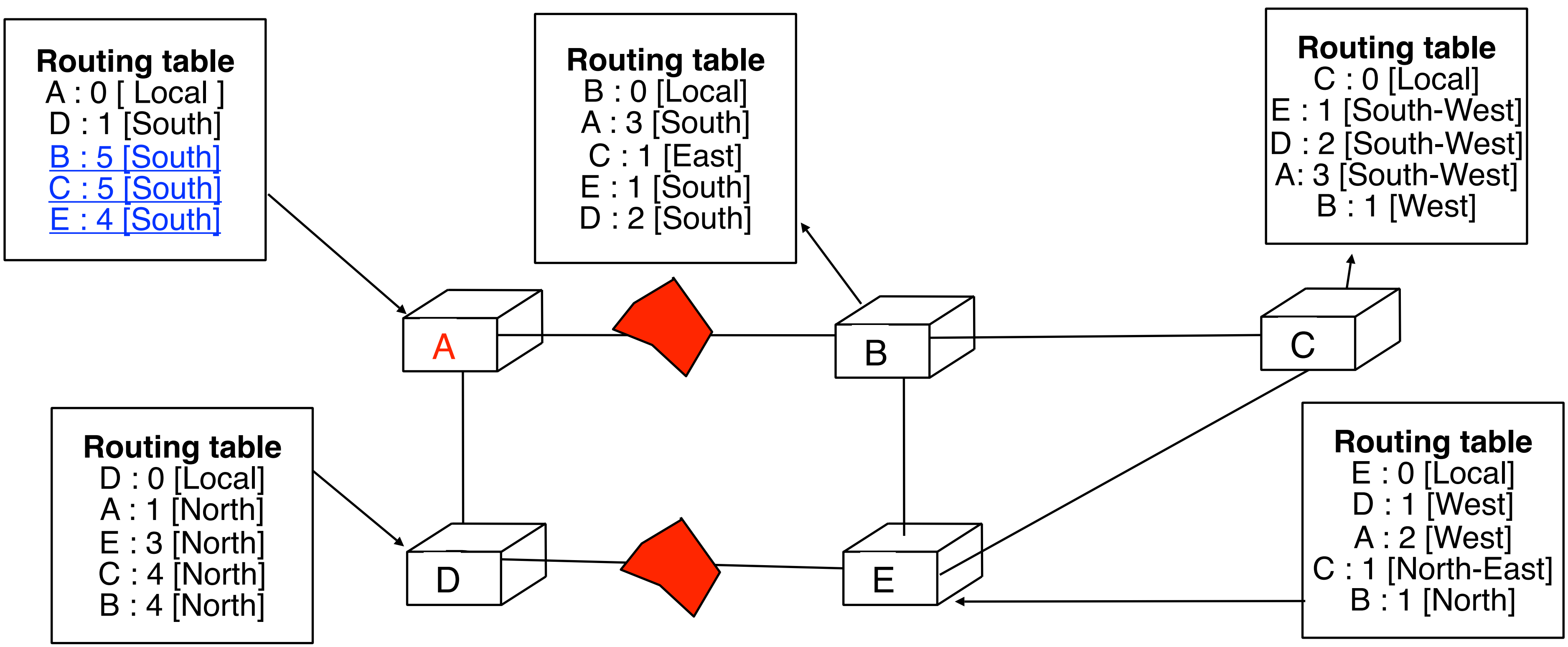


Second link failure (4)



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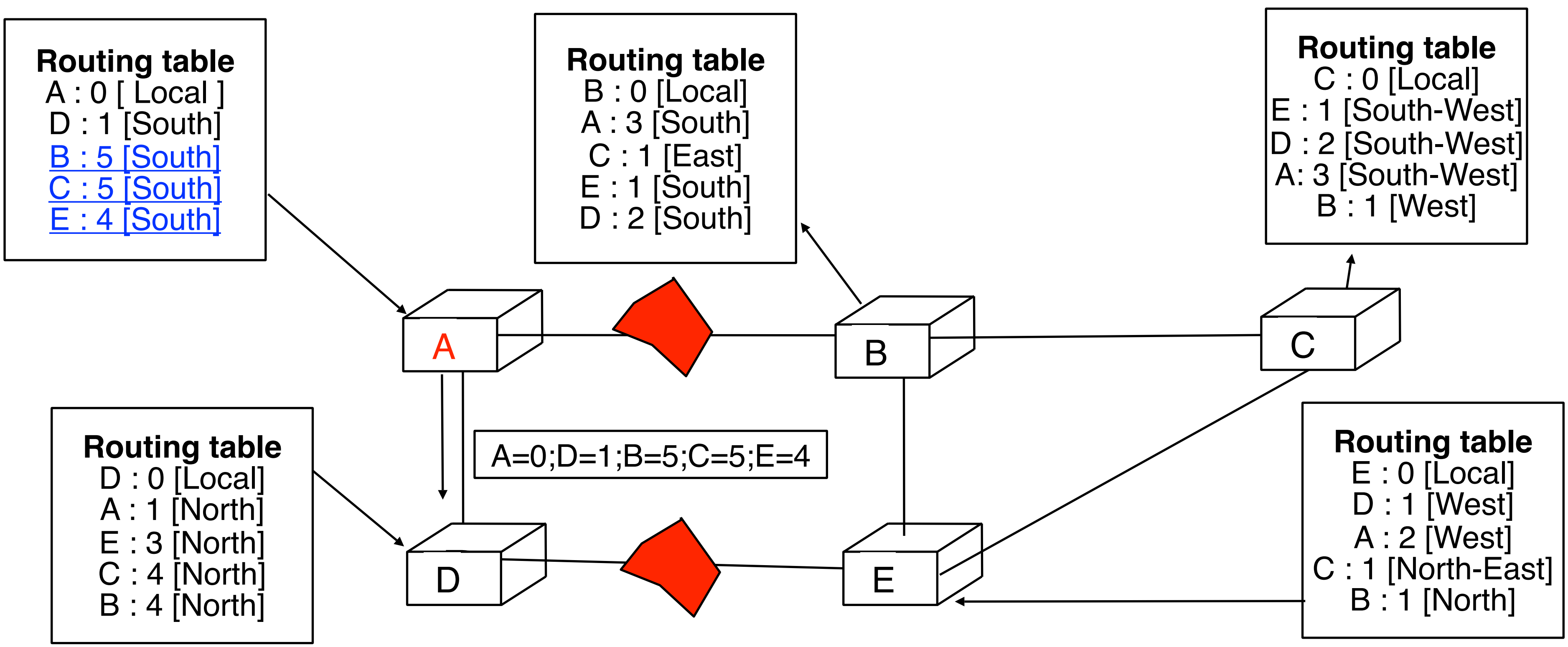

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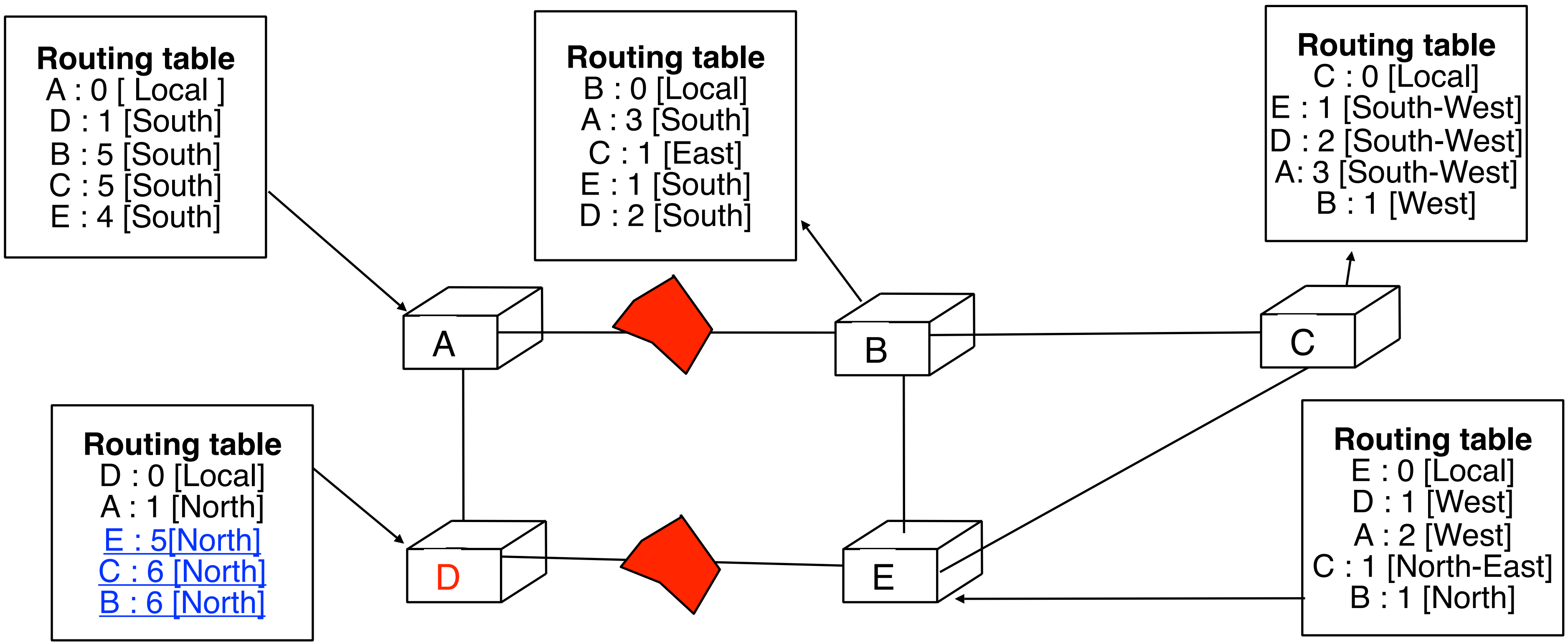
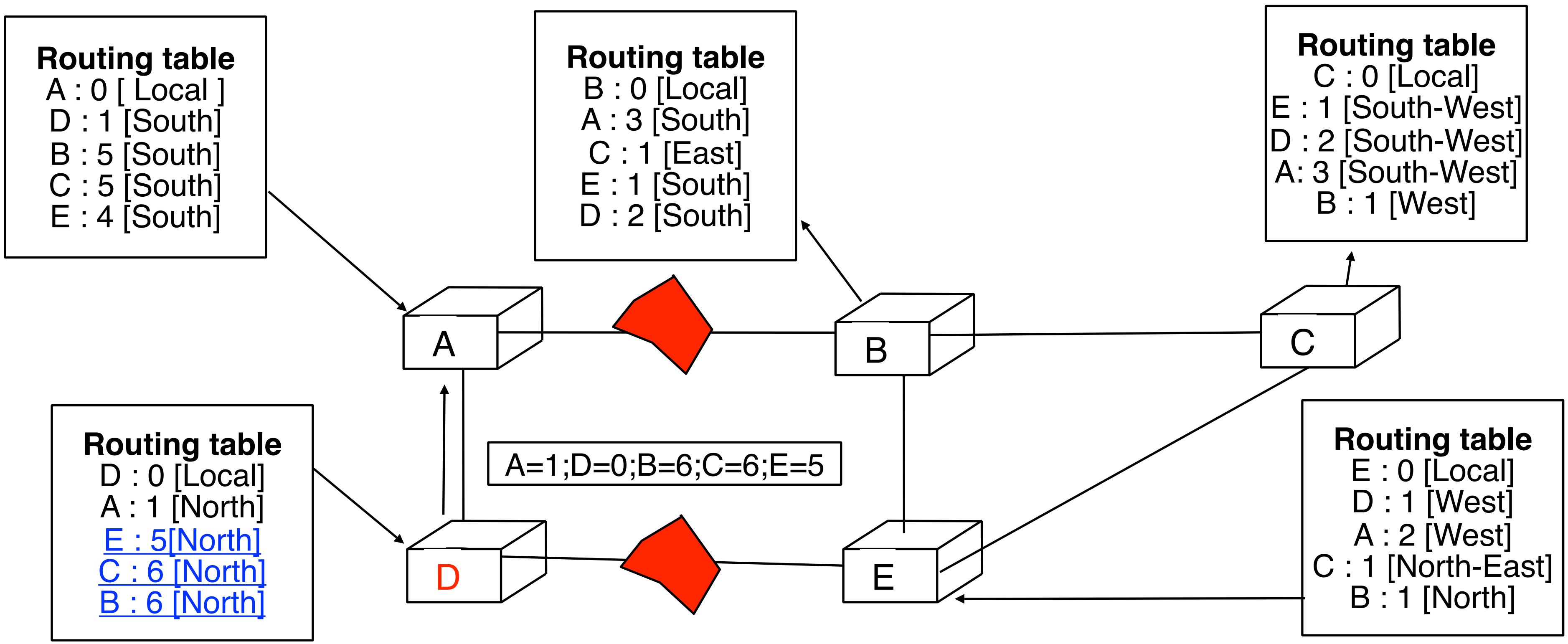


This problem is called counting to infinity

How can we avoid it ?

Second link failure (5)



This problem is called counting to infinity

How can we avoid it ?

Second link failure (6)

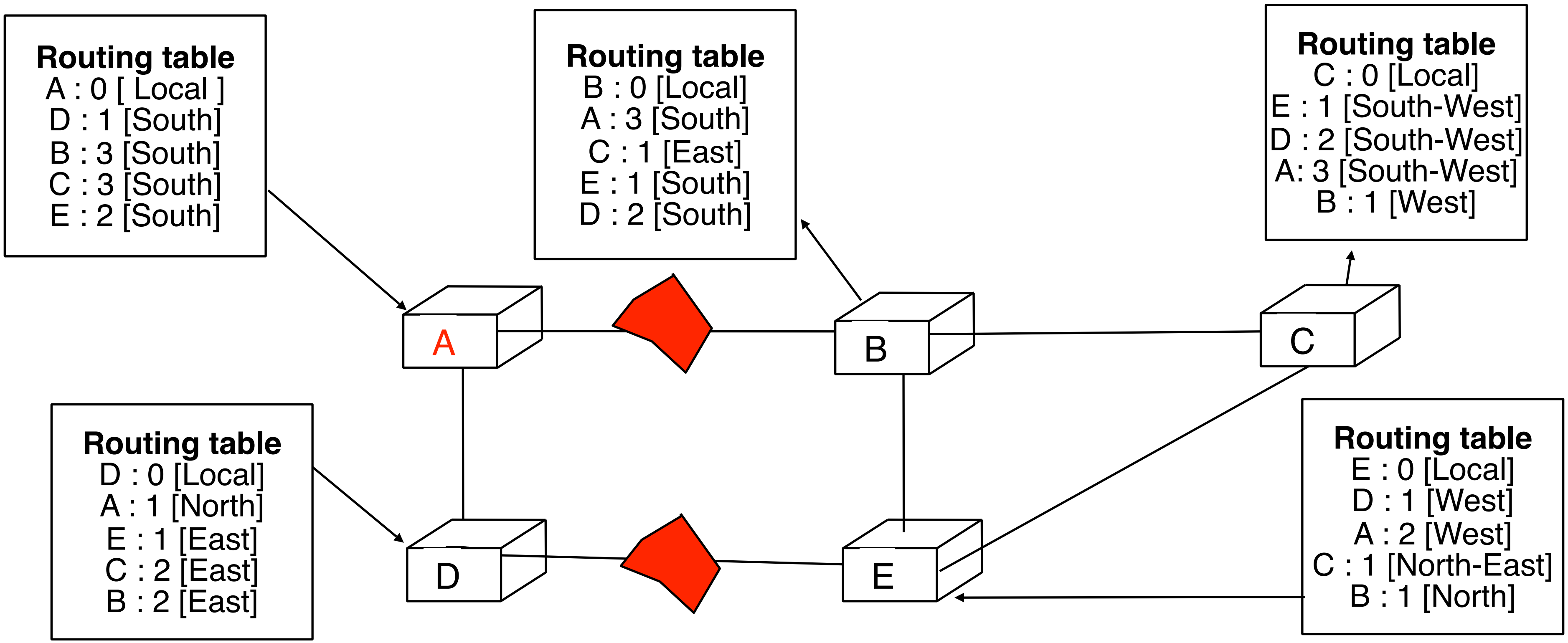
- Where does counting to infinity comes form ?
  - A router announces on a link routes that it has already learned via this link

- How to avoid counting to infinity ?
  - split horizon
    - each router creates a distance vector <u>for each link</u>
      - on link i, router does not announce the routers learned over link i

```
Pseudocode
Every N seconds:
 for each link=l
 { /* one different vector for each link */
  Vector=null;
  for each destination=d in R[]
  {
   if (R[d].link<>l)
    { Vector=Vector+Pair(d,R[d].cost); }
  }
  Send(Vector);
 }
```

Split horizon

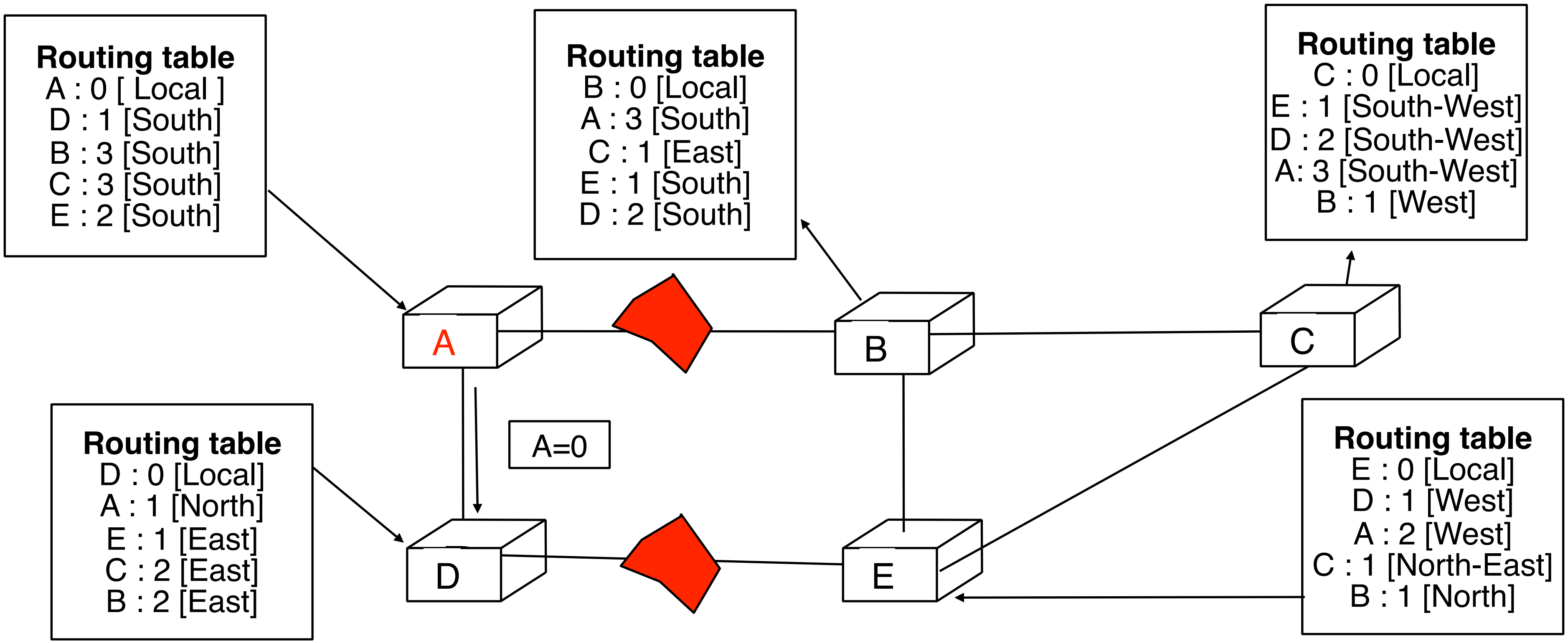
Back to previous example



A will not pollute D's routing table with split horizon

Split horizon

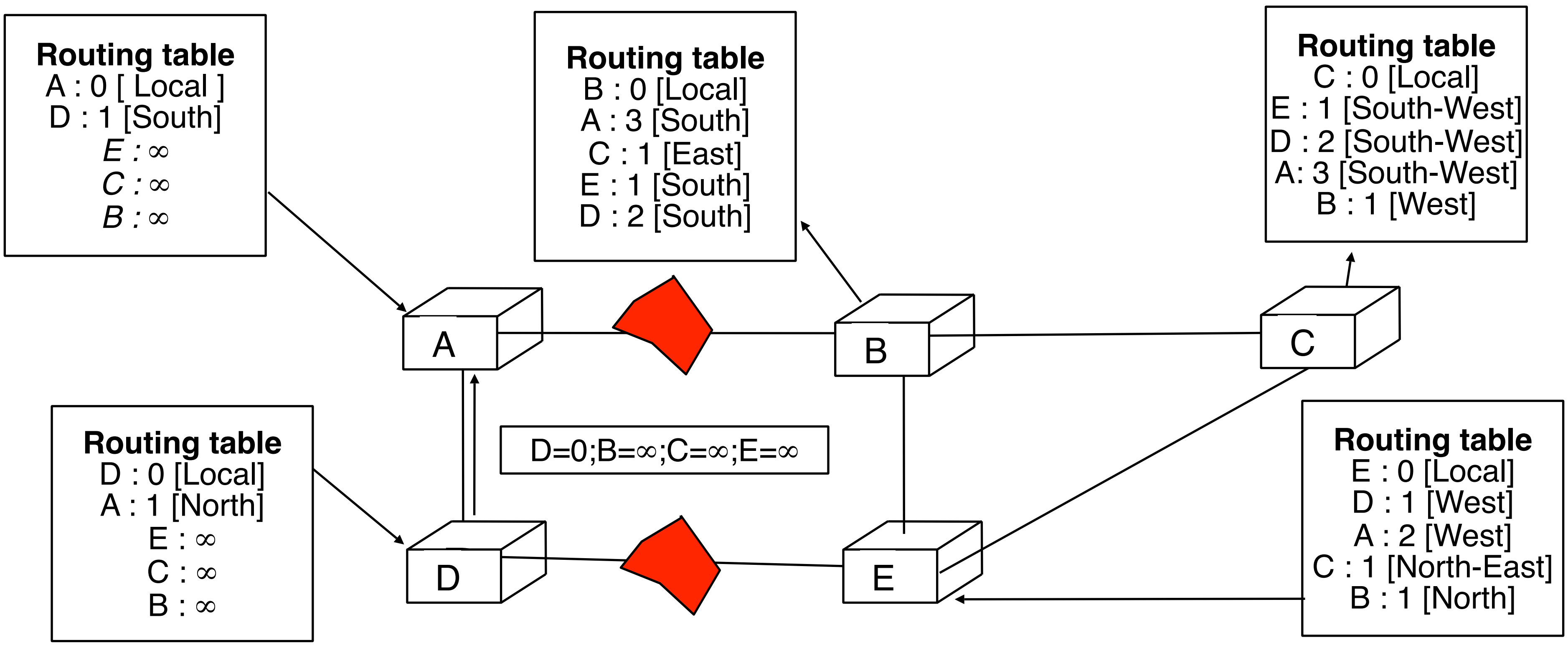
Back to previous example



A will not pollute D's routing table with split horizon

Split horizon (2)

D can also send its distance vector



Does split horizon allows to avoid all counting to infinity problems ?

Split horizon with poisoning

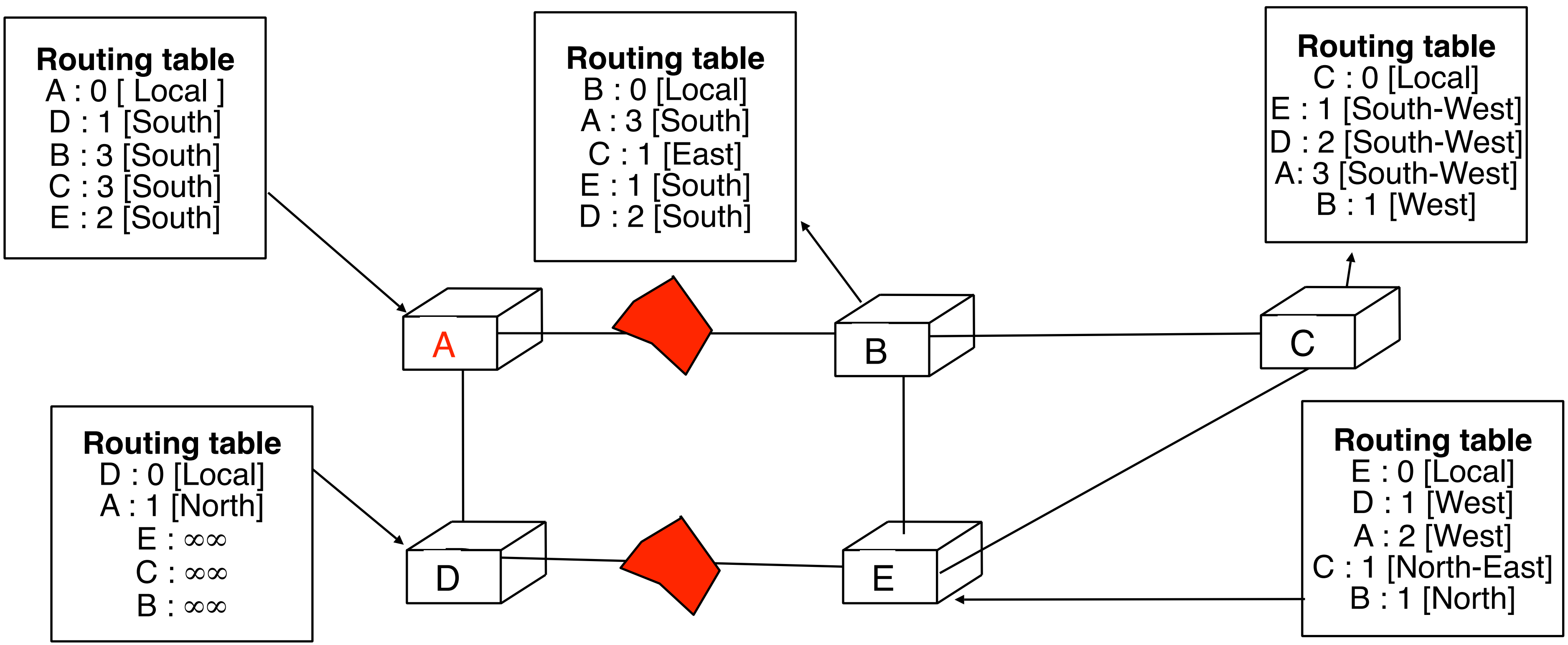
- Improvement
  - Instead of not advertising a route over the link from which it was learned, advertise it with an infinite cost

```
Pseudocode

Every N seconds:
 for each link=l
 { /* one different vector for each link */
  Vector=null;
  for each destination=d in R[]
  {
   if (R[d].link<>l)
   {
    Vector=Vector+Pair(d,R[d].cost);
   }
   else
   {
    Vector=Vector+Pair(d,∞);
   }
  }
  Send(Vector);
 }
```

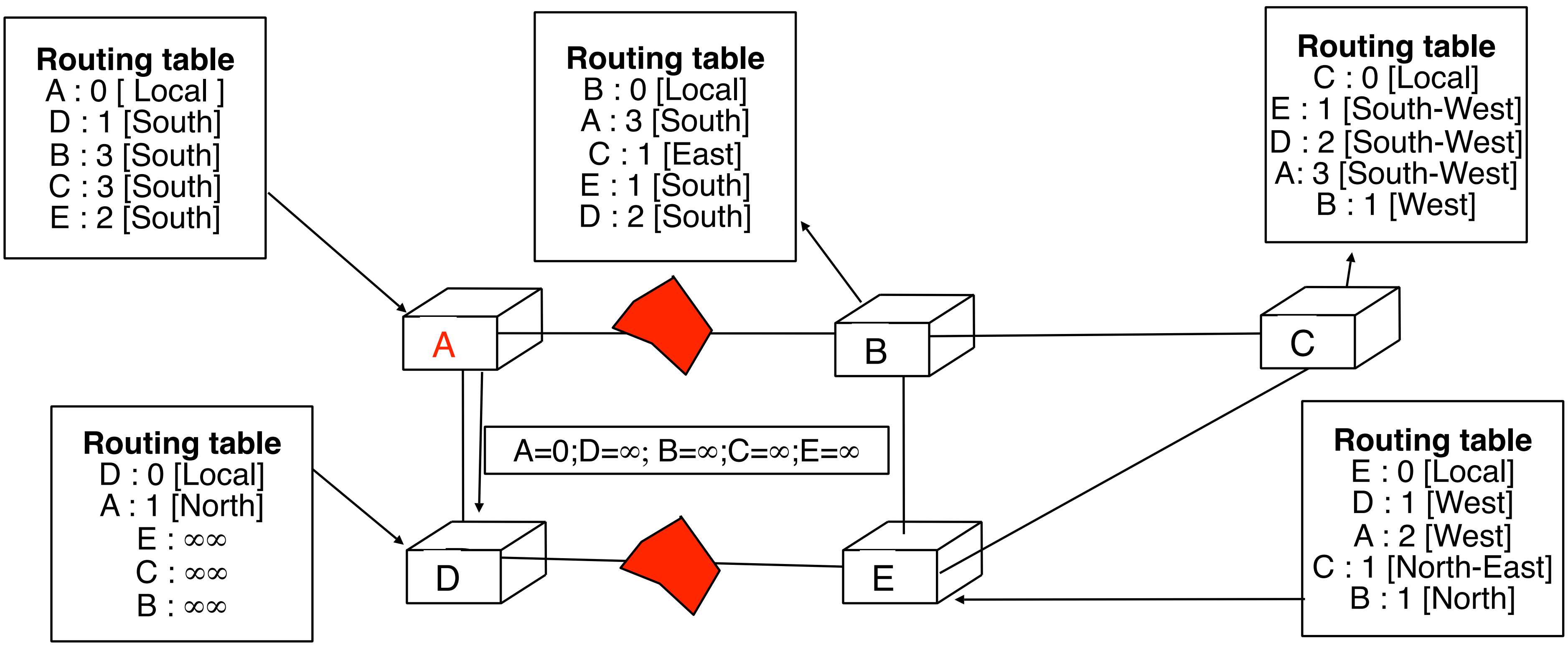
Split horizon with poisoning (2)

Back to previous example

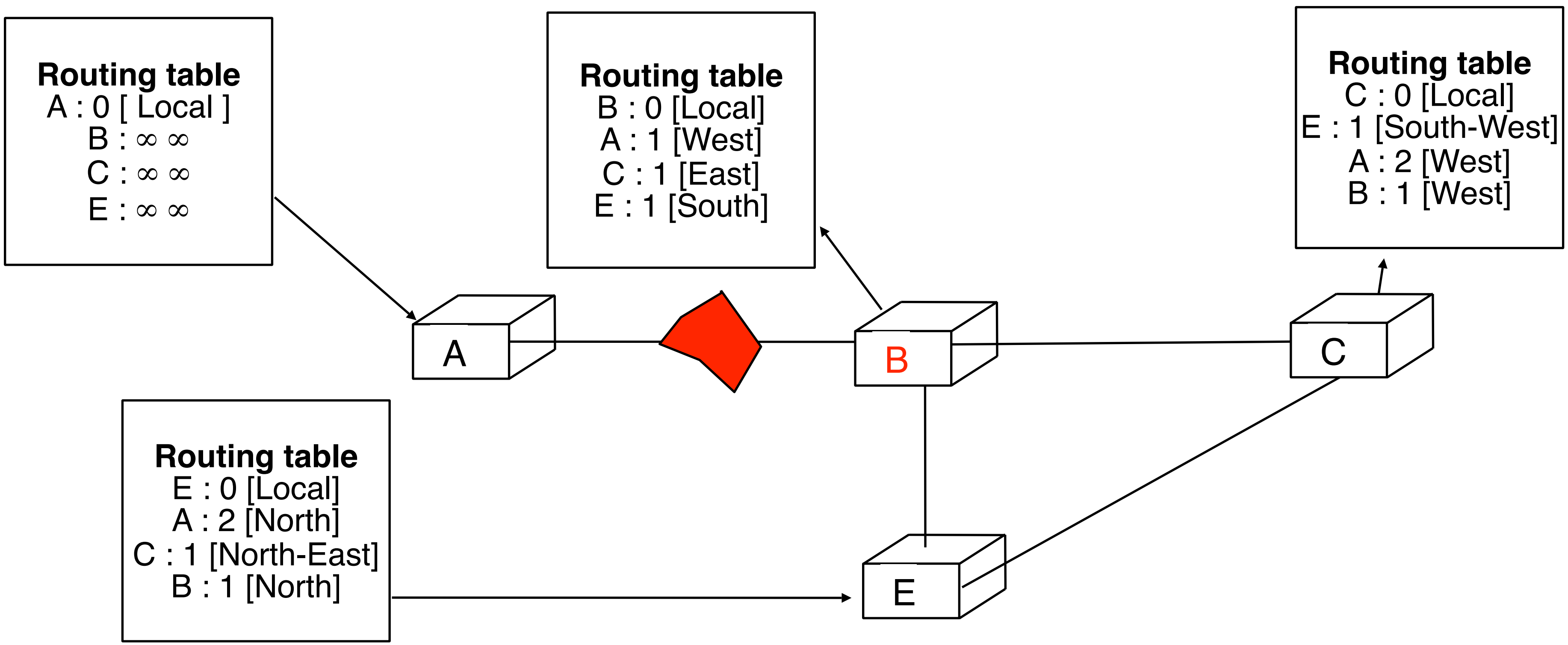


Split horizon with poisoning (2)

Back to previous example



Limitations to split horizon



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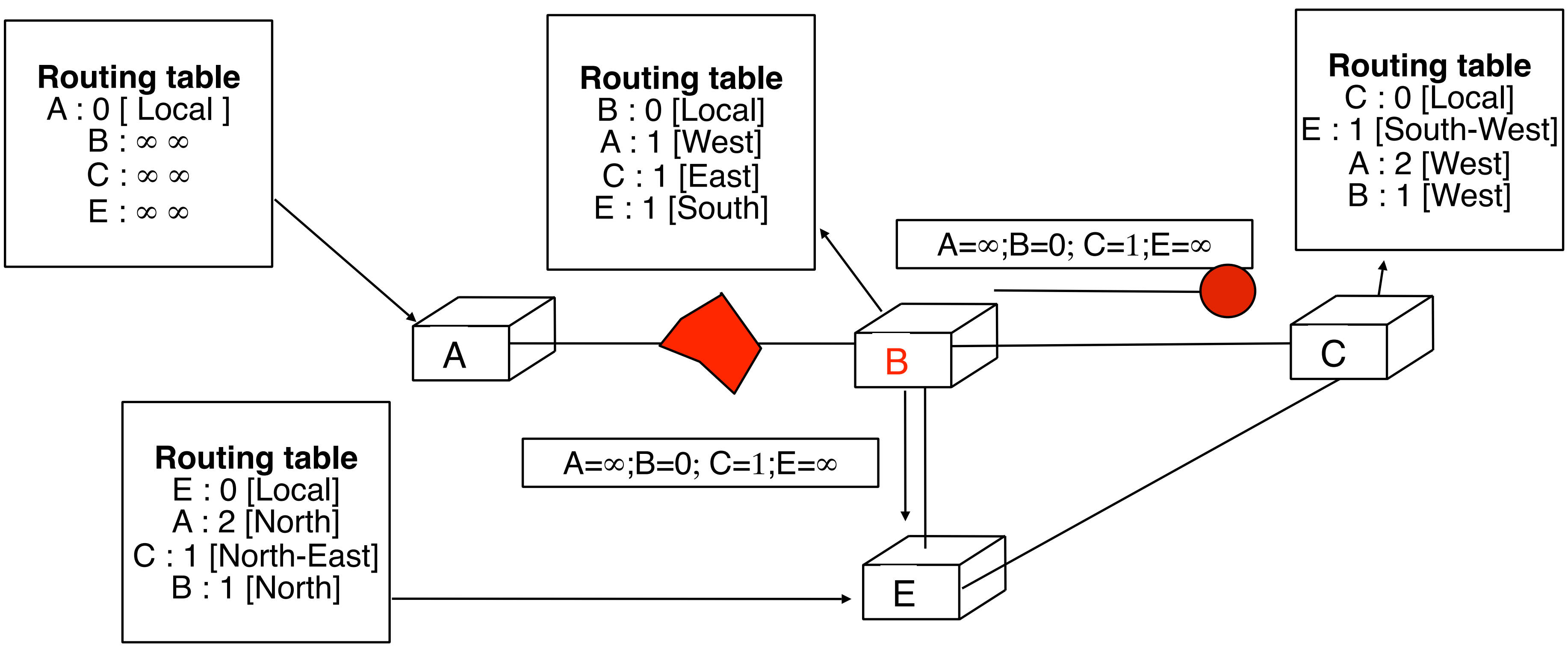

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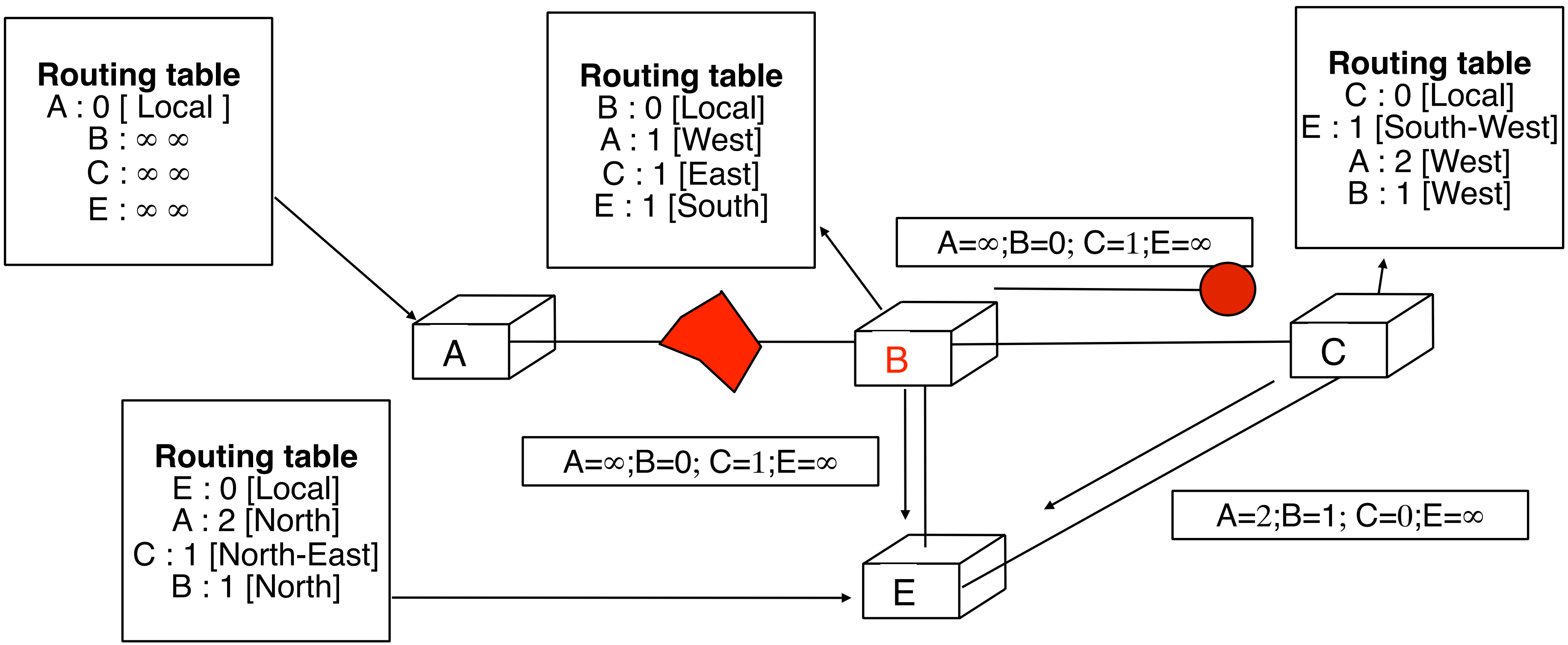
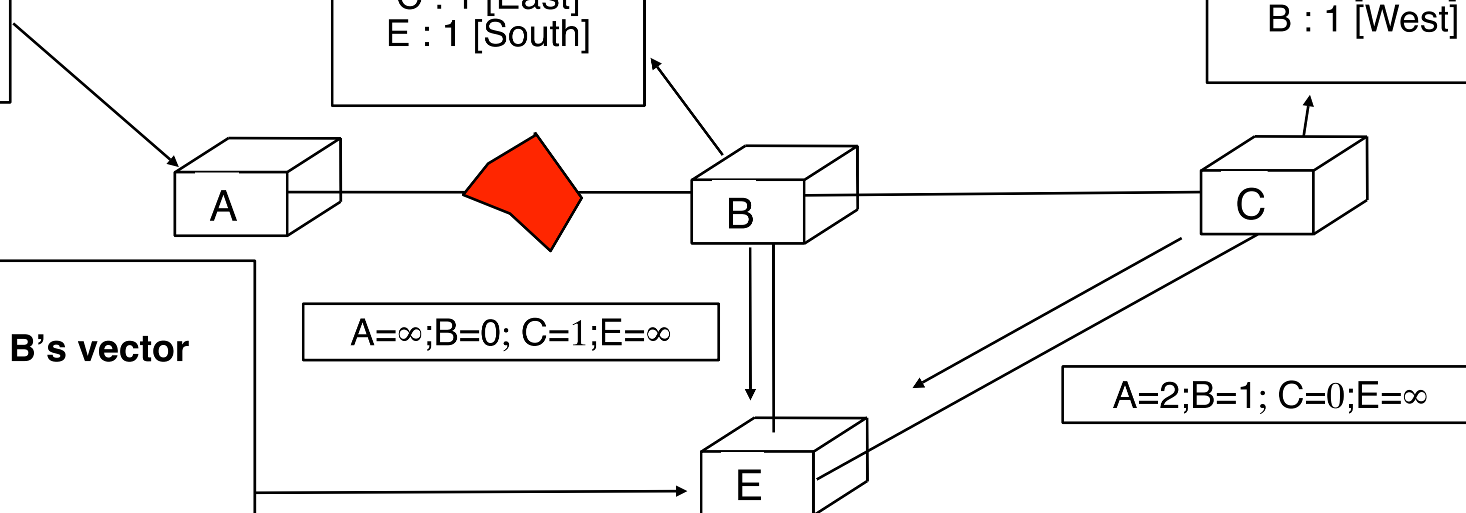


Limitations to split horizon (2)

Routing table
A : 0 [Local]
B : ∞∞
C : ∞ ∞
E : ∞ ∞

Routing table
B : 0 [Local]
A : 1 [West]
C : 1 [East]
E : 1 [South]

Routing table
C : 0 [Local]
E : 1 [South-West]
A : 2 [West]
B : 1 [West]



Routing table after B's vector
E : 0 [Local]
A : ∞
C : 1 [North-East]
B : 1 [North]

Routing table after C's vector
E : 0 [local]
<u>A : 3 [North-East]</u>
C : 1 [North-East]
B : 1 [North]

- E will send its own distance vector
  - B will discover a new route towards A via E and will advertise it to C
- New count to infinity problem

Network layer

Basics

Routing

- Static routing
- Distance vector routing
- Link state routing

IP : Internet Protocol

Routing in IP networks

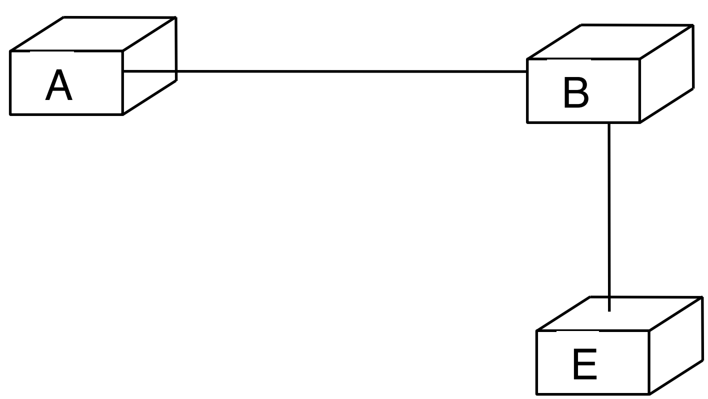
Link state routing

- Idea
  - Instead of distributing summaries of routing tables, wouldn't it be better to distribute network map ?
- How to build such as network map ?
  - Each router must discover its neighbours
  - It should be possible to associate a cost to each link since all links are not equal
  - Each router sends its local topology to all routes and assembles the information received from other routers
  - Routers build the network graph and used Dijkstra's algorithm to compute shortest paths

Neighbour discovery

How does a router discover its neighbours ?

- By manual configuration
  - Unreliable and difficult to manage
- By using HELLO packets
  - Every N seconds, each router sends a HELLO packet on each link with its address
  - Neighbours replay by sending their own address
  - Periodic transmission allows to verify that the link remains up and detect failures



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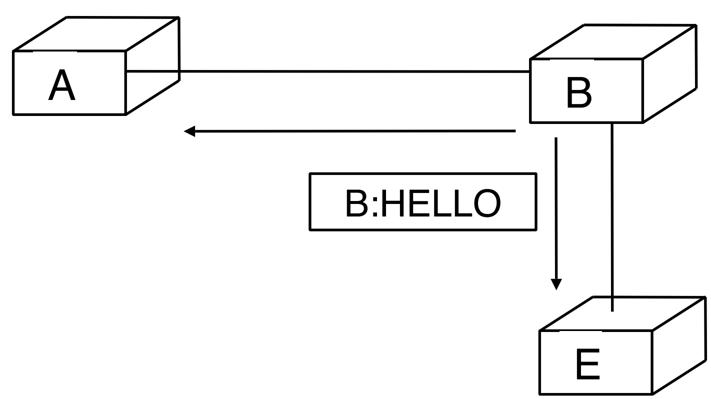

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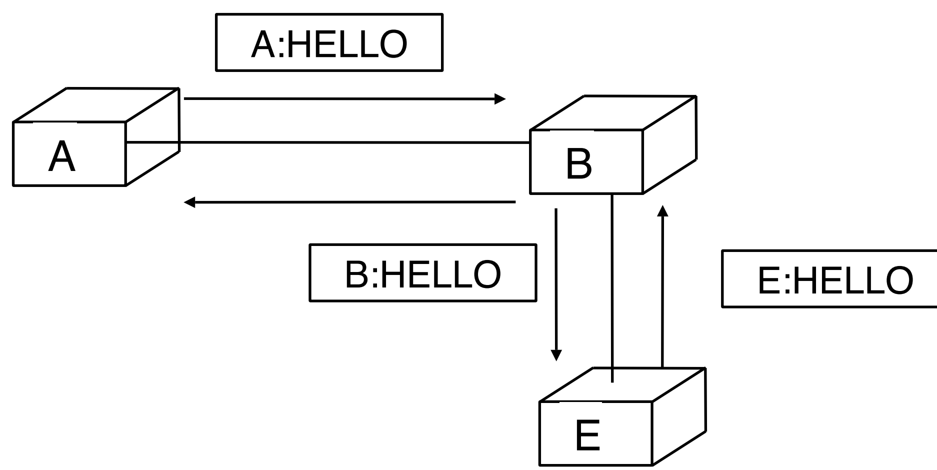

How to determine link costs ?

- Principle
  - one cost is associated with each link direction
- Commonly configured link costs
  - Unit cost
    - simplest solution but only suitable for homogeneous networks
  - Cost depends on link bandwidth
    - high cost for low bandwidth links
    - low cost for high bandwidth links
  - Cost depends on link delays
    - often used to avoid satellite links
- Cost based on measurements
  - Use HELLO to measure link rtt
    - allows to track link load, but be careful if the measurement is not stable enough as each delay change will cause a topology change ...

Assembling the network topology

- How to assemble the network topology
  - By receiving HELLOs, each routers builds its local part of the network map
  - Each router summarises its local topology inside one link state packet that contains
    - router identification
    - pairs (neighbour identification,cost to reach neighbour)
- When should a router send its link state packet ?
  - in case of modification to its local topology
    - allows to inform all other routers of the change
  - Every N seconds
    - allows to refresh information in all routers and makes sure that if an invalid information was stored on a router due to memory errors it will not remain in the router forever

How to distribute the link state packets ?

How to distribute the link state packets ?

- Naive solution
  - Each router sends one packet to each other router in the network
    - This solution can only work if
      - All routers know the address of all other routers in network
      - All routers already have routing tables that allow them to forward packets to any destination

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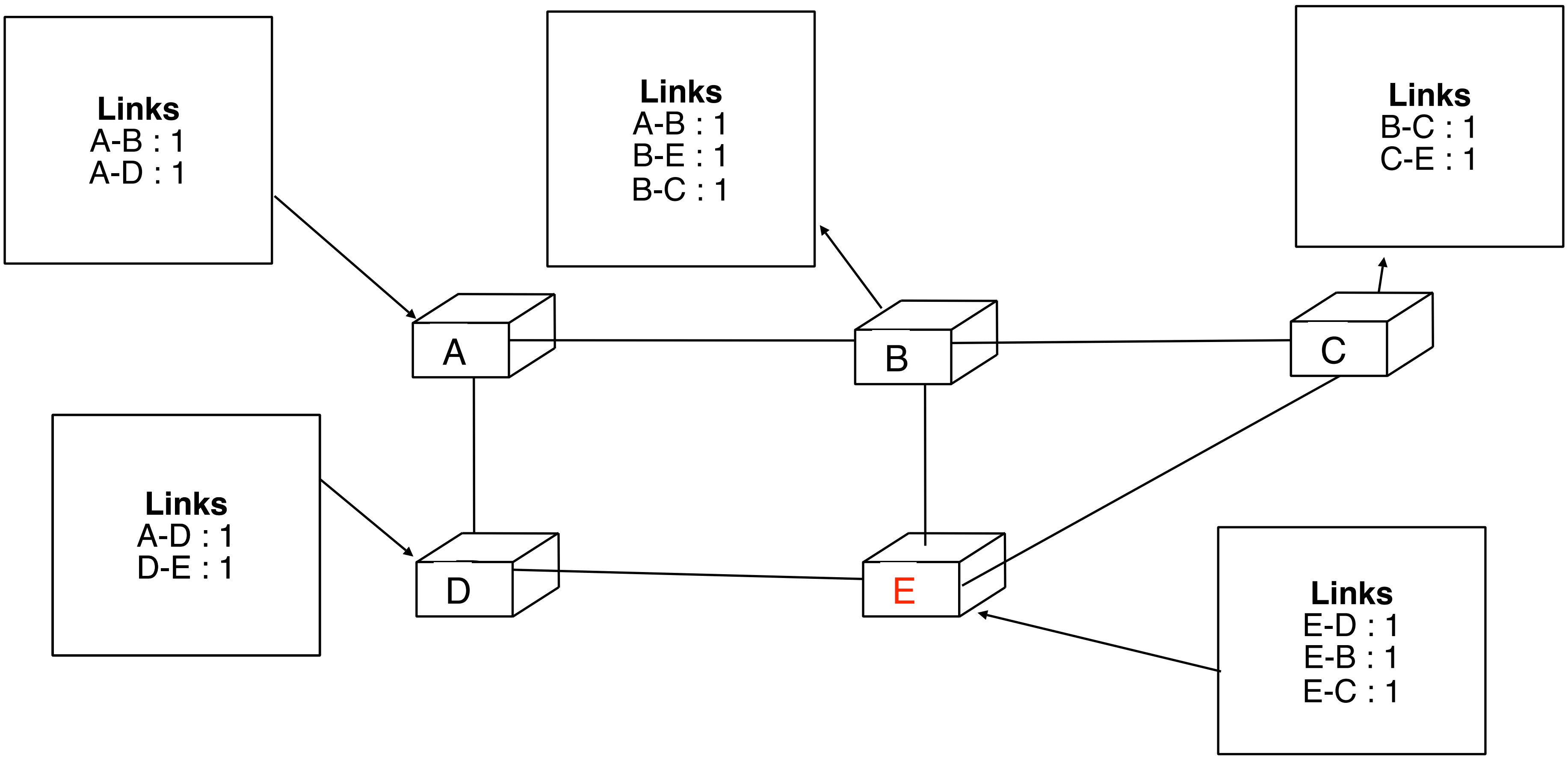
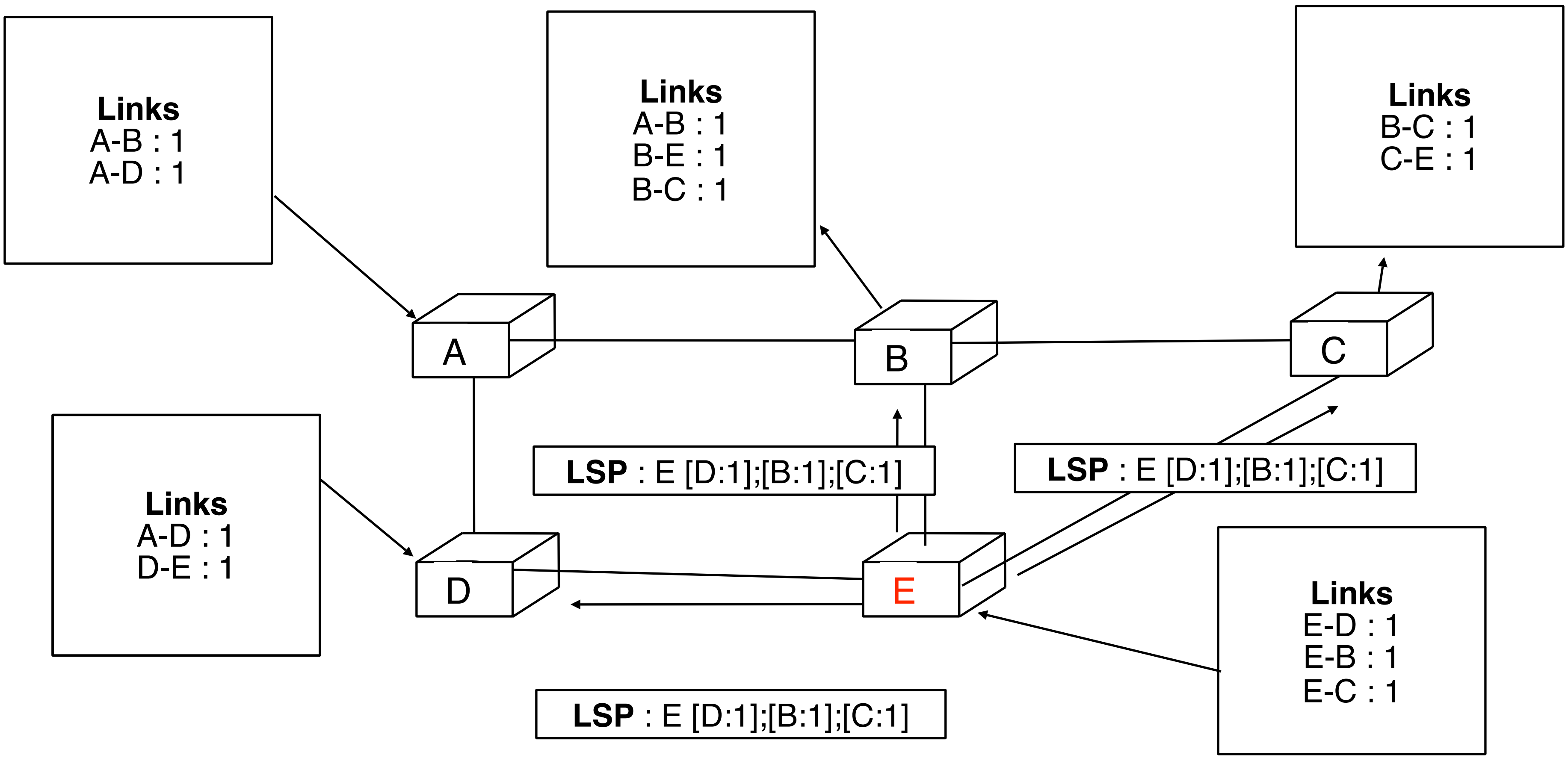
- Realistic solution
  - Does not rely on pre-existing routing tables
  - Each router must receive entire topology
  - First solution
    - Each router sends local topology in link state packet and sends it to all its outgoing links
    - When a router receives an LSP, it forwards it to all its outgoing links except the link from which it received it

LSP flooding



Assumes that all links have a unit cost

LSP flooding



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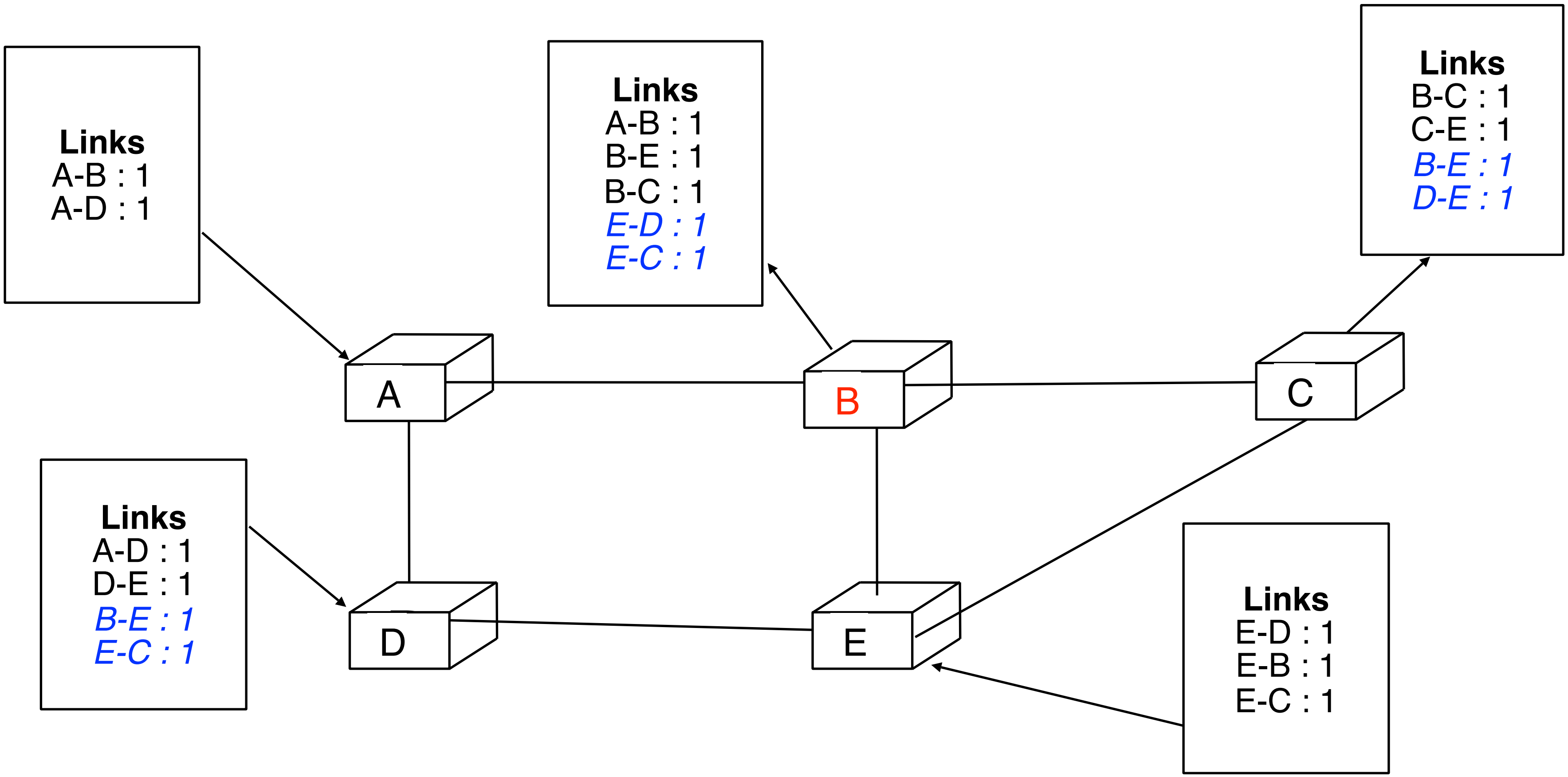
LSP flooding (2)



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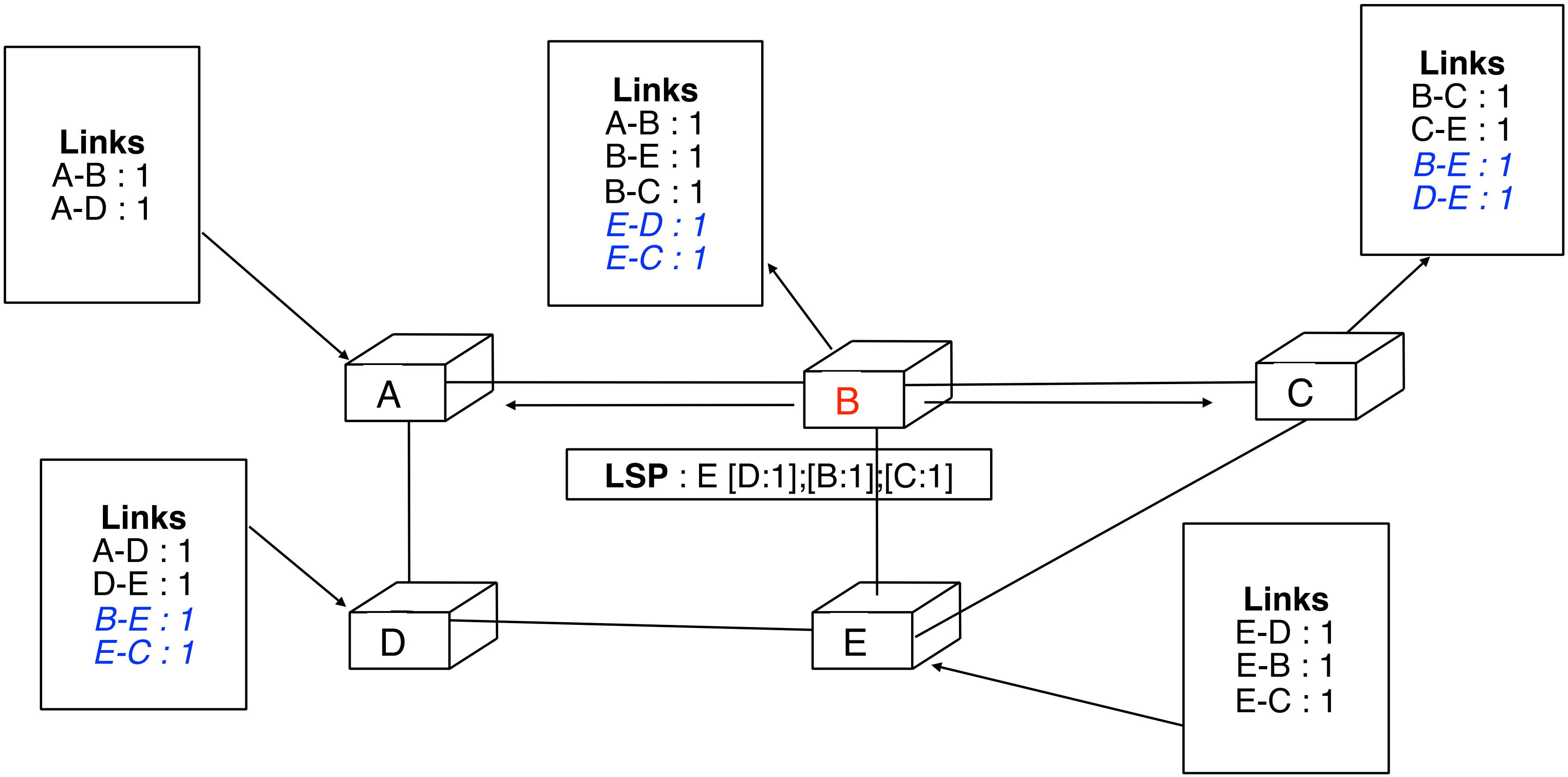

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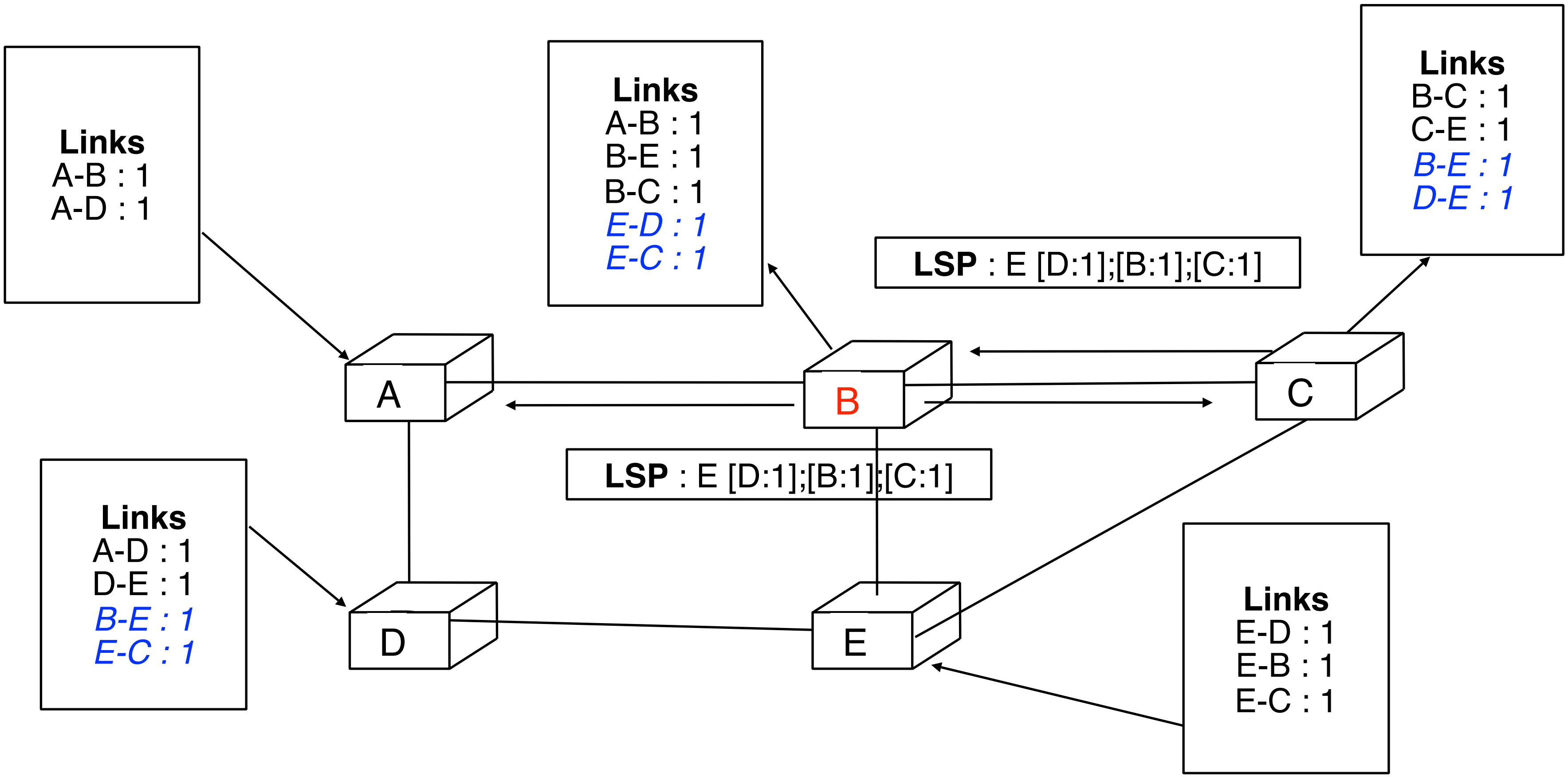

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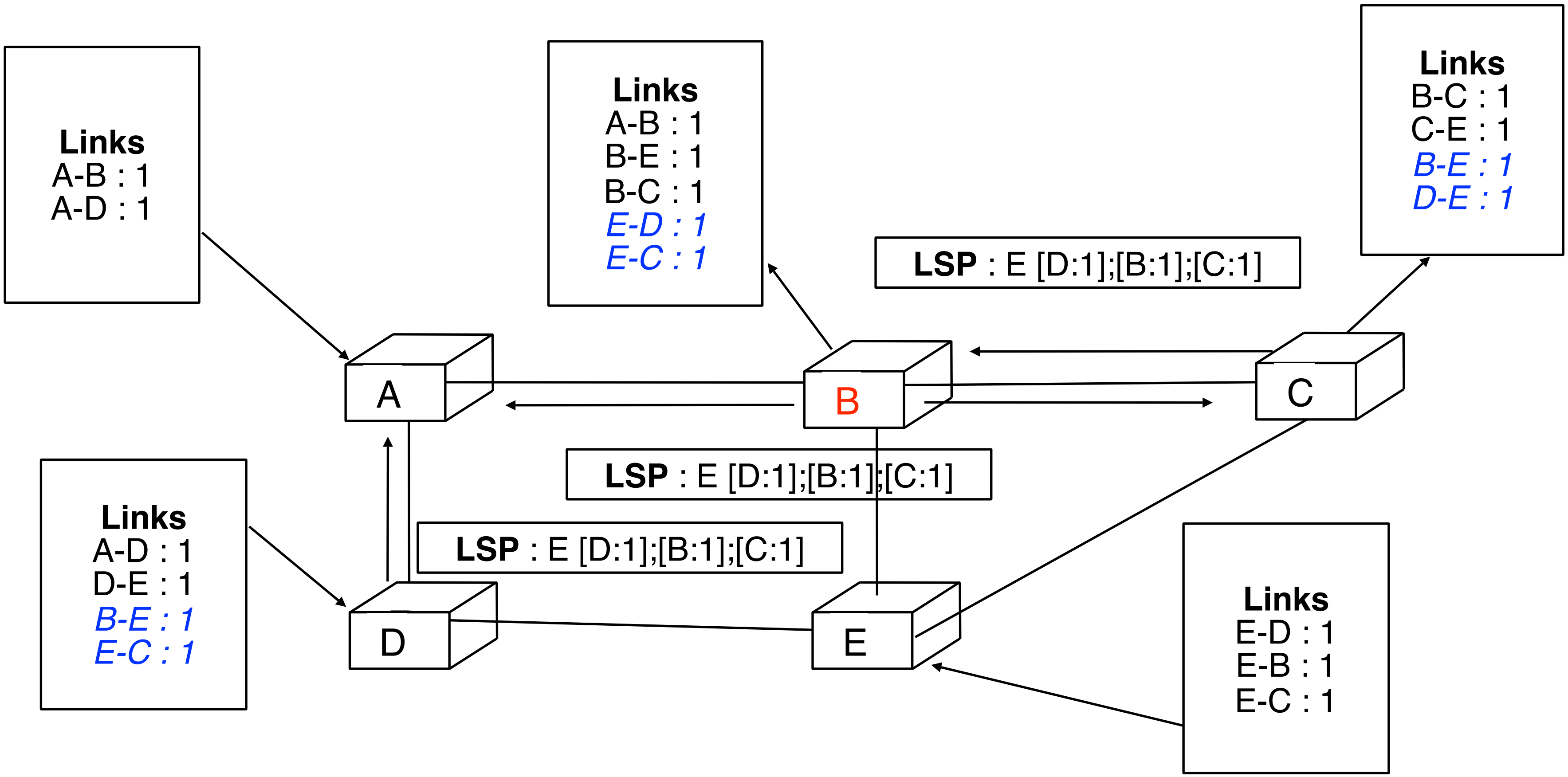

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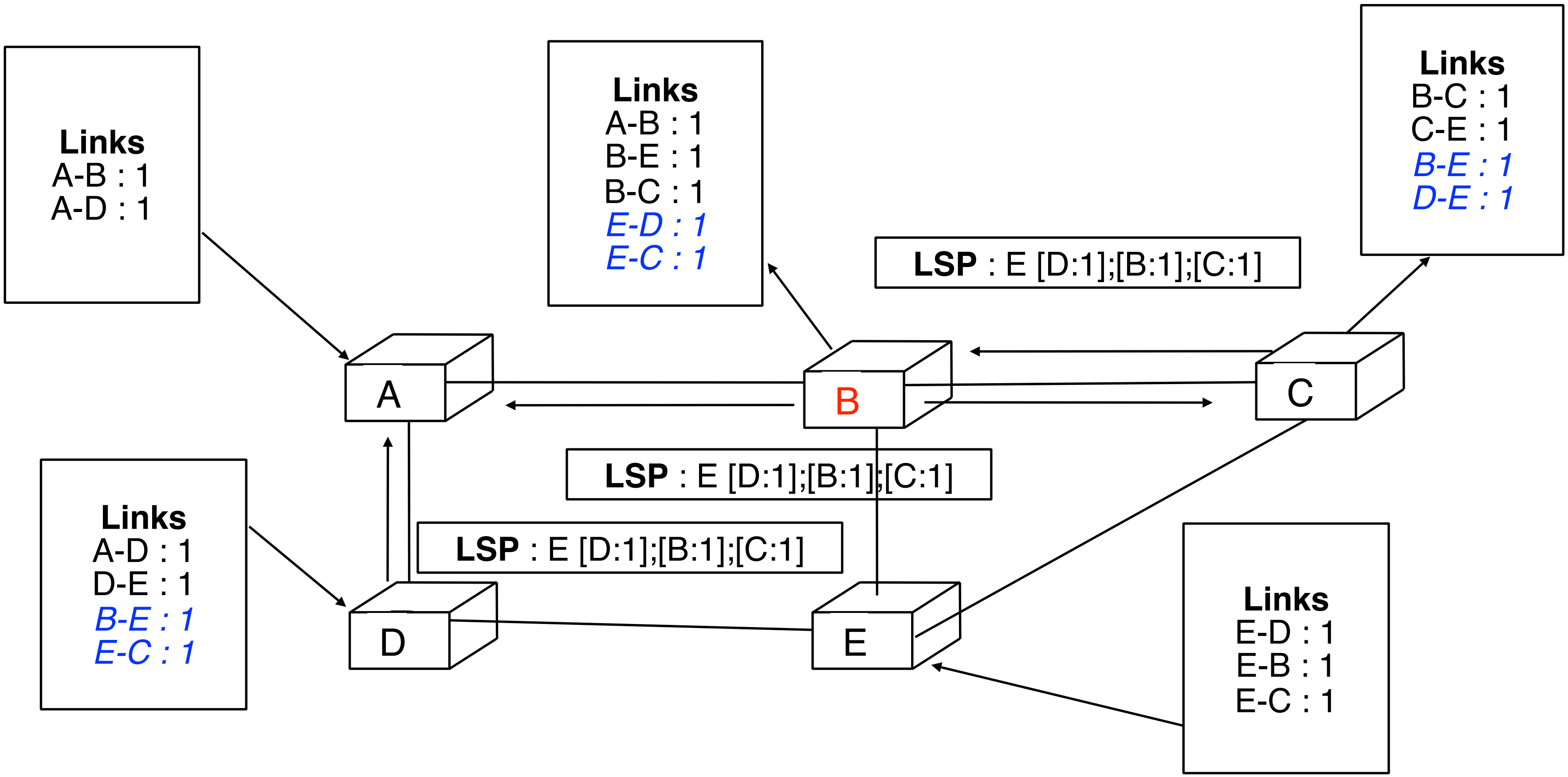
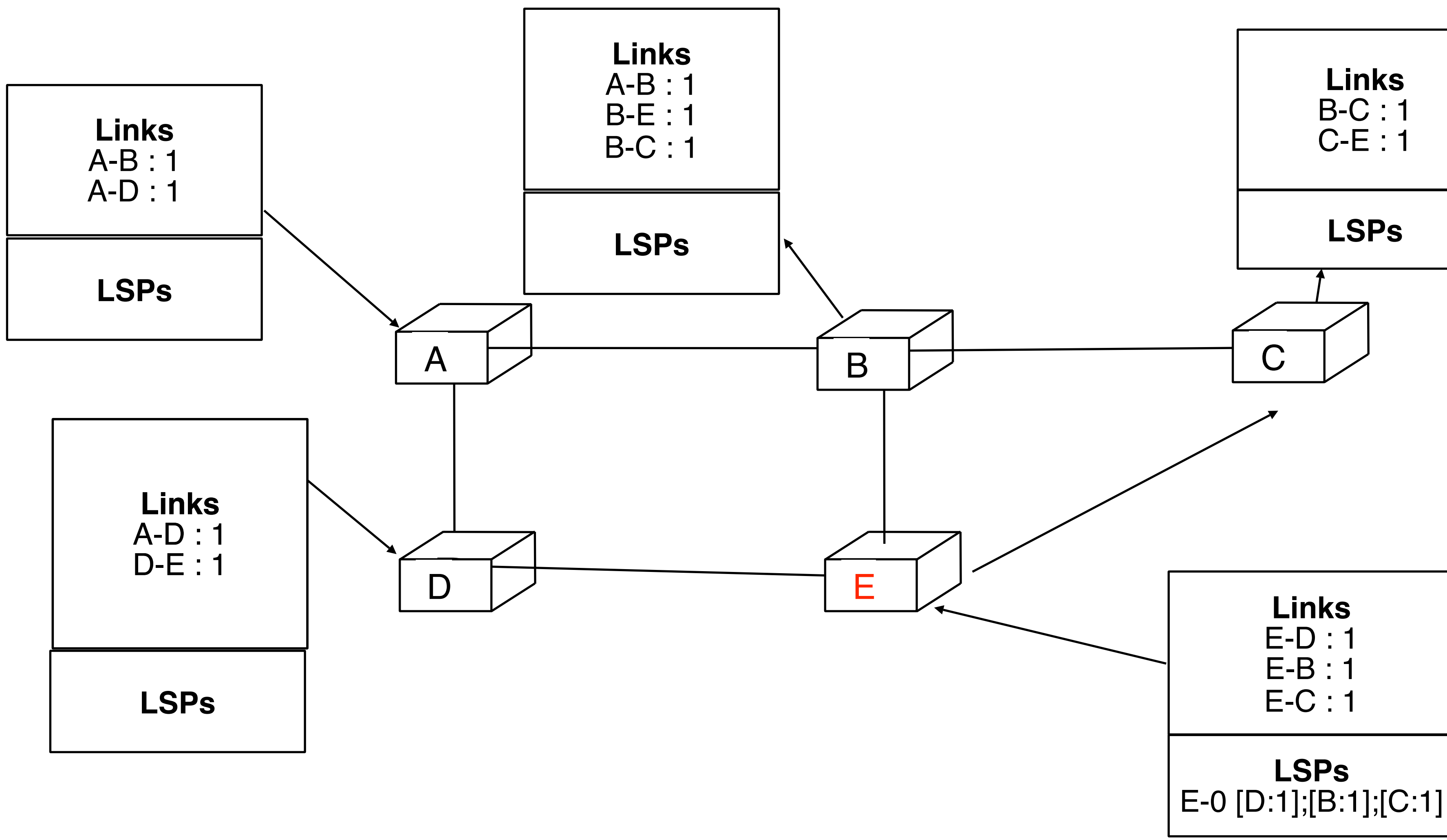


How to ensure that an LSP will not loop ?

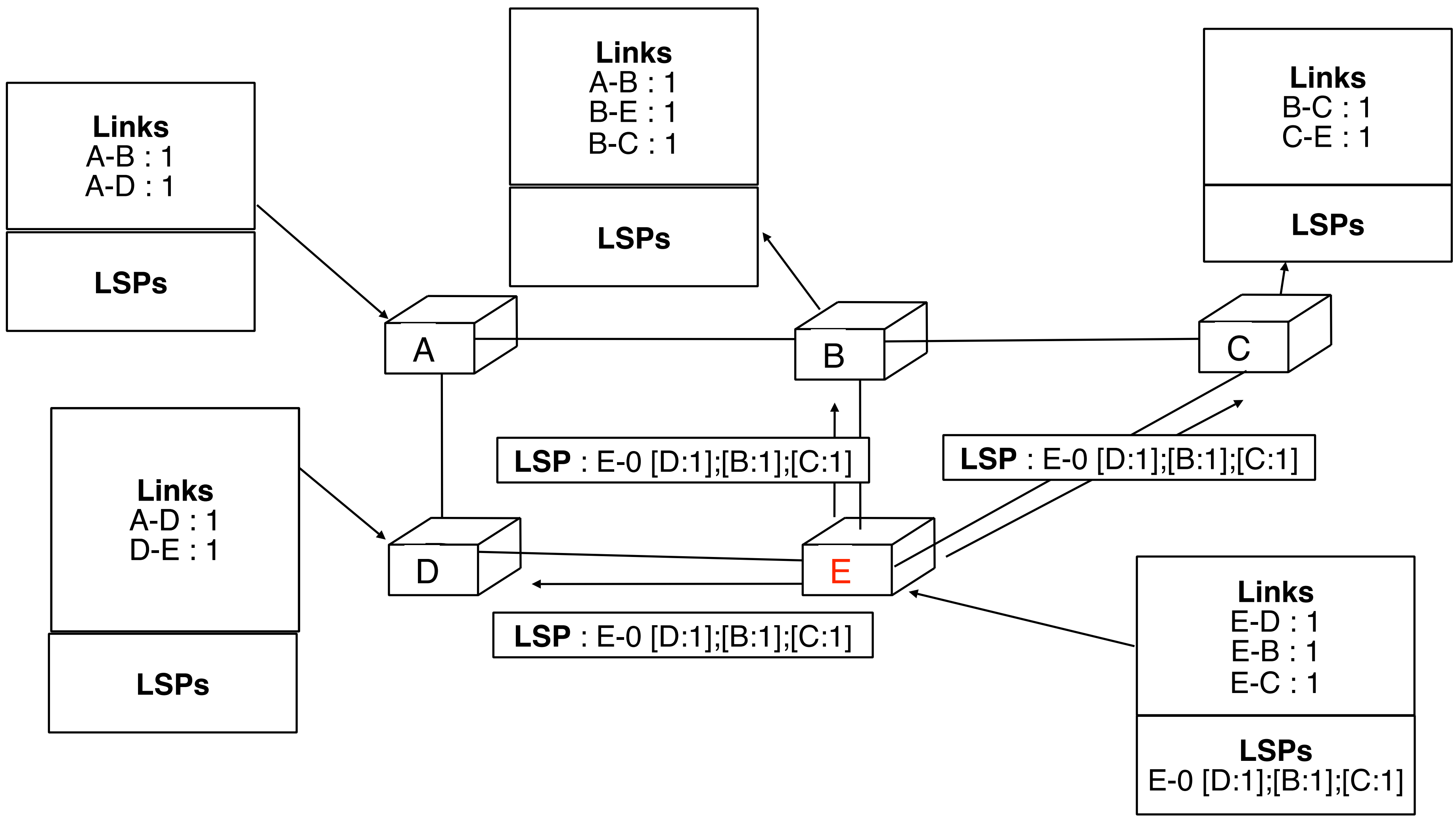
LSP flooding (3)

- How to avoid LSP flooding loops ?
  - A router should not reflood an LSP that it has already and flooded
- Solution
  - LSP contents
    - sequence number
      - incremented every time an LSP is generated by a router
    - address of LSP originator
    - pairs address:distance for all neighbours of the originator
  - Each router must store the last LSP received from each router of the network
  - A received LSP is processed and flooded only if is it more recent than the LSP stored in the LSDB

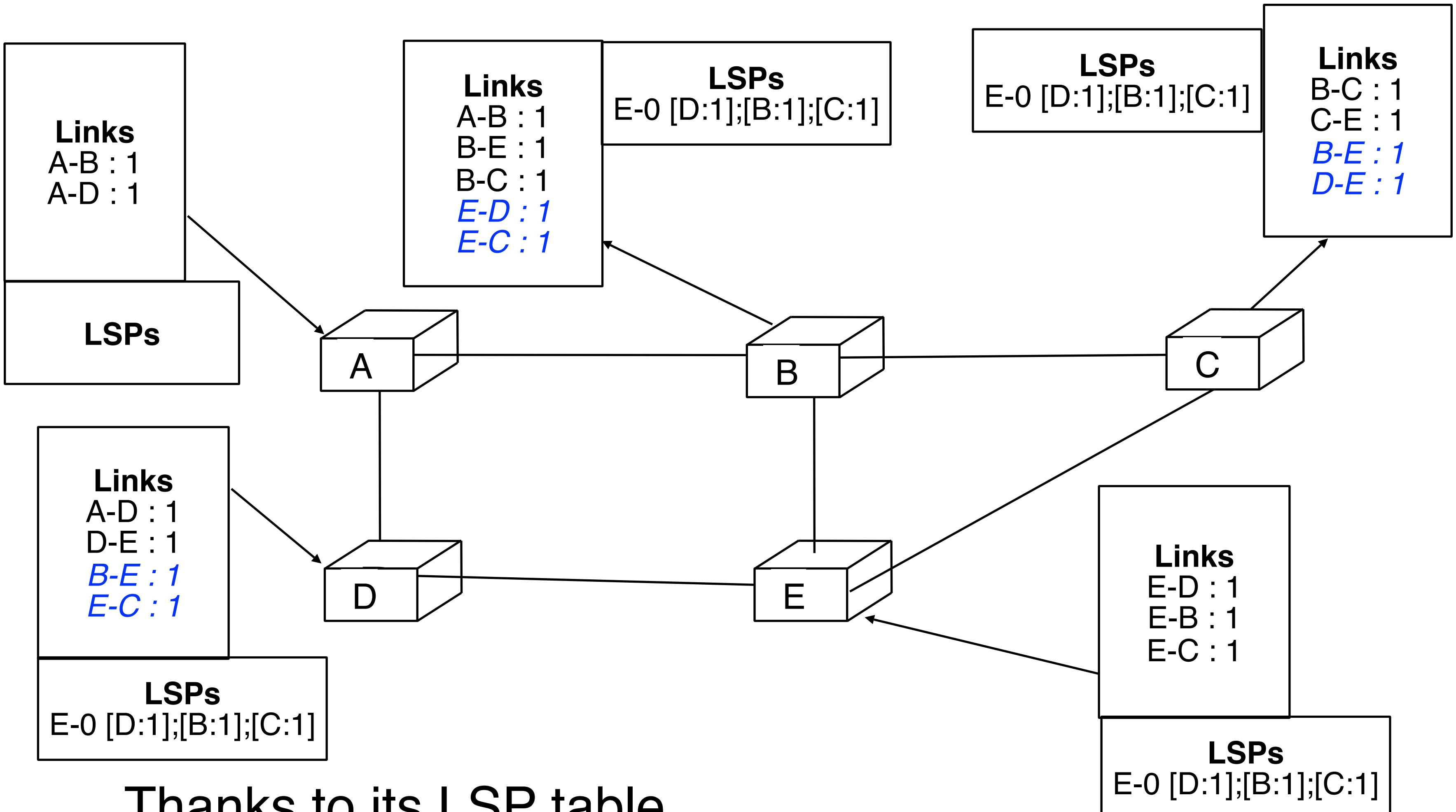
LSP flooding (4)



LSP flooding (4)

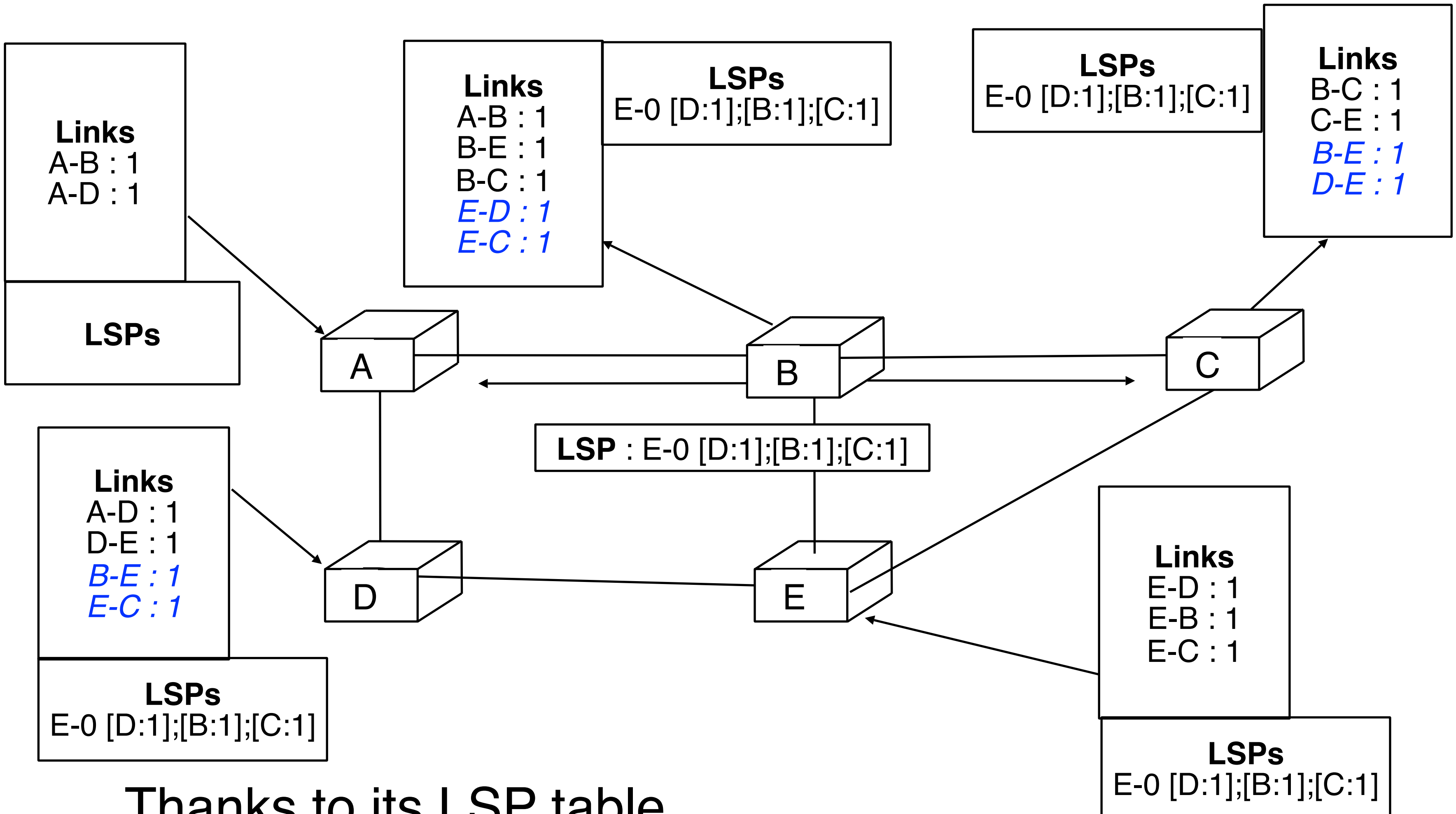


LSP flooding (5)



Thanks to its LSP table
- A can detect that it received same LSP via B and D
- C can detect that it received same LSP via B and E

LSP flooding (5)



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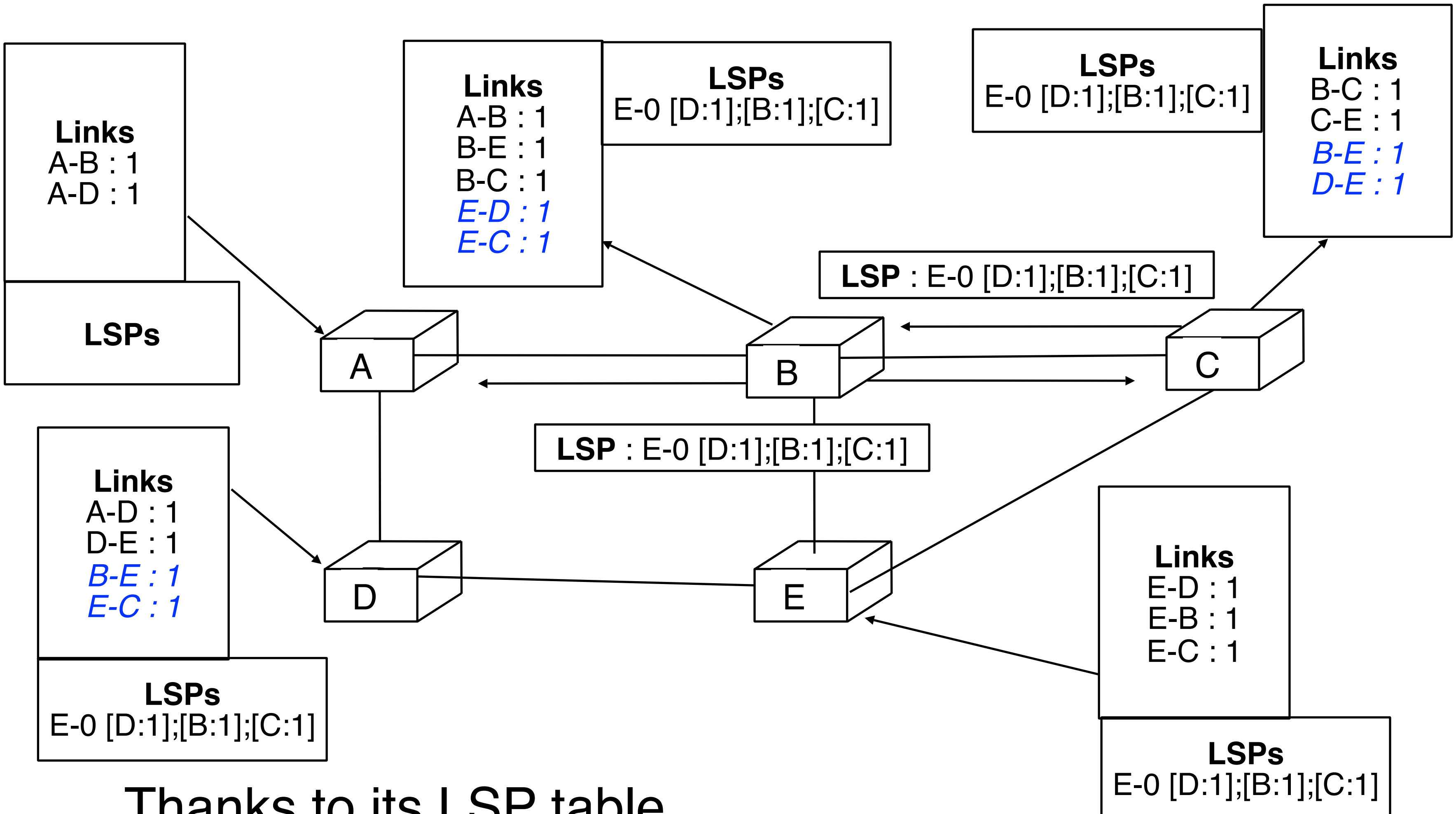

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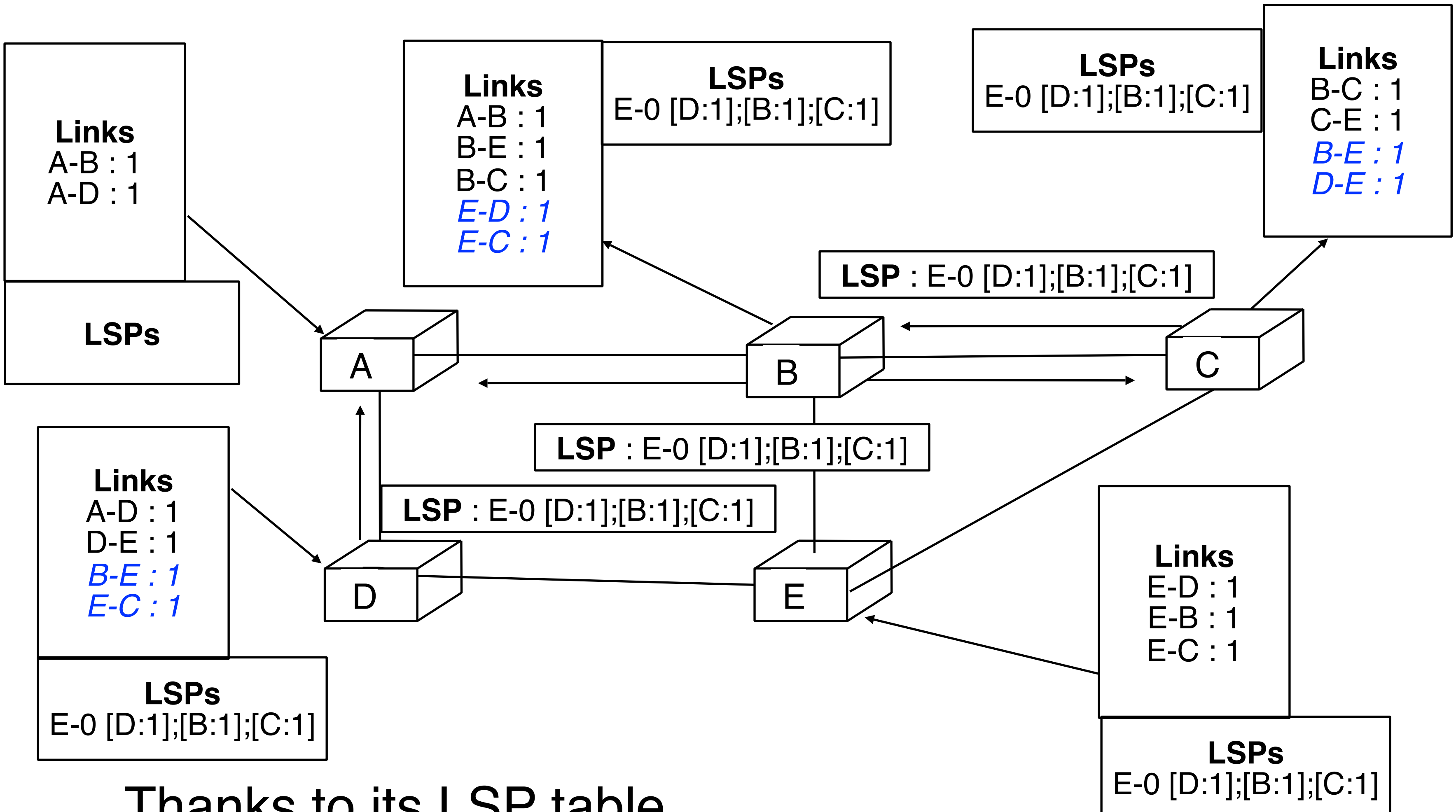

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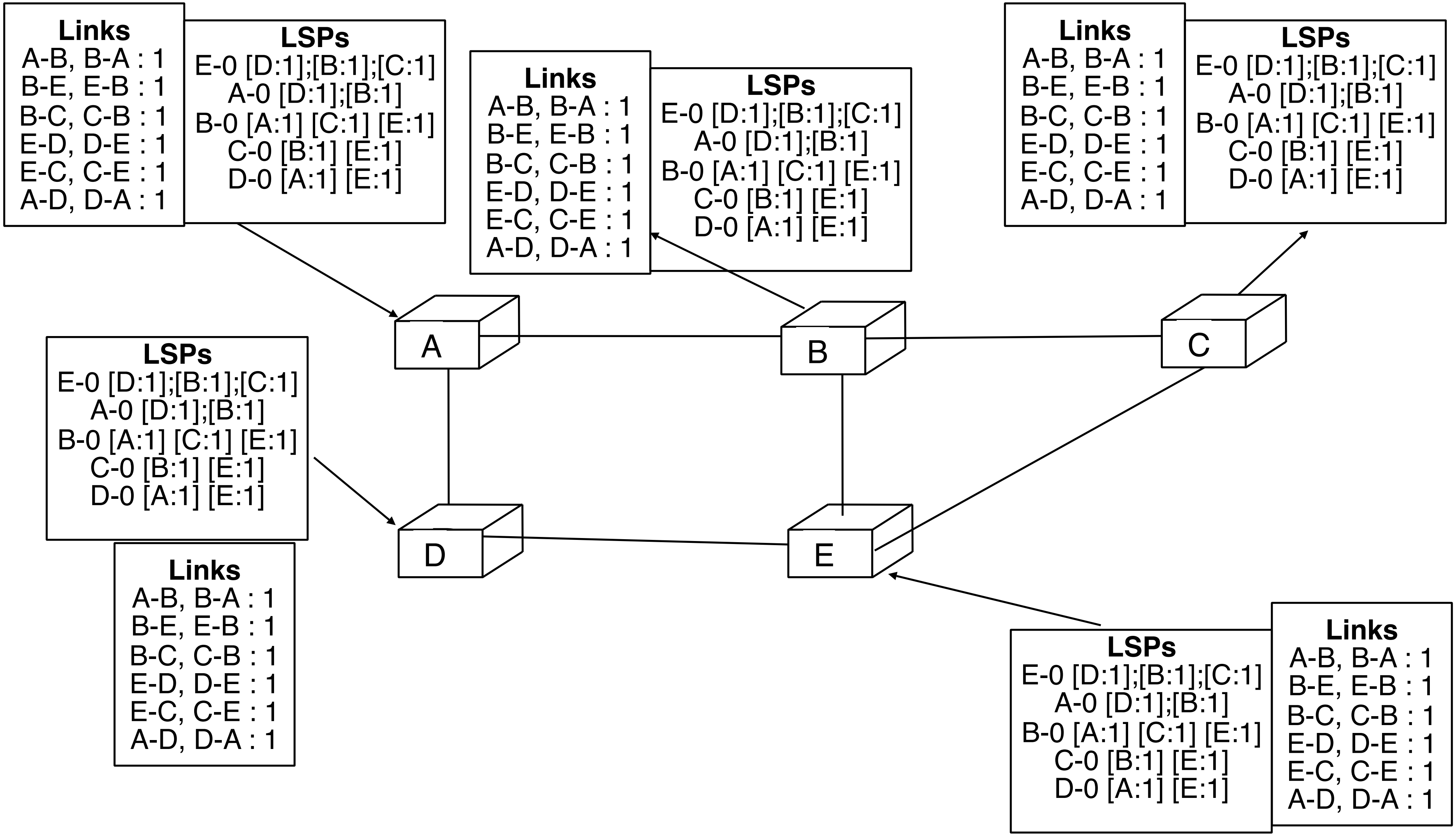
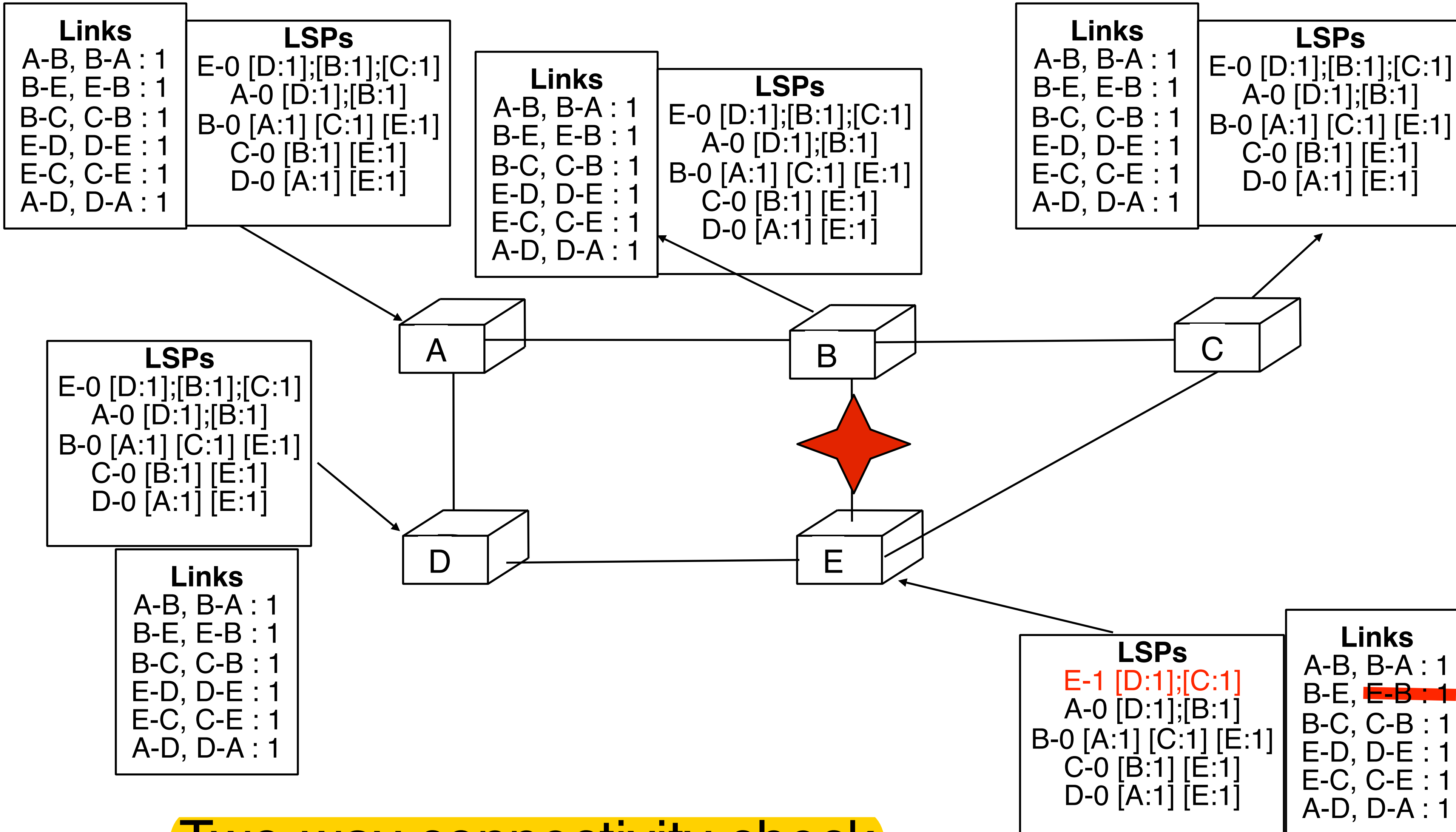
Full topology

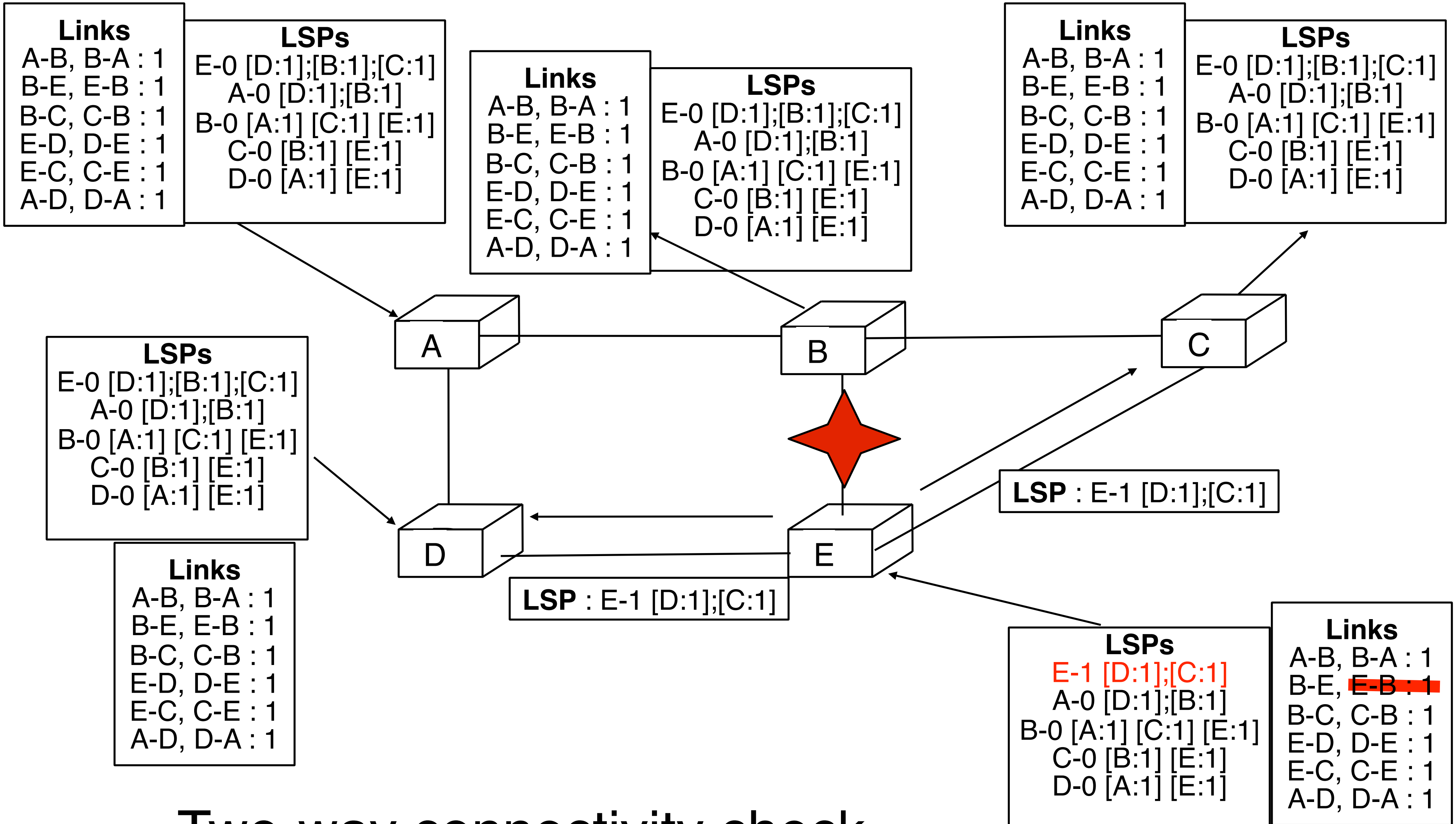


How to deal with link failures ?



- Two-way connectivity check
  - A link is only considered useable if both directions have been advertised

How to deal with link failures ?



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Router failures

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    - If older LSPs from same router were still in network, then the new LSP will not be flooded

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  - It will send its LSP with its sequence number set to zero
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- Solution
  - Add "age" field inside each LSP
  - Each router must decrement age regularly
    - even for the LSPs stored in its LSDB
  - LSP having age=0 is too old and must be deleted
  - Each router must flood regularly its own LSP with age>0 to ensure that it remains inside network

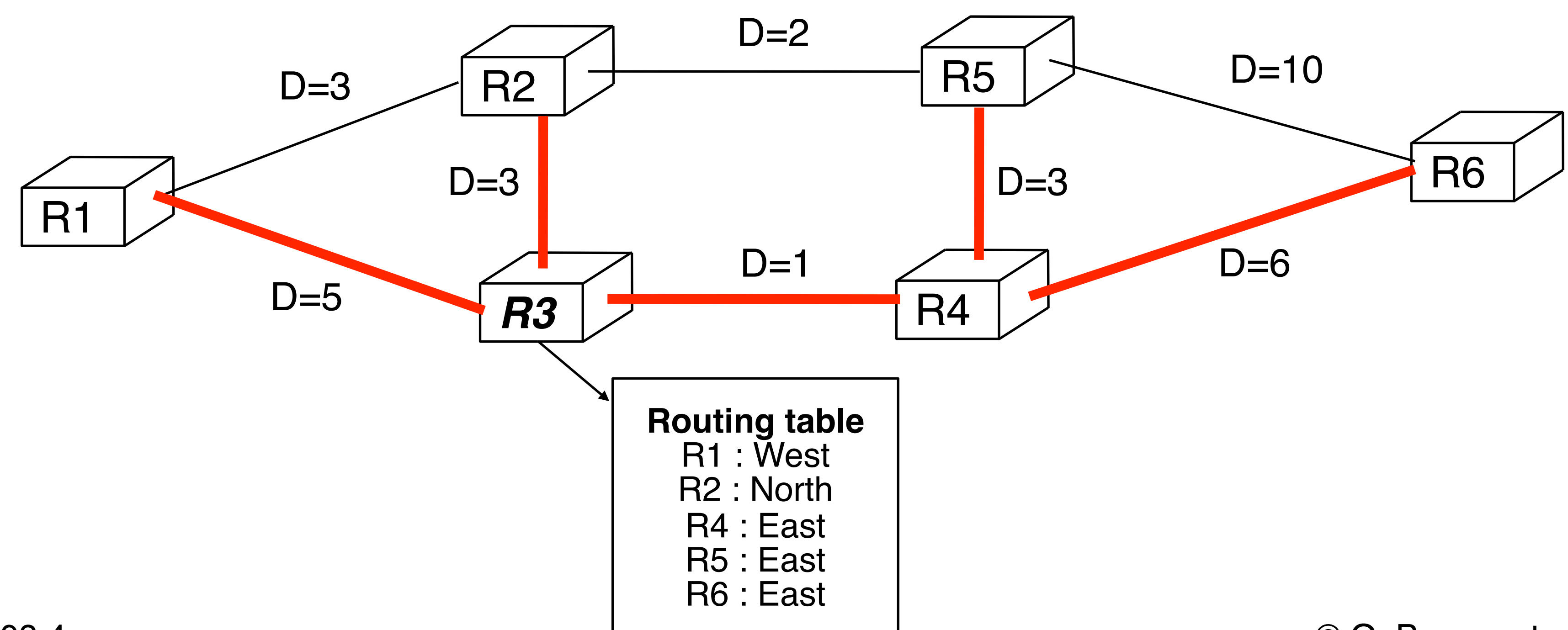
Improvements to LSP flooding

- Avoid sending twice same LSP on a link
  - When an LSP needs to be flooded on a link, wait some time to let other router flood the LSP
    - reduces number of LSPs exchanged on a link but increases flooding time
- Reliable flooding
  - CRC inside each LSP to detect transmission errors
  - Acknowledgements on each link for the LSPs exchanged on this link
    - each transmission is protected by a timer
- Link state database exchange/synchronisation
  - Routers can compare the content of their LSDB and exchange only missing LSPs form neighbour
    - useful when the router boots and wants to receive quickly all LSPs from the network

Computation of routing table

Principle

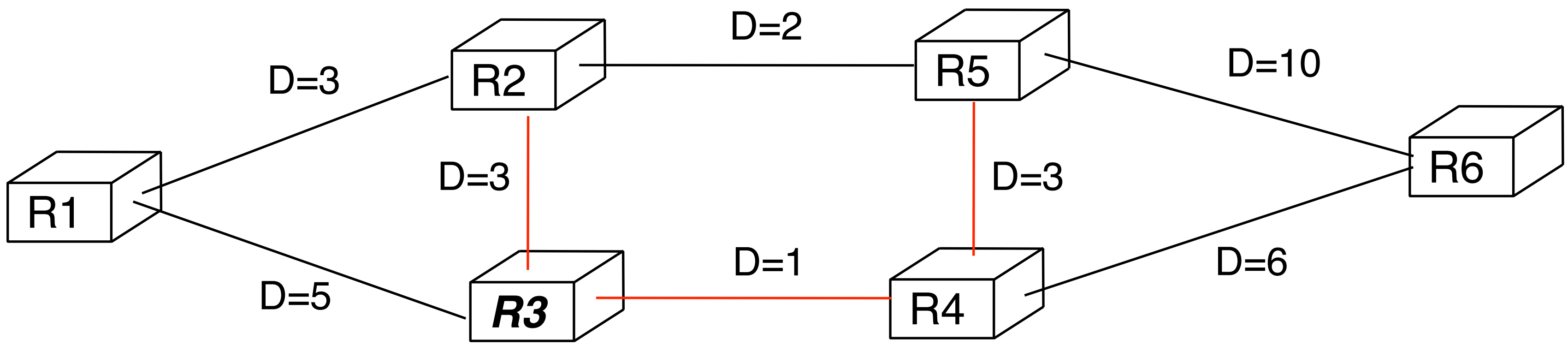
- Each router uses the received LSPs to build a graph and then computes the shortest spanning tree rooted on itself
  - From this spanning tree, it is easy to compute the routing table



Dijkstra’s shortest path

- Computing the shortest path tree
  - At the beginning, the tree only contains the root node
  - Adjacent routers are placed with the cost of their link in the candidates list
  - Candidate router with lowest cost is chosen and added to the tree
  - Consider the neighbours of the chosen candidate router and update the candidate router list if
    - one of the new neighbours was not already in the candidates list
    - one of the new neighbours was already in the candidates list but with a longer path than the one in the current list
  - Algorithm continues with the new candidates list and ends when all routers belong to shortest path tree

Dijkstra’s shortest path (2)



1) Routers : [R1, R2, R4, R5,R6] ; Candidates : [-] ; Tree : R3
2) Routers : [R5, R6] ; Candidates : [R1(5) ; R2(3) ; R4 (1)]
   selected candidate : R4
   New tree : R3 - R4
   New Candidates ? [R1(5) ; R2 (3) ; R5(R4-4) ; R6(R4-7)]
3) Routers [-]
   Selected candidate : R2 ; New tree : R2 - R3 - R4
   New Candidates ? [R1(5) ; R5(R4-4) ; R6 (R4-7)]
4) Selected candidate : R5 ; New tree : R2 - R3 - R4 - R5
   New candidates ? [R1(5) ; R6(R4-7)]
5) ...

Network layer

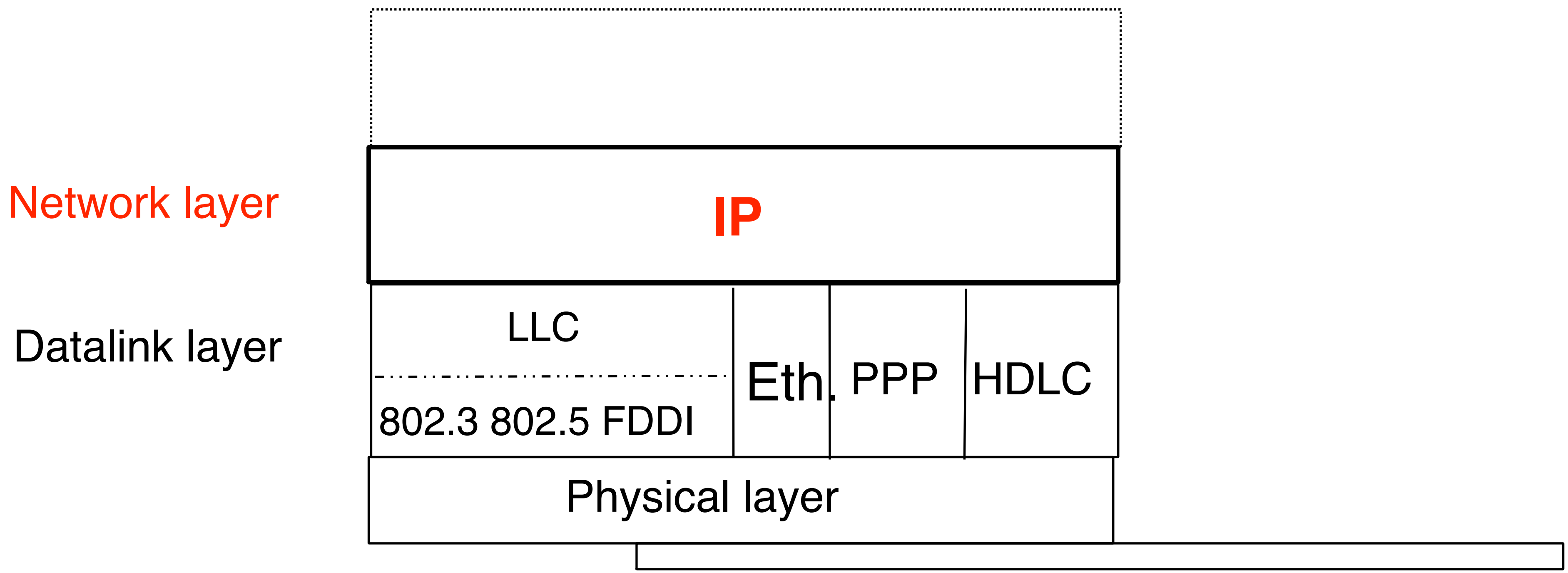
Basics

Routing
- Static routing
- Distance vector routing
- Link state routing

IP : Internet Protocol
- IP version 4
- IP version 6

Routing in IP networks

IP : Internet Protocol

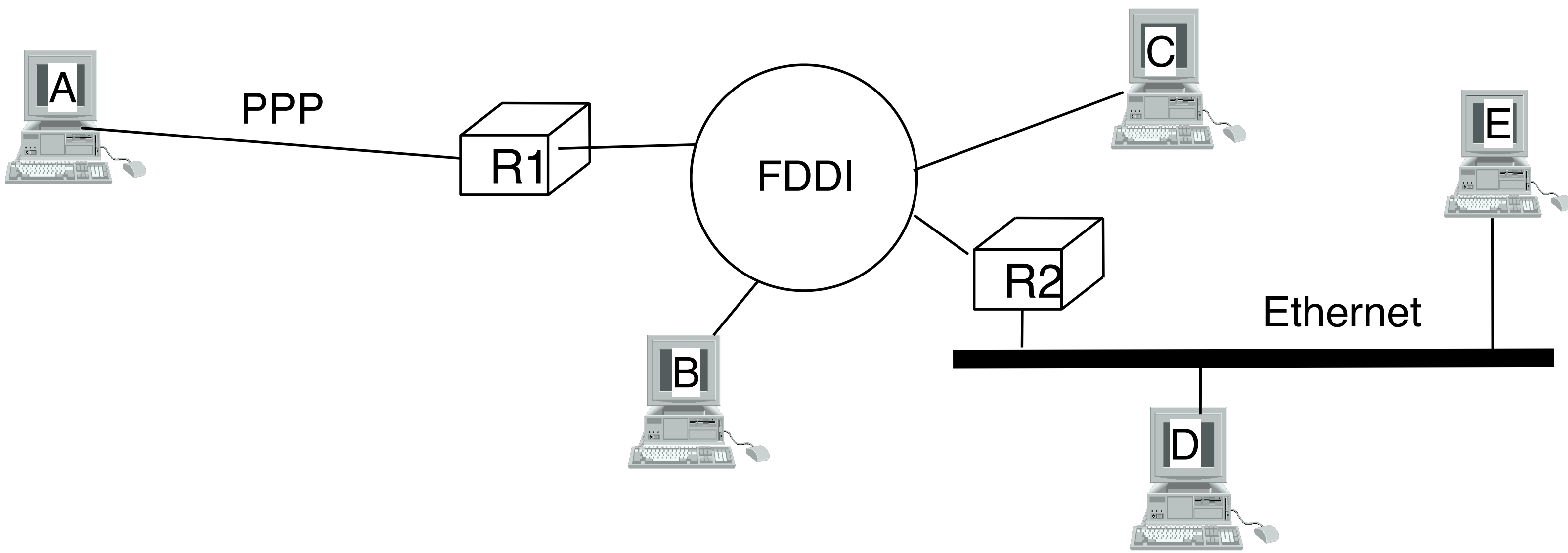


- Internet network layer
  - provides unreliable connectionless service
    - some packets can be lost
    - packets can suffer from transmission errors
    - packets can be misordered

IPv4 is defined in RFC791

Basic principles

Datagram mode

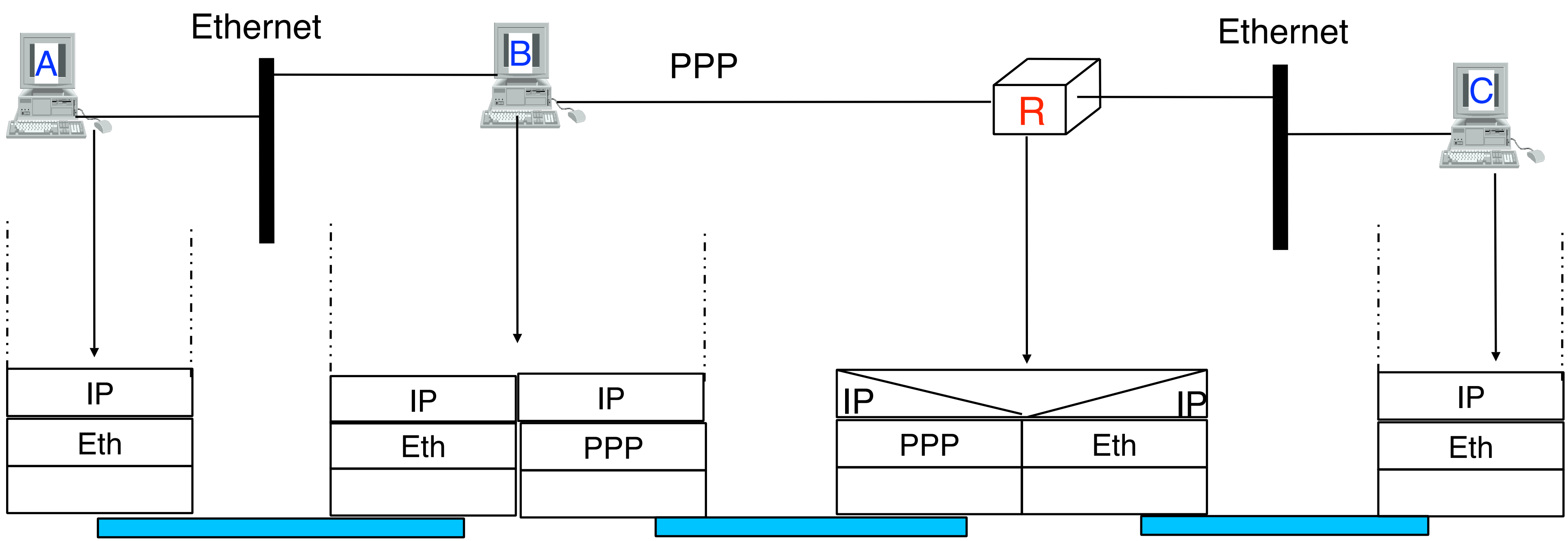


Each host is identified by one IP address (encoded as 32 bits number)

Each host knows how to reach at least one router

Routers know how to reach other routers

Basic principles (2)



- Endhost
  - equipment able to send and receive packets originated by or destined to it
- Router
  - equipment able to send and receive packets originated by or destined to it
  - equipment able to forward toward theirs destination packets that it did not originate

IP Addressing

IP Addressing

Utilisation of IP address

- identify a host/router that implements IP
  - usually, one IP address identifies one (physical) interface on one endhost or router
    - (physical) interface is access point to datalink layer
    - usually endhosts have a single interface
    - routers have more than one interface

- Encoding of 32 bits IP address
  - 10001010 00110000 00011010 00000001
  - **138 . 48 . 26 . 1**

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- Encoding of 32 bits IP address
  - 10001010 00110000 00011010 00000001
  - **138 . 48 . 26 . 1**

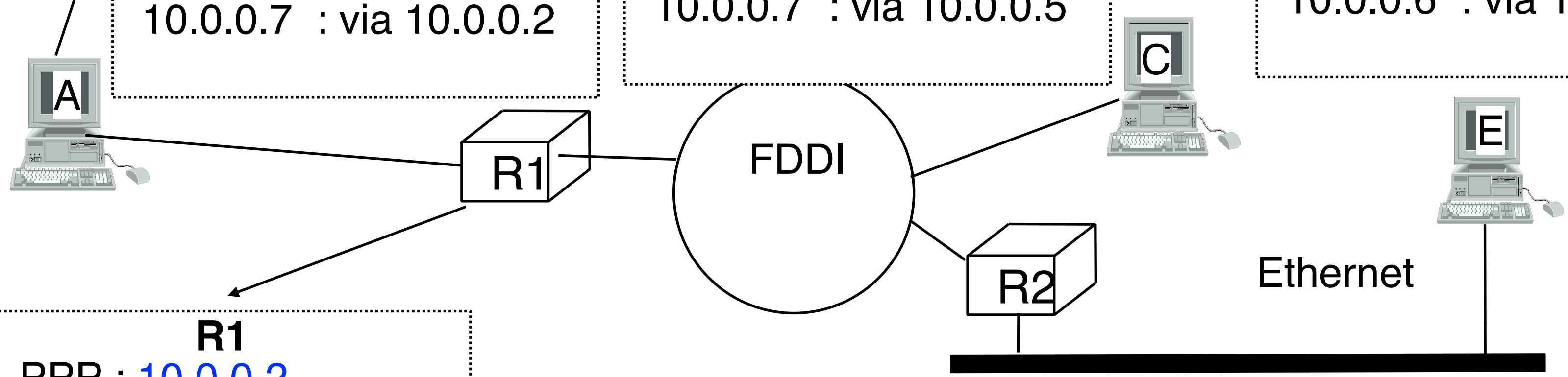
- How to allocate IP addresses to hosts in a campus network
  - Naive solution
    - First come first served

Naive IP addressing

A
PPP: 10.0.0.1
Routes
10.0.0.2 : PPP
10.0.0.3 : via 10.0.0.2
10.0.0.4 : via 10.0.0.2
10.0.0.5 : via 10.0.0.2
10.0.0.6 : via 10.0.0.2
10.0.0.7 : via 10.0.0.2

C
FDDI : 10.0.0.4
Routes
10.0.0.1 : via 10.0.0.3
10.0.0.2 : via 10.0.0.3
10.0.0.3 : FDDI
10.0.0.5 : FDDI
10.0.0.6 : via 10.0.0.5
10.0.0.7 : via 10.0.0.5

E
Ethernet : 10.0.0.7
Routes
10.0.0.1 : via 10.0.0.6
10.0.0.2 : via 10.0.0.6
10.0.0.3 : via 10.0.0.6
10.0.0.4 : via 10.0.0.6
10.0.0.5 : Ethernet
10.0.0.6 : via 10.0.0.6



R1
PPP : 10.0.0.2
FDDI : 10.0.0.3
Routes
10.0.0.1 : PPP
10.0.0.4 : FDDI
10.0.0.5 : FDDI
10.0.0.6 : via 10.0.0.5
10.0.0.7 : via 10.0.0.5

R2
FDDI : 10.0.0.5
Ethernet : 10.0.0.6
Routes
10.0.0.1 : via 10.0.0.3
10.0.0.2 : via 10.0.0.3
10.0.0.3 : FDDI
10.0.0.4 : FDDI
10.0.0.7 : Ethernet

Hierarchical allocation of IP addresses

- Allocation of IP addresses
  - one address per interface
  - each address composed of two parts
    1. subnetwork identifier
       - M high order bits of IP address
    2. equipment identifier inside the subnetworks
       - *32-M* bits low order bits of IP address
  - Example

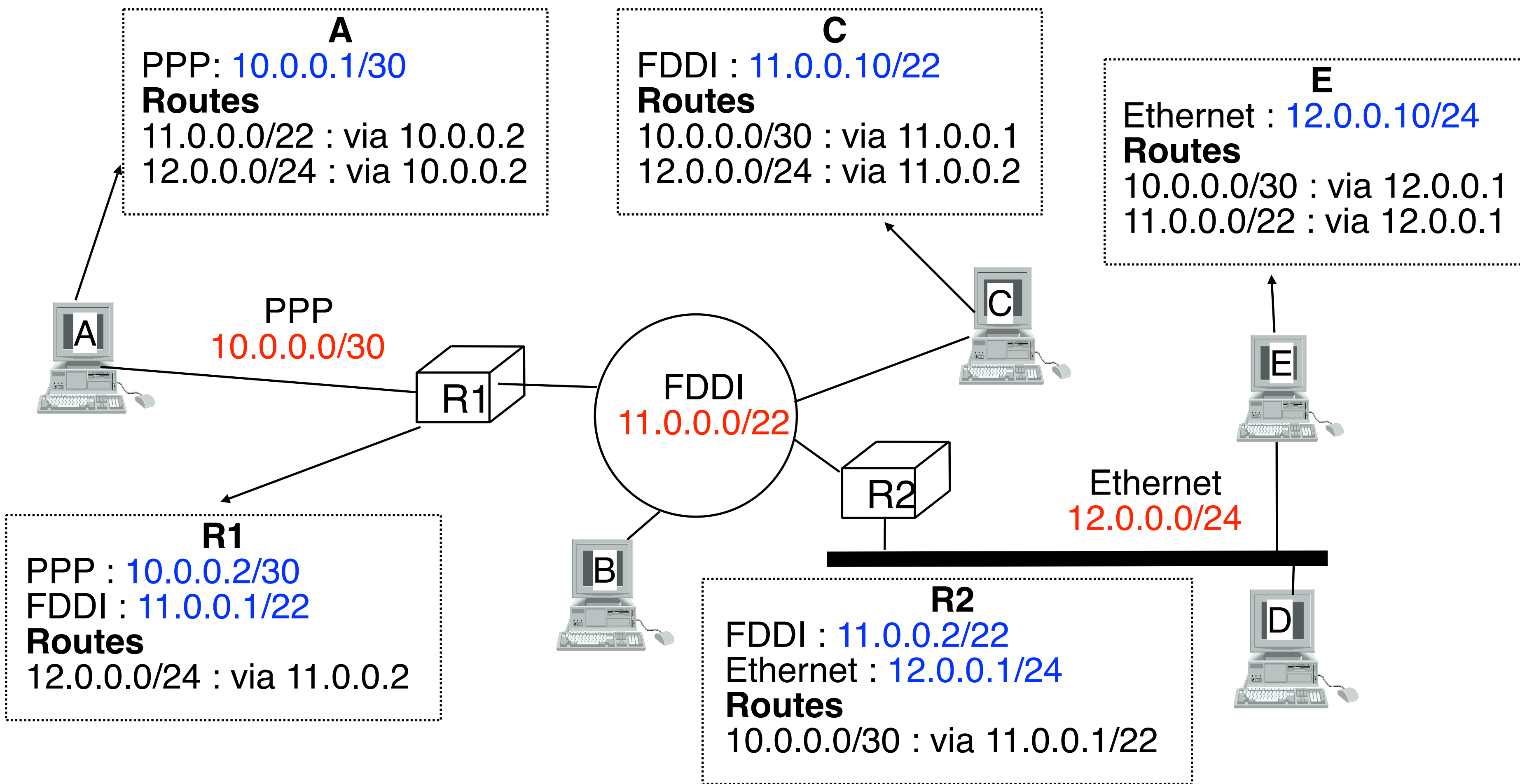
10001010 00110000 0001101*0 00000001*

subnetwork id — *host id*

Notation 138.48.26.1/23 or 138.48.26.1 255.255.254.0

All hosts that belong to the same subnetwork can directly exchange frames through datalink layer

IP addressing : examples



Drawbacks of subnetworks
- most subnetworks are not fully occupied
- a campus network will need more IP addresses than the number of hosts attached to the network

IP addresses

IP addresses

Most addresses are allocated by IANA
and the regional registries RIPE, ARIN, ...

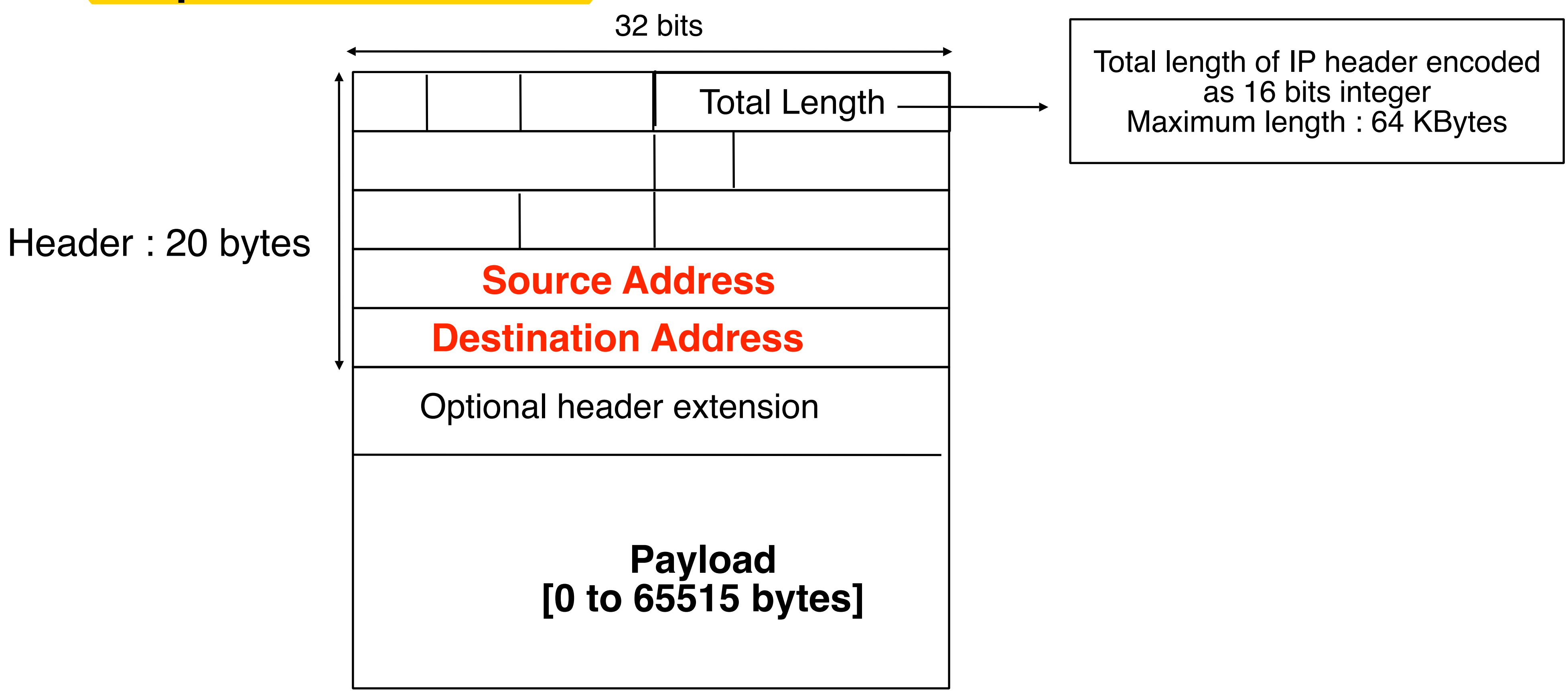
IP addresses

- Most addresses are allocated by IANA and the regional registries RIPE, ARIN, ...

- But some addresses play a special role
  - 127.0.0.1
    - Loopback address on each host
      - Allows to reach servers on the local host
  - 10.0.0.0/8, 172.16.0.0/12 and 192.168.0.0/16
    - used for private networks (not directly attached to Internet)
  - 218.0.0.0/8 - 223.0.0.0/8 and 240.0.0.0/8 - 255.0.0.0/8
    - reserved for further utilization
  - 224.0.0.0/8 - 239.0.0.0/8
    - used by IP multicast
  - 255.255.255.255
    - broadcast address
  - 0.0.0.0
    - used when a host is booting and does not yet know its address

IP Packets

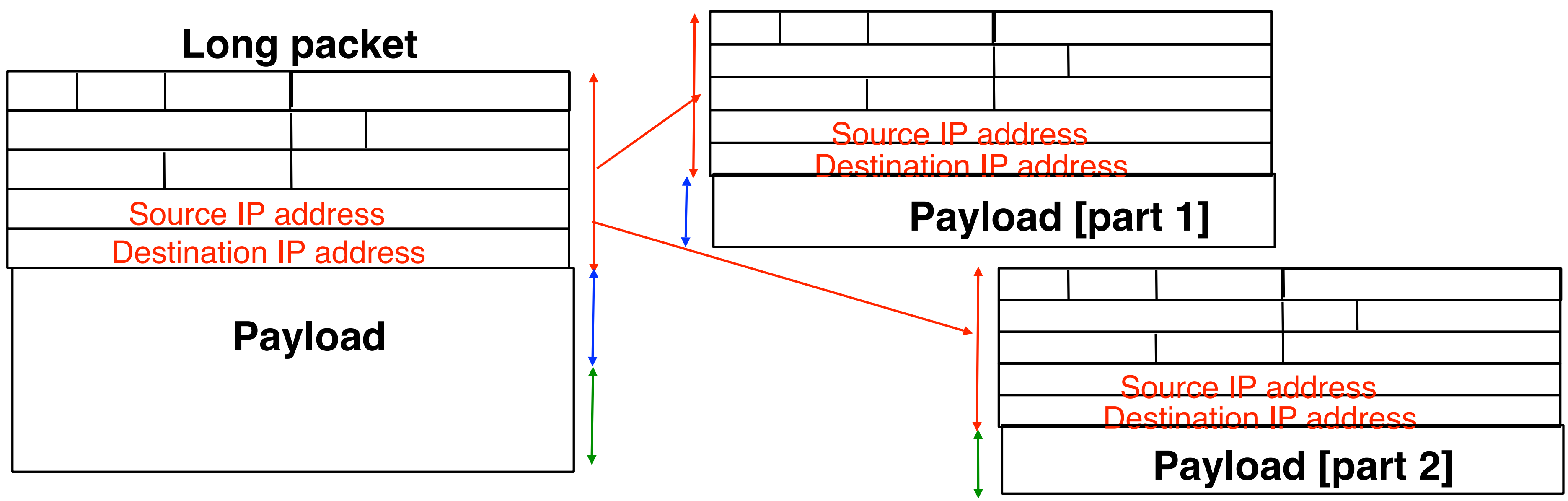
IP packet format



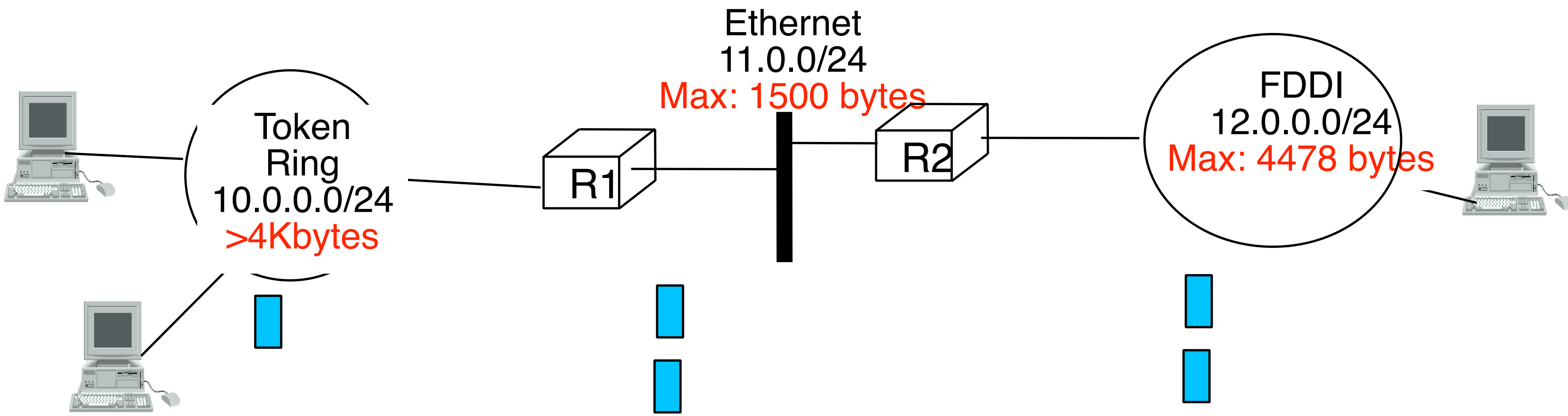
How can we transmit a 64 KBytes packet ?

Transmission of long IP packets

- Principe
  - Each host and each router can fragment packets
    - Each fragment is a complete IP packet that contains source and destination IP addresses
  - Only the destination host performs reassembly



Transmission of long IP packets (2)



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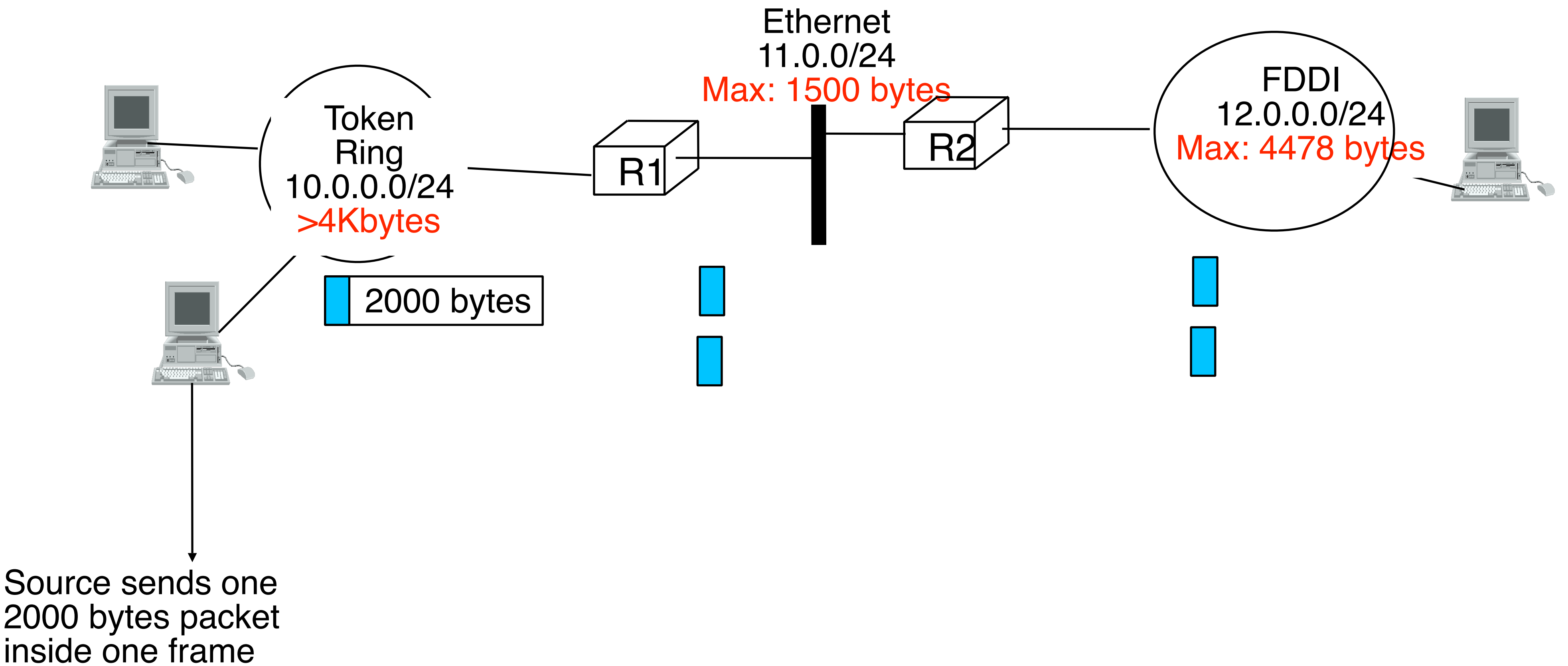

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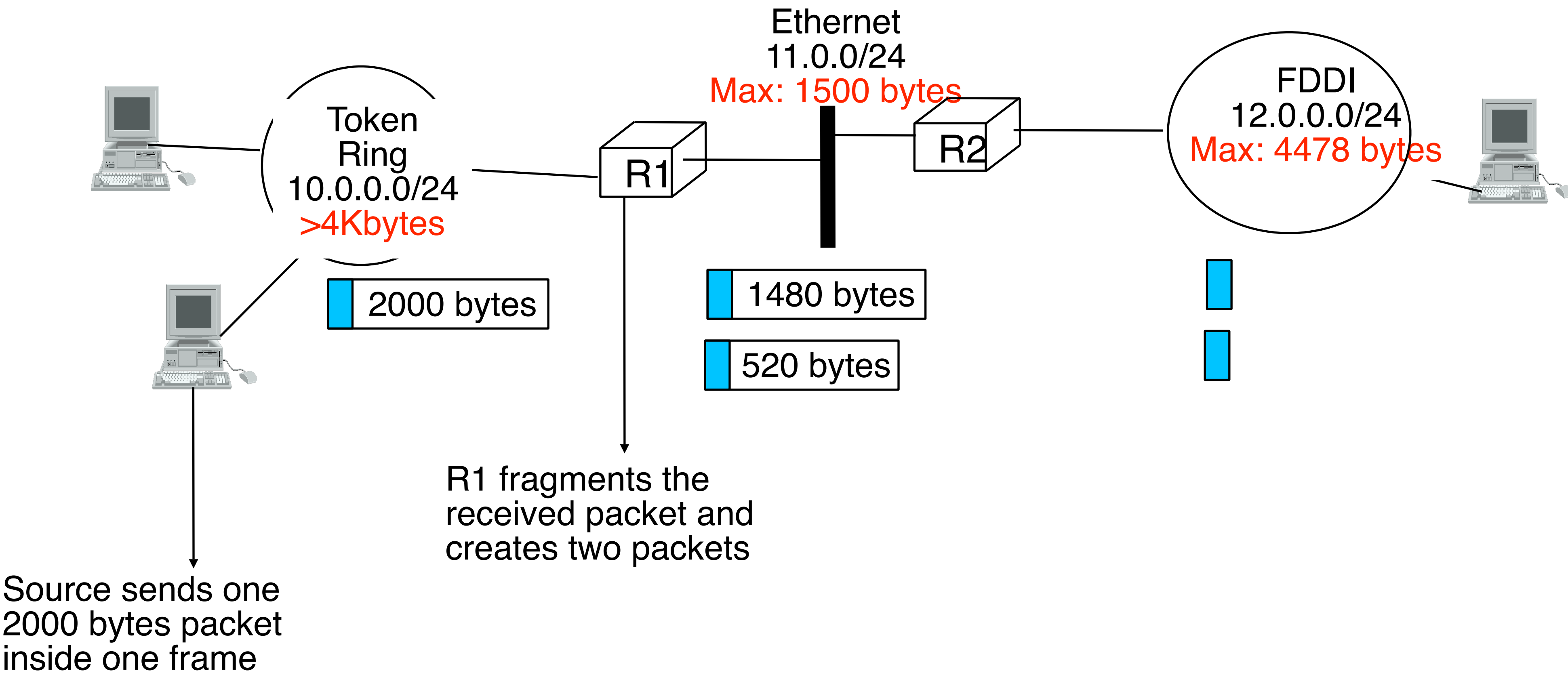

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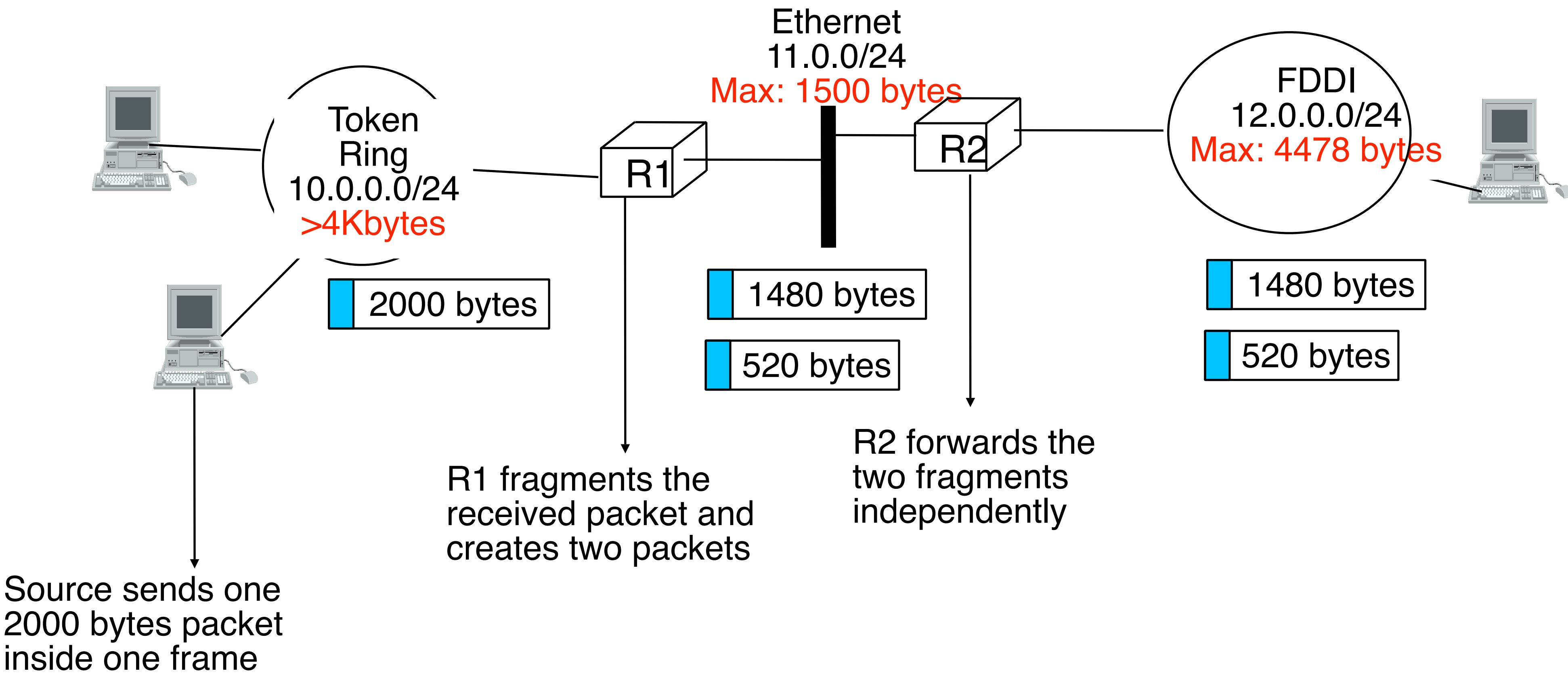

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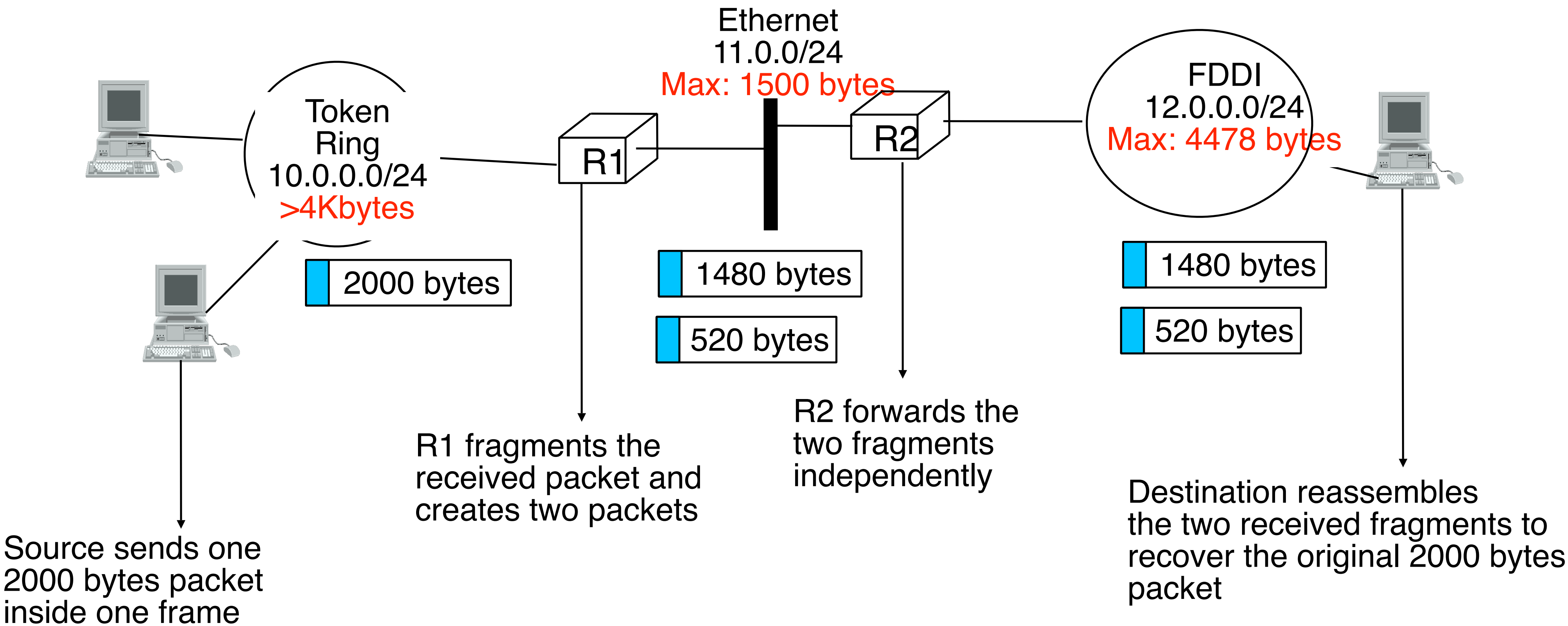
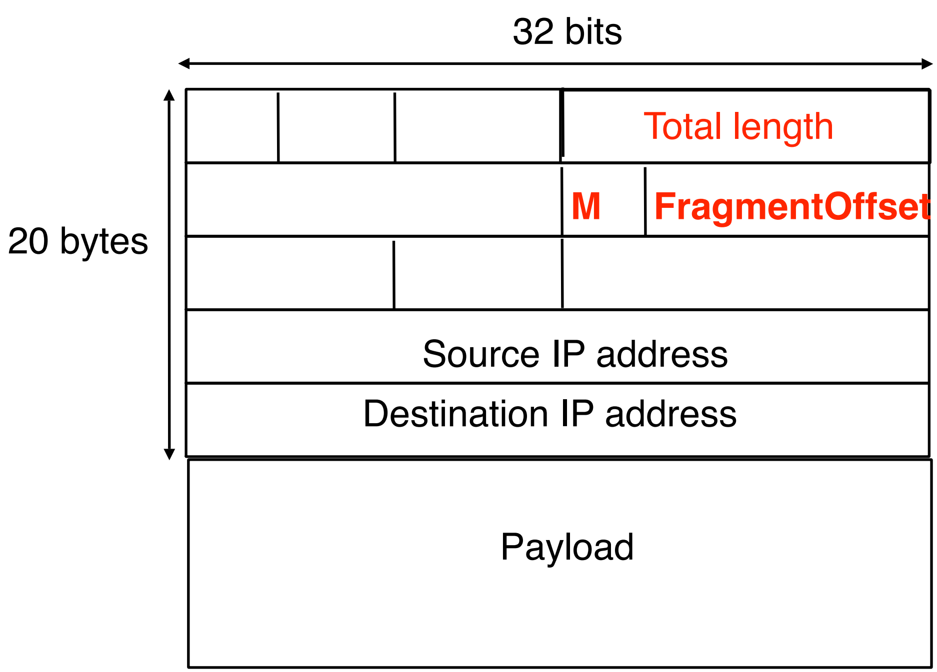


How to deal with limited MTU links ?

IP fragmentation
- Fragment the payload of IP packet
- Each fragment must be number to recover from misordering



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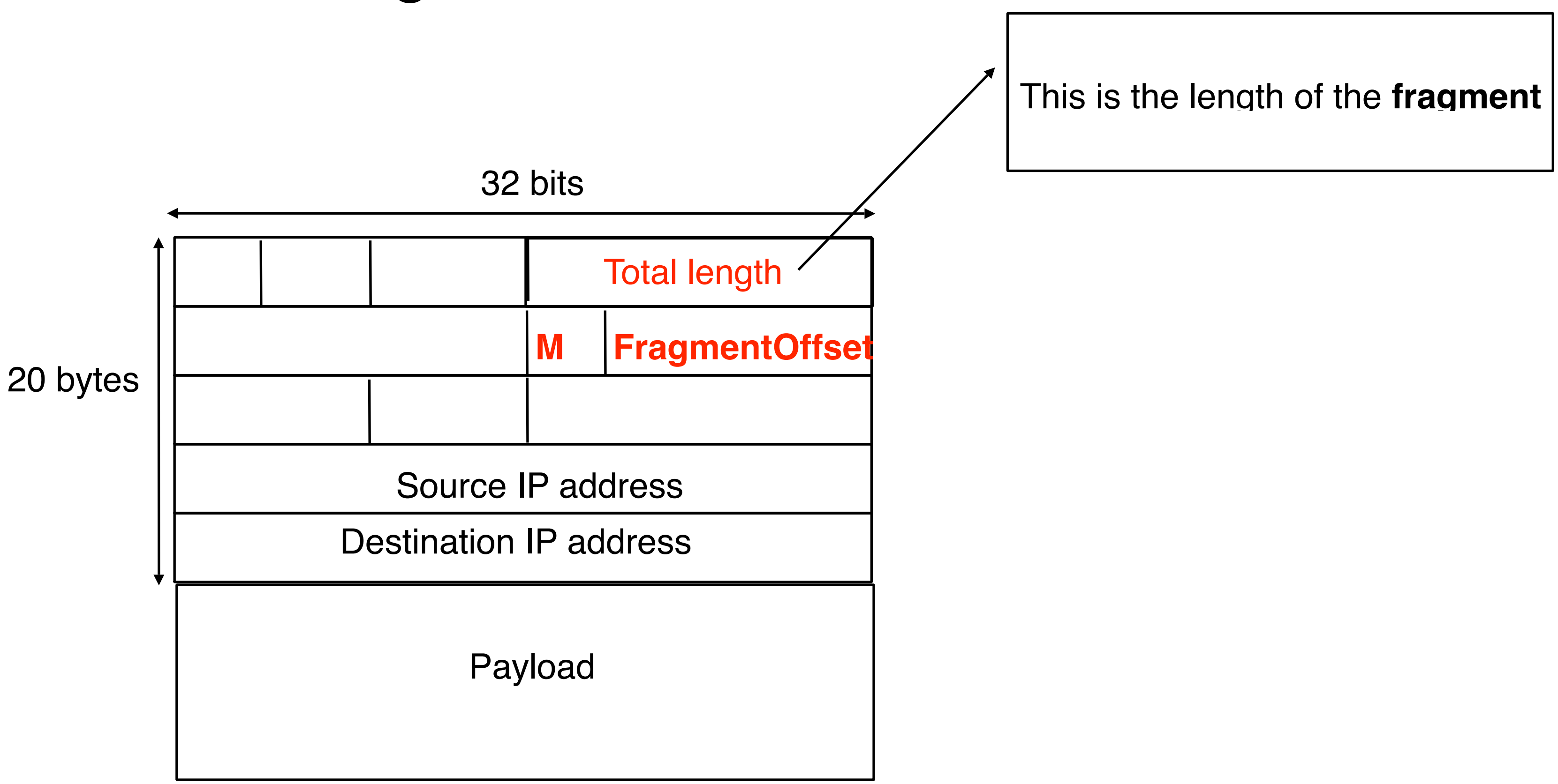

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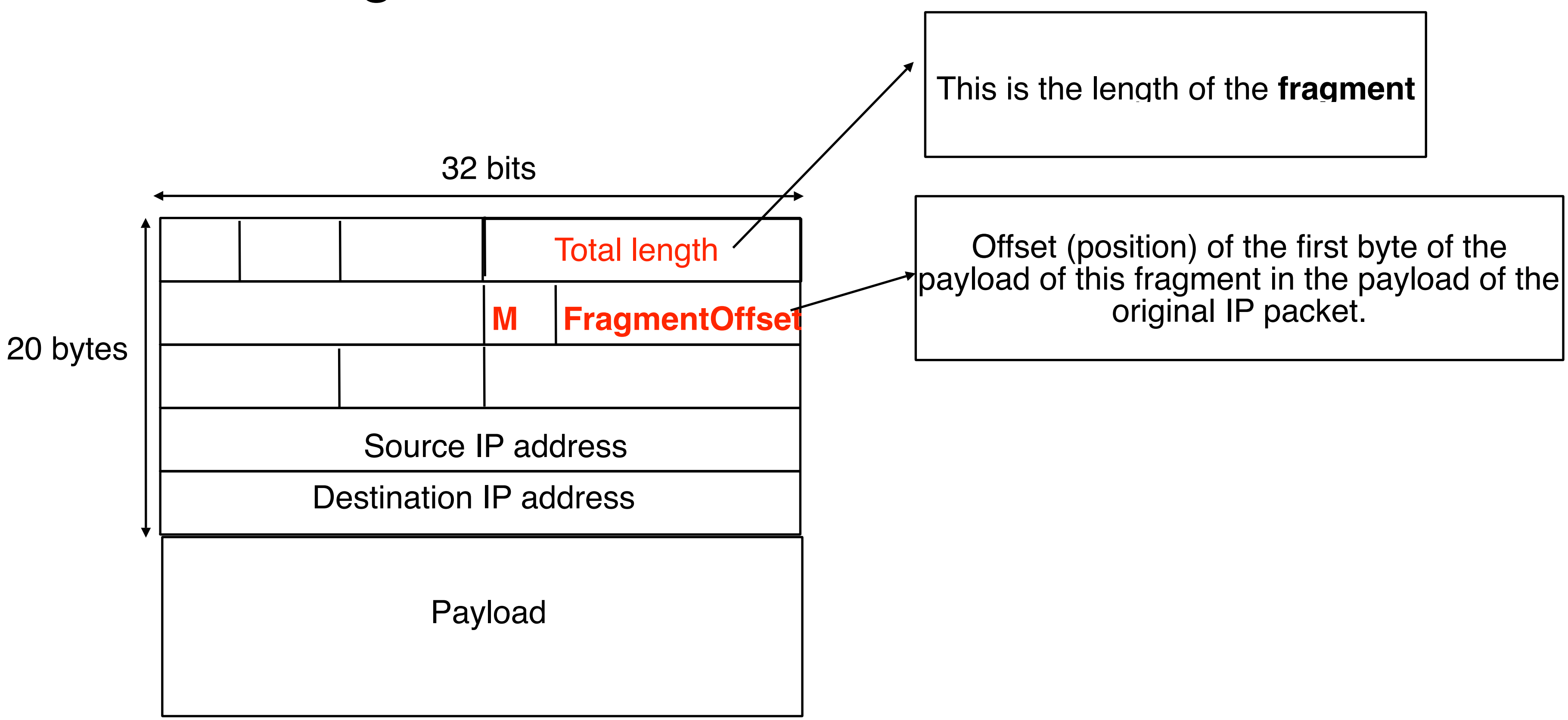

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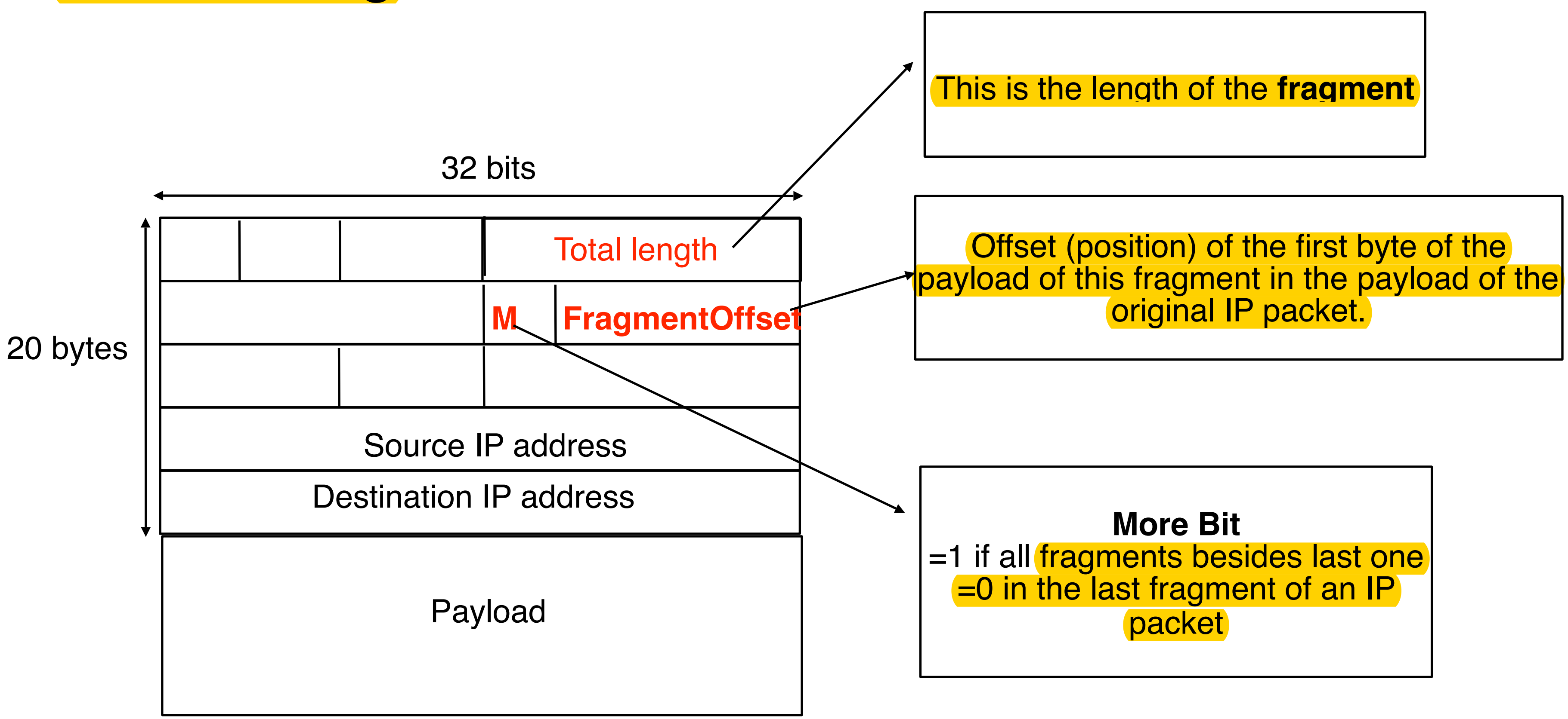
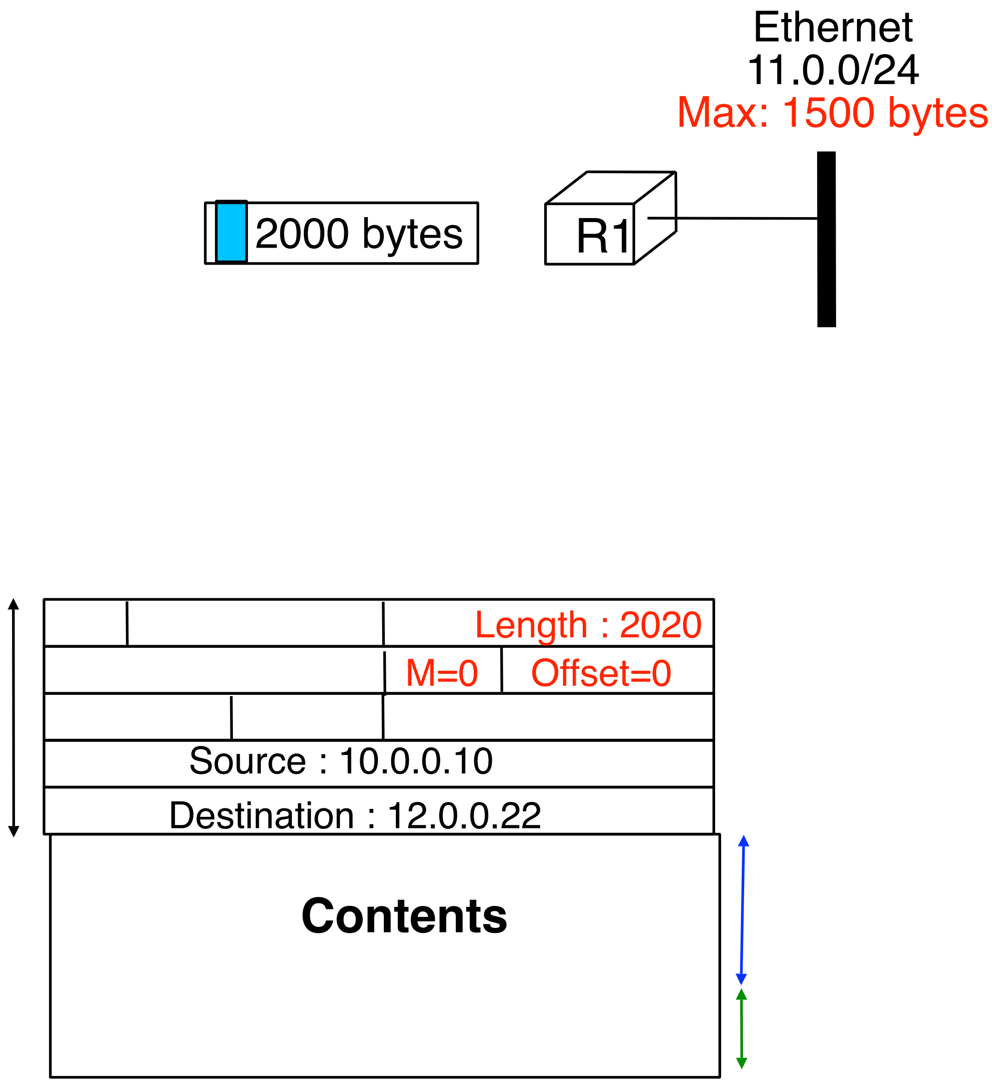


Fragmentation : example



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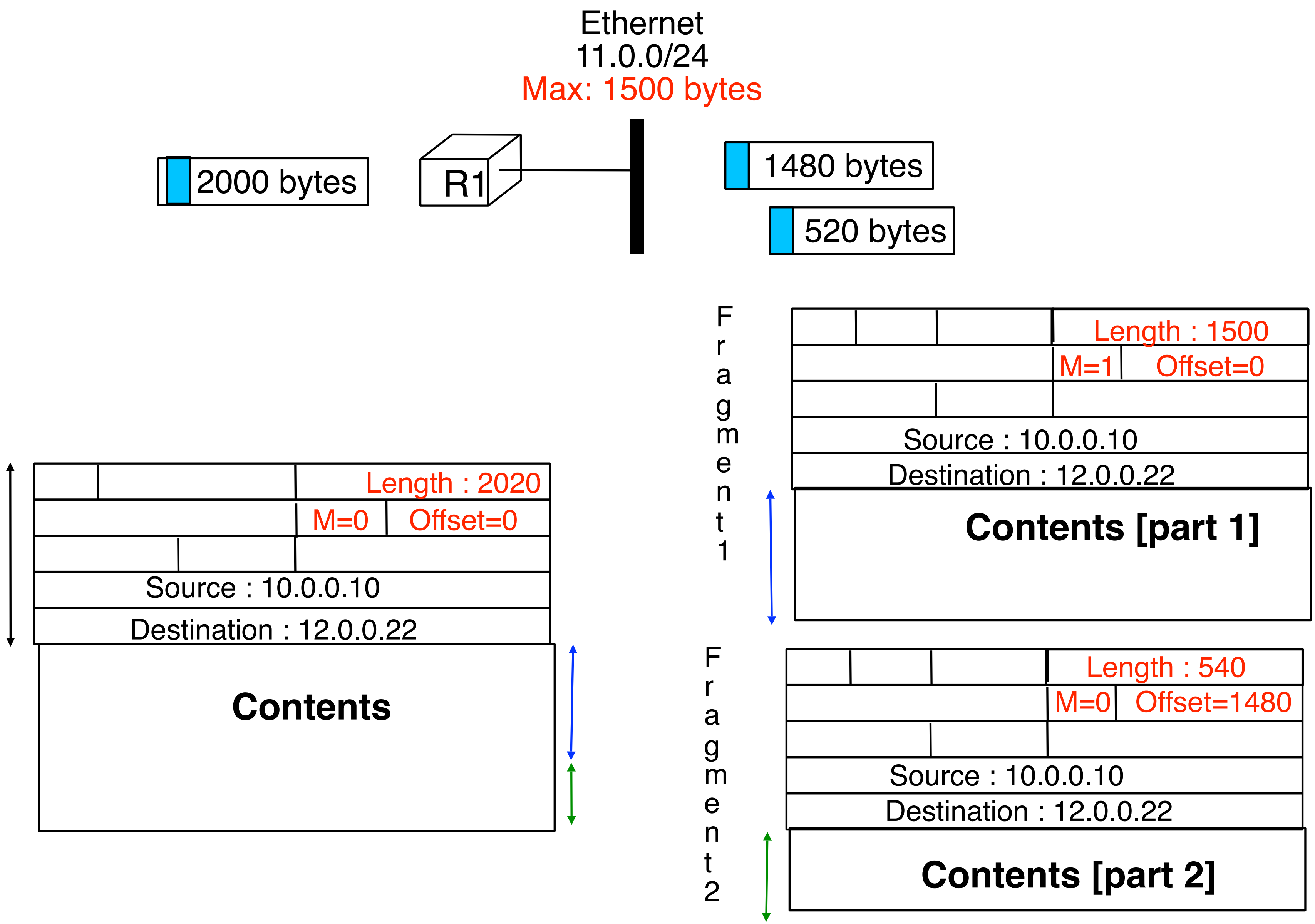
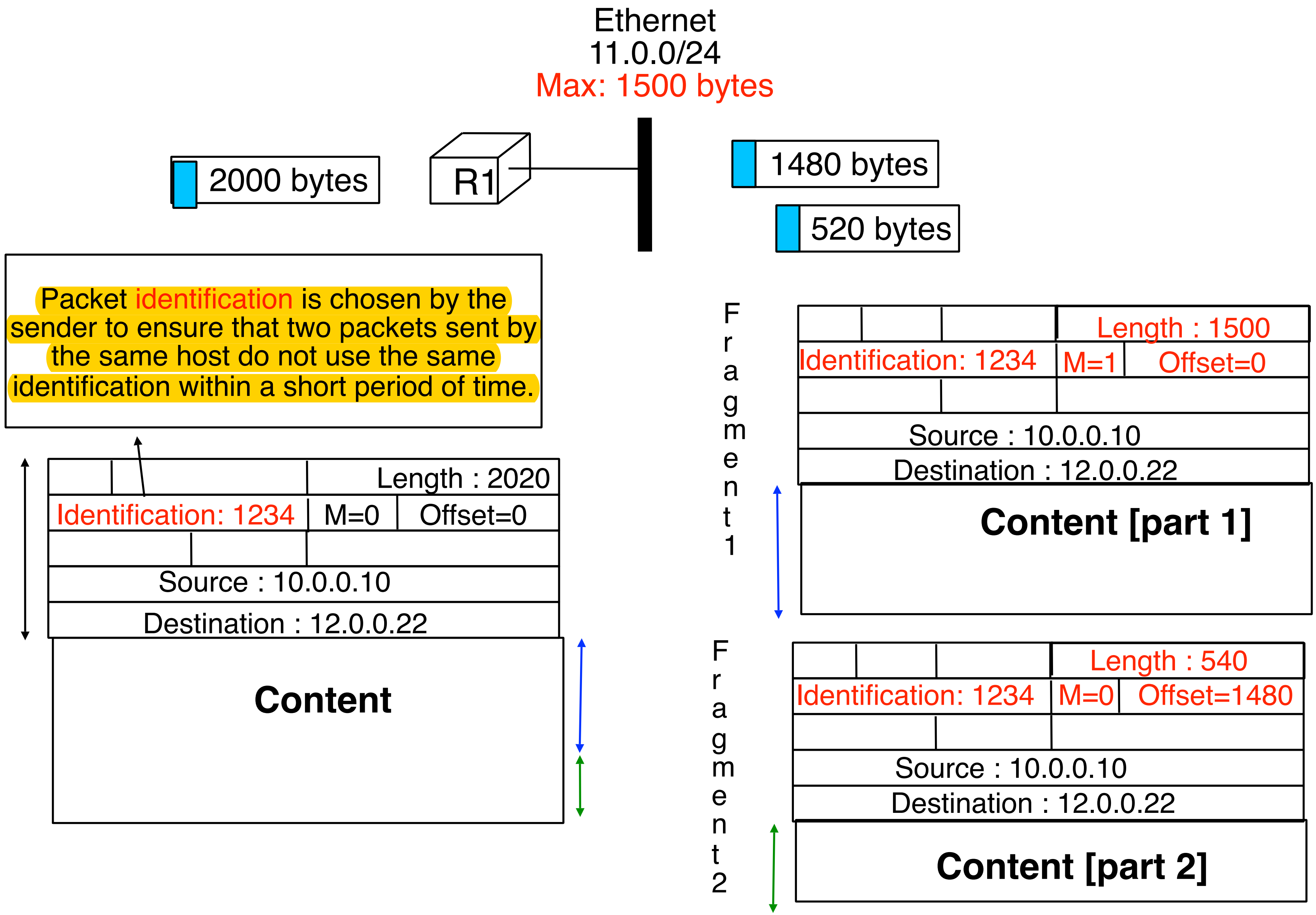


Reassembly

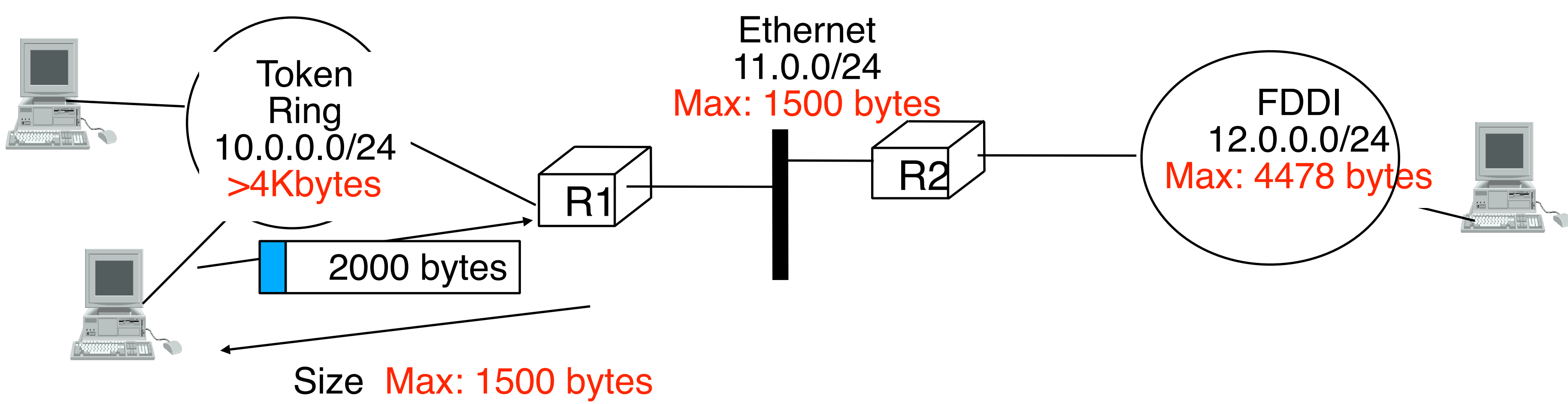
- Issues
  - When does the destination has received all fragments ?
    - Last fragment contains bit More=0
    - How to handle lost fragments ?
      - the IP packet will not be reassembled by destination and received fragments of this packet will be discarded
  - How to deal with misordering
    - Offset field allows to reorder fragments from same packet
    - But misordering can cause fragments from multiple packets to be mixed
      - Each fragment must contain an identification of the original packet from which is was created

Packets and fragments identification



How to avoid fragmentation ?

- Problem
  - How can a host determine the maximum packet size that he can use to reach a destination ?
  - Solution
    - Instead of performing fragmentation, the router could indicate the maximum packet size that it supports



- Knowing this maximum packet size, the endhost can send correctly sized packets

Transmission errors

How should IP react to transmission errors ?

- Transmission error inside packet content
  - some applications may continue to work despite this error
  - IP : no detection of transmission errors in packet payload
- Transmission error inside packet header
  - could cause more problems
    - imagine that the transmission error changes the source or destination IP address
  - IP uses a checksum to detect transmission errors in header
    - 16 bits checksum (same as TCP/UDP) computed only on header
    - each router and each end host verifies the chacksum of all packets that it receives. A packet with an errored header is immediately discarded

Transient and permanent loops

Transient and permanent loops

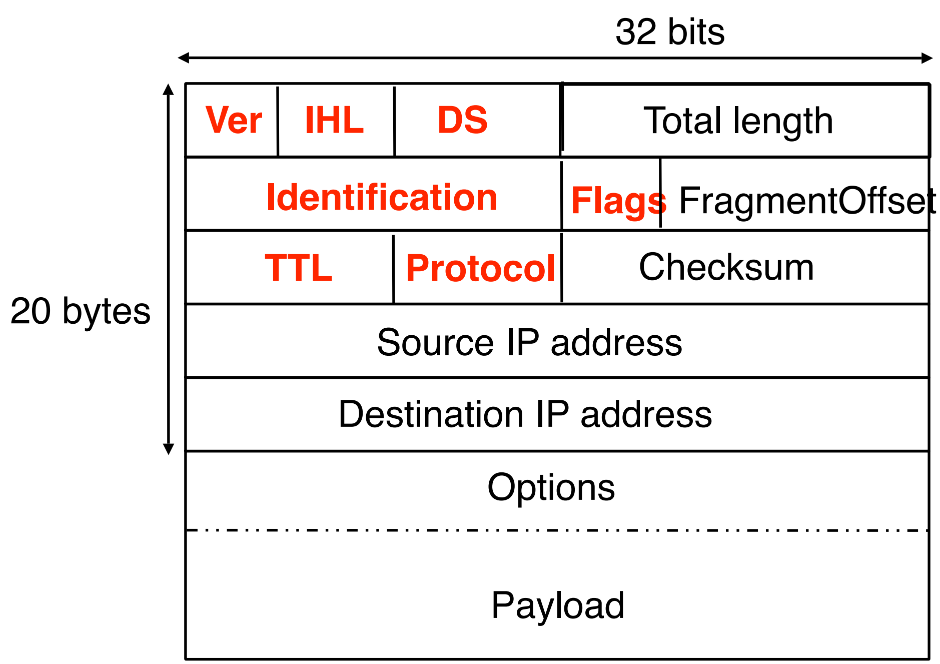
Problem

- Loops can occur in an IP network
  - permanent loops due to configuration errors
  - transient loops while routing tables are being updated

Transient and permanent loops

- Problem
  - Loops can occur in an IP network
    - permanent loops due to configuration errors
    - transient loops while routing tables are being updated
- Solution
  - Each packet contains a Time-to-Live (TTL) that indicates the maximum number of intermediate routers that the packet can cross
    - many hosts set the initial TTL of their packets to 32 or 64
  - each router checks the TTL of all packets
    - If TTL=1, packet is discarded and source is notified
    - If TTL>1, packet is forwarded and TTL is decremented by at least 1
      - routers thus must recompute checksum of all forwarded packets
  - Utilisation of TTL is a means to bound the lifetime of packets inside the Internet

IP header format



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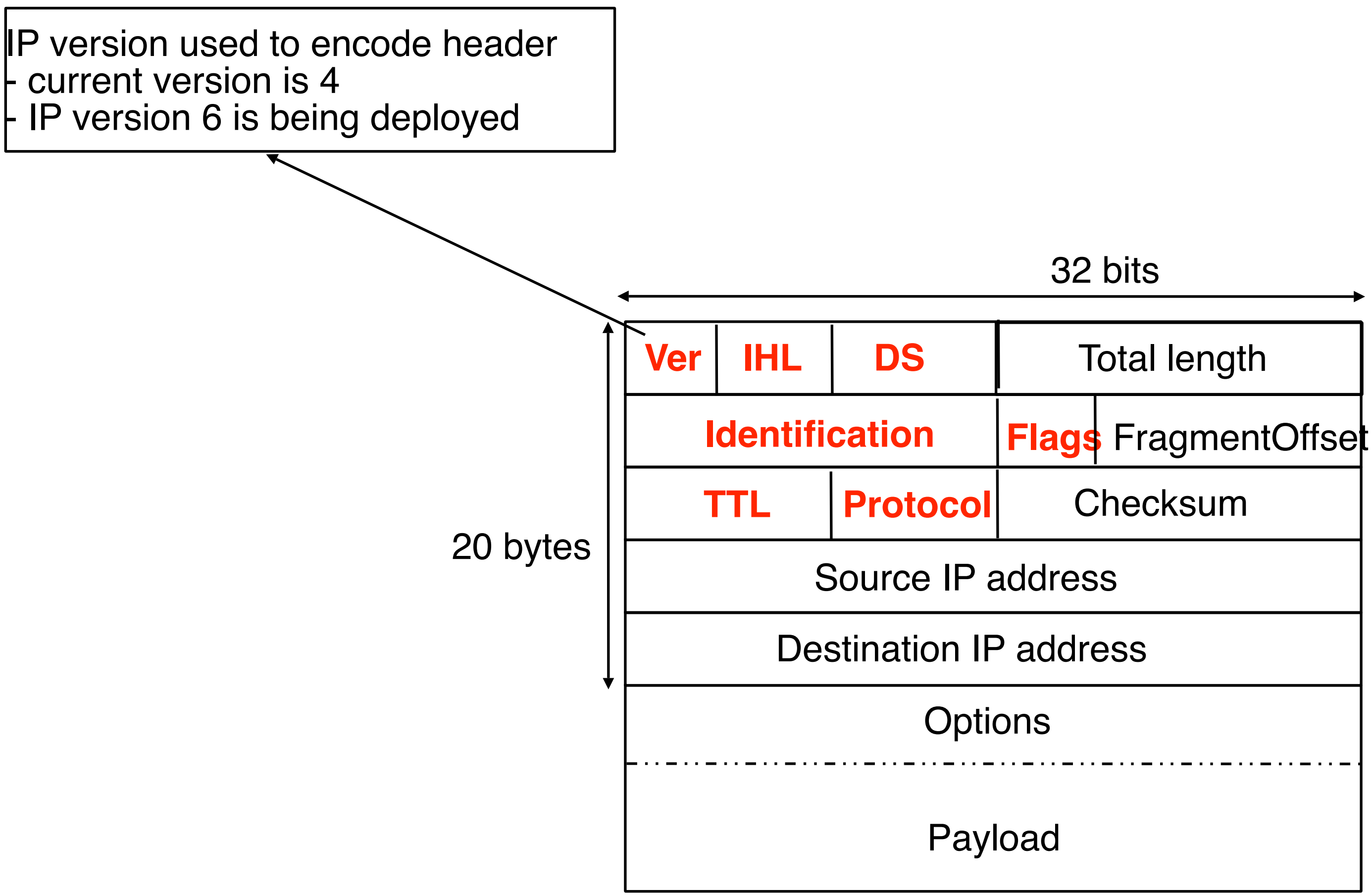

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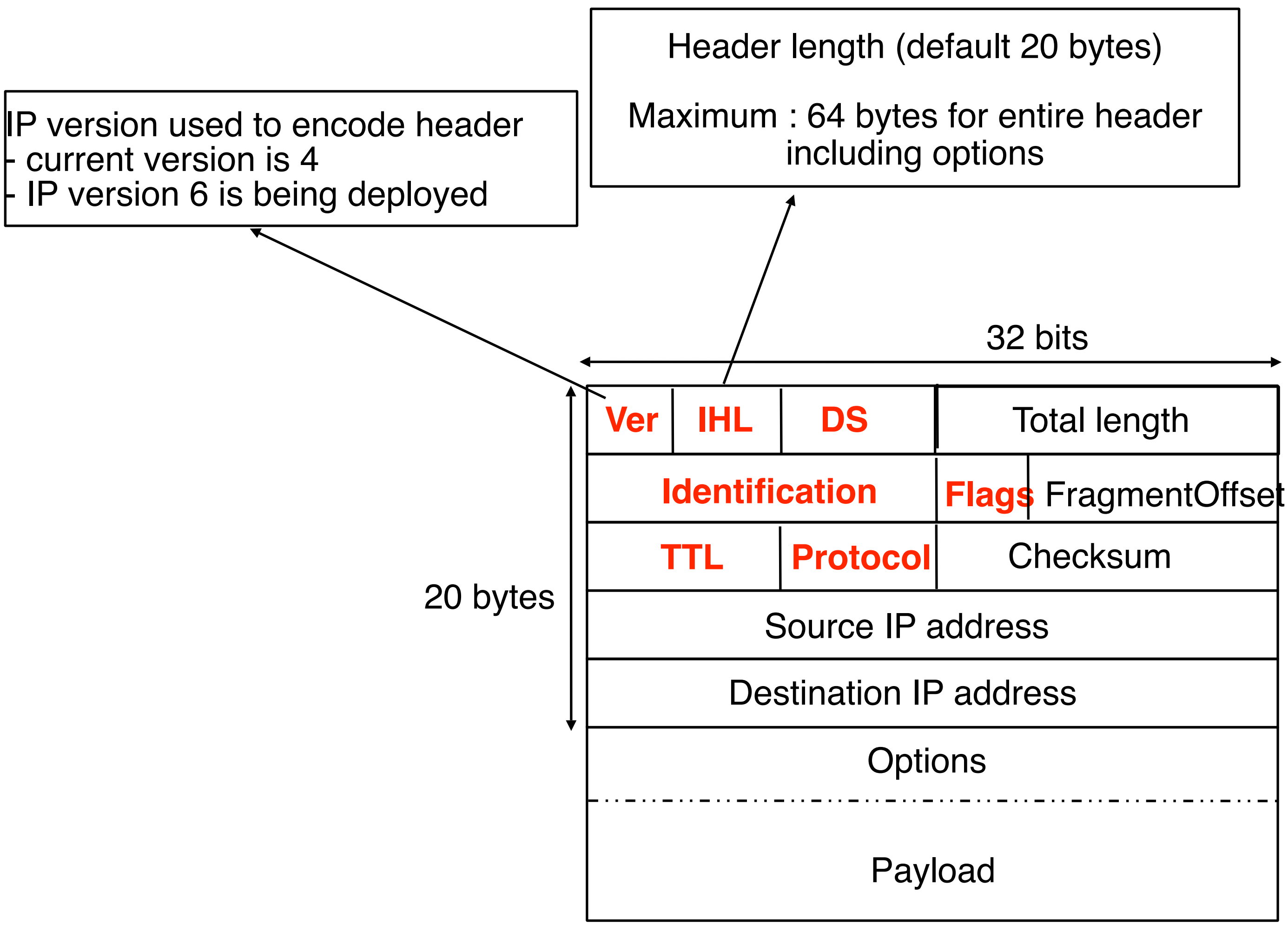

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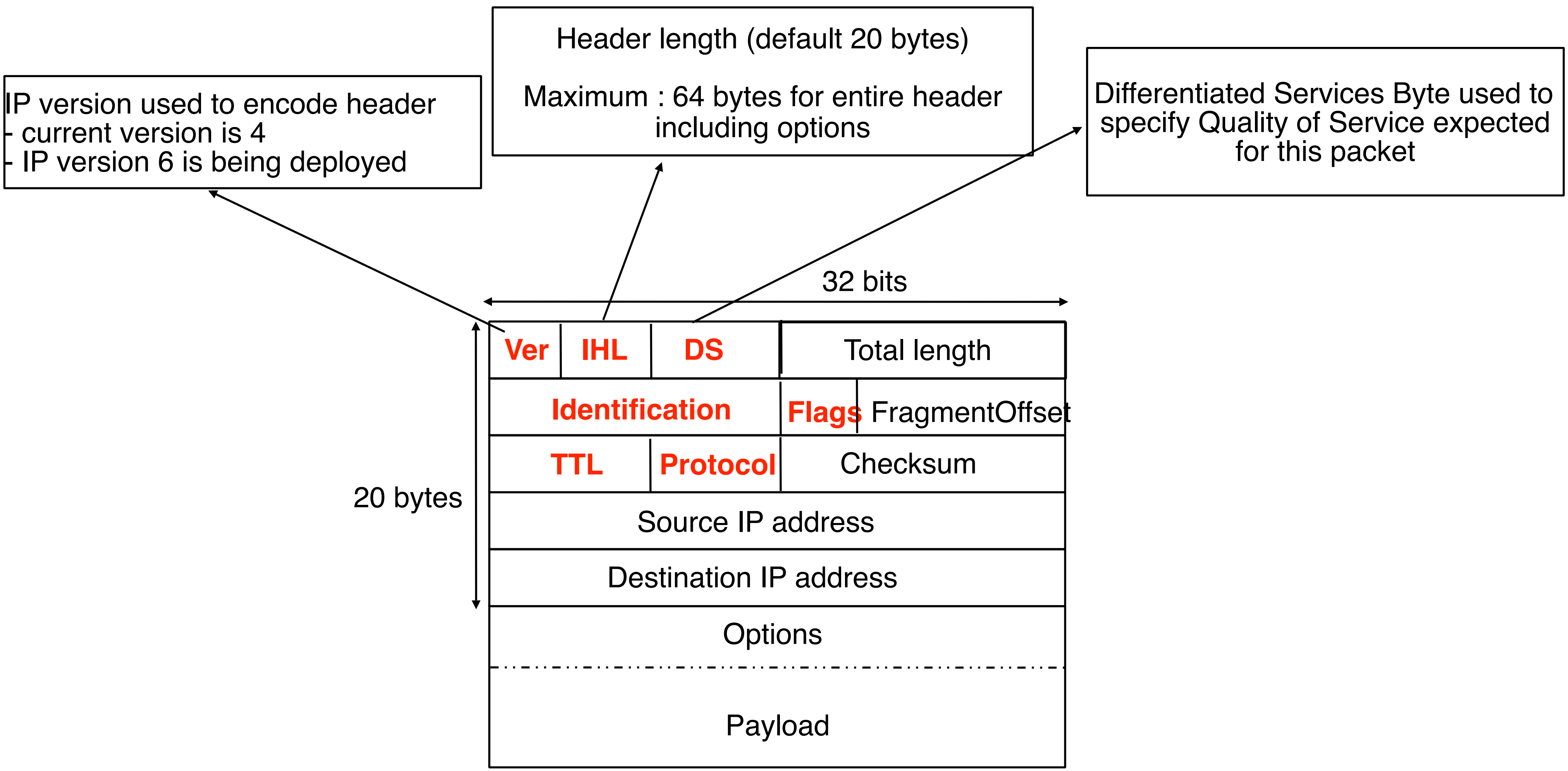

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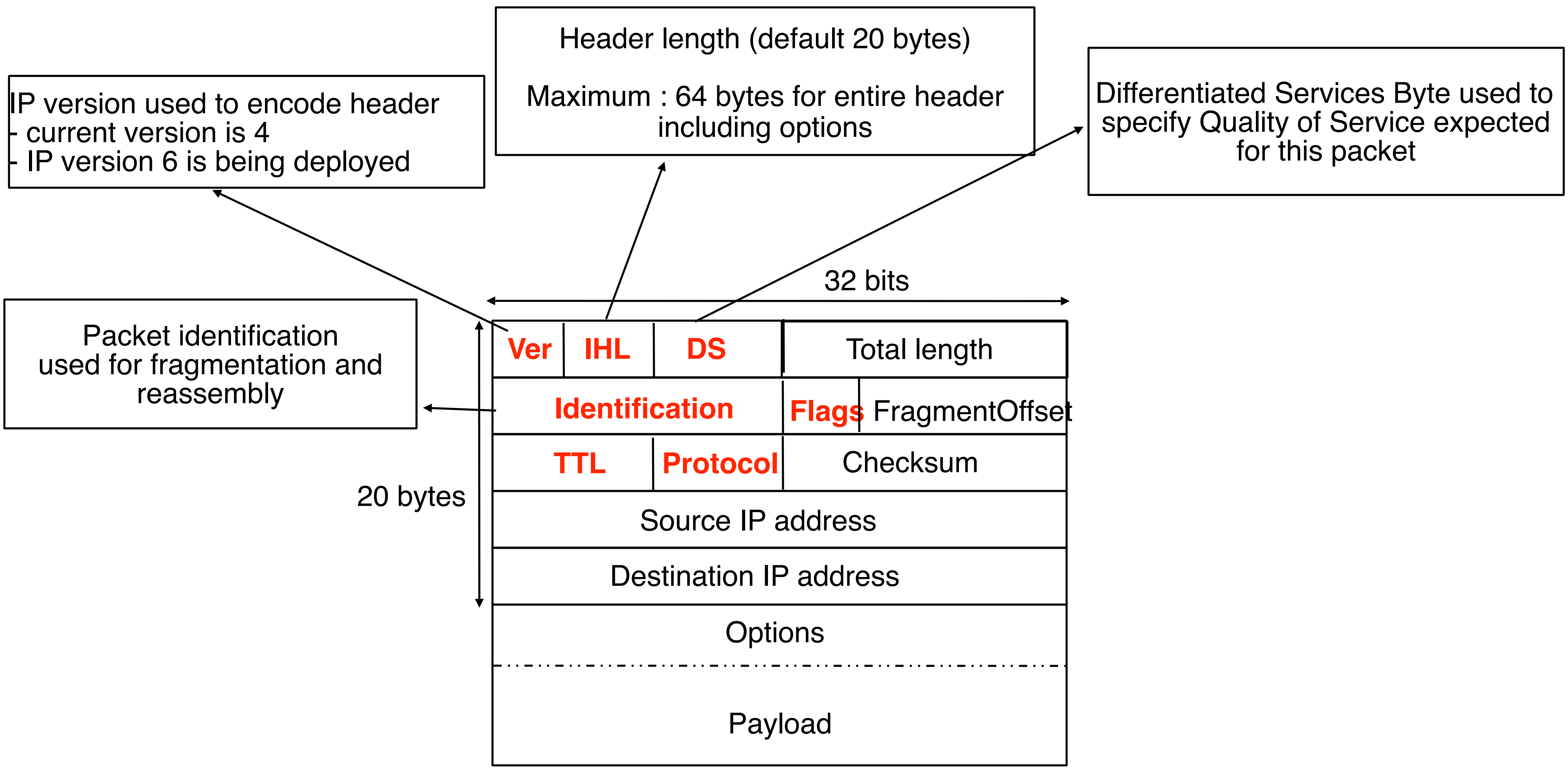

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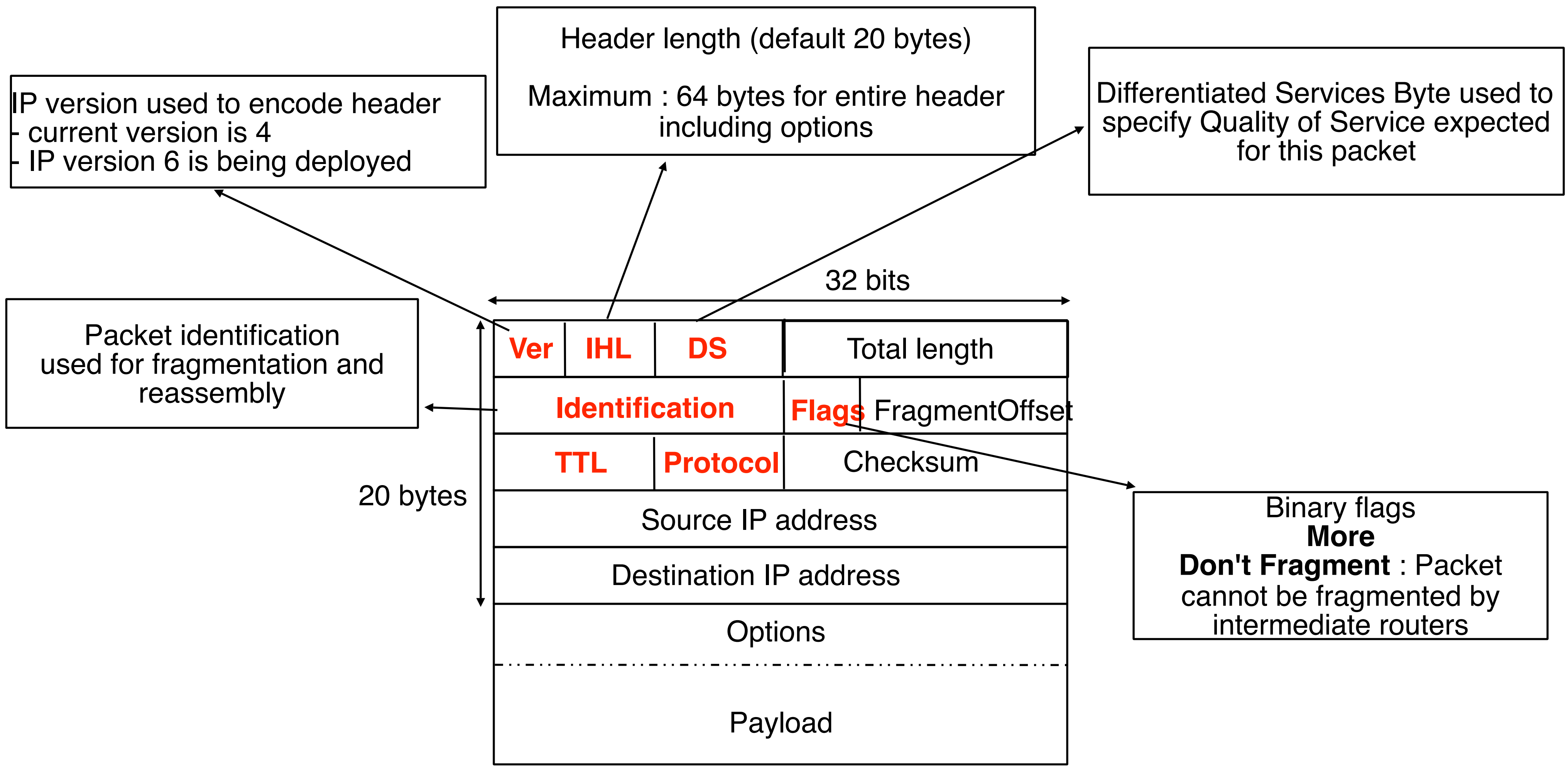

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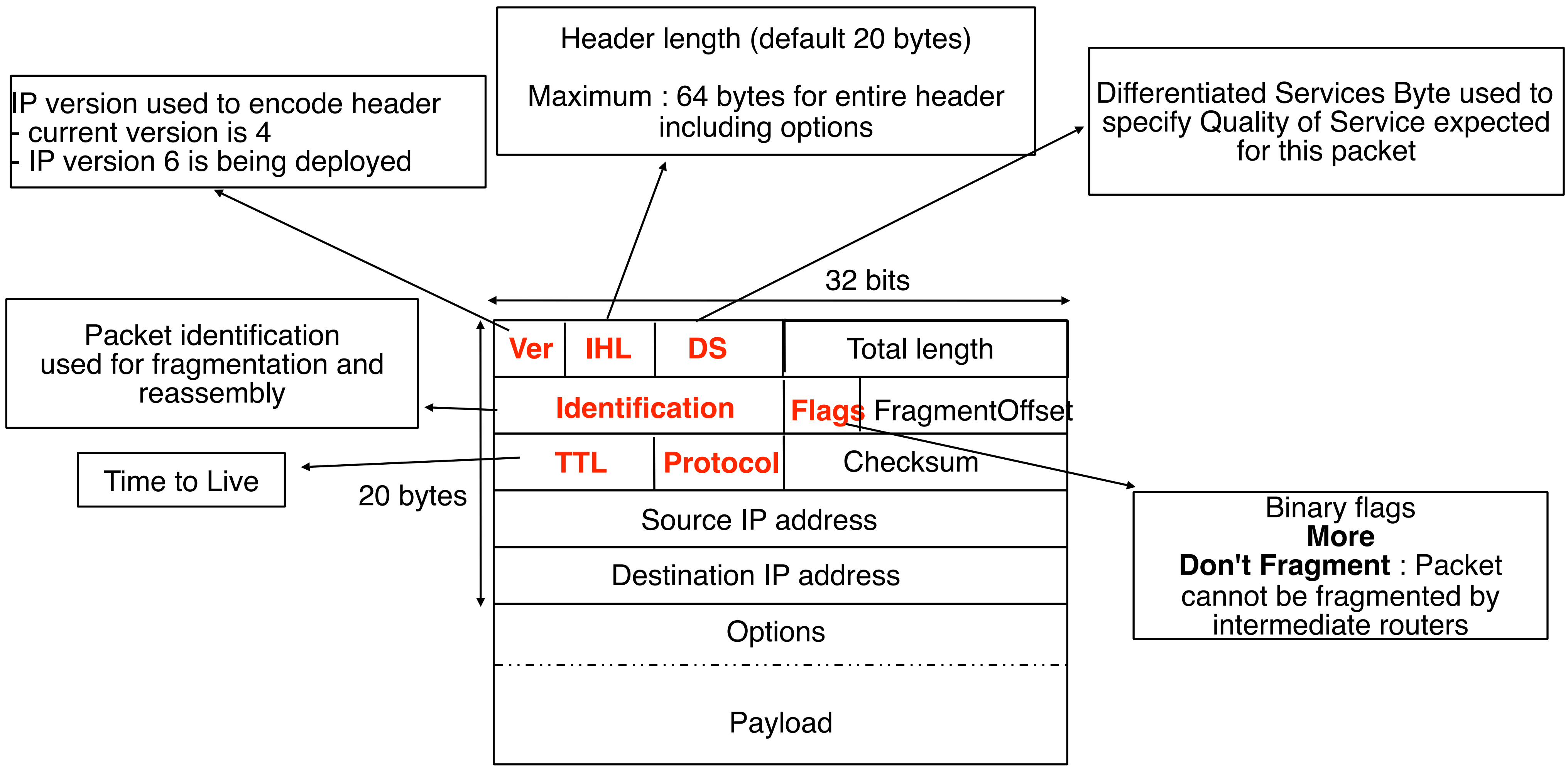

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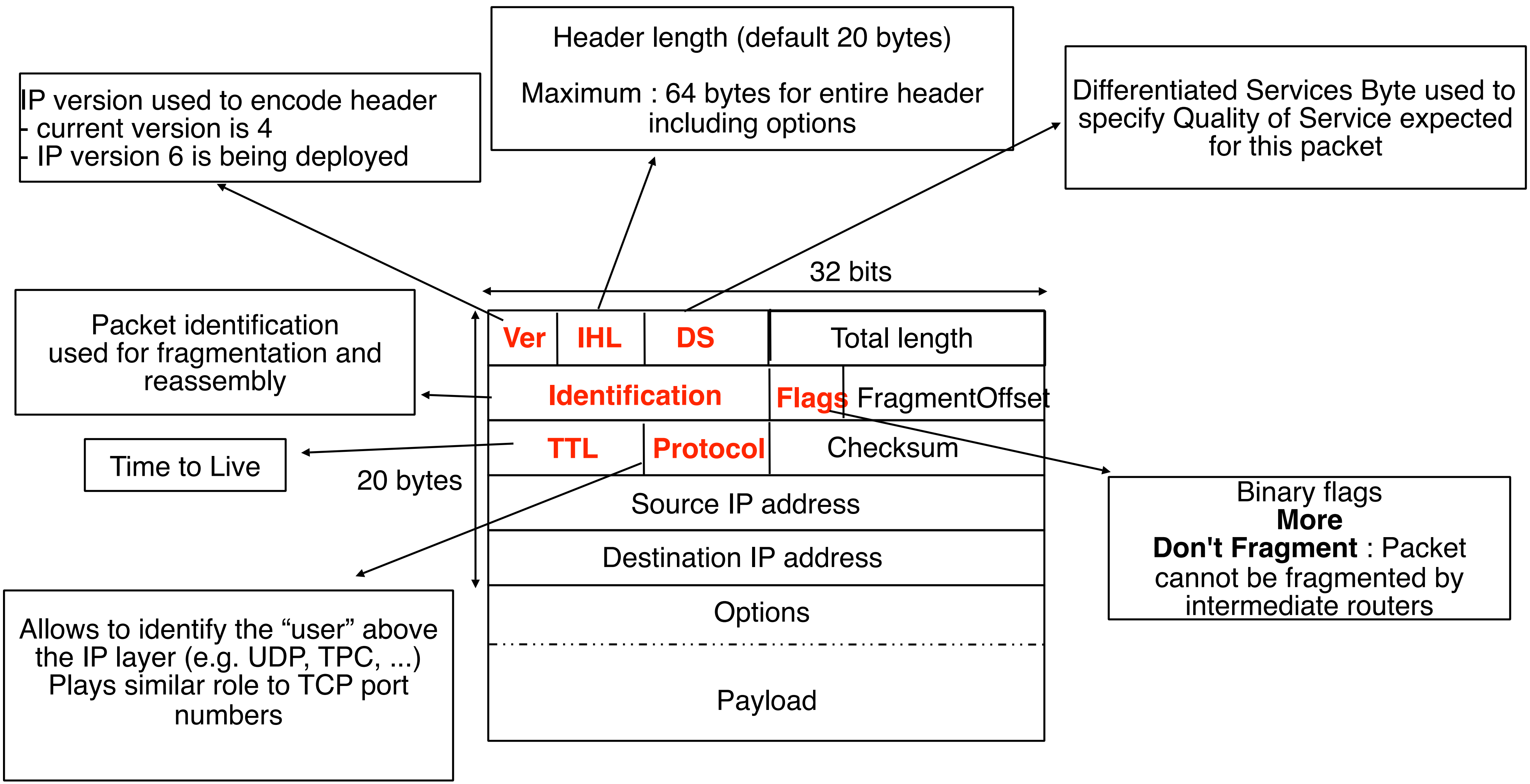

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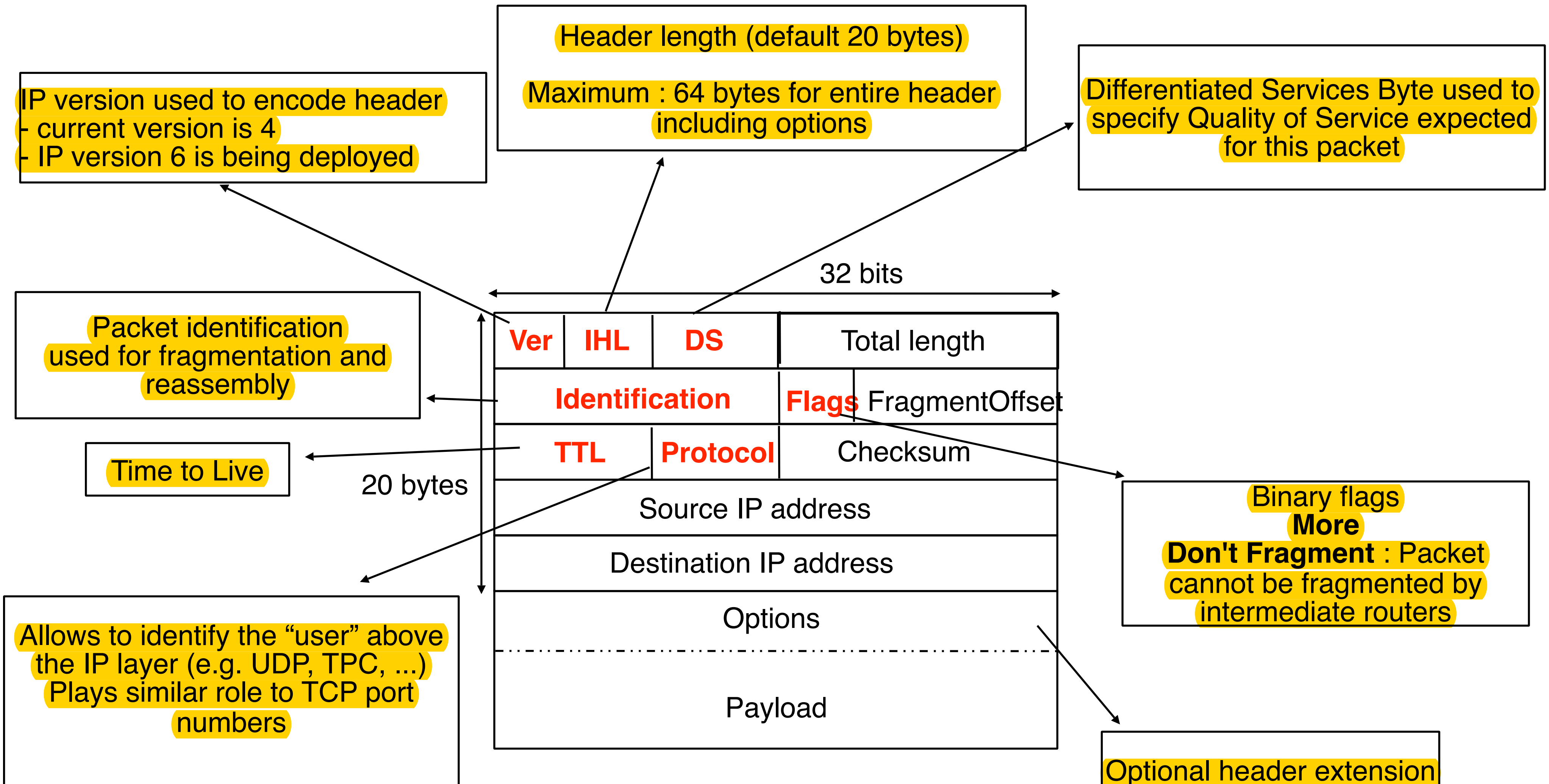


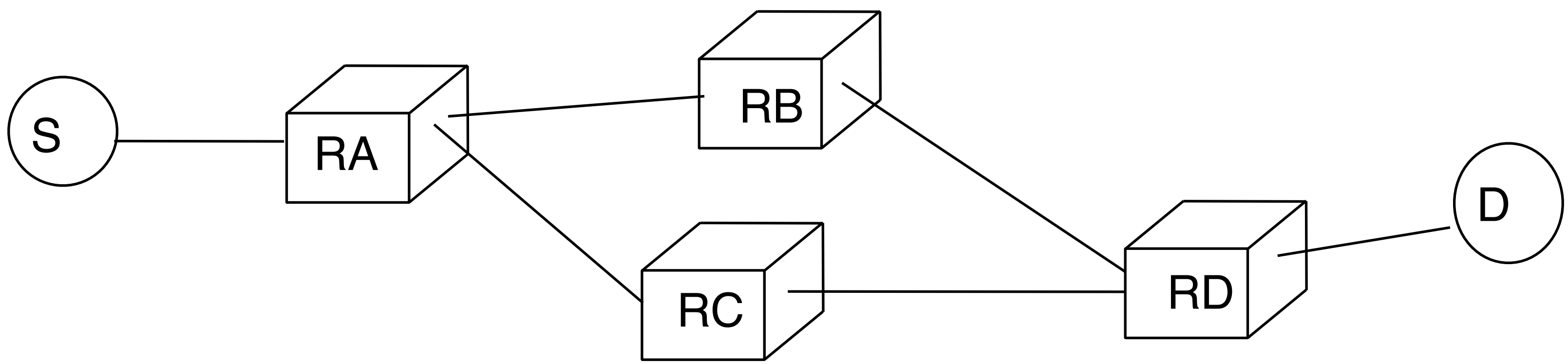
IP Options

- Sample IP header options
  - Strict source route option
    - allows the source to list IP addresses of all intermediate routers to reach destination between source and destination
  - Loose source route option
    - allows the source to list IP addresses of some intermediate routers to reach destination between source and destination
  - Record route option
    - allows each router to insert its IP address in the header
      - rarely used because limited header length
  - Router alert
    - allows the source to indicate to routers that there is something special to be done when processing this packet

Constraint : maximum header size with option 64 bytes

IP Source Routing

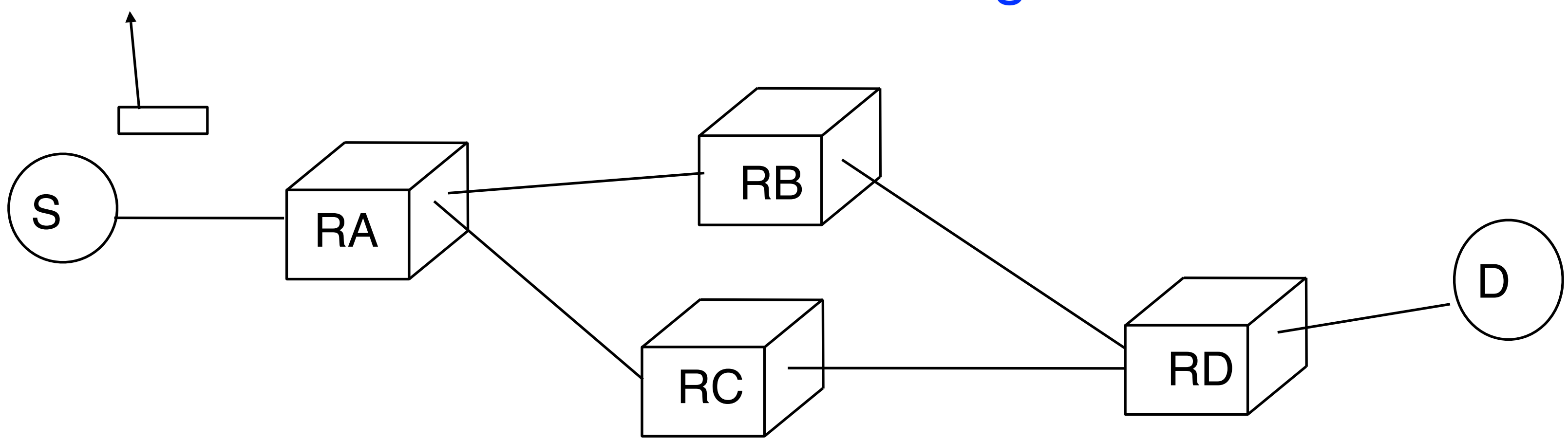
Strict
source routing



IP Source Routing

Source : S
Destination : D
Path : RA,RB,RD

Strict
source routing



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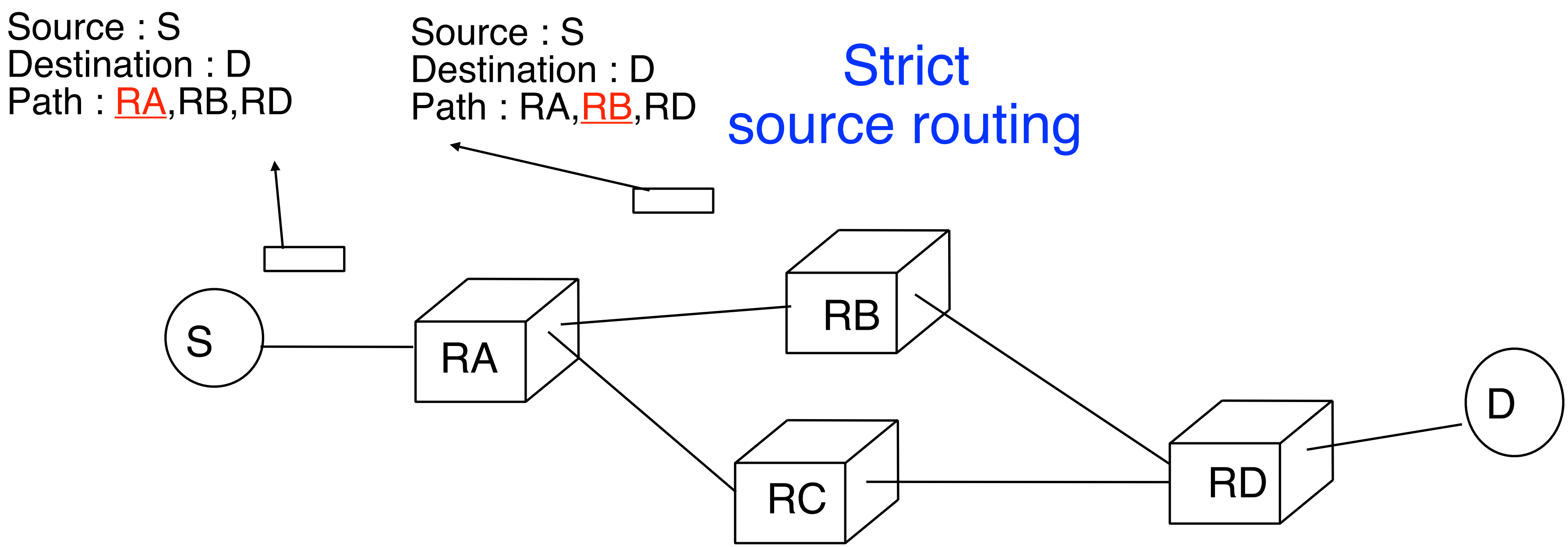

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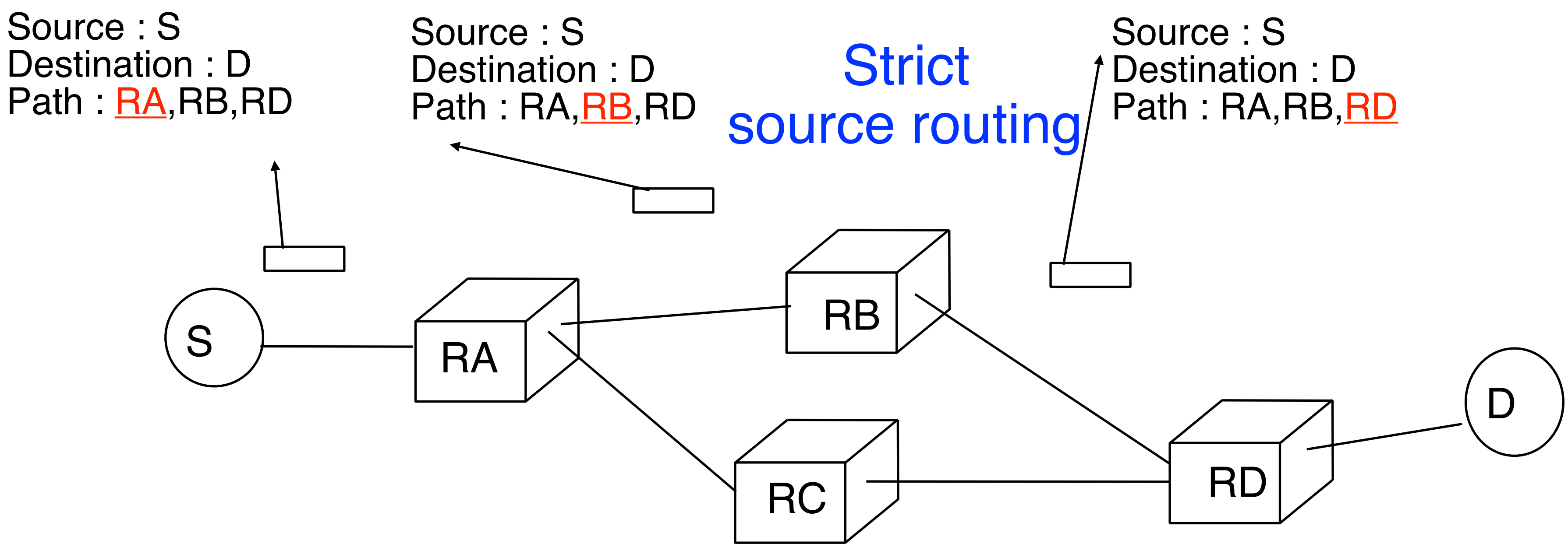

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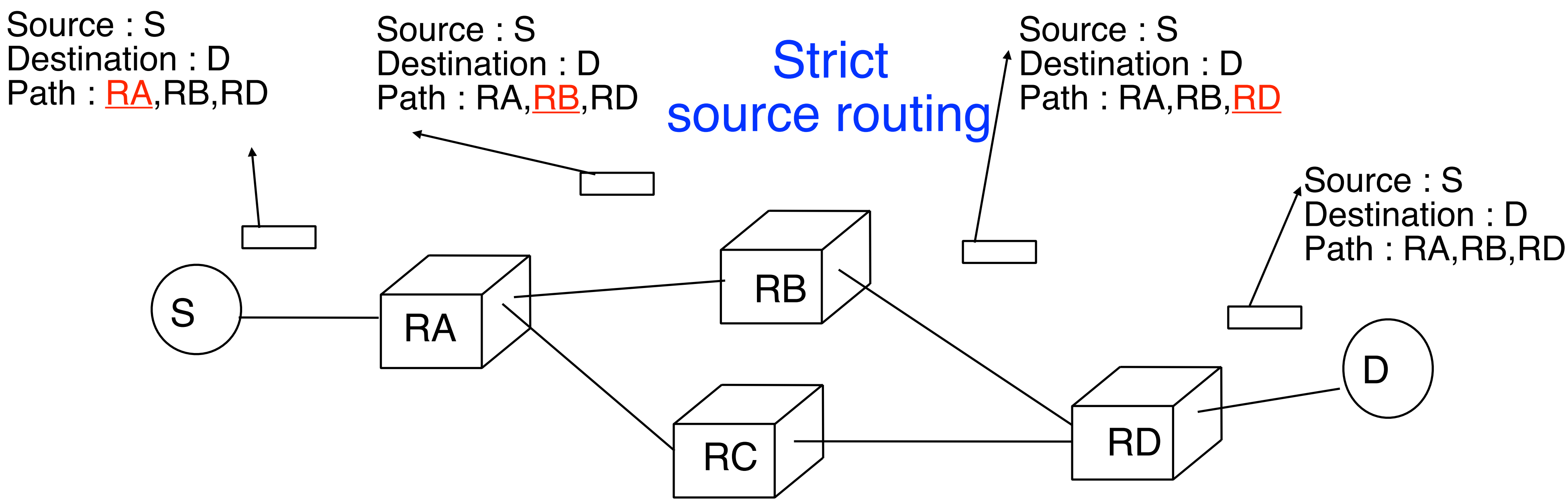

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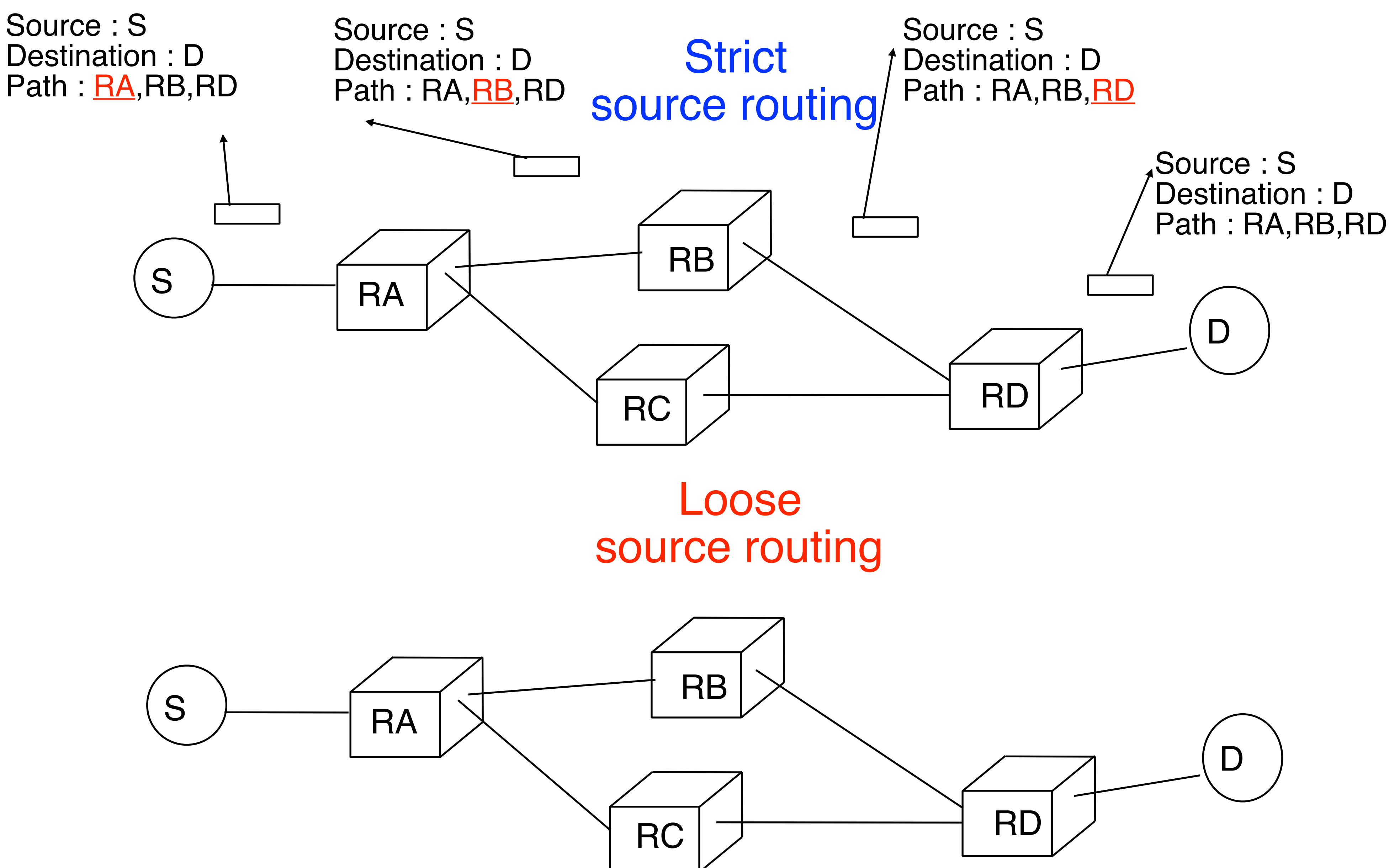

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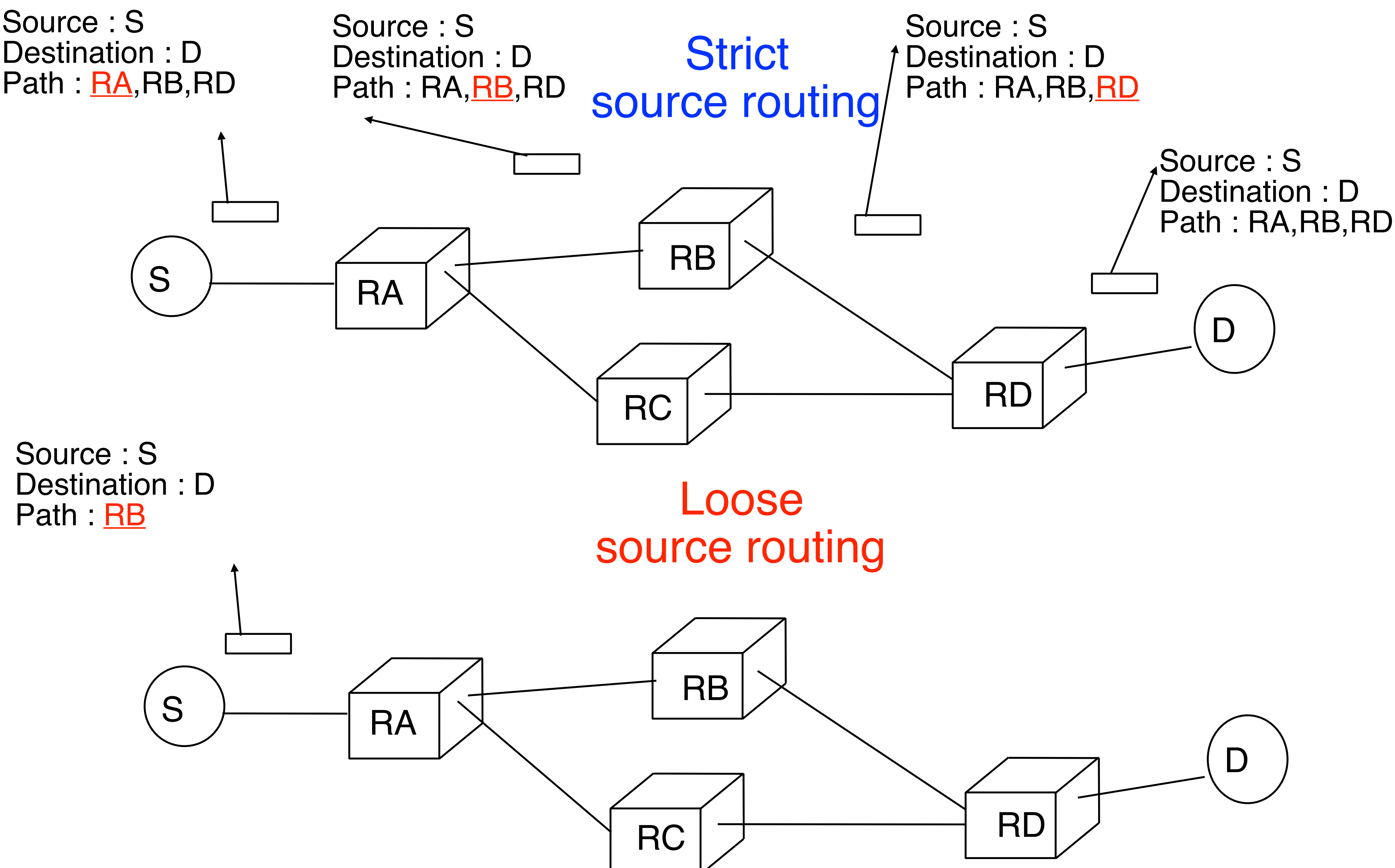

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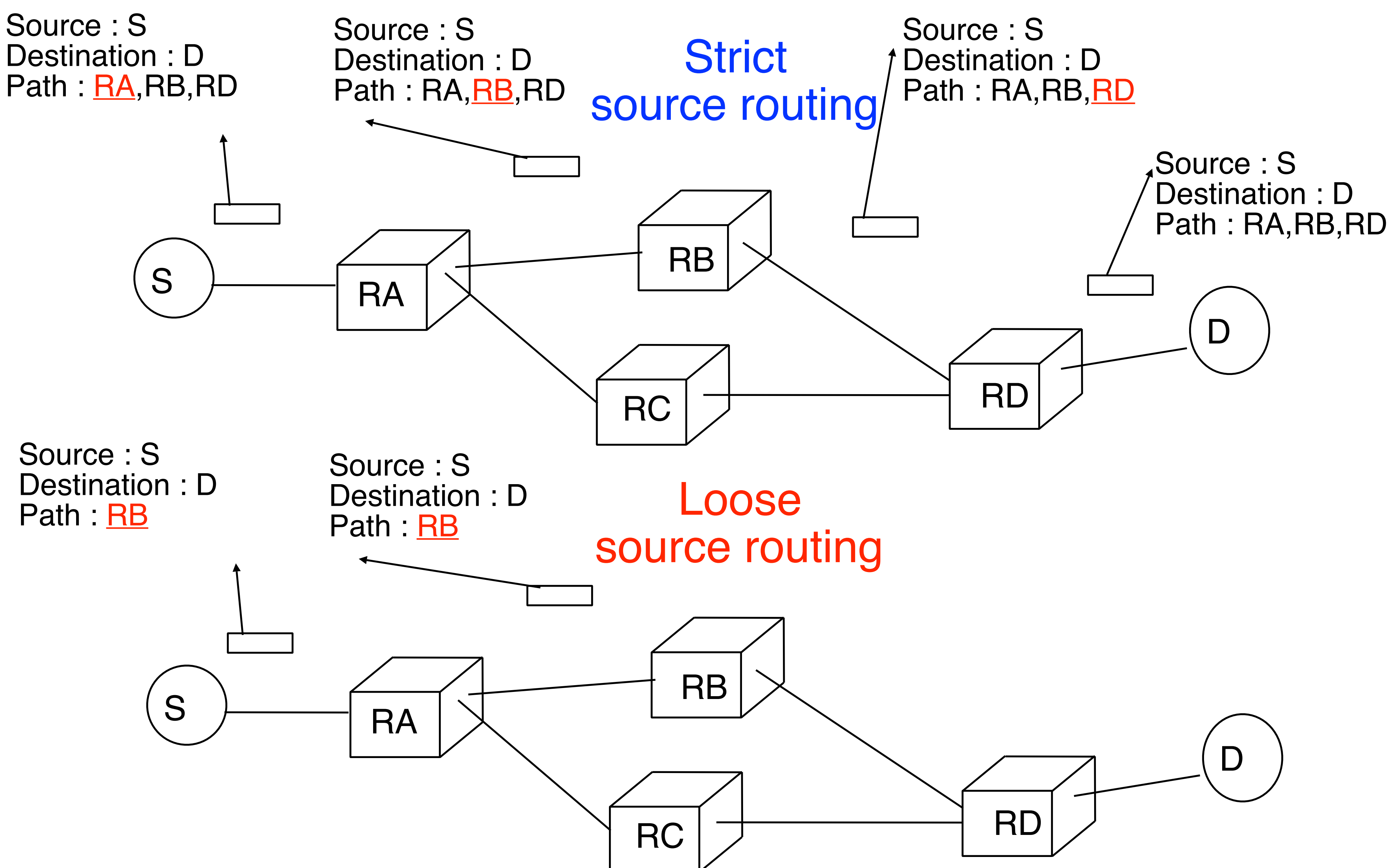
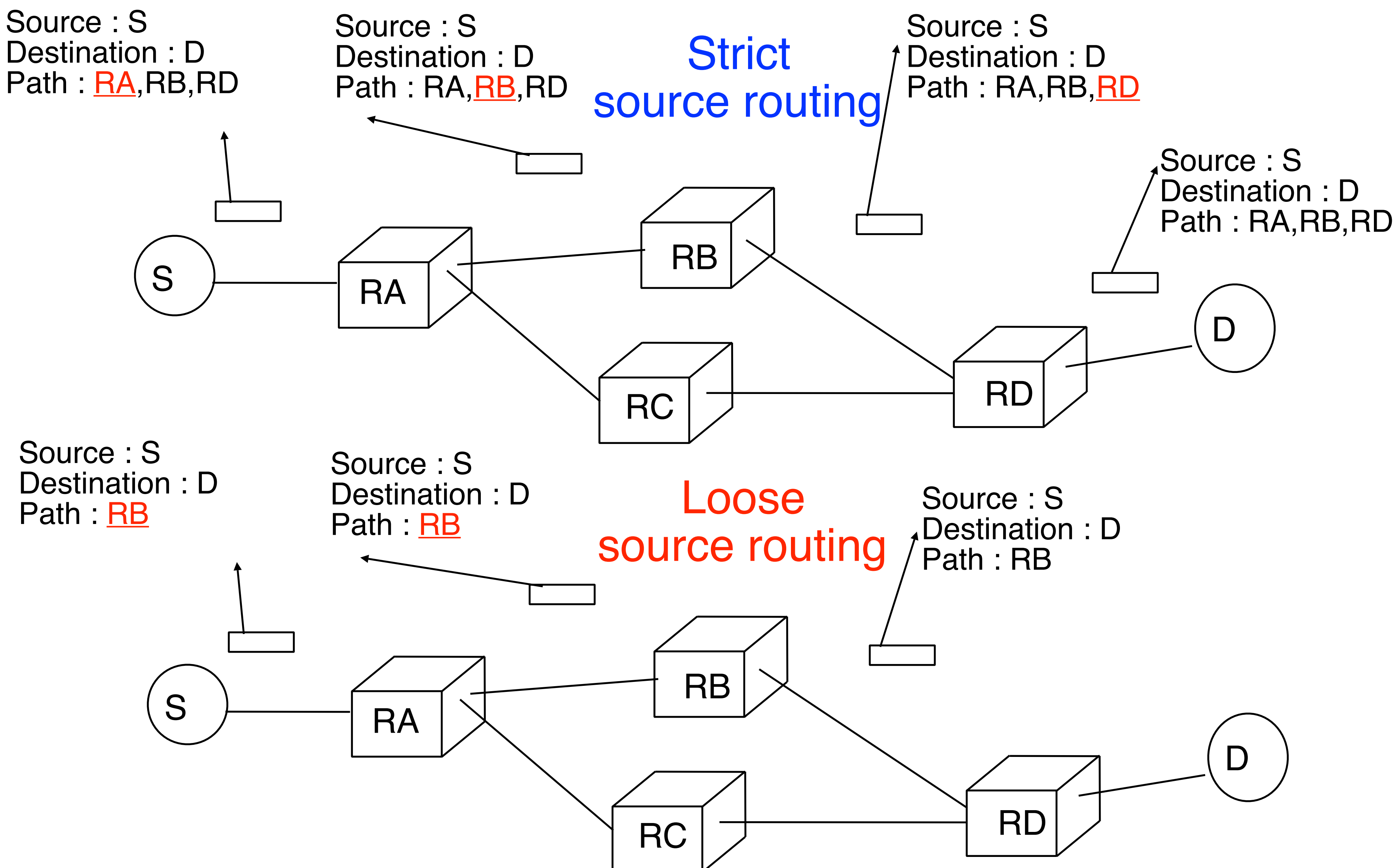
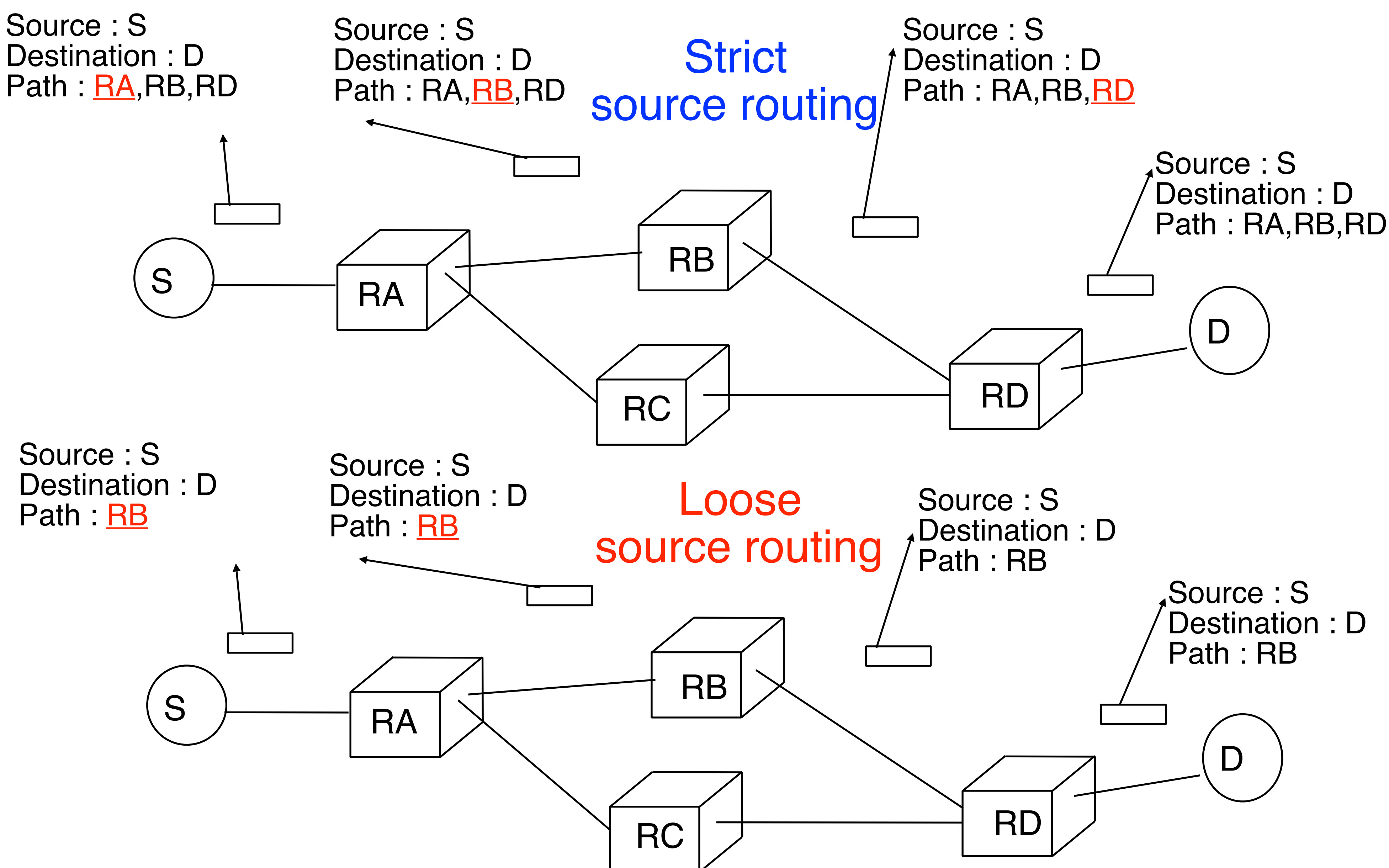


IP Source Routing



IP Source Routing



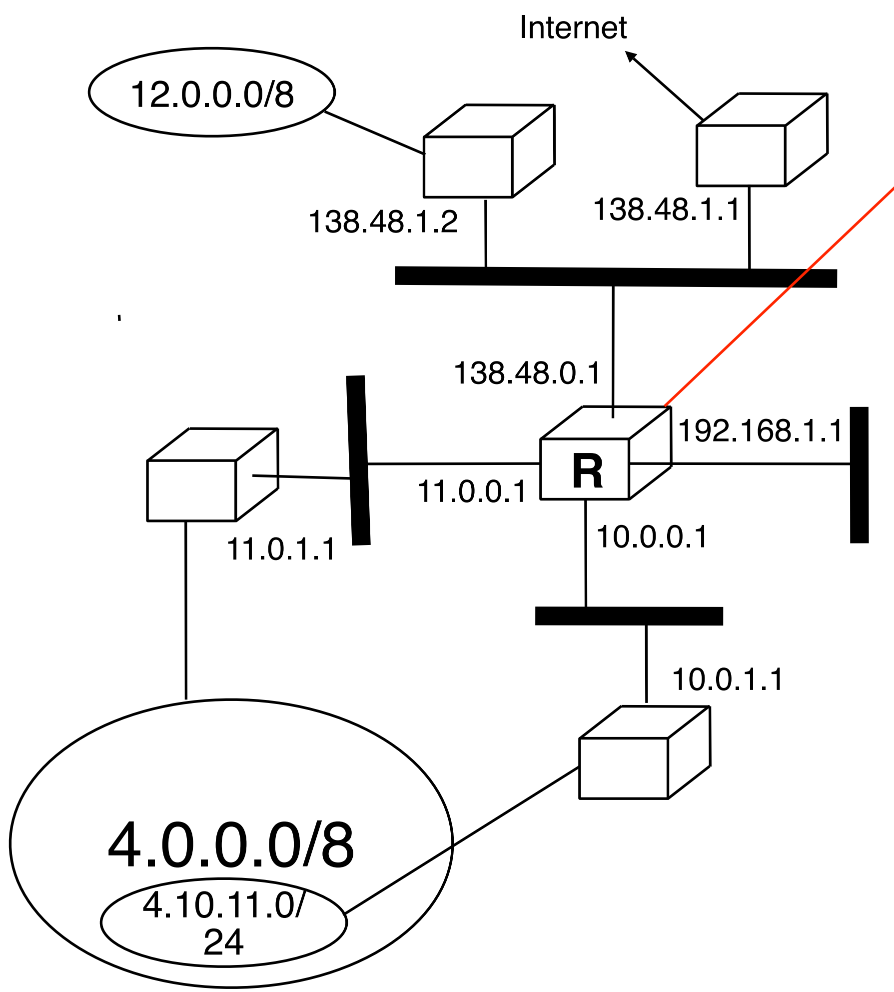
Operation of an IP endhost

- Required information on an IP endhost
  - IP addresses of its interfaces
    - For each address, the subnet mask allows the endhost to determine the addresses that are directly reachable through the interface
  - (small) routing table
    - Directly connected subnets
      - From the subnet mask of its own IP addresses
    - Default router
      - Router used to reach any unknown address
      - By convention, default route is 0.0.0.0/0
    - Other subnets known by endhost
      - Could be manually configured or learned through routing protocols are special packets (see later)

IP address configuration

- How does a host know its IP address
  - Manual configuration
    - Used in many small networks
  - Server-based autoconfiguration RARP
    - DHCP
      - Dynamic Host Configuration Protocol
      - Principle
      - When it attaches to a subnet, endhost broadcasts a request to find DHCP server
      - DHCP server replies and endhost can contact it to obtain IP address
      - DHCP server allocates an IP address for some time period and can also provide additional information (subnet, default router, DNS resolver, ...)
        - DHCP servers can be configured to always provide the same IP address to a given endhost or not
        - Endhost reconfirms its allocation regularly
  - Serverless autoconfiguration
    - Used by IPv6

Example



Local addresses
11.0.0.1 ; 138.48.0.1 ; 192.168.1.1 ; 10.0.0.1

Routing table
138.48.0.0/16 [North]
11.0.0.0/8 [West]
192.168.1.0/24 [East]
10.0.0.0/8 [South]
4.0.0.0/8 via 11.0.1.1 [West]
4.10.11.0/24 via 10.0.1.1 [South]
12.0.0.0/8 via 138.48.1.2 [North]
0.0.0.0/0 via 138.48.1.1 [North]

Operation of an IP router

Required information on an IP router

- IP addresses of its interfaces
  - For each address, the subnet mask allows the endhost to determine the addresses that are directly reachable through the interface

- Routing table
  - Directly connected subnets
    - From the subnet mask of its own IP addresses
  - Other known subnets
    - Usually learned via routing protocols, sometimes manually configured
  - Default router
    - Router used to reach any unknown address
    - By convention, default route is 0.0.0.0/0

Operation of an IP router (2)

Operations performed for each packet

1. Check whether the packet's destination address is one of the router's addresses
   - If yes, packet reached destination

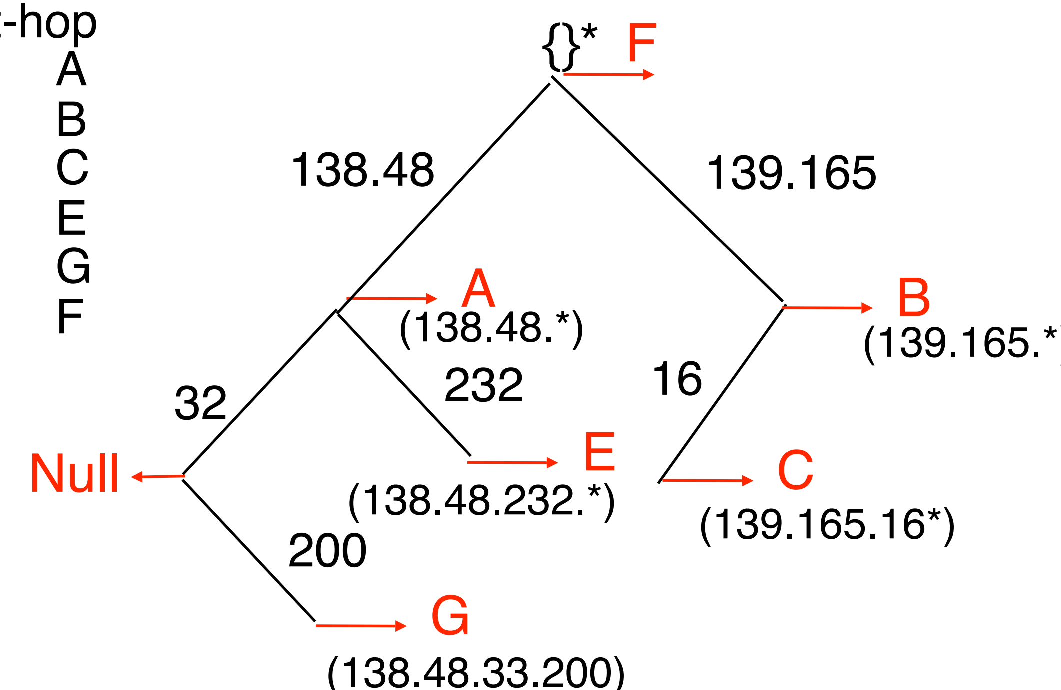
2. Query Forwarding Information Base that contains
   - list of directly connected networks with masks
   - list of reachable networks and intermediate router

3. Lookup the most specific route in FIB
   - For each route A.B.C.D/M via Rx
   - compare M higher order bits of destination address with M higher order bits of routes to find longest match
   - forward packet along this route

Forwarding Information Base Lookup

How to find most specific route ?
- similar to longest prefix match in a text
- Trie

Subnet	Prefix	Next-hop
138.48.0.0	16	A
139.165.0.0	16	B
139.165.16.0	24	C
138.48.232.0	24	E
138.48.32.200	32	G
0.0.0.0	0	F



Cost of lookup
- f(average length of prefixes)
  - comparisons
  - memory accesses
- caches for most frequently used routes

Handling IP packets in error

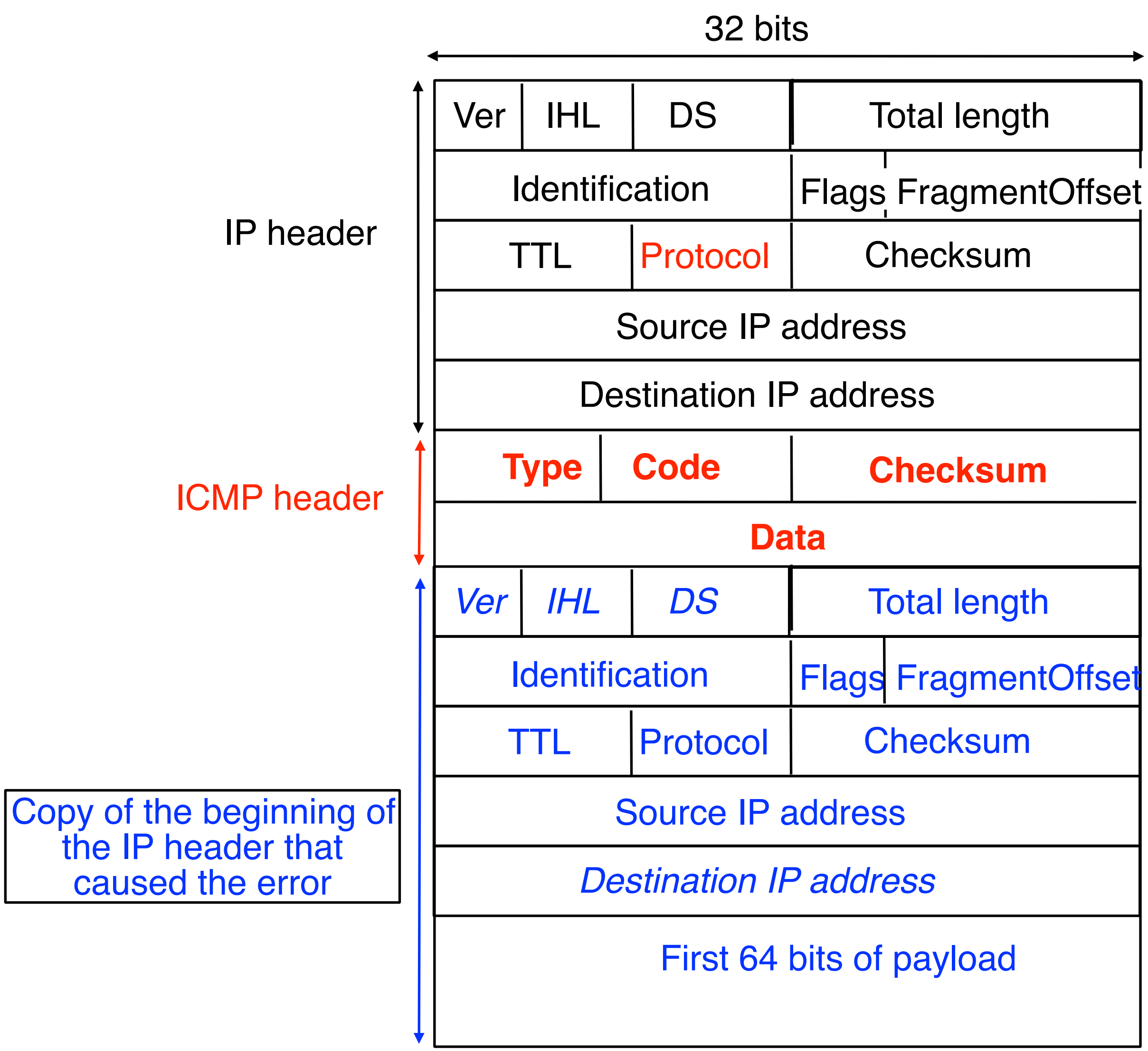
- Problem
  - What should a router/host do when it receives an errored packet
    - Example
      - Packet whose destination is not the current endhost
      - Packet containing a header with invalid syntax
      - Packet received with TTL=1
      - Packet destined to protocol not supported by host
- Solutions
  - Ignore and discard the errored packet
  - Send a message to the packet's source to warn it about the problem
    - ICMP : Internet Control Message Protocol
    - ICMP messages are sent inside IP packets by routers (mainly) and hosts
      - To avoid performance problems, most hosts/routers limit the amount of ICMP messages that they send

ICMP is defined in RFC792

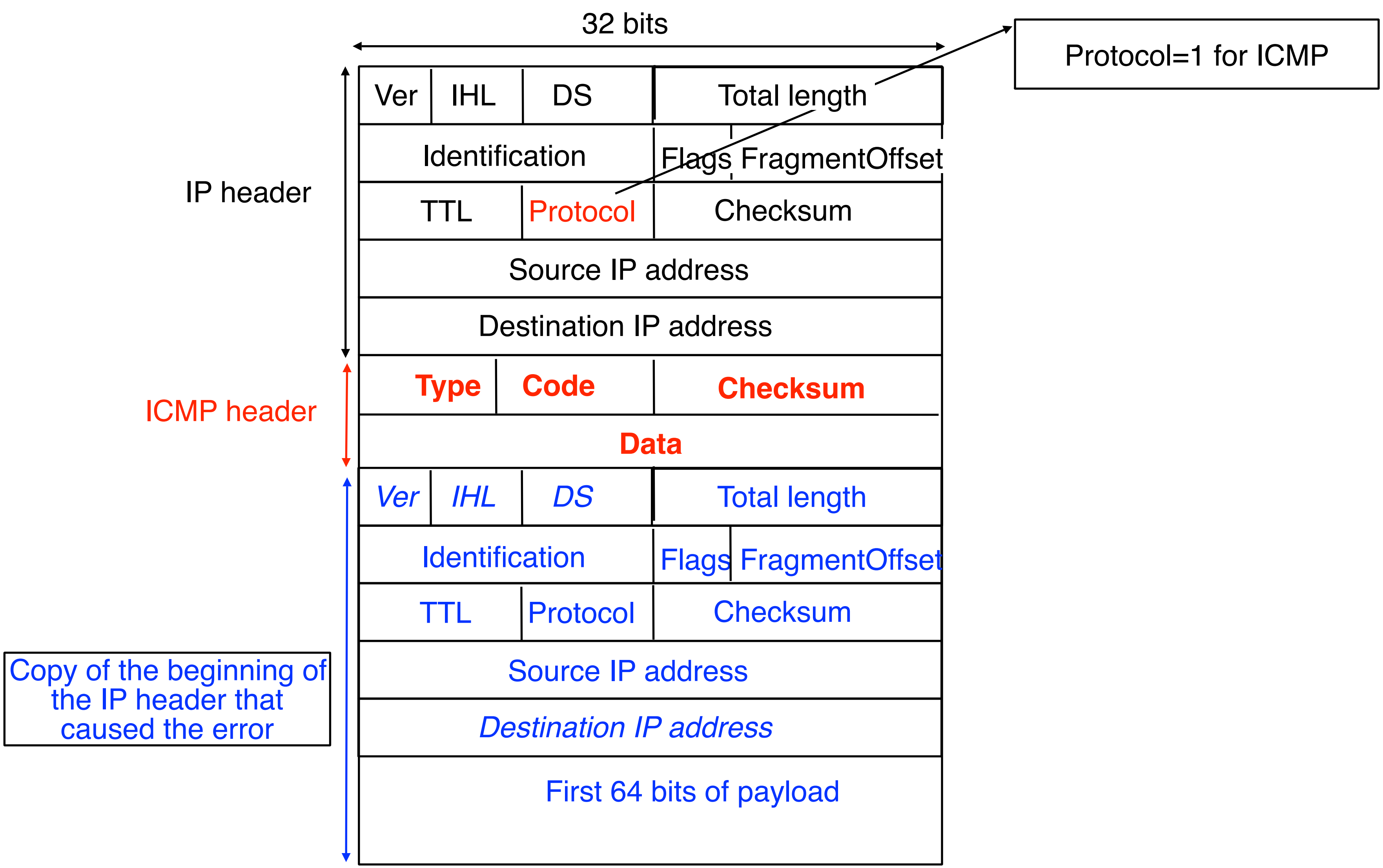
Sample ICMP messages

- Routing error
  - Destination unreachable
    - Final destination of packet cannot be reached
      - Network unreachable for entire subnet
      - Host unreachable for an individual host
      - Protocol/Port unreachable for protocol/port on a reachable host
    - Redirect
      - The packet was sent to an incorrect first-hop router and should have been instead sent to another first-hop router
- Error in the IP header
  - Parameter Problem
    - Incorrect format of IP packet
  - TTL Exceeded
    - Router received packet with TTL=1
  - Fragmentation
    - the packet should have been fragmented, but its DF flag was true

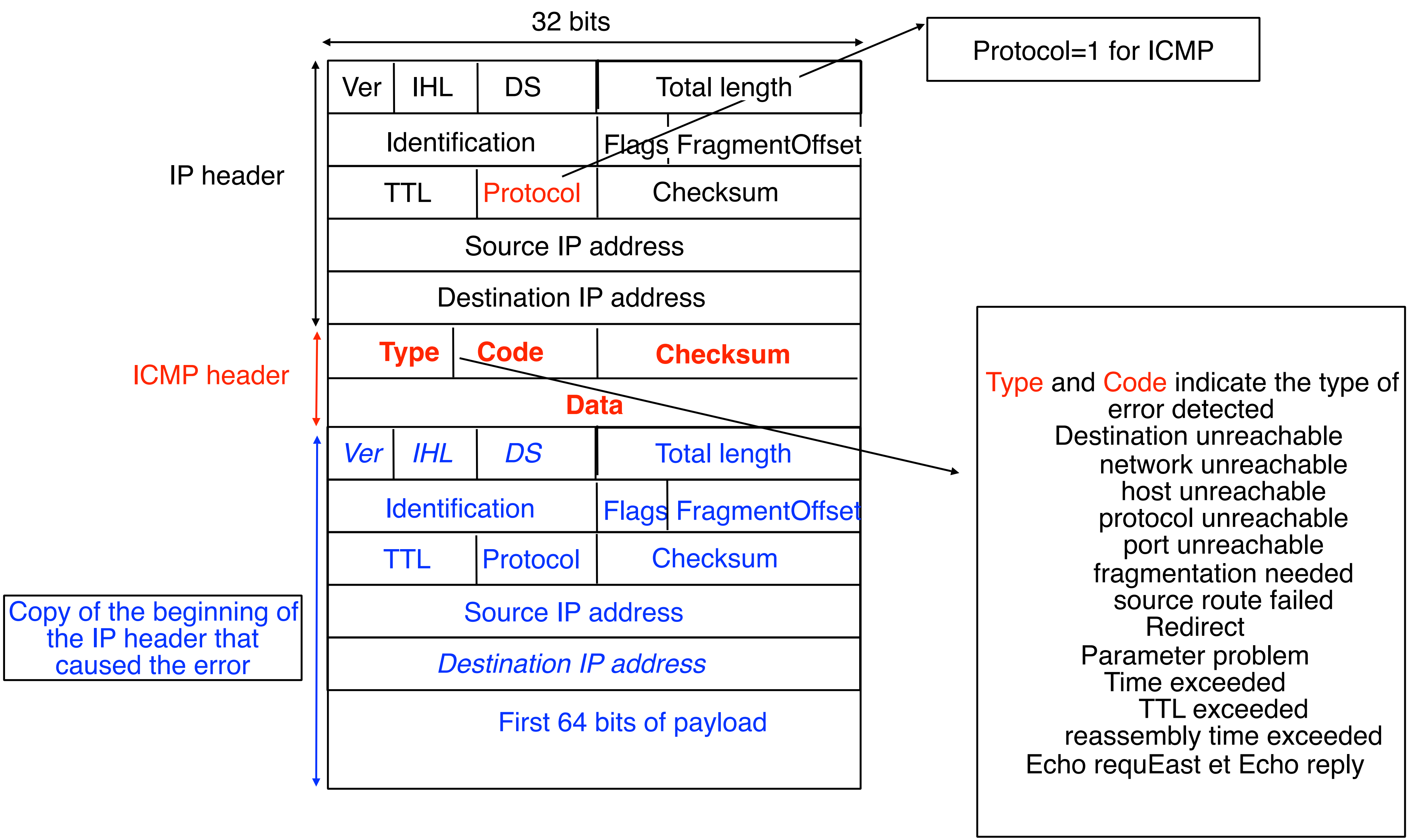
ICMP messages



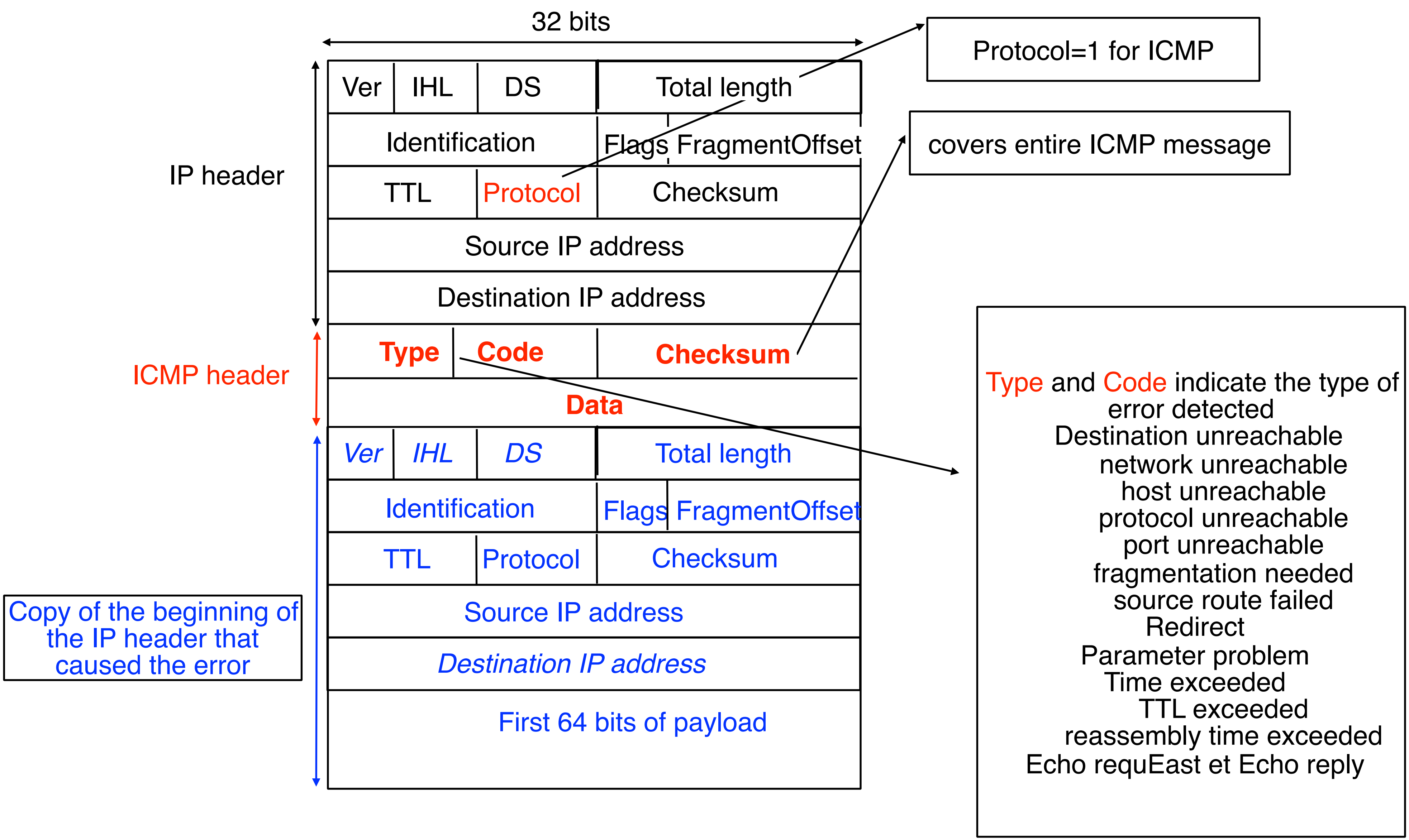
ICMP messages



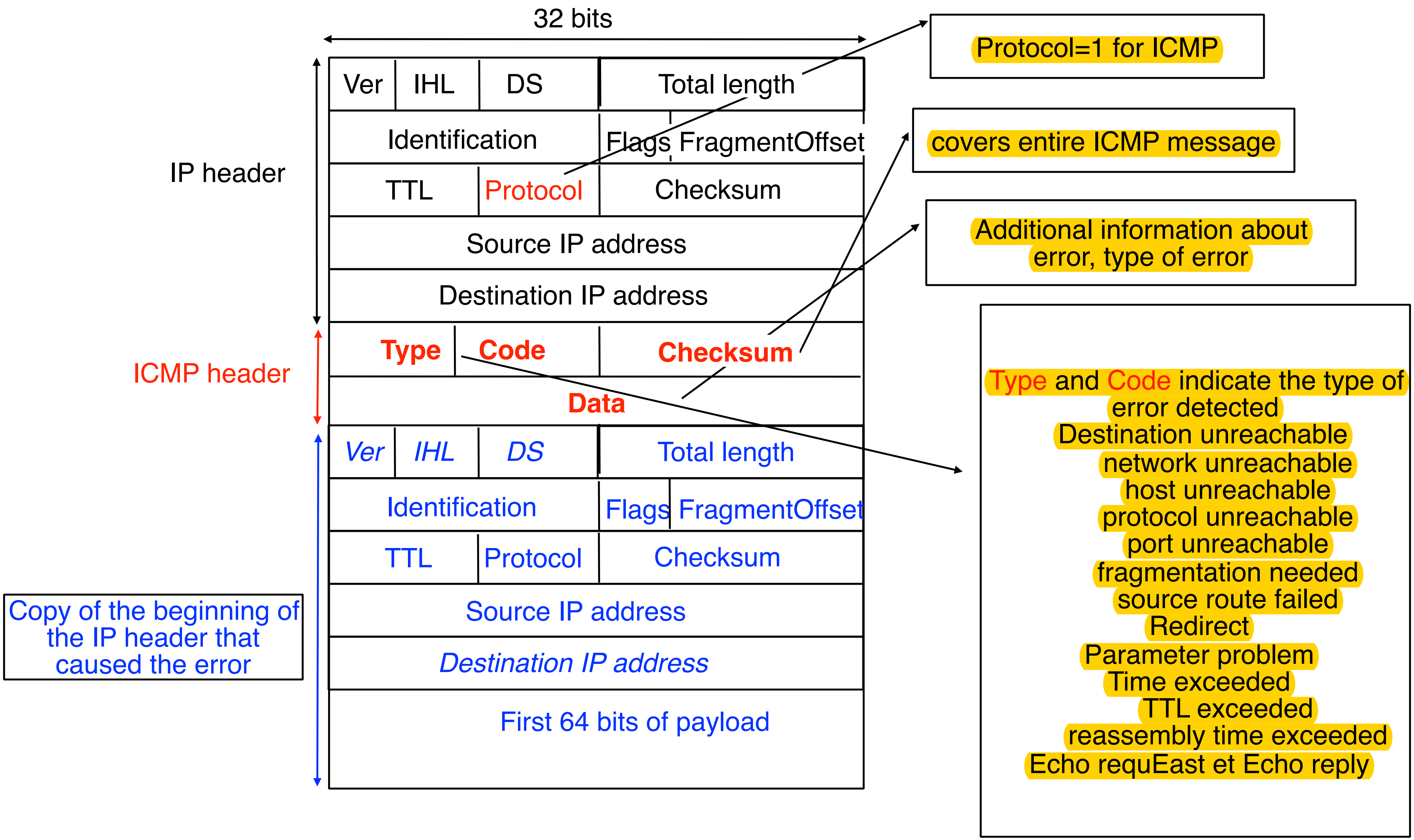
ICMP messages



ICMP messages



ICMP messages



Usage of ICMP messages

Examples

- destination unreachable
  - the router sending this message did not have a route to reach the destination
- time exceeded
  - the router sending the message received an IP packet with TTL=0
  - used by `traceroute`
- redirect
  - to reach destination, another router must be used and ICMP message provides address of this router
- echo request / echo reply
  - used by `ping`
- fragmentation impossible
  - the packet should have been fragmented by the router sending the ICMP message by this packet had "Don't Fragment" set to true

Middleboxes

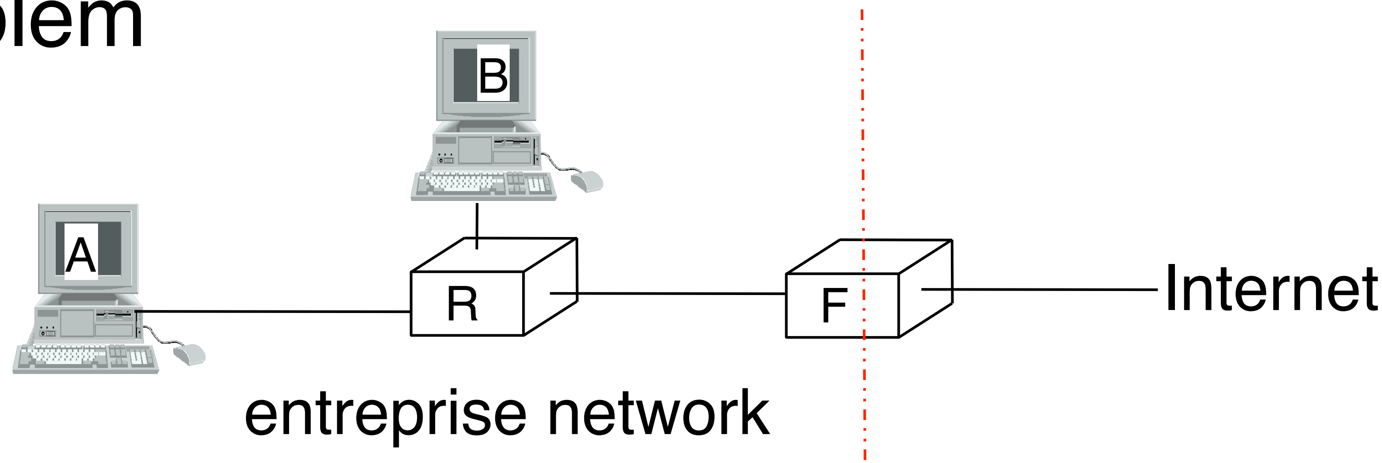
The original TCP/IP architecture only defined hosts and routers

Today's networks contain devices that
- process
- analyse
- and possibly modify IP packets

Examples
- Firewall
- Network Address Translator
- Traffic shaper
- Deep Packet Inspection
- Intrusion Detection System
- Load balancer

Firewall

Problem



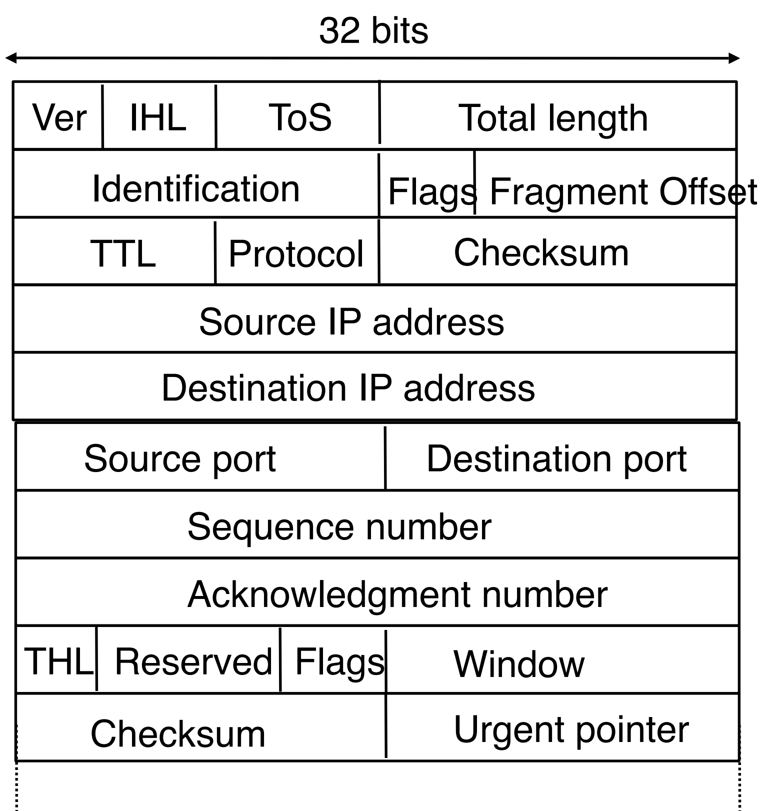
- How to control the packets entering the entreprise network ?
  - only allow external access to some servers
  - allow internal clients to use web
  - allow smtp (inbound and outbound) only on some dedicated servers
  - ...

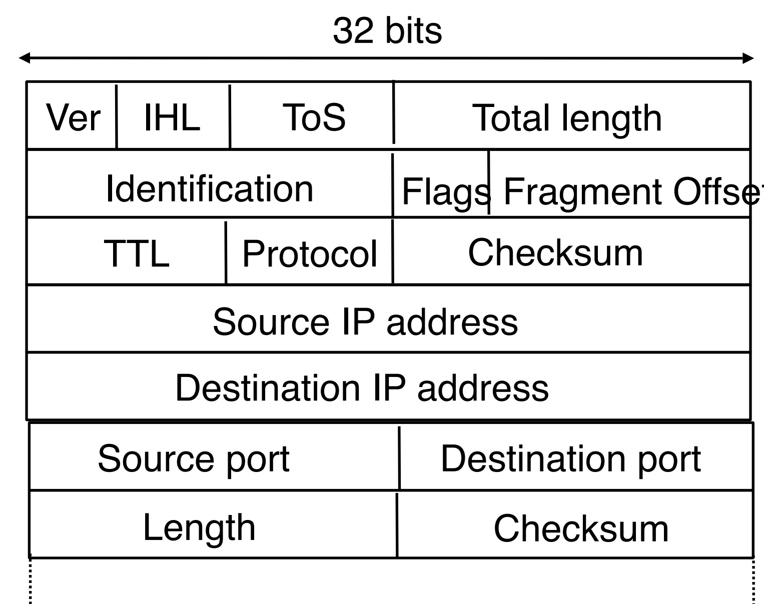
Firewalls (2)

Principle

- Firewall analyses all packet headers
- rules specify which packets should be accepted and rejected

TCP





UDP

Firewalls : example

Wifi UCLouvain

Outbound

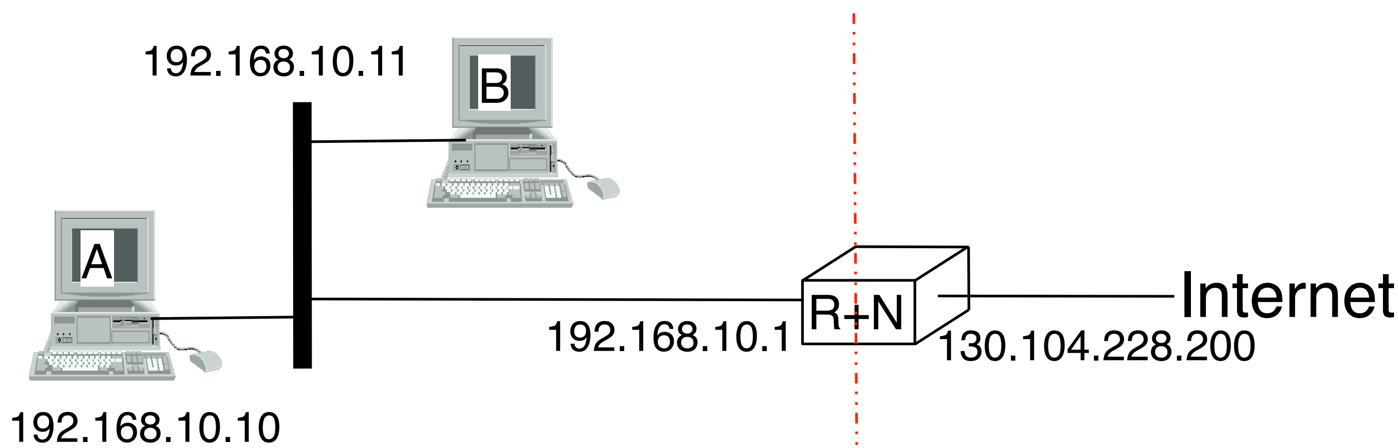
- Standard IPSec VPN...
- SSH: TCP/22
- HTTP: TCP/80, HTTPS: TCP/443
- IMAP2+4: TCP/143, IMAP3: TCP/220, IMAPS: TCP/993, POP: TCP/110, POP3S: TCP/995, SMTPS: TCP/465, SMTP submit with STARTTLS: TCP/587
- Passive (S)FTP: TCP/21
- RDP: TCP/3389
- IPv6 Tunnel Broker service: IP protocol 41

Inbound

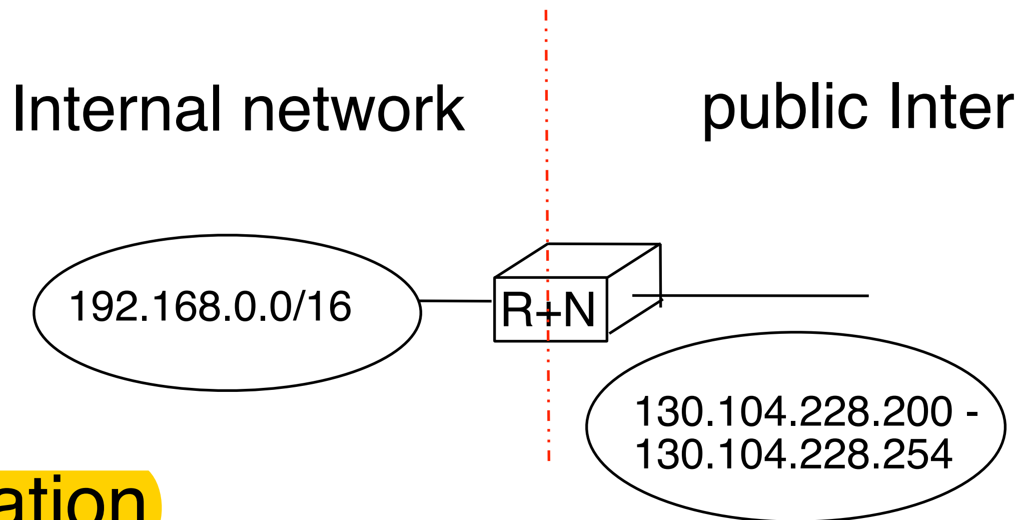
- OpenVPN 2.0: UDP/1194, IPsec NAT-Traversal UDP/4500, PPTP VPN: IP protocol 47 (GRE), Standard IPSec VPN: IP protocols 50 (ESP) and 51 (AH)
- IPv6 Tunnel Broker service: IP protocol 41

Network Address Translator

- Problem
  - Limited number of public IPv4 addresses
- Solution
  - Use private addresses inside enterprise and home networks
  - Use one or a few public addresses
  - translate packets sent to public Internet



Simple enterprise NAT



Operation

Mapping table

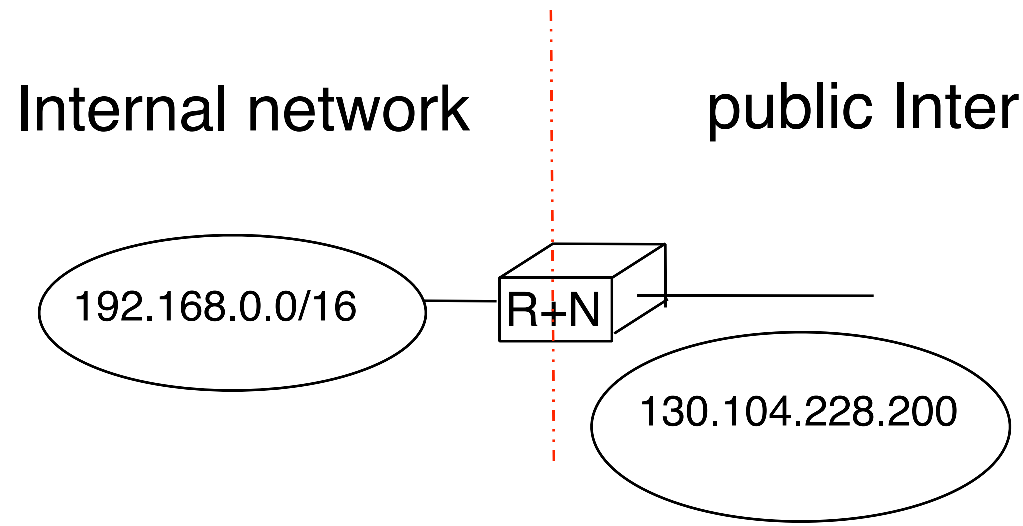
Internal address <-> public address

Packet arrival from internal network

Packet arrival from public network

How long should mapping remain ?

Single address NAT



Single address NAT

- NAT translates IP addresses and TCP/UDP port numbers

Private address	Protocol	Port inside	public address	Port outside
192.168.10.10	UDP	2340	130.104.228.200	4567
192.168.10.10	TCP	512	130.104.228.200	520
192.168.10.11	TCP	1024	130.104.228.200	2048

Network layer

Basics

Routing

IP : Internet Protocol

Routing in IP networks

- Internet routing organisation
- Intradomain routing : RIP
- Intradomain routing : OSPF
- Interdomain routing : BGP

Internet organisation

- Internet is an internetwork with a large number of Autonomous Systems (AS)
  - an AS is a set of routers that are managed by the same administrative entity
    - Examples : BELNET, UUNET, SKYNET, ...
    - about 20000 ASes in 2007
  - Autonomous Systems are interconnected to allow the transmission of IP packets from any source to any destination
    - On the Internet, most packets need to travel through several transit Autonomous Systems

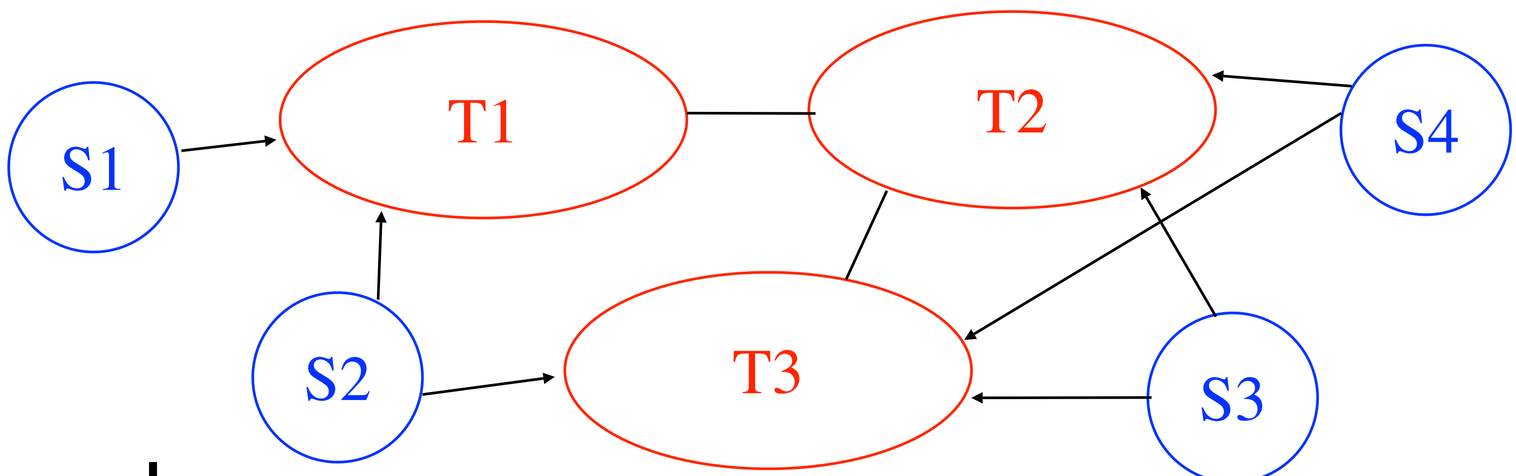
Organisation of the Internet

- Internet is composed of about 30.000 autonomous routing domains
  - A domain is a set of routers, links, hosts and local area networks under the same administrative control
    - A domain can be very large...
      - AS568: SUMNET-AS DISO-UNRRA contains 73154560 IP addresses
    - A domain can be very small...
      - AS2111: IST-ATRIUM TE Experiment a single PC running Linux...
  - Domains are interconnected in various ways
    - The interconnection of all domains should in theory allow packets to be sent anywhere
    - Usually a packet will need to cross a few ASes to reach its destination

Types of domains

Transit domain

A transit domain allows external domains to use its own infrastructure to send packets to other domains

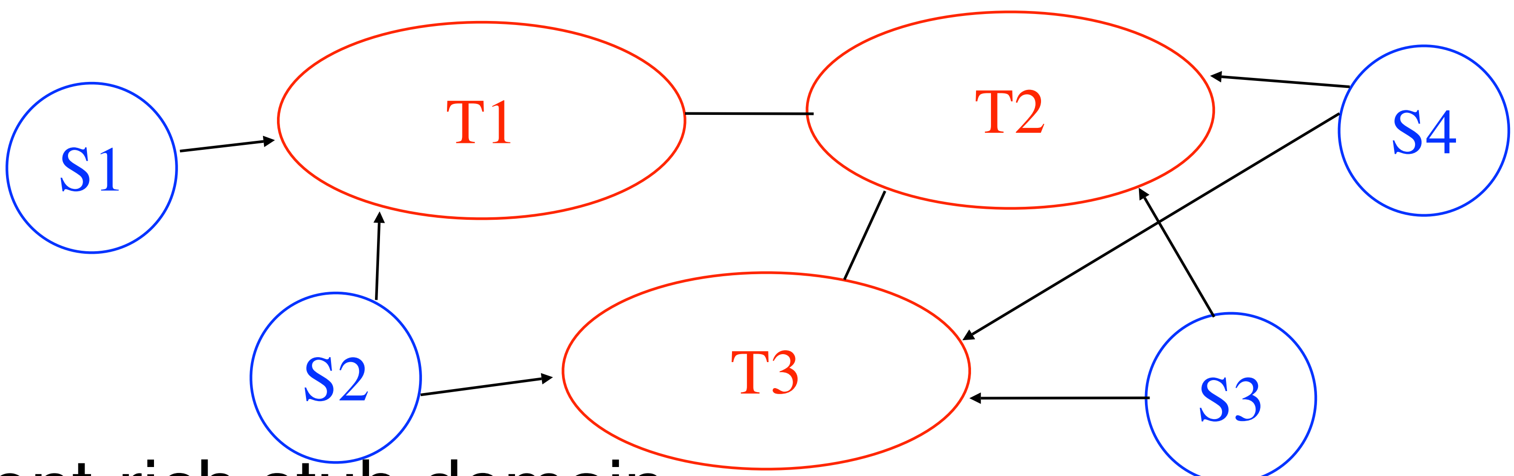


Examples

UUNet, OpenTransit, GEANT, Internet2, RENATER, EQUANT, BT, Telia, Level3,...

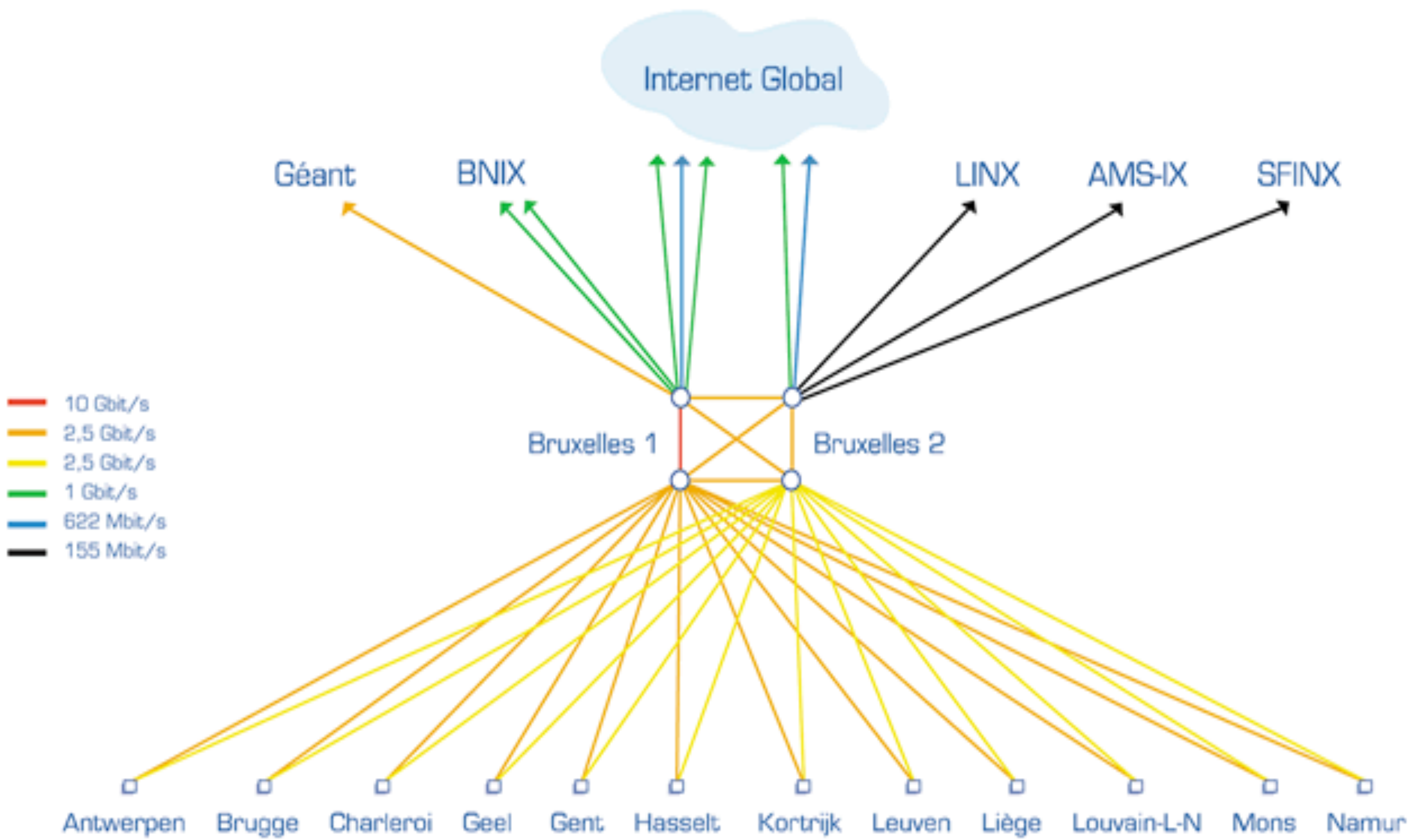
Types of domains (2)

- Stub domain
  - A stub domain does not allow external domains to use its infrastructure to send packets to other domains
    - A stub is connected to at least one transit domain
      - Single-homed stub : connected to one transit domain
      - Dual-homed stub : connected to two transit domains



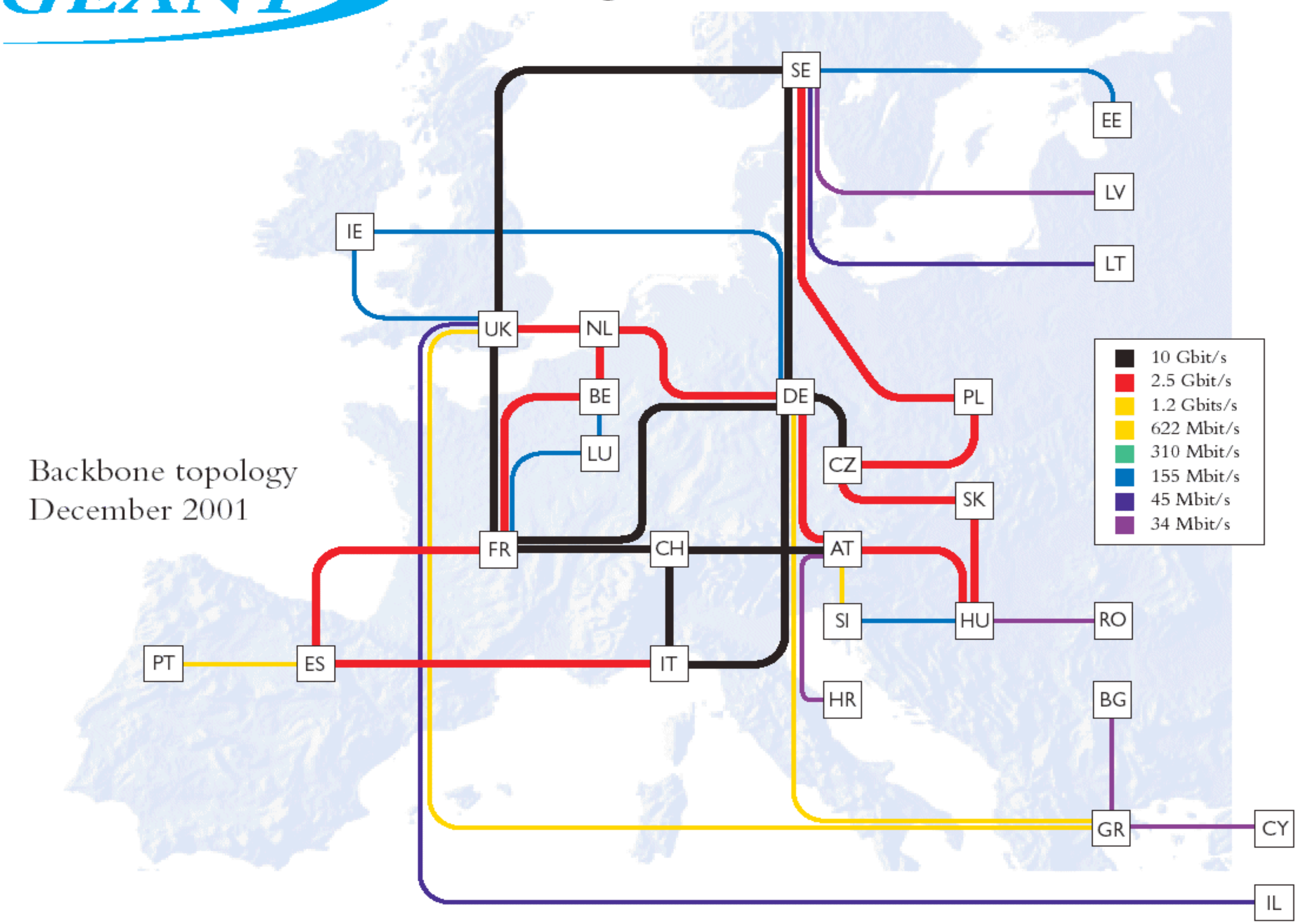
- Content-rich stub domain
  - Large web servers : Yahoo, Google, MSN, TF1, BBC,...
- Access-rich stub domain
  - ISPs providing Internet access via CATV, ADSL, ...

Sample network : Belnet

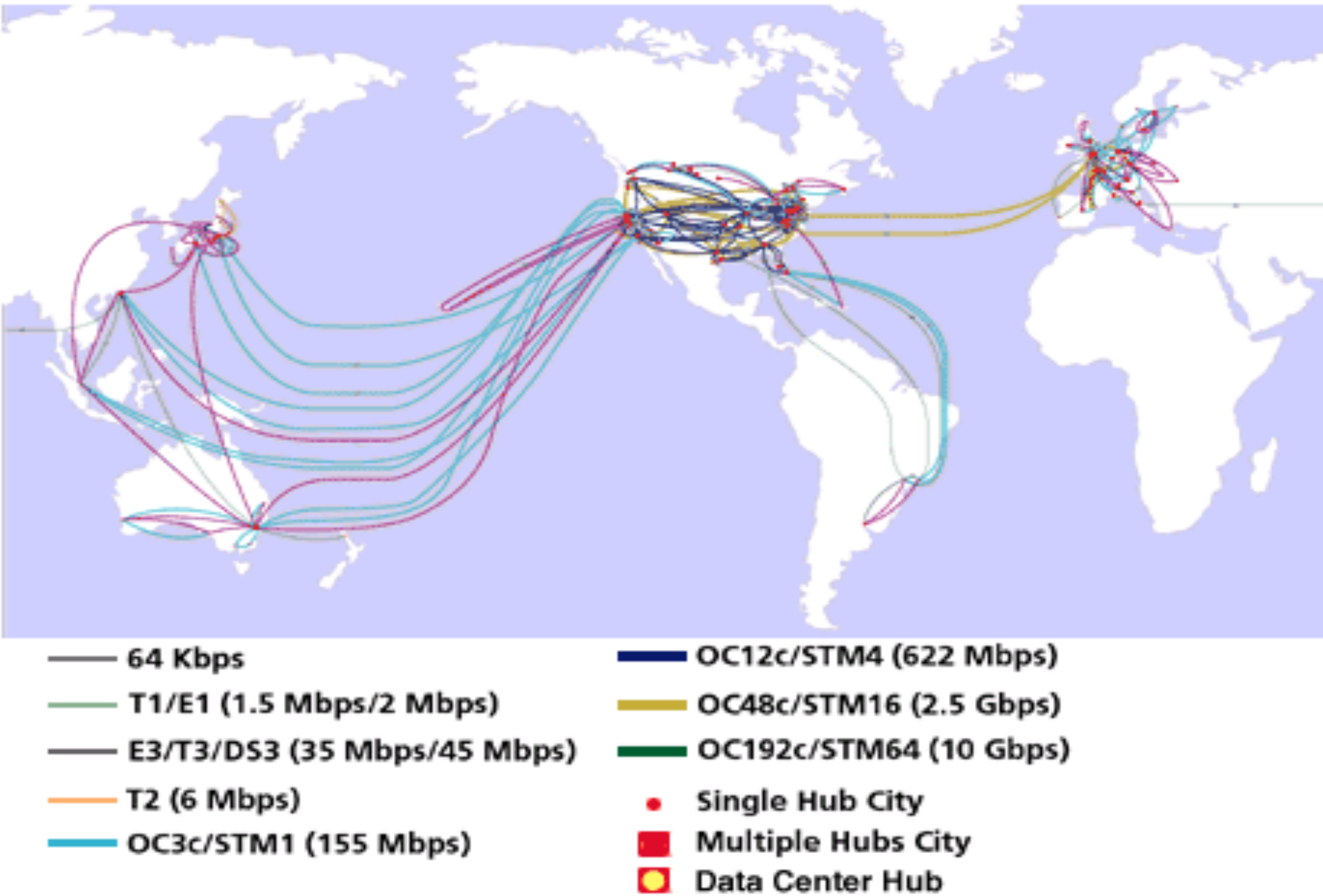


Sample network : GEANT

GEANT The Gigabit Research Network

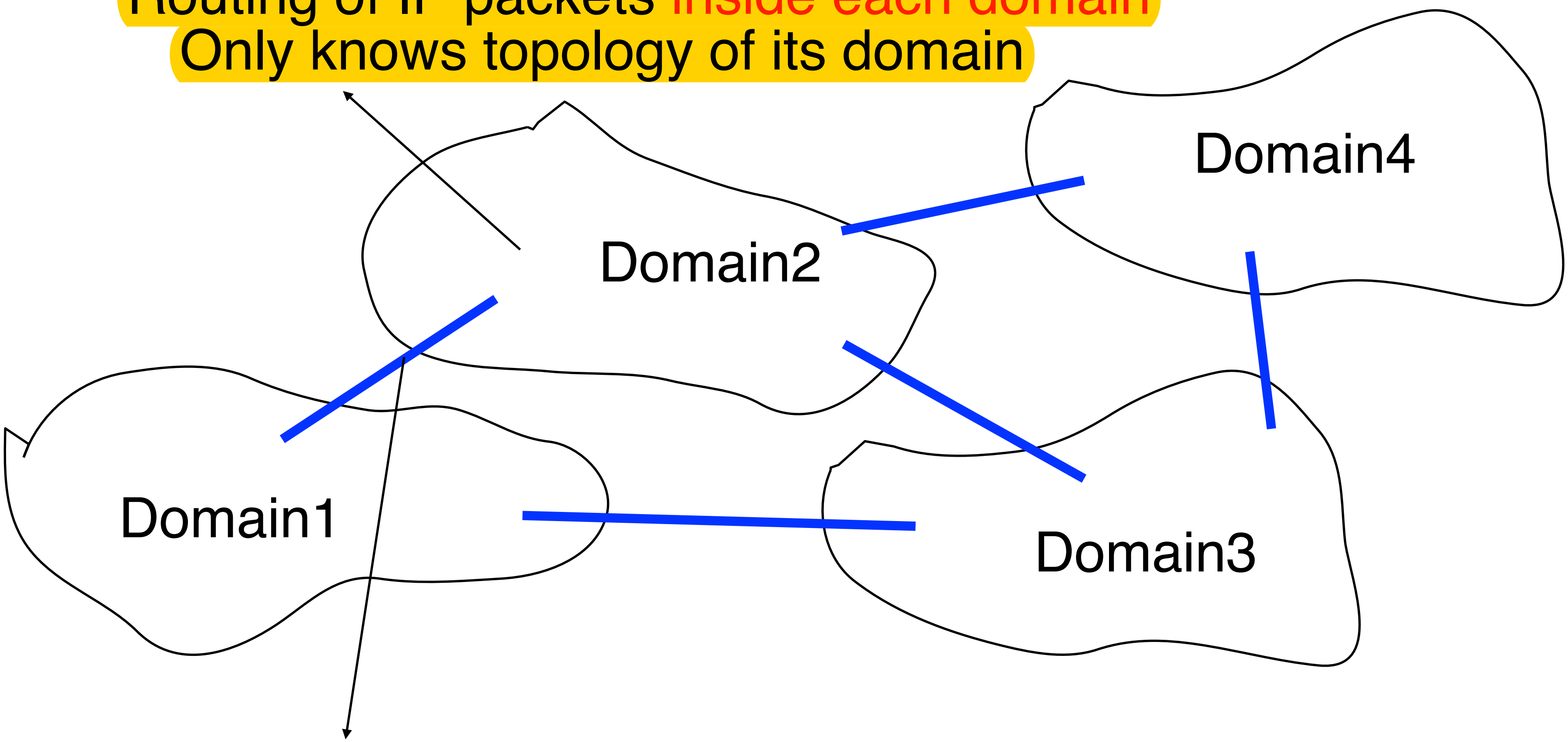


A large worldwide network : UUNet



Internet routing

Interior Gateway Protocol (IGP)
- Routing of IP packets inside each domain
- Only knows topology of its domain



Exterior Gateway Protocol (EGP)
- Routing of IP packets between domains
- Each domain is considered as a blackbox

Intradomain routing

- Goal
  - Allow routers to transmit IP packets along the best path towards their destination
    - best usually means the shortest path
      - Shortest measured in seconds or as number of hops
    - sometimes best means the less loaded path
  - Allow to find alternate routes in case of failures

- Behaviour
  - All routers exchange routing information
    - Each domain router can obtain routing information for the whole domain
    - The network operator or the routing protocol selects the cost of each link

Three types of Interior Gateway Protocols

- Static routing
  - Only useful in very small domains

- Distance vector routing
  - Routing Information Protocol (RIP)
    - Still widely used in small domains despite its limitations

- Link-state routing
  - Open Shortest Path First (OSPF)
    - Widely used in enterprise networks
  - Intermediate System- Intermediate-System (IS-IS)
    - Widely used by ISPs

Network layer

Basics

Routing

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- Intradomain routing : RIP
- Intradomain routing : OSPF
- Interdomain routing : BGP

RIP
Routing Information Protocol

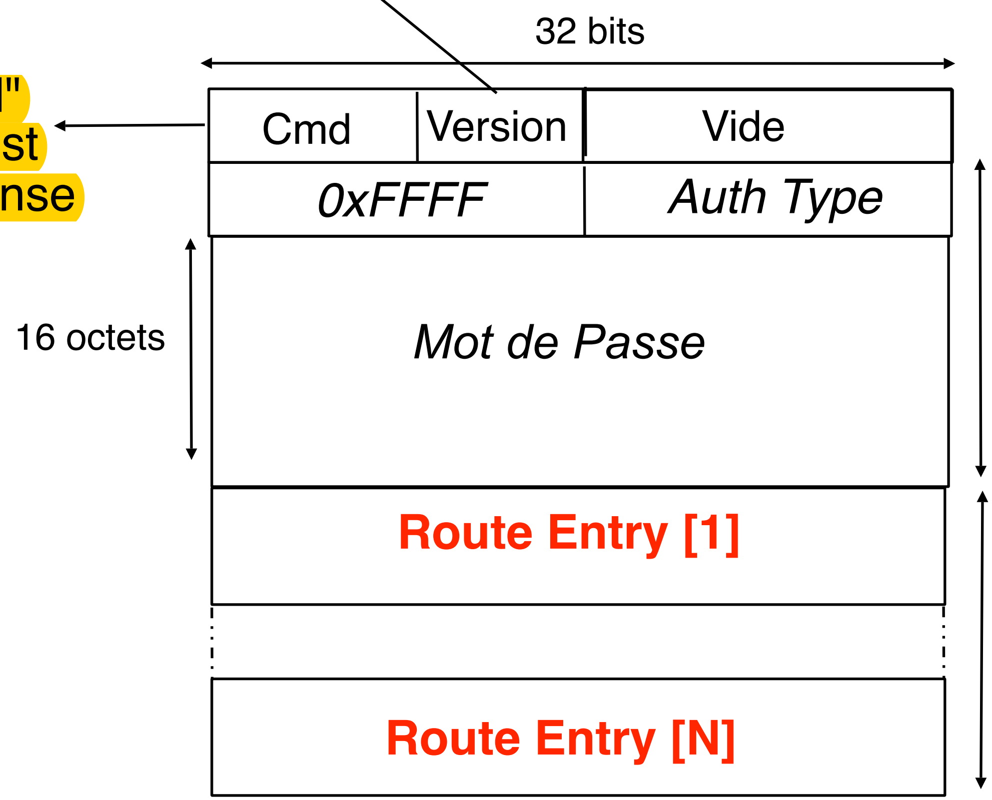
- Simple routing protocol that relies on distance vectors
  - Defined in RFC2453

- Principle
  - Each router periodically sends its distance vectors
    - default period : 30 seconds
    - distance vector is sent in UDP message with TTL=1 to all routers in local subnets (via IP multicast)
  - Optional extension : send a distance vector when the routing table changes
    - simple solution : send distance vector after each change
    - but some links flaps...
      - solution : send a distance vector if routing table changed and we did not send another vector within the last 5 seconds

RIP : message format

Version
1 : Prehistoric
2 : Usable

"Command"
1 : Request
2 : Response



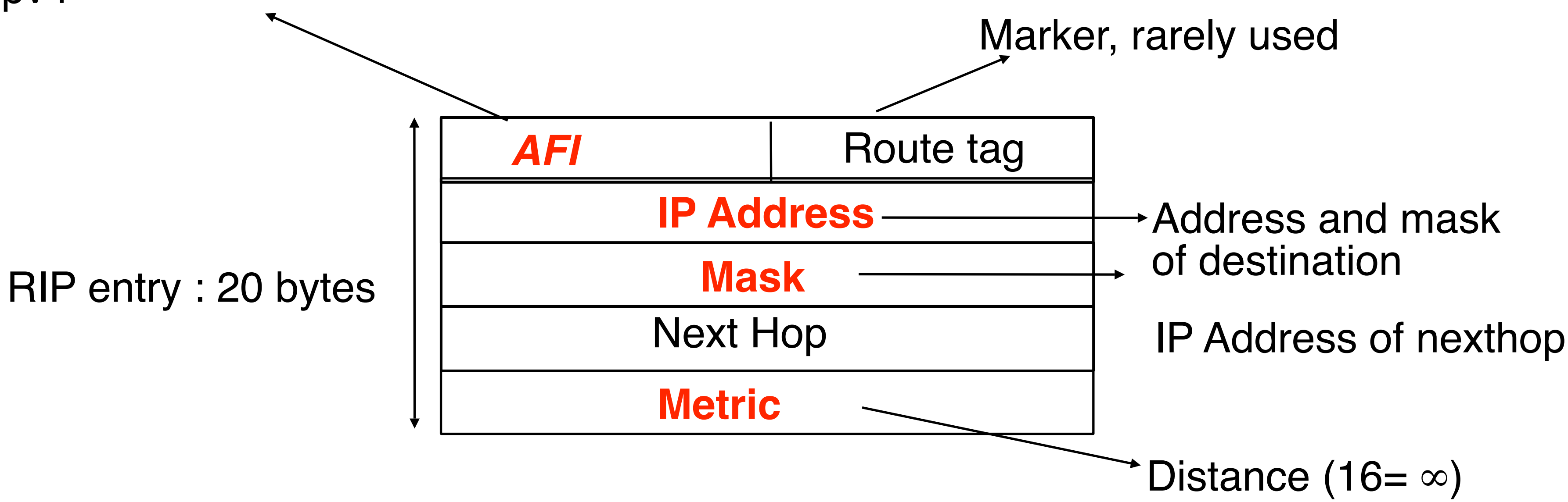
Authentication
Optional. Configure all routers with the same password.
Slightly improves security

Distance vector
One Route Entry (20 bytes) for each route to be advertised

RIP messages are sent by UDP port 520

RIP : Route Entries

AFI : Address Family Identifier
type of addresses used
2= Ipv4



- Default route
  - IP Address = 0.0.0.0, Mask = 0
- Each RIP message can contain up to 25 route entries (24 with authentication)
- If the routing table is larger than 25 entries, router will need to send several RIP messages

RIP timers

- Operation
  - At each expiration of its 30-sec timer, each router sends its distance vector and restarts its timer
- Problem
  - After a power failure, all routers might restart at same time and have synchronised RIP timers
    - Each router will need to process bursts of RIP messages
- Solution
  - Add some randomness to the timers
    - Restart timer after random[27.5, 32.5] instead of 30 seconds
      - commonly used technique to avoid synchronisation problems in distributed protocols

Network layer

Basics

Routing

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OSPF

Standardised link state routing protocol

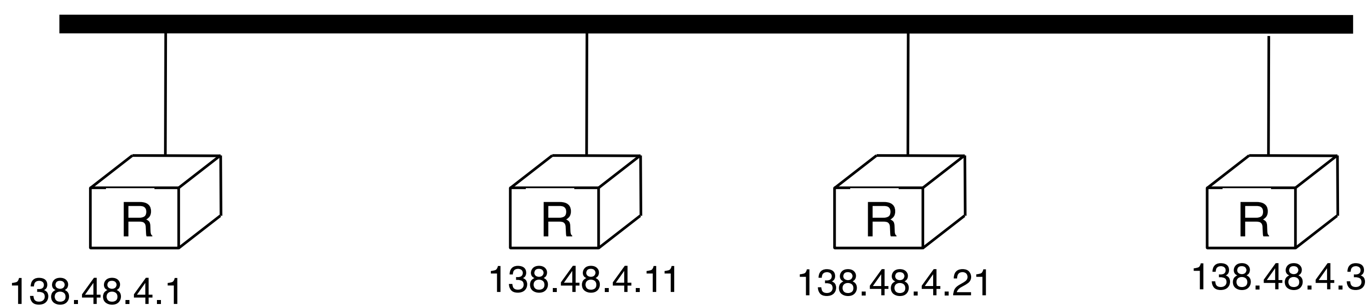
Operation
- Router startup
  - HELLO packets to discover neighbours
- Update of routing tables
  - Link state packets
    - acknowledgements, sequence numbers, age
  - periodic transmission
  - transmission upon link changes
- Database description
  - provides the list of sequence numbers of all LSPs stored by router
- Link state Request
  - used when a router boots to request link state packets from neighbours

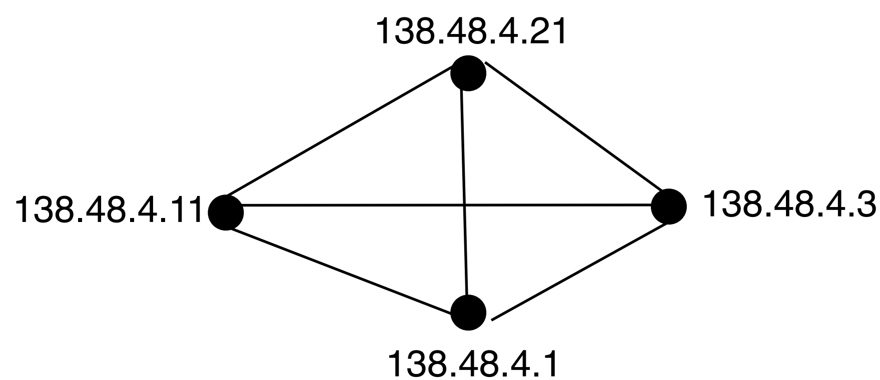
OSPF is defined in RFC2328

OSPF details

Routers are often attached to LANs

- How to describe a LAN full of routers as a graph





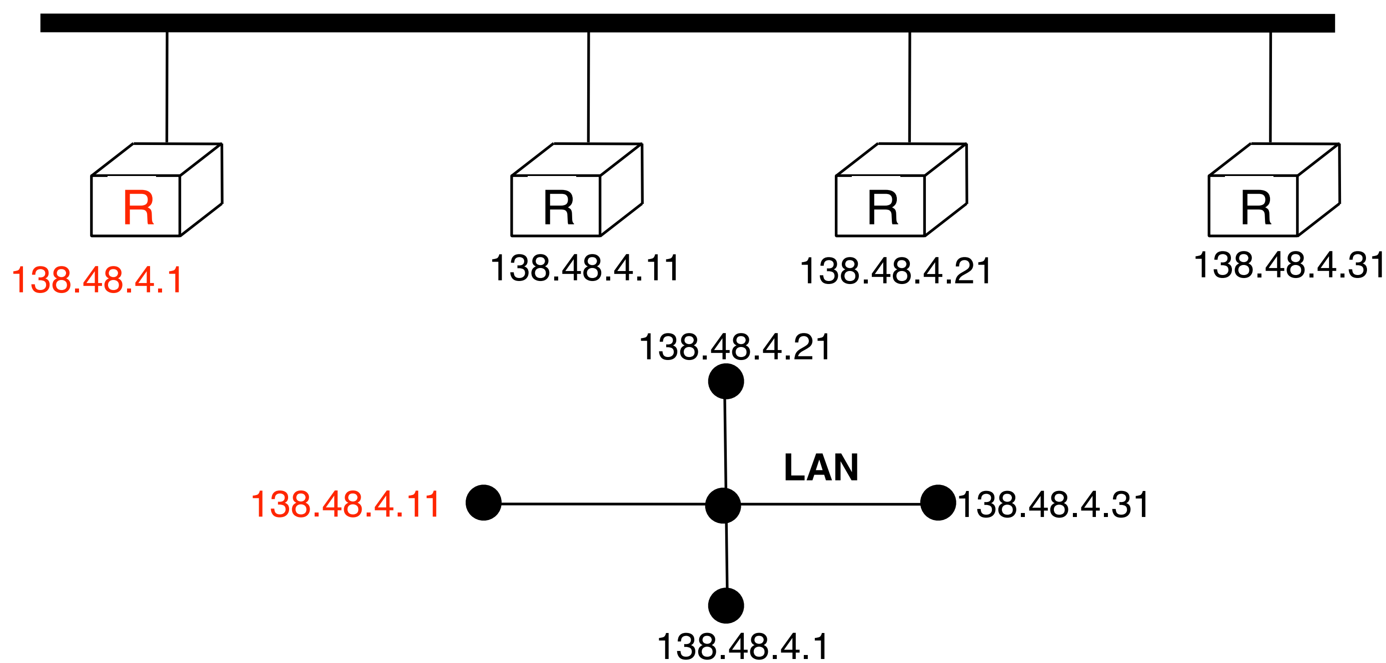
Drawbacks

- Graph contains many links
- Routers need to exchange lots of HELLOs
- Does not really describe the LAN
  - a failure of the LAN would cause a disconnection of all routers while the graph indicates a redundant topology

OSPF details (2)

Solution

- represent the LAN as a star with one router acting as the LAN
  - Designated router
    - One router is elected in the LAN to originate link state packets for the LAN
  - Adjacent router
    - Maintain adjacencies with the designated router



OSPF details (3)

OSPF details (3)

OSPF in large networks

avoid too large routing tables in OSPF routers

OSPF details (3)

OSPF in large networks
- avoid too large routing tables in OSPF routers

Solution
- Divide network in areas
- Backbone area : network backbone
  - all routers connected to two or more areas belong to the backbone area
- All non-backbone areas must be attached to the backbone area
  - at least one router inside each area must be attached to the backbone

OSPF details (3)

OSPF in large networks

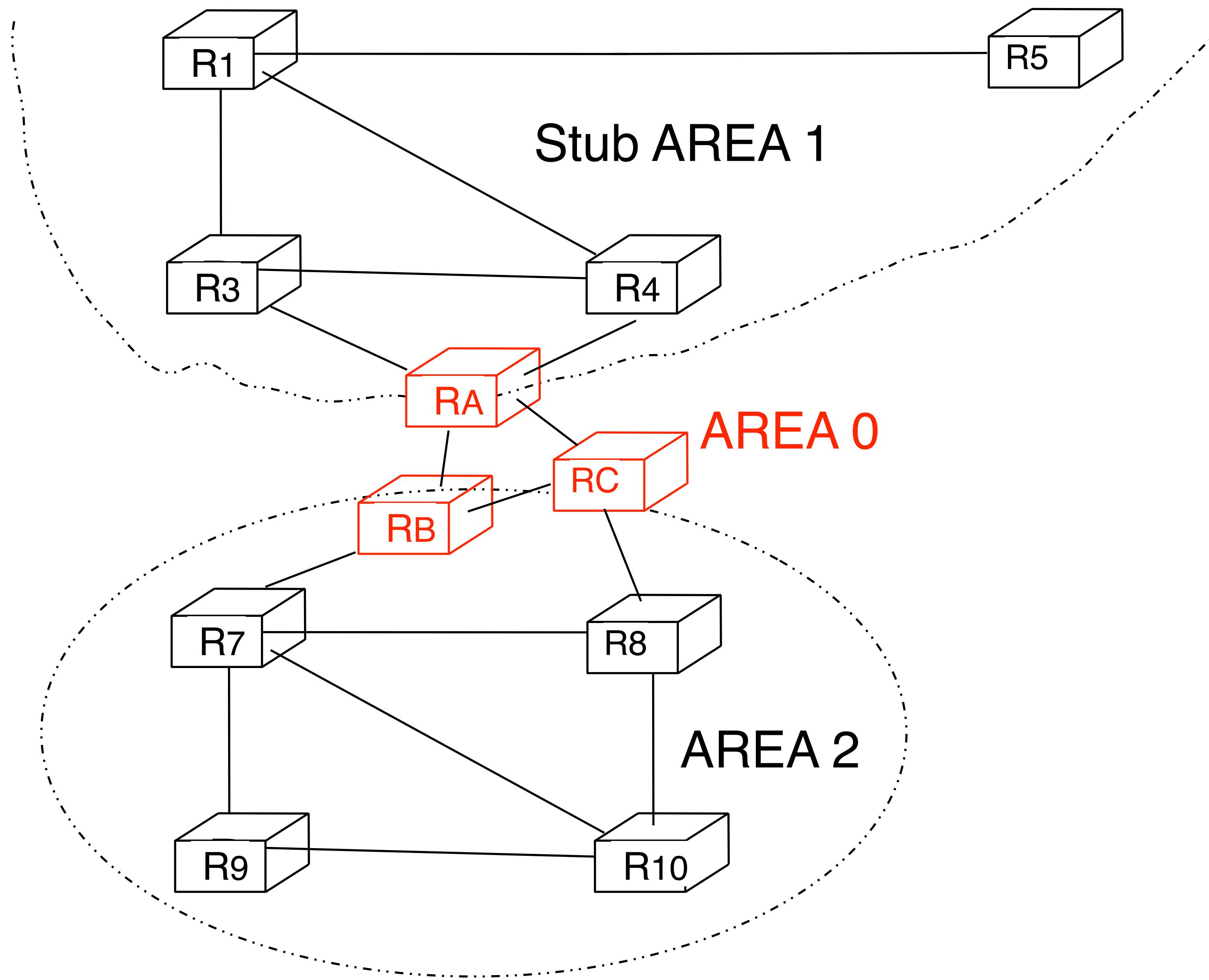
- avoid too large routing tables in OSPF routers

Solution

- Divide network in areas
- Backbone area : network backbone
  - all routers connected to two or more areas belong to the backbone area
- All non-backbone areas must be attached to the backbone area
  - at least one router inside each area must be attached to the backbone

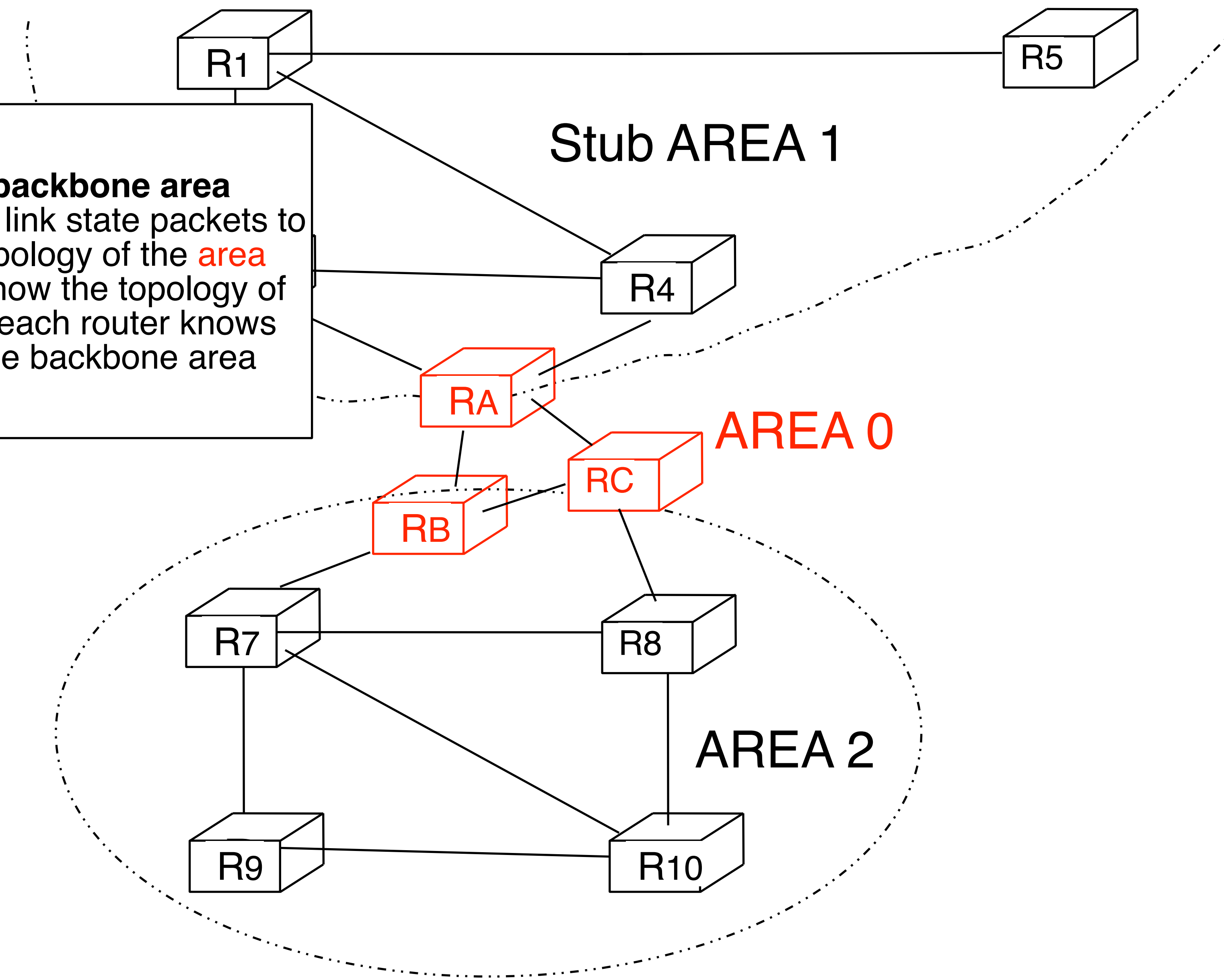
OSPF routing must allow any router to send packets to any other router

OSPF details (4)

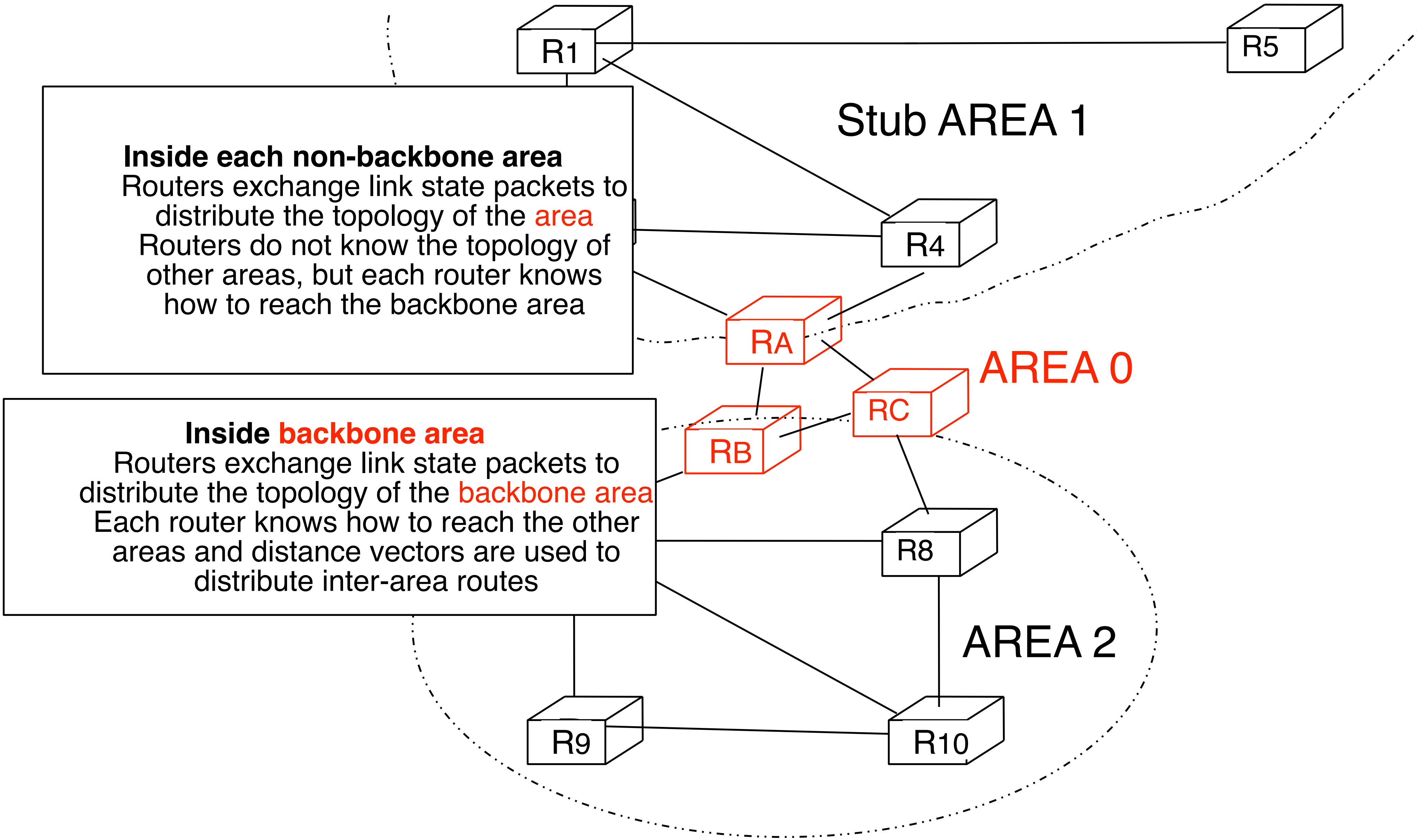


OSPF details (4)

Inside each non-backbone area
Routers exchange link state packets to distribute the topology of the area
Routers do not know the topology of other areas, but each router knows how to reach the backbone area



OSPF details (4)



Inside each non-backbone area
Routers exchange link state packets to distribute the topology of the area
Routers do not know the topology of other areas, but each router knows how to reach the backbone area

Inside backbone area
Routers exchange link state packets to distribute the topology of the backbone area
Each router knows how to reach the other areas and distance vectors are used to distribute inter-area routes

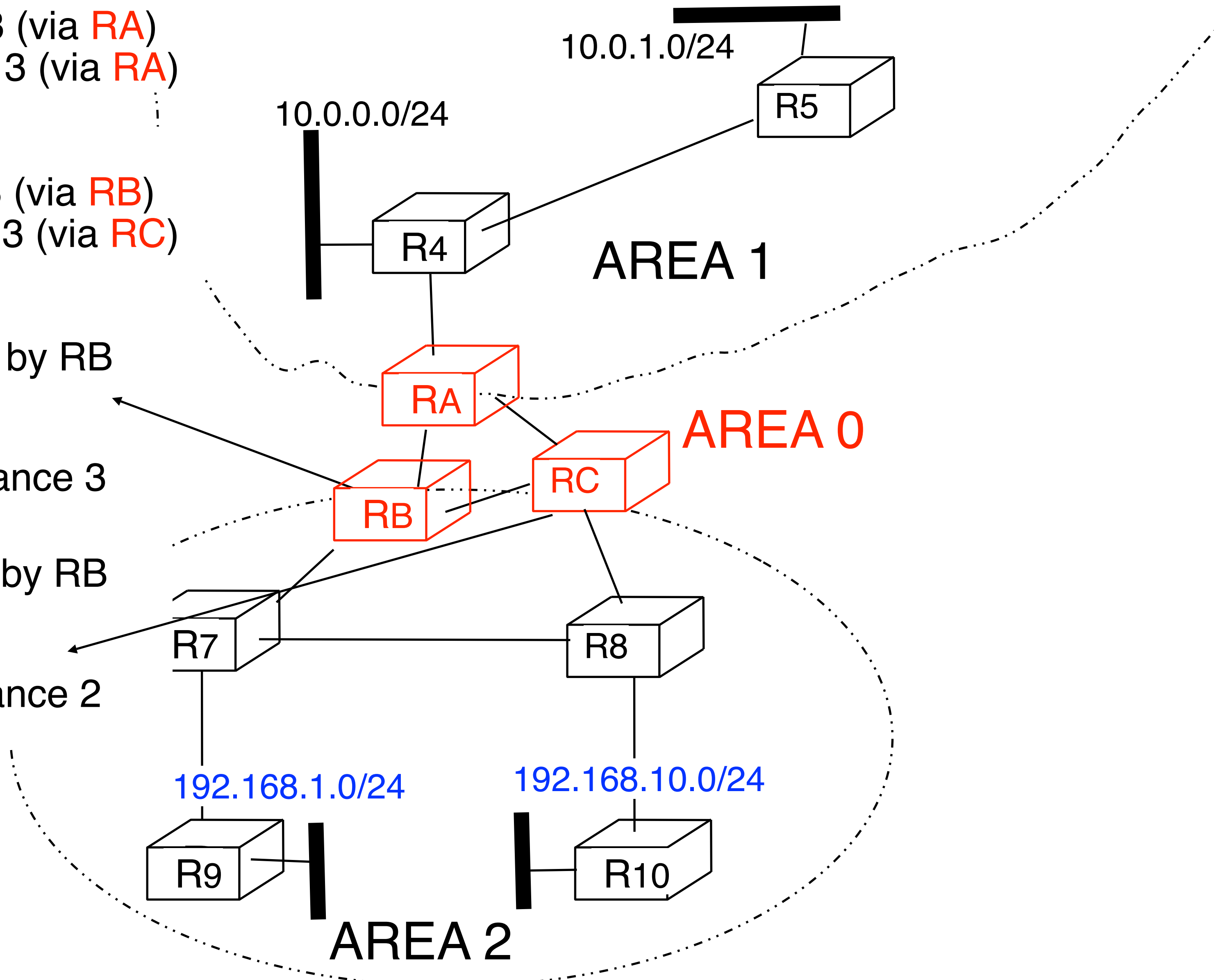
OSPF areas : Example

Routes learned by R4
192.168.1.0/24, distance 3 (via RA)
192.168.10.0/24, distance 3 (via RA)

Routes chosen par RA
192.168.1.0/24, distance 3 (via RB)
192.168.10.0/24, distance 3 (via RC)

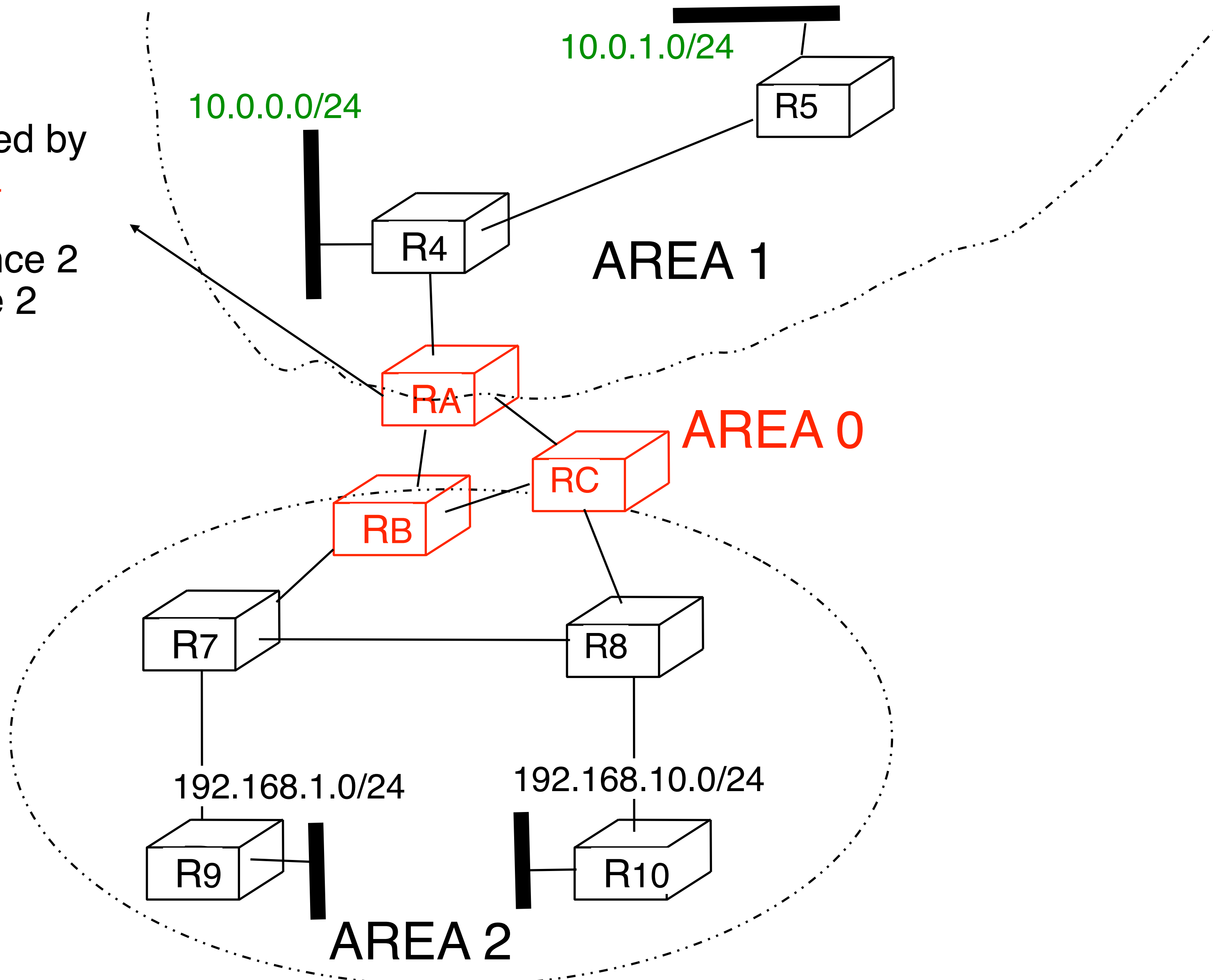
Distance vectors advertised by RB in backbone area
192.168.1.0/24, distance 2
and 192.168.10.0/24, distance 3

Distance vectors advertised by RB in backbone area
192.168.1.0/24, distance 3
and 192.168.10.0/24, distance 2



Areas OSPF : Example (2)

Distance vector advertised by RA in the backbone area
10.0.0.0/24, distance 1
and 10.0.1.0/24, distance 2
or 10.0.0.0/23, distance 2



Network layer

Basics

Routing

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Routing in IP networks
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- Intradomain routing : OSPF
- Interdomain routing : BGP

Interdomain routing

Goals

Allow to transmit IP packets along the best path towards their destination through several transit domains while taking into account the routing policies of each domain without knowing the detailed topology of those domains

From an interdomain viewpoint, best path often means *cheapest* path

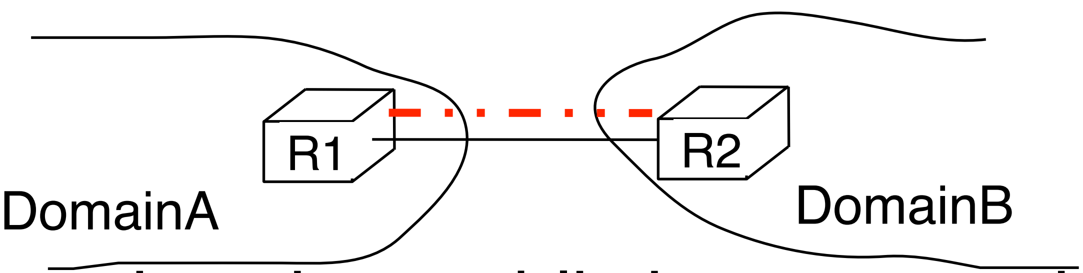
Each domain is free to specify inside its routing policy the domains for which it agrees to provide a transit service and the method it uses to select the best path to reach each destination

Types of interdomain links

Two types of interdomain links

Private link

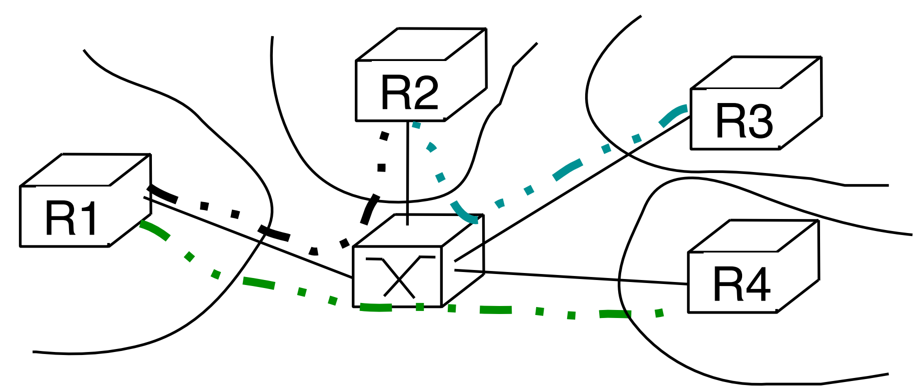
Usually a leased line between two routers belonging to the two connected domains



Connection via a public interconnection point

Usually Gigabit or higher Ethernet switch that interconnects routers belonging to different domains

Physical link
Interdomain link



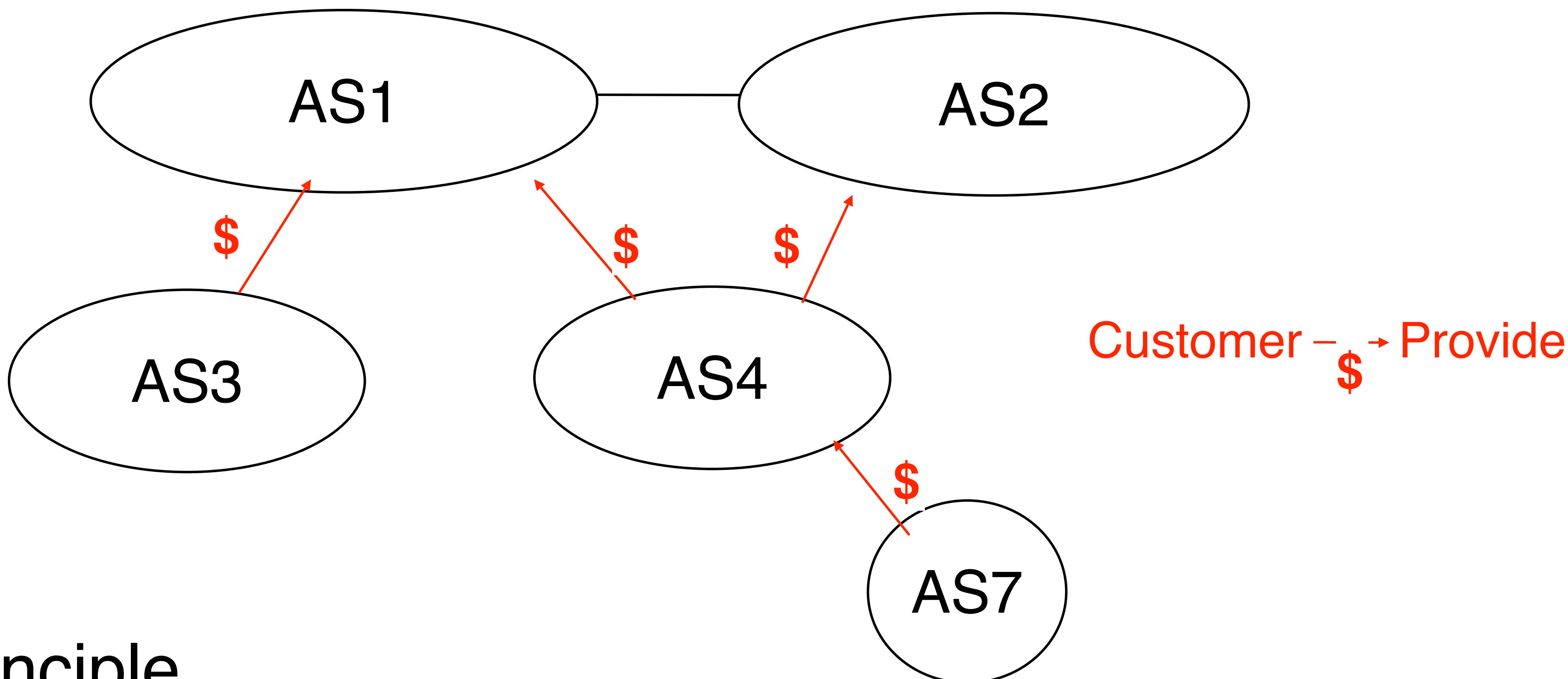
Routing policies

In theory BGP allows each domain to define its own routing policy...

In practice there are two common policies

- customer-provider peering
  - **Customer c** buys Internet connectivity from **provider P**
- shared-cost peering
  - **Domains x** and **y** agree to exchange packets by using a direct link or through an interconnection point

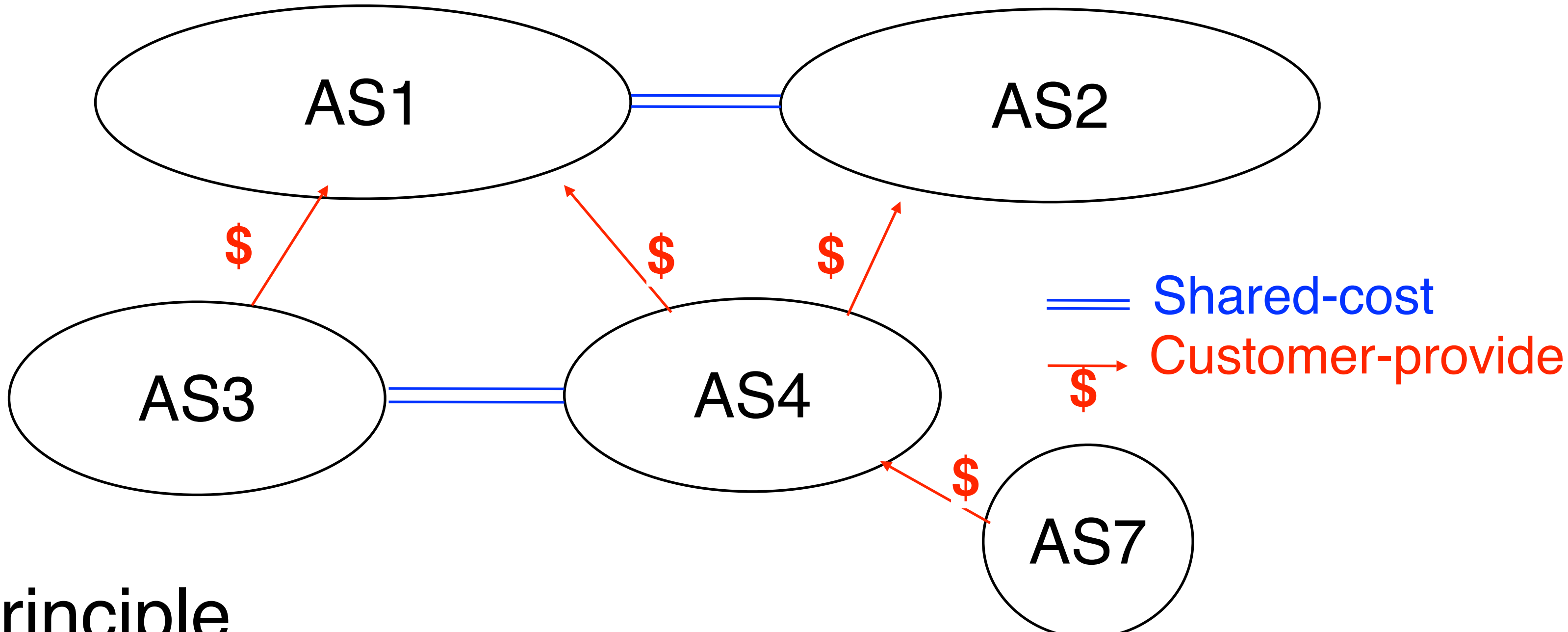
Customer-provider peering



Principle

- Customer sends to its provider its internal routes and the routes learned from its own customers
  - Provider will advertise those routes to the entire Internet to allow anyone to reach the Customer
- Provider sends to its customers all known routes
  - Customer will be able to reach anyone on the Internet

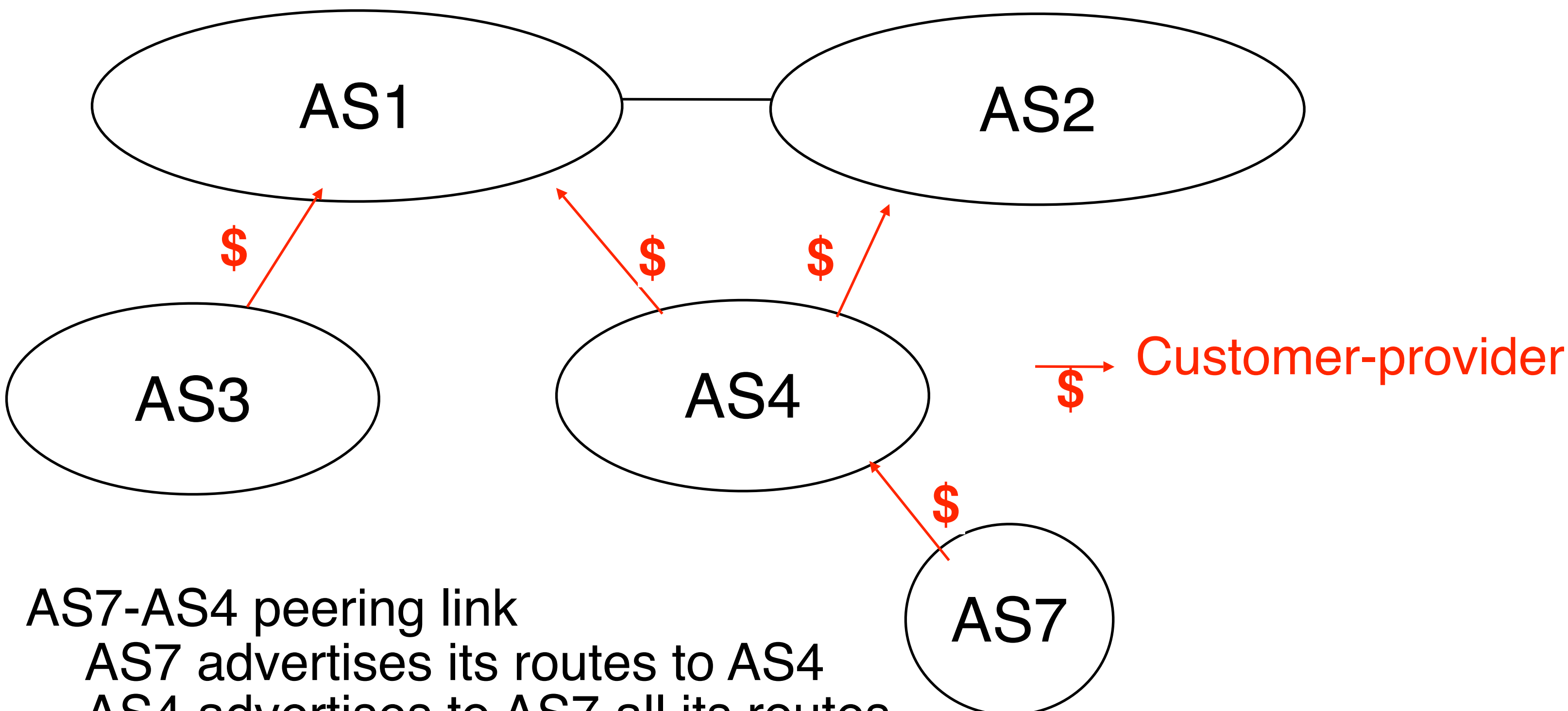
Shared-cost peering



Principle

- PeerX sends to PeerY its internal routes and the routes learned from its own customers
  - PeerY will use shared link to reach PeerX and PeerX's customers
  - PeerX's providers are not reachable via the shared link
- PeerY sends to PeerX its internal routes and the routes learned from its own customers
  - PeerX will use shared link to reach PeerY and PeerY's customers
  - PeerY's providers are not reachable via the shared link

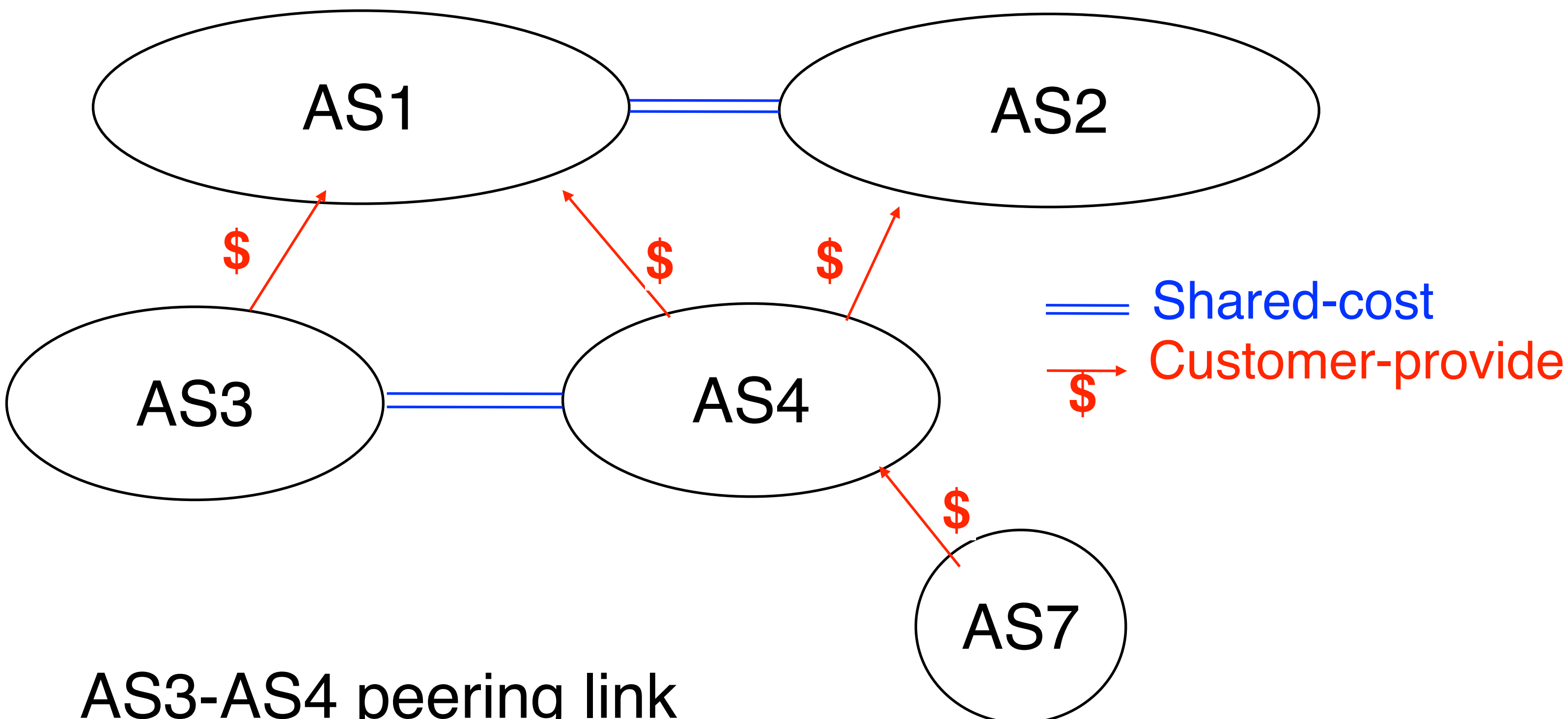
Customer-provider peering : example



AS7-AS4 peering link
- AS7 advertises its routes to AS4
- AS4 advertises to AS7 all its routes

AS4-AS2 peering link
- AS4 advertises its own routes et those of its customers (AS7)
- AS2 advertises to AS2 all known routes

Shared-cost peering : example



AS3-AS4 peering link

- AS3 advertises its own routes
- AS4 advertises its own routes and those received from its clients (AS7)

AS1-AS2 peering link

- AS1 advertises its own routes and those received from its clients (AS3 and AS4)
- AS1 advertises its own routes and those received from its clients (AS4)

Routing policies

A domain specifies its routing policy by defining on each BGP router two sets of filters for each peer

- Import filter
  - Specifies which routes can be accepted by the router among all the received routes from a given peer
- Export filter
  - Specifies which routes can be advertised by the router to a given peer

Filters can be defined in RPSL

- Routing Policy Specification Language
  - defined in RFC2622 and examples in RFC2650
    - See also http://www.ripe.net/ripencc/pub-services/whois.html

RPSL

Simple import policies

Syntax

```
import: from AS# accept list_of_AS
```

Examples

```
Import: from Belgacom accept Belgacom WIN
Import: from Provider accept ANY
```

Simple export policies

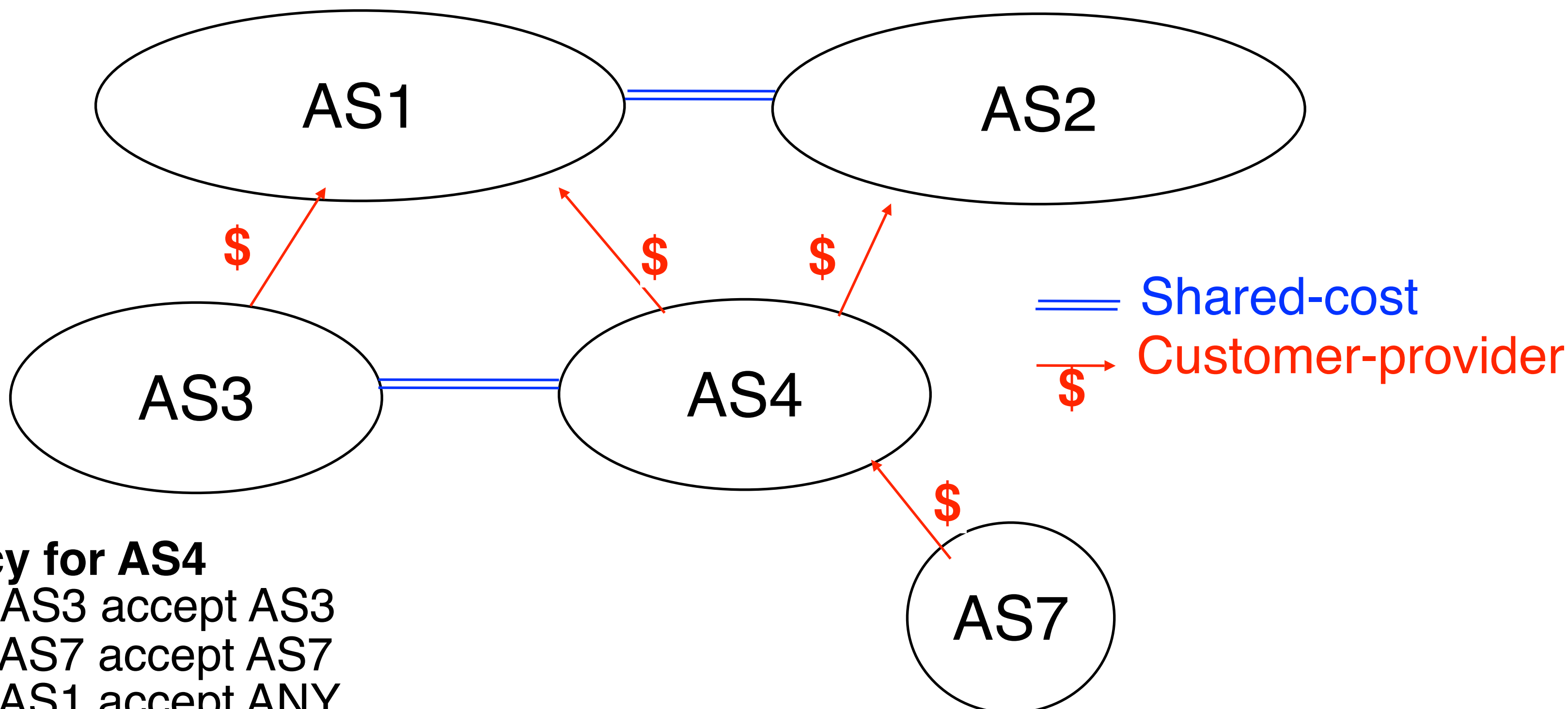
Syntax

```
Export: to AS# announce list_of_AS
```

Example

```
Export: to Customer announce ANY
Export: to Peer announce Customer1 Customer2
```

Routing policies
Simple example with RPSL



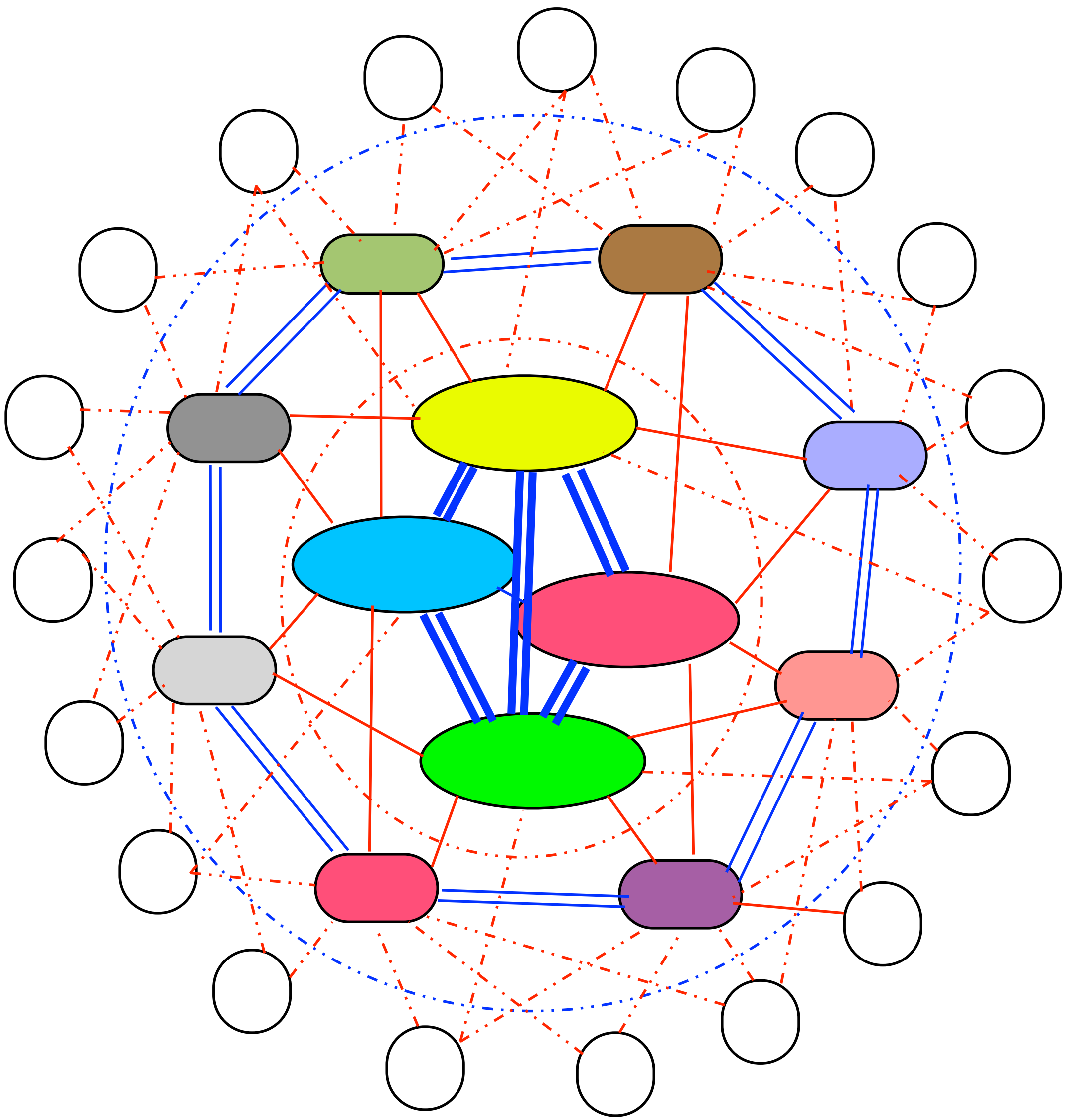
Import policy for AS4
Import: from AS3 accept AS3
import: from AS7 accept AS7
import: from AS1 accept ANY
import: from AS2 accept ANY

Export policy for AS4
export: to AS3 announce AS4 AS7
export: to AS7 announce ANY
export: to AS1 announce AS4 AS7
export: to AS2 announce AS4 AS7

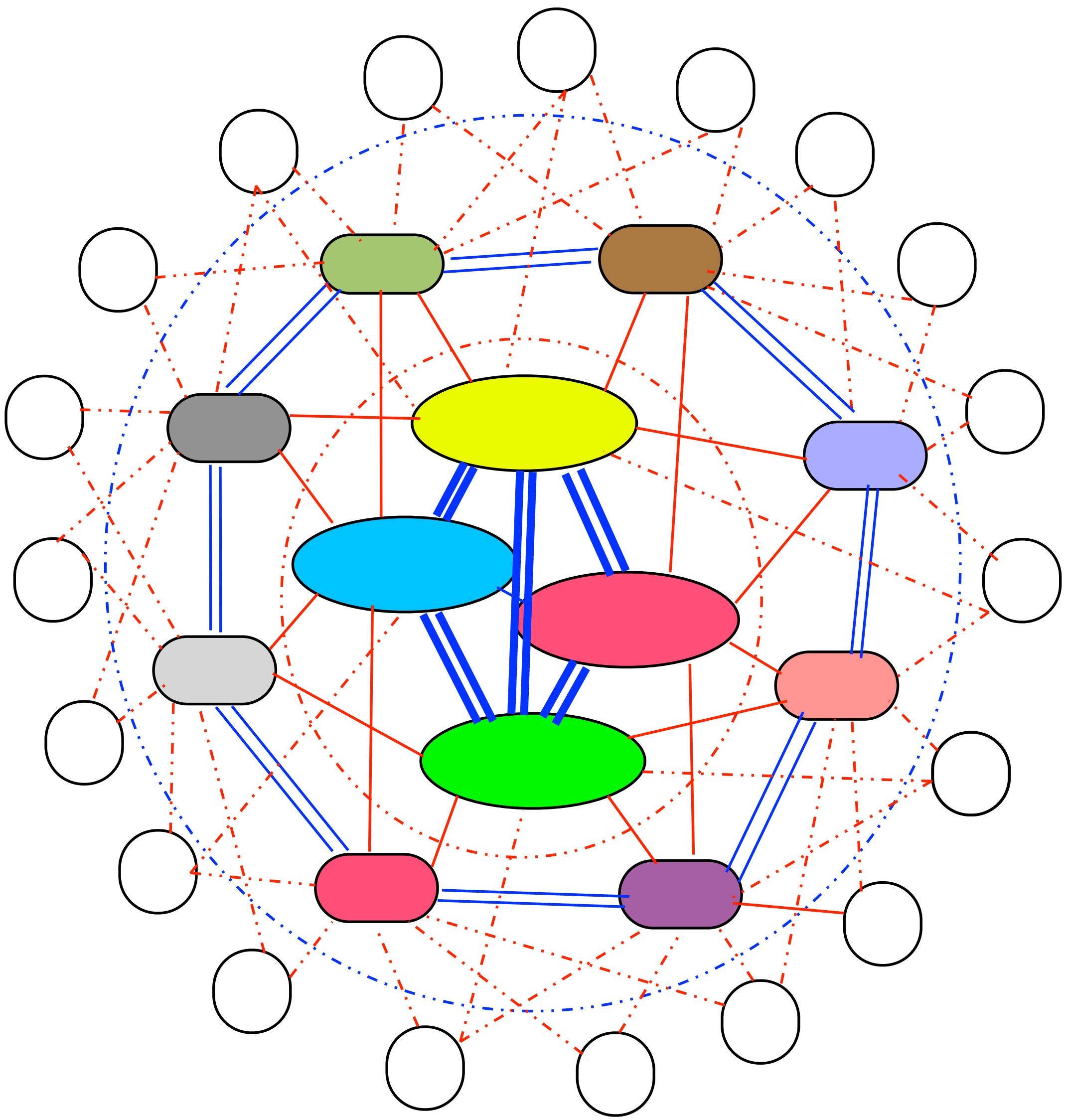
Import policy for AS7
Import: from AS4 accept ANY

Export policy for AS4
export: to AS4 announce AS7

The organisation of the Internet



The organisation of the Internet



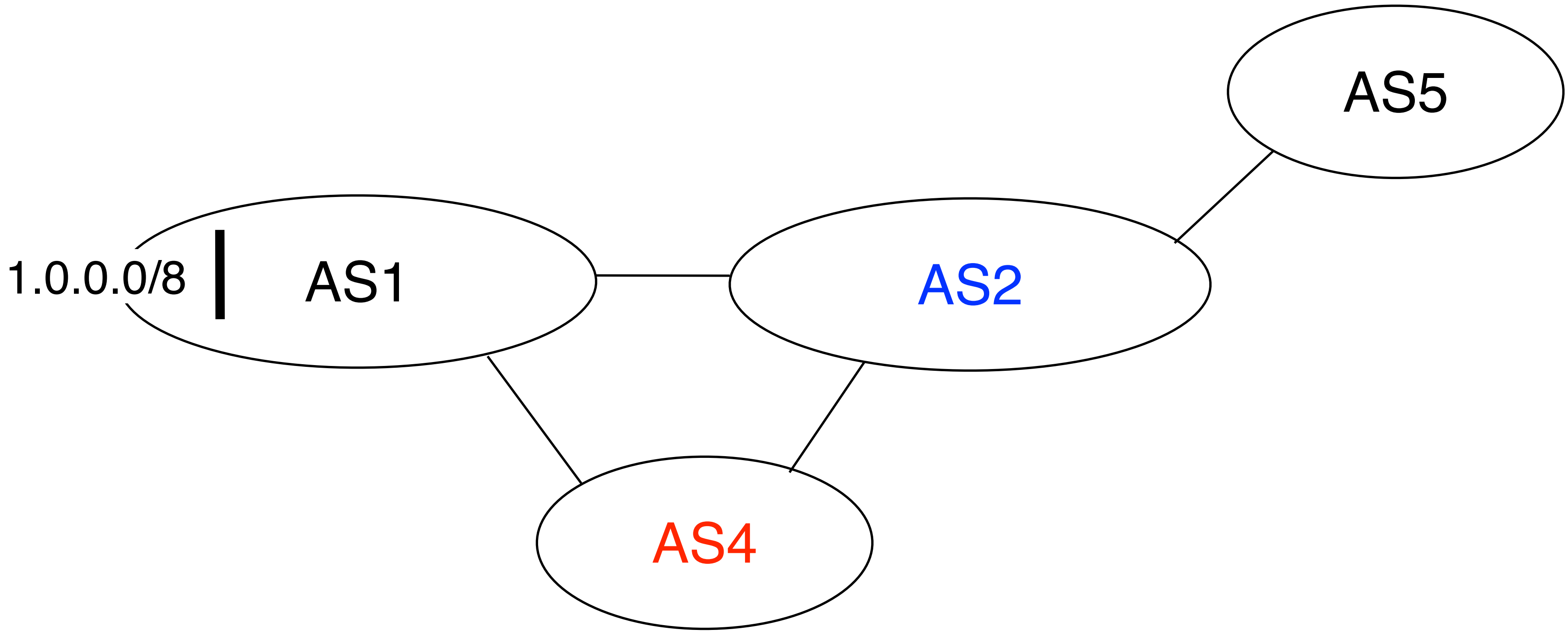
Tier-1 ISPs
- Dozen of large ISPs interconnected by shared-cost
- Provide transit service
  - Uunet, Level3, OpenTransit, ...

Tier-2 ISPs
- Regional or National ISPs
- Customer of T1 ISP(s)
- Provider of T3 ISP(s)
- shared-cost with other T2 ISPs
  - France Telecom, BT, Belgacom

Tier-3 ISPs
- Smaller ISPs, Corporate Networks, Content providers
- Customers of T2 or T1 ISPs
- shared-cost with other T3 ISPs

The Border Gateway Protocol

Principle
- Path vector protocol
  - BGP router advertises its best route to each destination

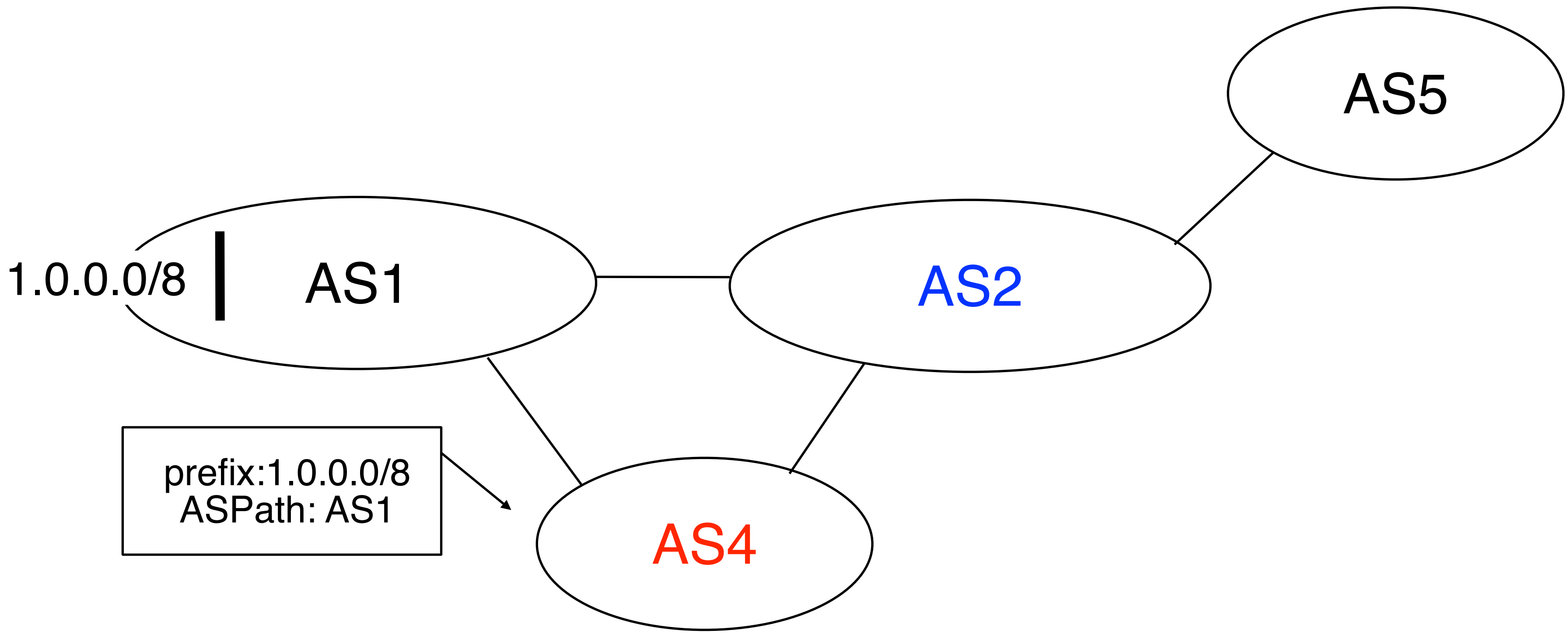


BGP is defined in RFC4271

The Border Gateway Protocol

Principle

- Path vector protocol
  - BGP router advertises its best route to each destination



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The Border Gateway Protocol

Principle

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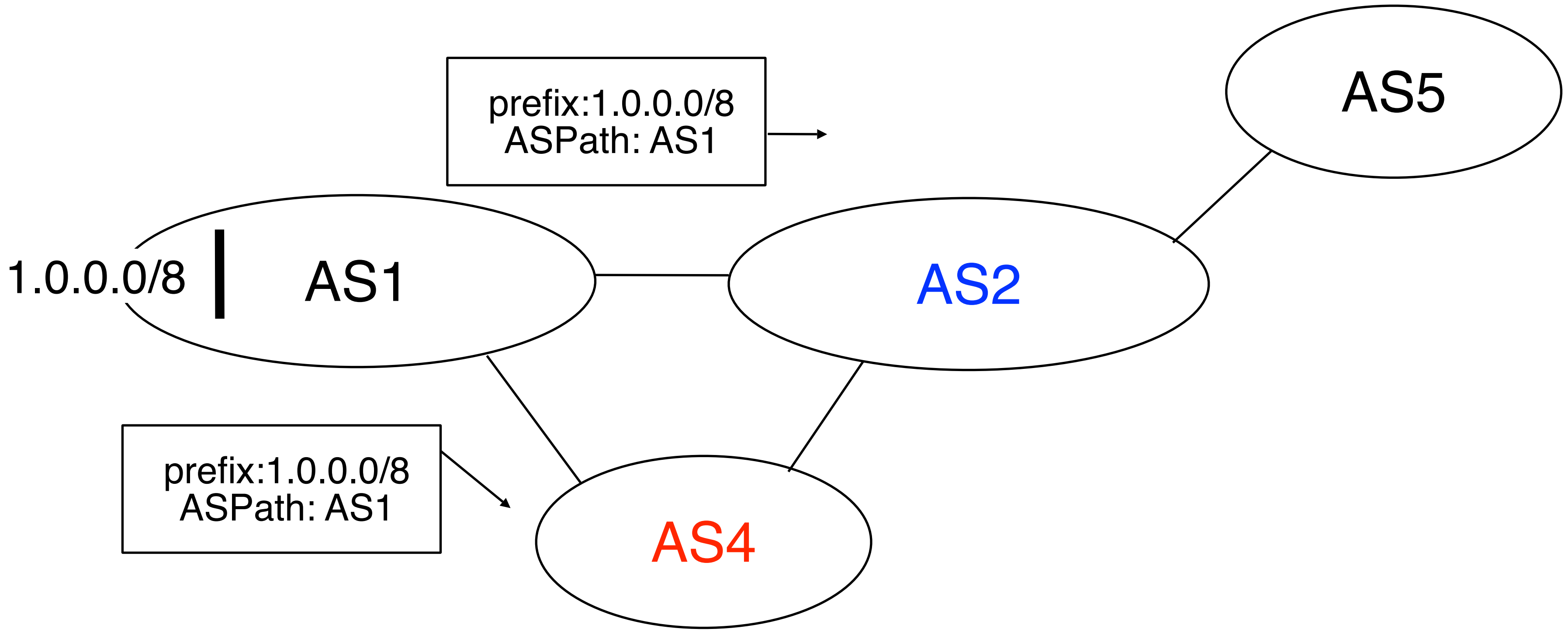

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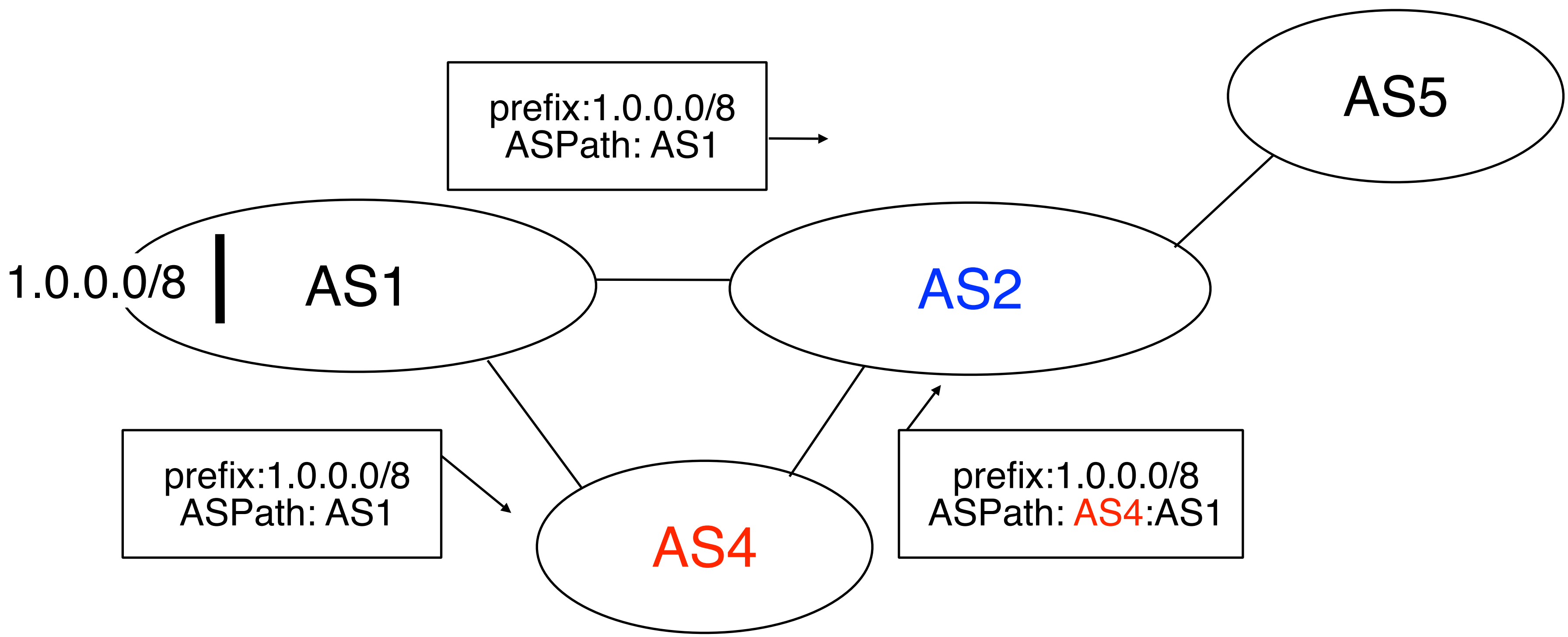
The Border Gateway Protocol

Principle

Path vector protocol

BGP router advertises its best route to each destination



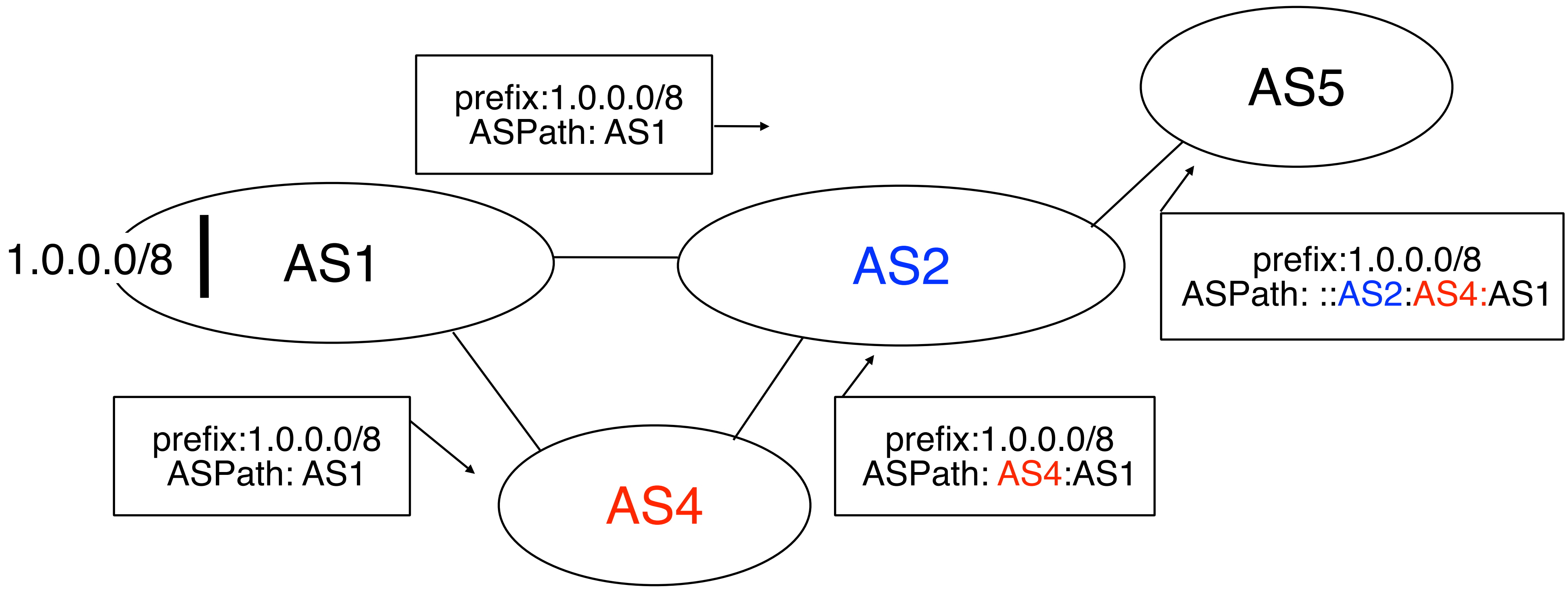
BGP is defined in RFC4271

The Border Gateway Protocol

Principle

Path vector protocol

BGP router advertises its best route to each destination



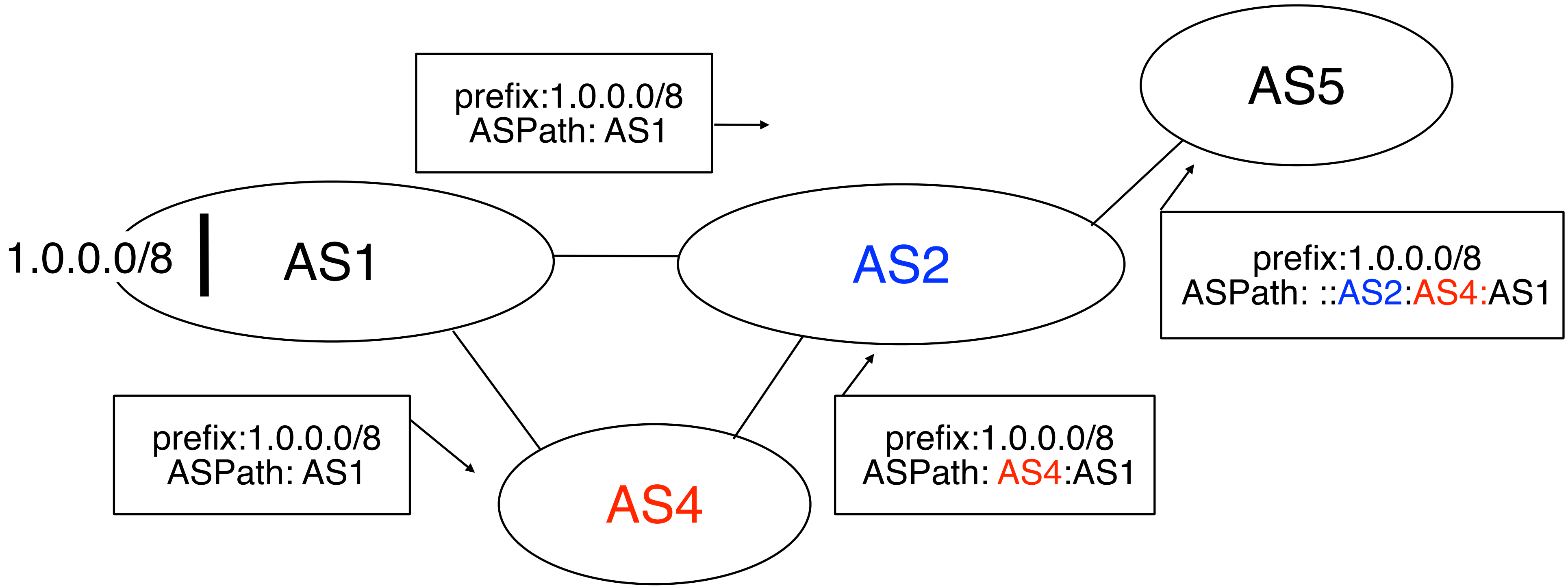
BGP is defined in RFC4271

The Border Gateway Protocol

Principle

Path vector protocol

BGP router advertises its best route to each destination



... with incremental updates

Advertisements are only sent when their content changes

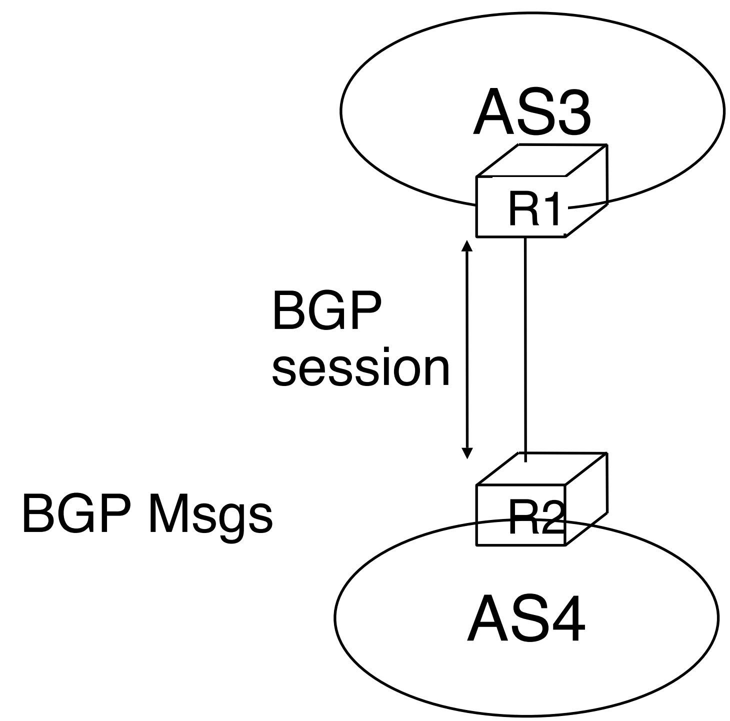
BGP is defined in RFC4271

BGP : Principles of operation

Principles

BGP relies on the

incremental exchange of path vectors

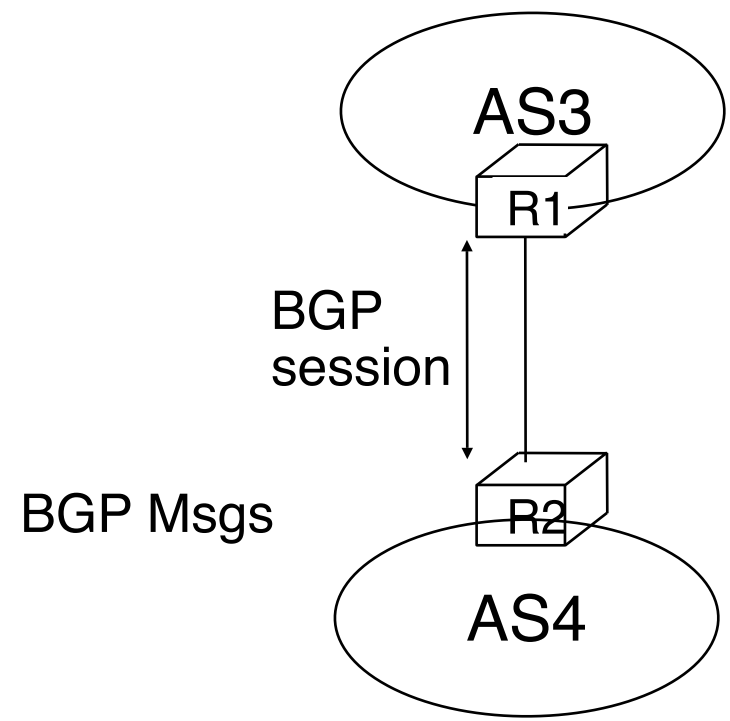


BGP : Principles of operation

Principles

BGP relies on the
incremental exchange of path vectors

BGP session established
over
TCP connection between
peers



BGP : Principles of operation

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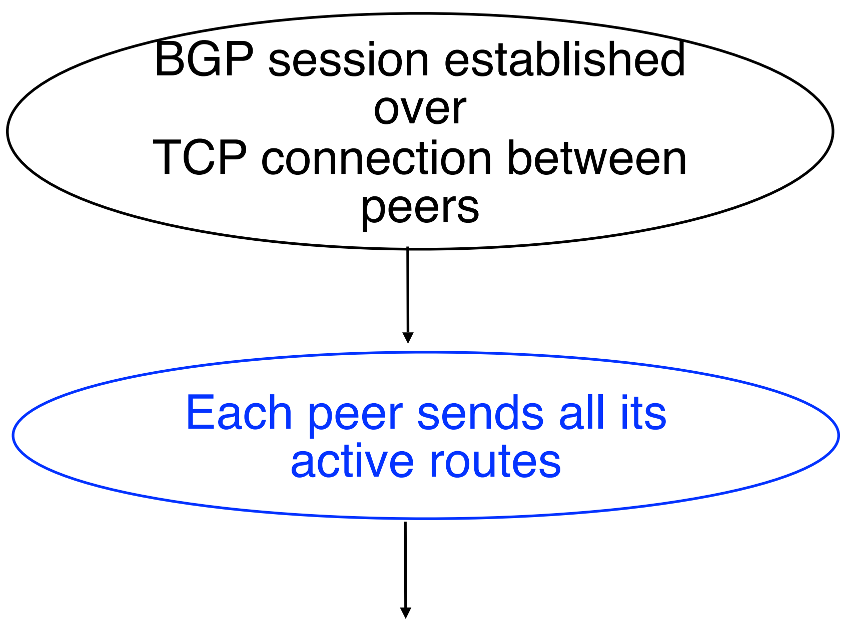

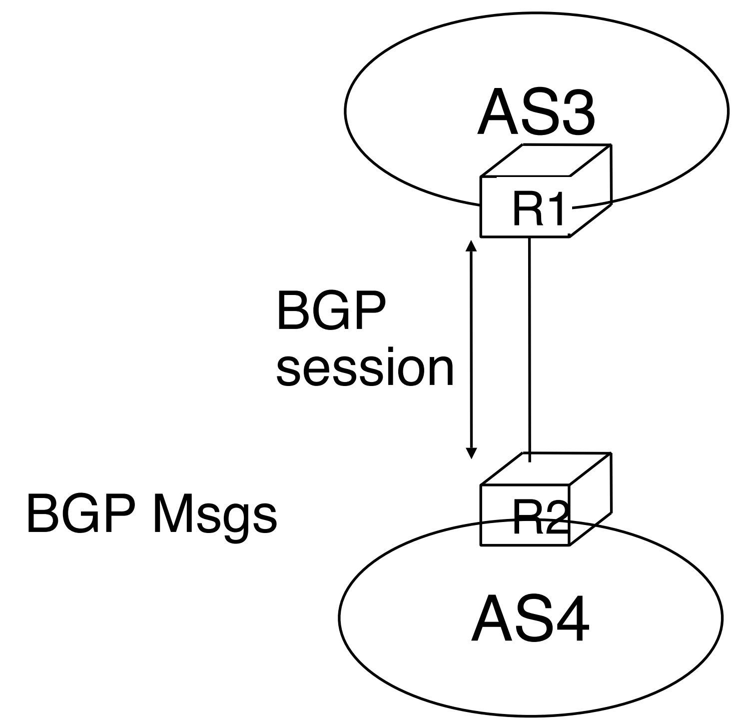

BGP : Principles of operation

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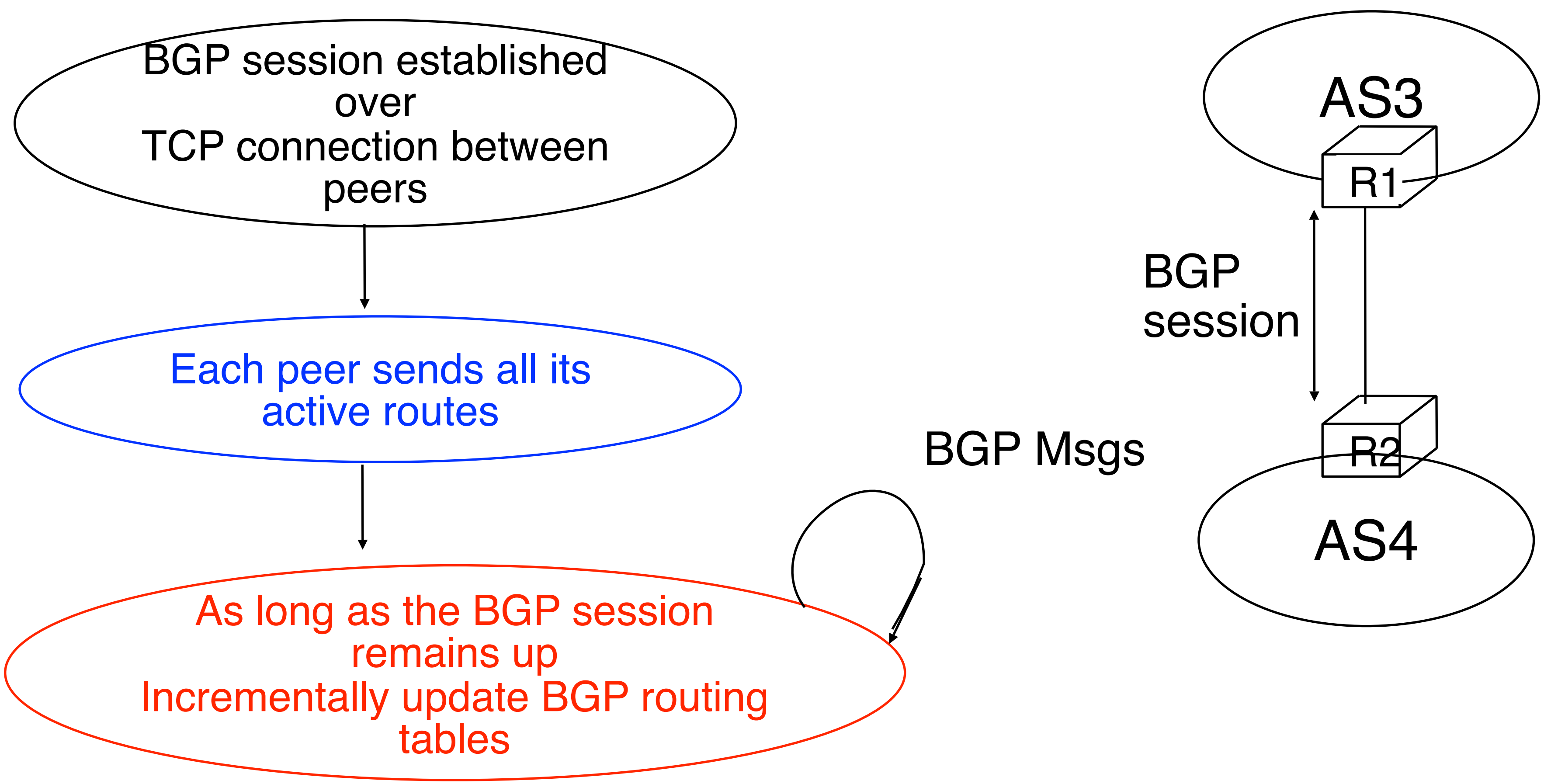
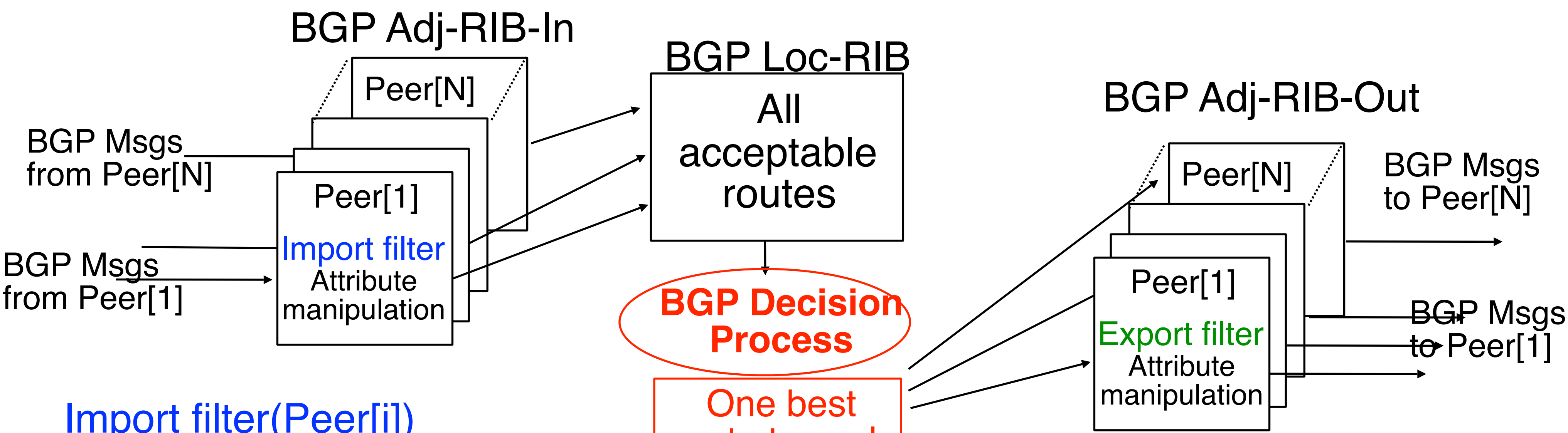


BGP : Principles of operation (2)

- Simplified model of BGP
  - 2 types of BGP path vectors
  - UPDATE
    - Used to announce a route towards one prefix
    - Content of UPDATE
      - Destination address/prefix
      - Interdomain path used to reach destination (AS-Path)
      - Nexthop (address of the router advertising the route)
  - WITHDRAW
    - Used to indicate that a previously announced route is not reachable anymore
    - Content of WITHDRAW
      - Unreachable destination address/prefix

Conceptual model of a BGP router



Import filter(Peer[i])
Determines which BGM Msgs are acceptable from Peer[i]

Export filter(Peer[i])
Determines which routes can be sent to Peer[i]

BGP Routing Information Base
Contains all the acceptable routes learned from all Peers + internal routes
BGP decision process selects *the* best route towards each destination

Where do the routes advertised by BGP routers come from ?

- Learned from another BGP router
  - Each BGP router advertises best route towards each destination
- Static route
  - Configured manually on the router
    - Ex : The BGP router at UCL advertises 130.104.0.0/16
    - Drawback
      - Requires manual configuration
    - Advantage
      - BGP advertisements are stable
- Learned from an intradomain routing protocol
  - BGP might try to aggregate the route before advertising it
  - Advantage :
    - BGP advertisements correspond to network status
  - Drawback
    - Routing instabilities inside a domain might propagate in Internet

BGP : Session Initialization

```
Initialize_BGP_Session(RemoteAS, RemoteIP)
{ /* Initialize and start BGP session */
/* Send BGP OPEN Message to RemoteIP on port 179*/
/* Follow BGP state machine */

/* advertise local routes and routes learned from peers*/
foreach (destination=d inside RIB)
 {
  B=build_BGP_UPDATE(d);
  S=apply_export_filter(RemoteAS,B);
  if (S<>NULL)
     { /* send UPDATE message */
       send_UPDATE(S,RemoteAS, RemoteIP)
     }
 }
/* entire RIB was sent */
/* new UPDATE will be sent only to reflect local or distant
   changes in routes */
...
}
```

Events during a BGP session

1. Addition of a new route to RIB
   - A new internal route was added on local router
     - static route added by configuration
     - Dynamic route learned from IGP
   - Reception of UPDATE message announcing a new or modified route
2. Removal of a route from RIB
   - Removal of an internal route
     - Static route is removed from router configuration
     - Intradomain route declared unreachable by IGP
   - Reception of WITHDRAW message
3. Loss of BGP session
   - All routes learned from this peer removed from RIB

Export and Import filters

```
BGPMsg Apply_export_filter(RemoteAS, BGPMsg)
{ /* check if Remote AS already received route */
if (RemoteAS isin BGPMsg.ASPath)
   BGPMsg==NULL;
/* Many additional export policies can be configured : */
/* Accept or refuse the BGPMsg */
/* Modify selected attributes inside BGPMsg */
}

BGPMsg apply_import_filter(RemoteAS, BGPMsg)
{ /* check that we are not already inside  ASPath */
 if (MyAS isin BGPMsg.ASPath)
   BGPMsg==NULL;
/* Many additional import policies can be configured : */
/* Accept or refuse the BGPMsg */
/* Modify selected attributes inside BGPMsg */
}
```

BGP : Processing of UPDATES

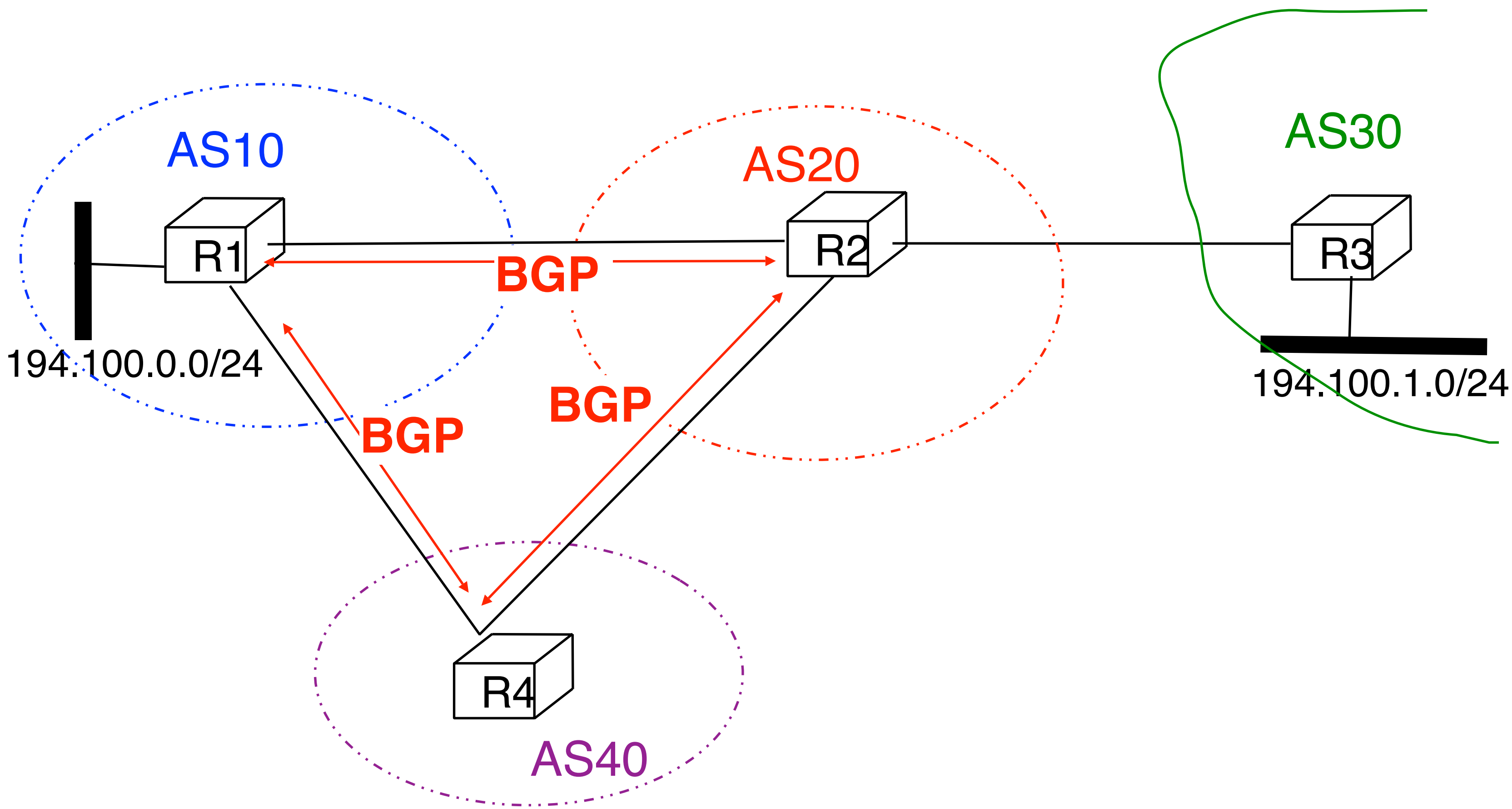
```
Recvd_BGPMsg(Msg, RemoteAS)
{
 B=apply_import_filer(Msg,RemoteAS);
 if (B==NULL) /* Msg not acceptable */
     exit();
 if IsUPDATE(Msg)
 {
  Old_Route=BestRoute(Msg.prefix);
  Insert_in_RIB(Msg);
  Run_Decision_Process(RIB);
  if (BestRoute(Msg.prefix)<>Old_Route)
  { /* best route changed */
    B=build_BGP_Message(Msg.prefix);
    S=apply_export_filter(RemoteAS,B);
    if (S<>NULL) /* announce best route */
     send_UPDATE(S,RemoteAS);
    else if (Old_Route<>NULL)
     send_WITHDRAW(Msg.prefix);
 } ...
```

BGP : Processing of WITHDRAW

```
Recvd_Msg(Msg, RemoteAS)
...
if IsWITHDRAW(Msg)
 {
  Old_Route=BestRoute(Msg.prefix);
  Remove_from_RIB(Msg);
  Run_Decision_Process(RIB);
  if (Best_Route(Msg.prefix)<>Old_Route)
  { /* best route changed */
    B=build_BGP_Message(d);
    S=apply_export_filter(RemoteAS,B);
    if (S<>NULL) /* still one best route */
       send_UPDATE(S,RemoteAS, RemoteIP);
    else if(Old_Route<>NULL)/* no best route anymore */
       send_WITHDRAW(Msg.prefix,RemoteAS,RemoteIP);
  }
 }
}
```

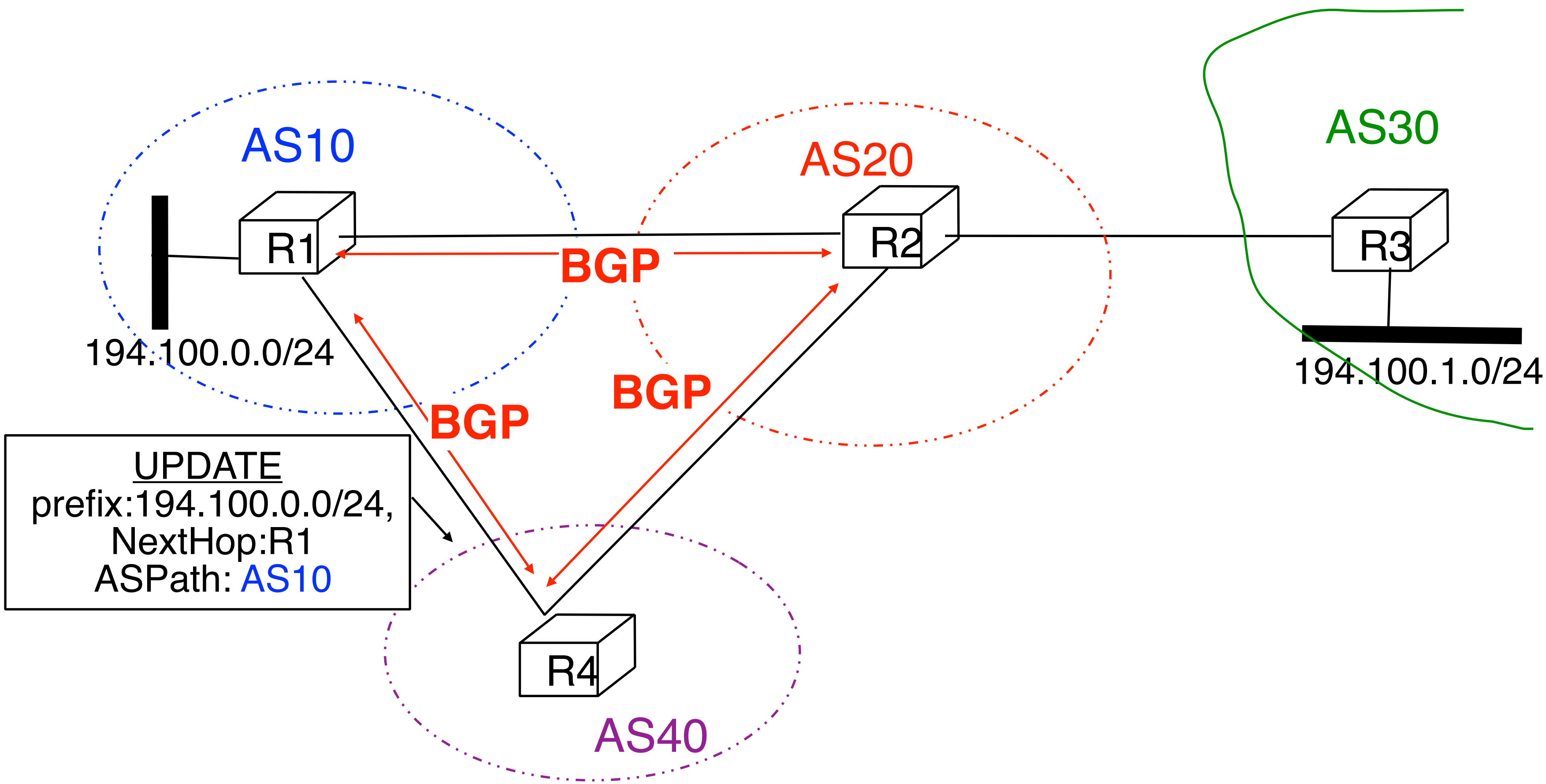
BGP and IP
A first example

Initial updates



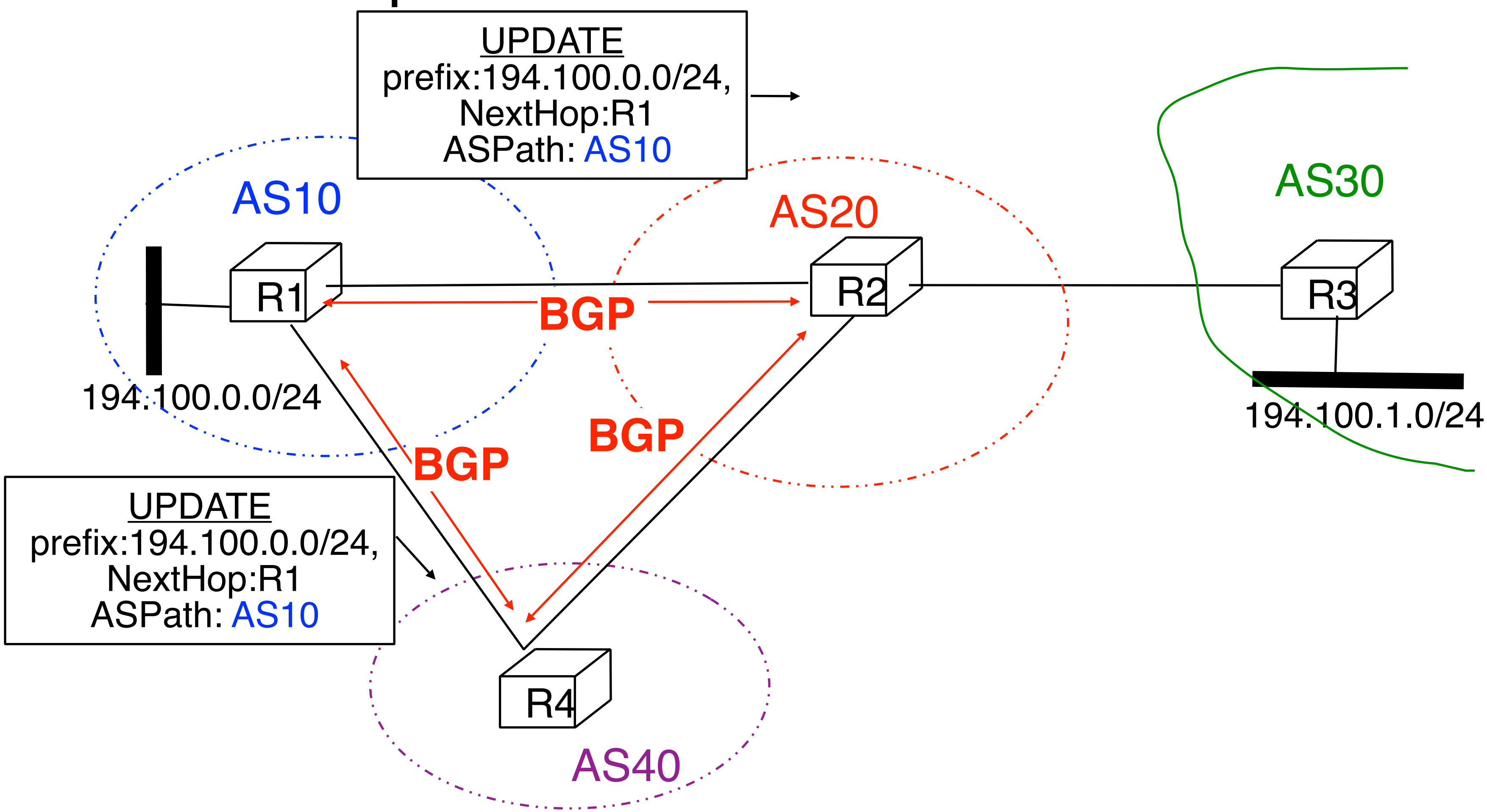
BGP and IP
A first example

Initial updates



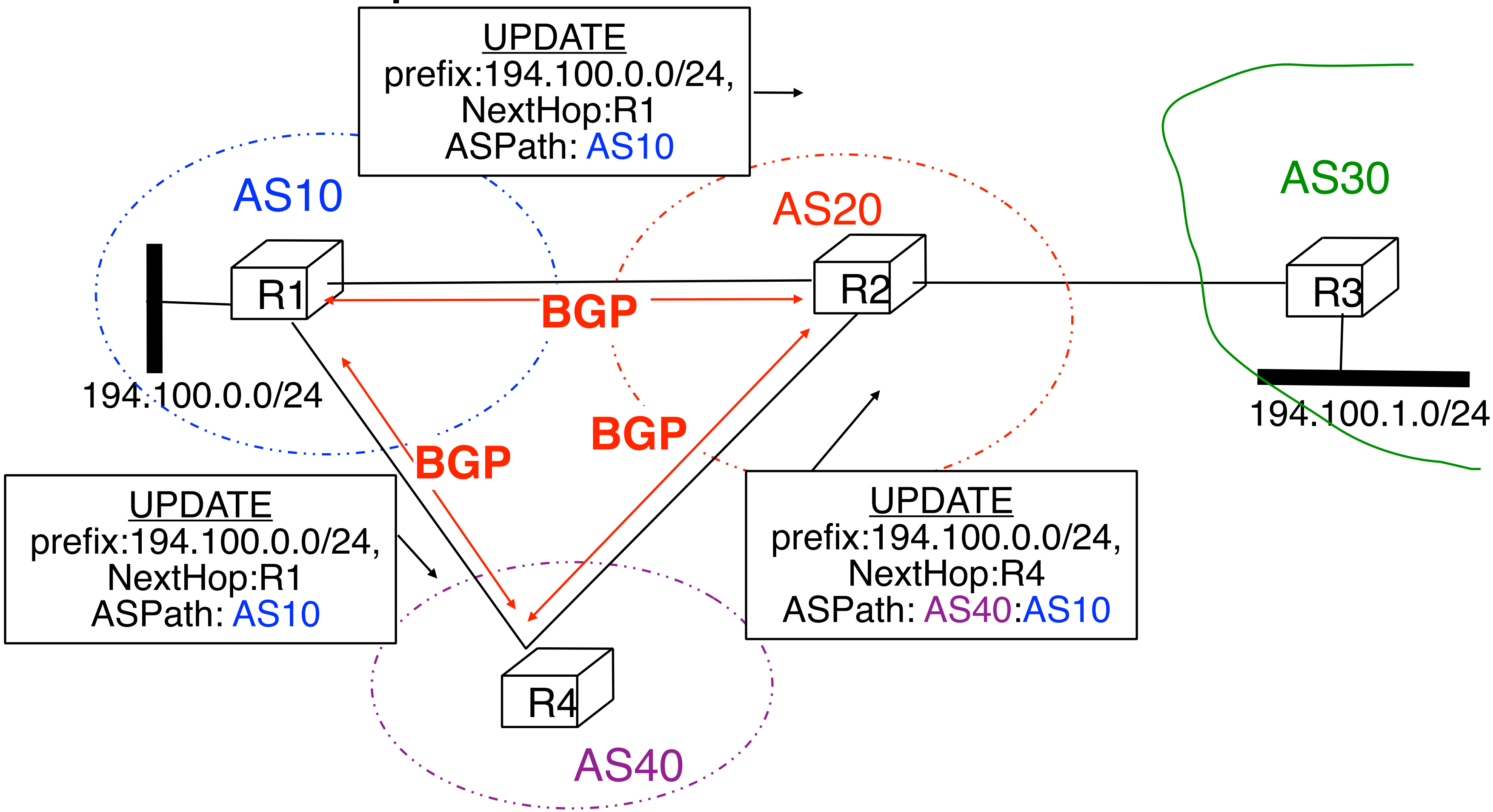
BGP and IP
A first example

Initial updates



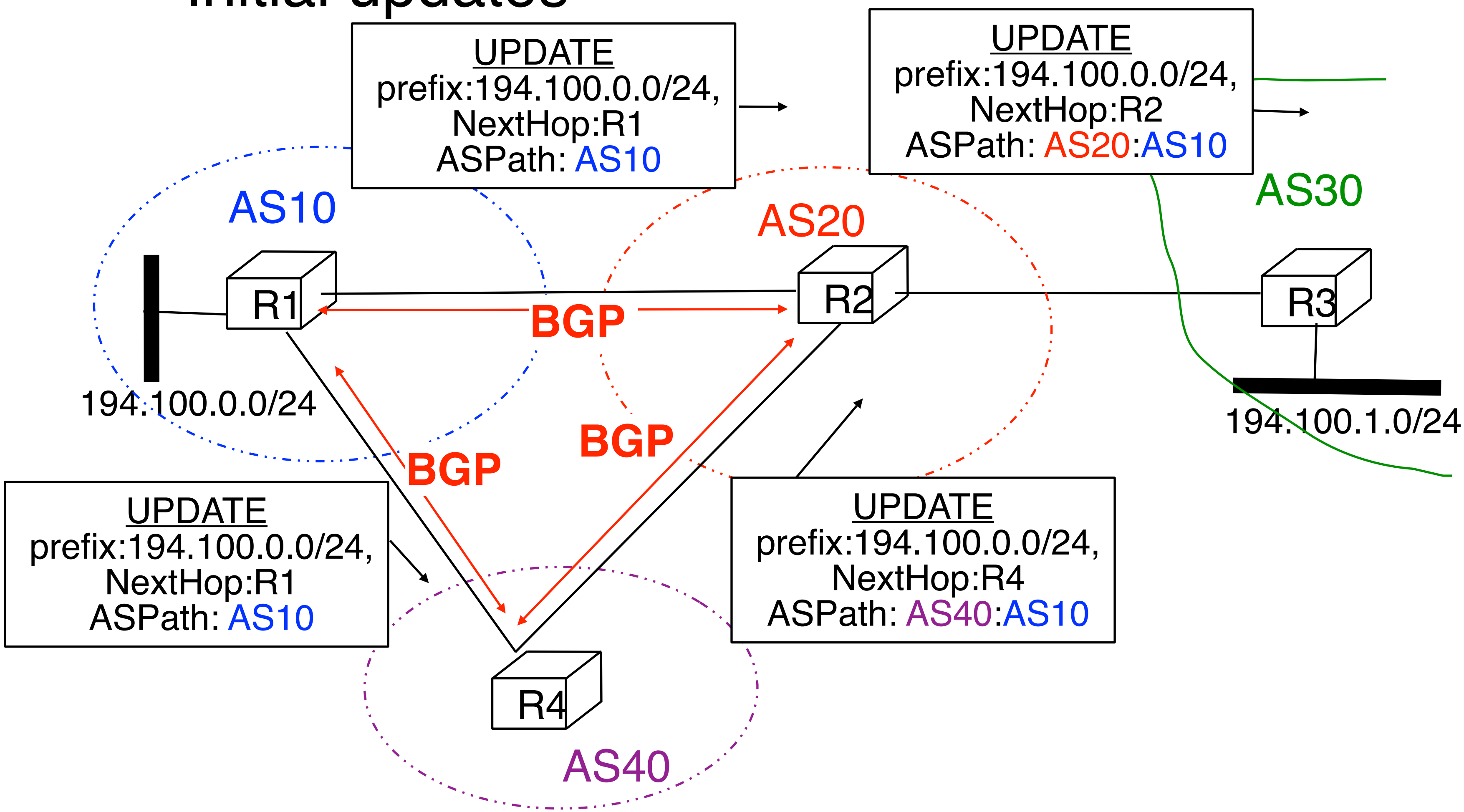
BGP and IP
A first example

Initial updates



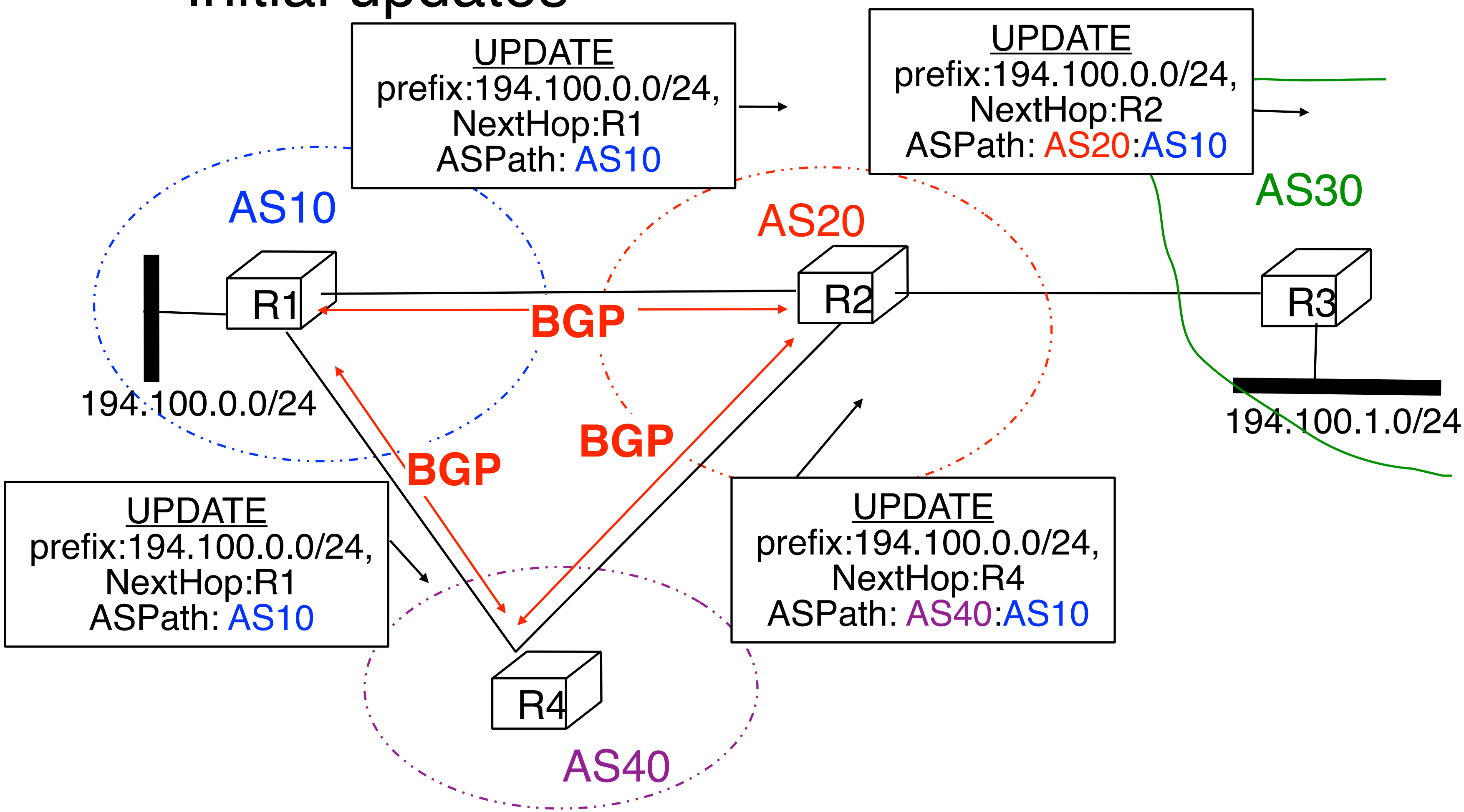
BGP and IP
A first example

Initial updates



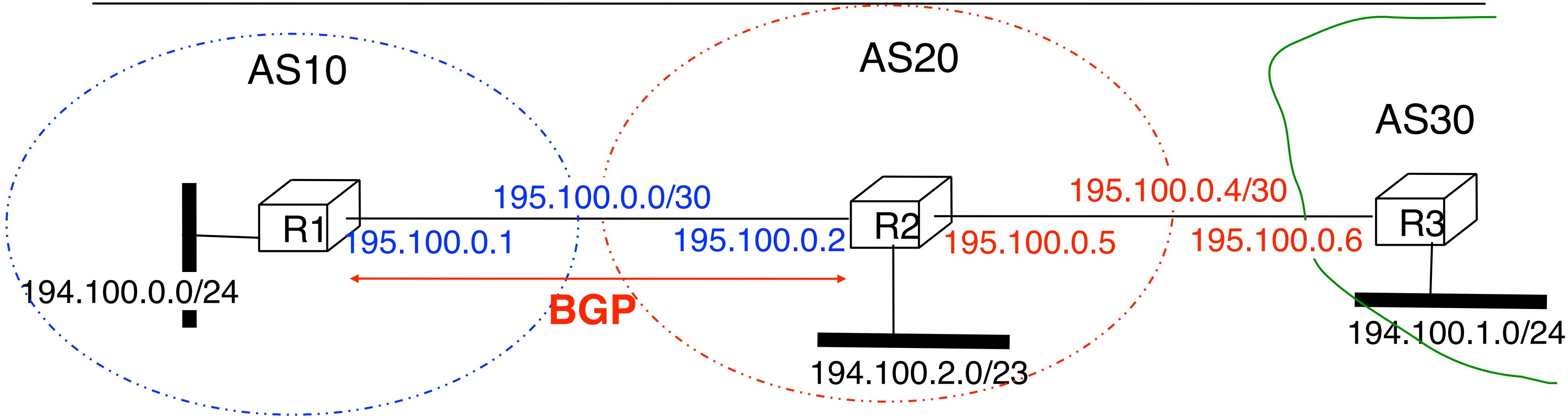
BGP and IP
A first example

Initial updates



What happens if link AS10-AS20 goes down ?

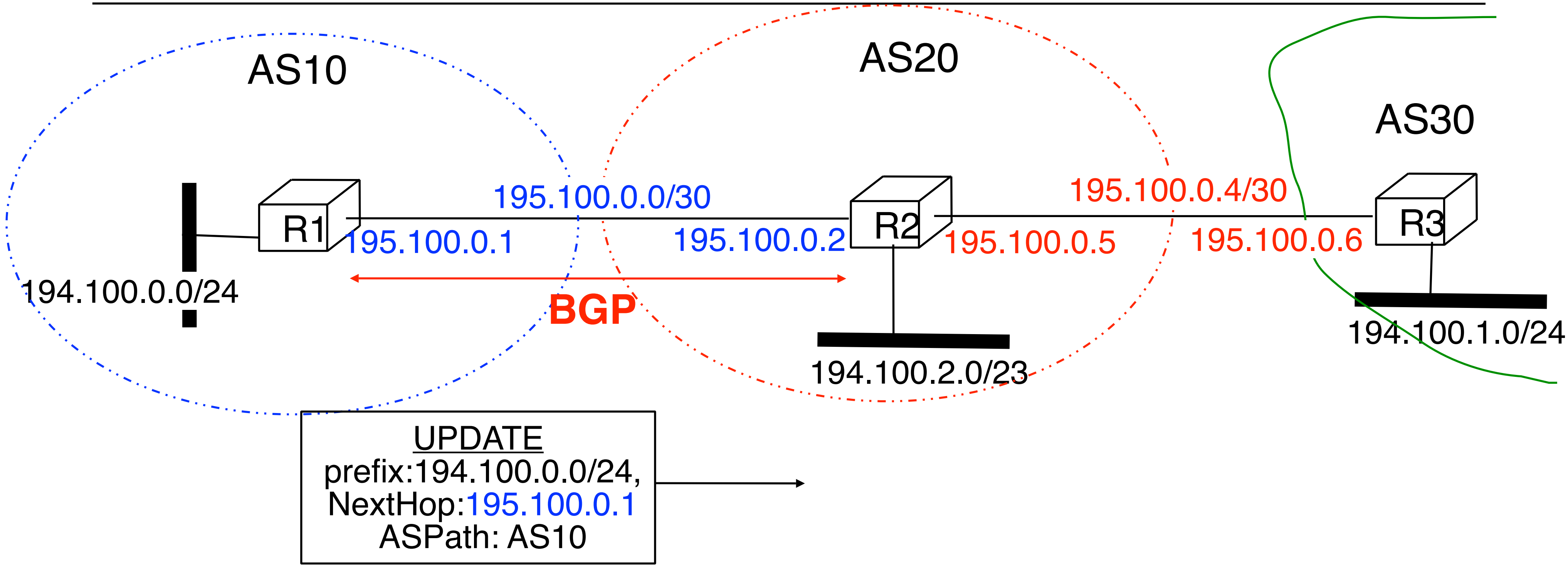
BGP and IP
A second example



Main Path attributes of UPDATE message

- NextHop : IP address of router used to reach destination
- ASPath : Path followed by the route advertisement

BGP and IP
A second example



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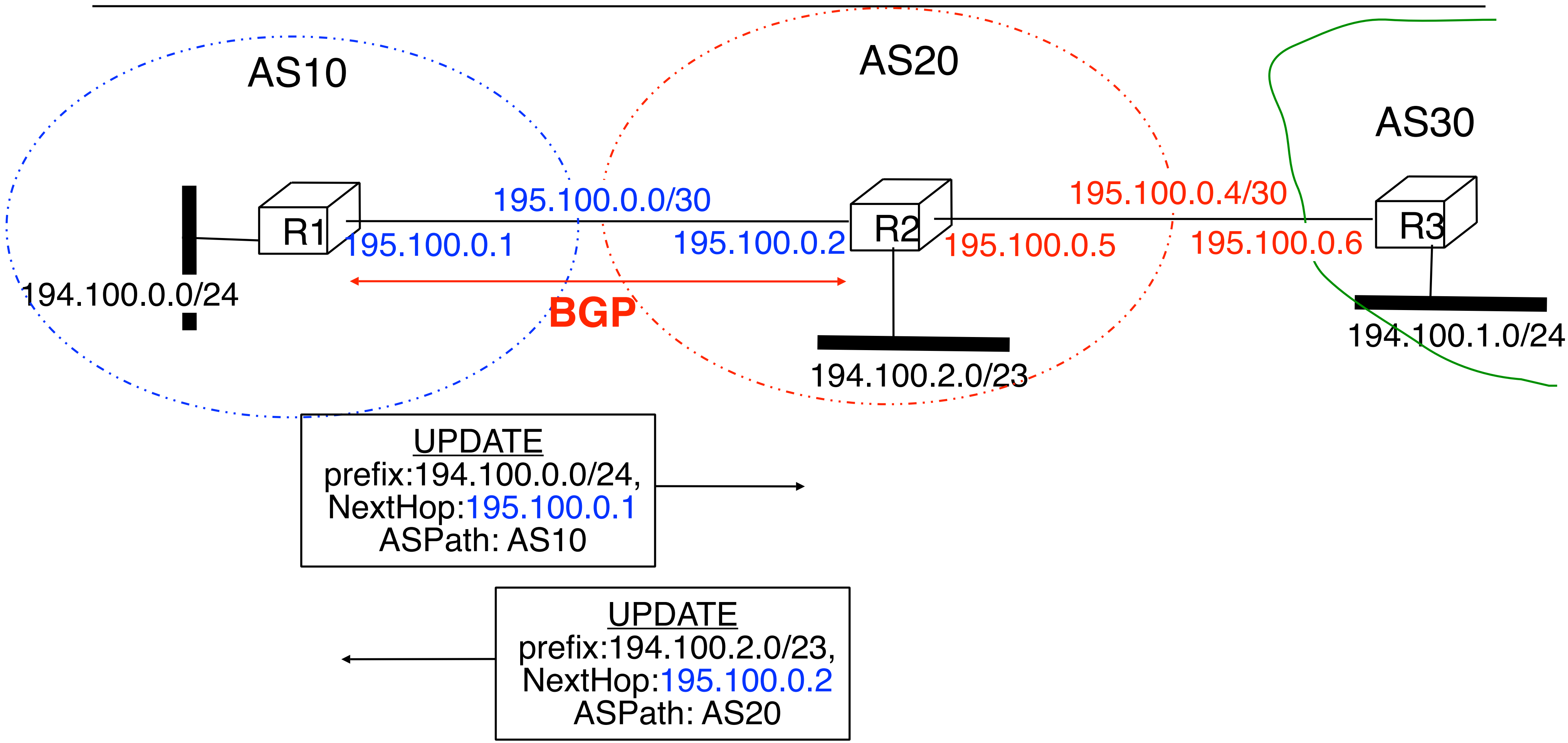
BGP and IP
A second example

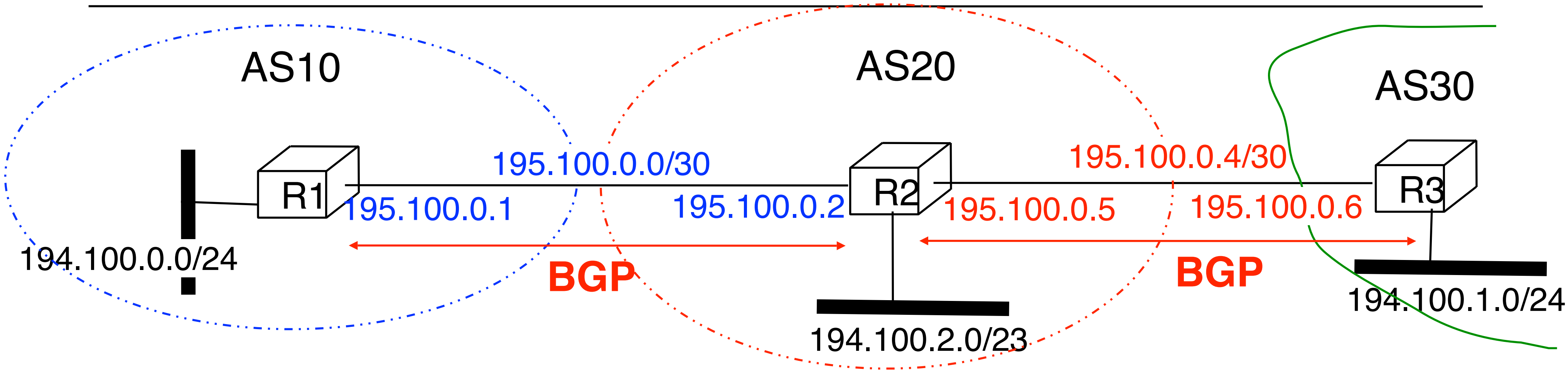


Main Path attributes of UPDATE message

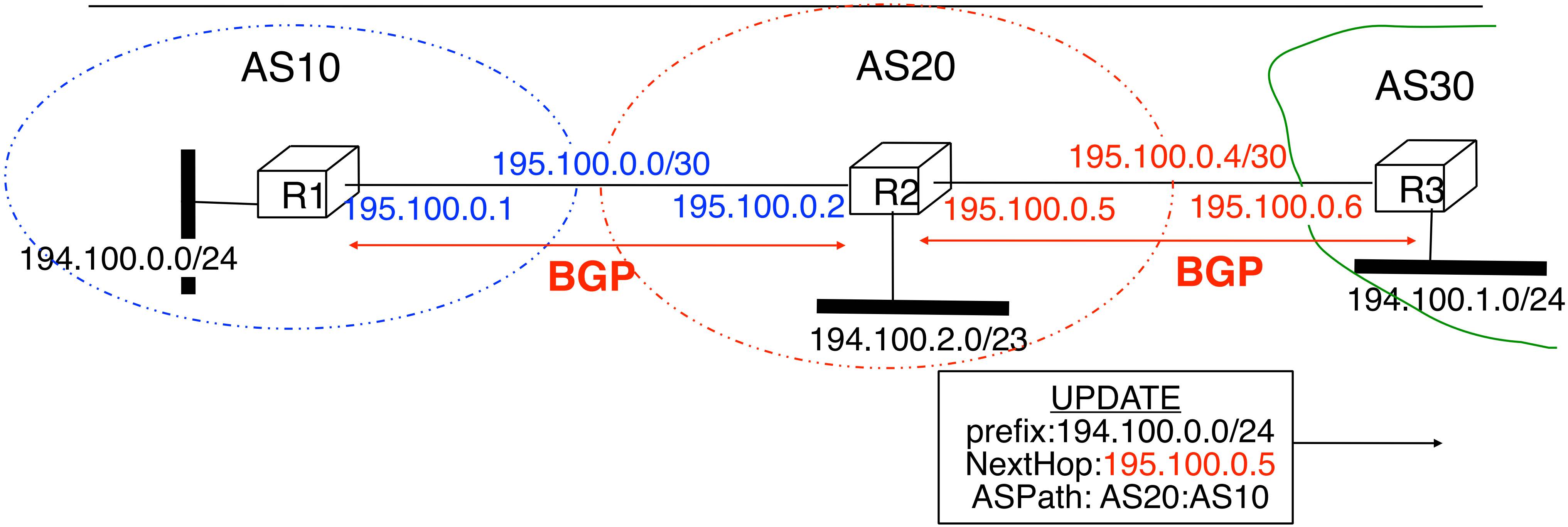
NextHop : IP address of router used to reach destination

ASPath : Path followed by the route advertisement

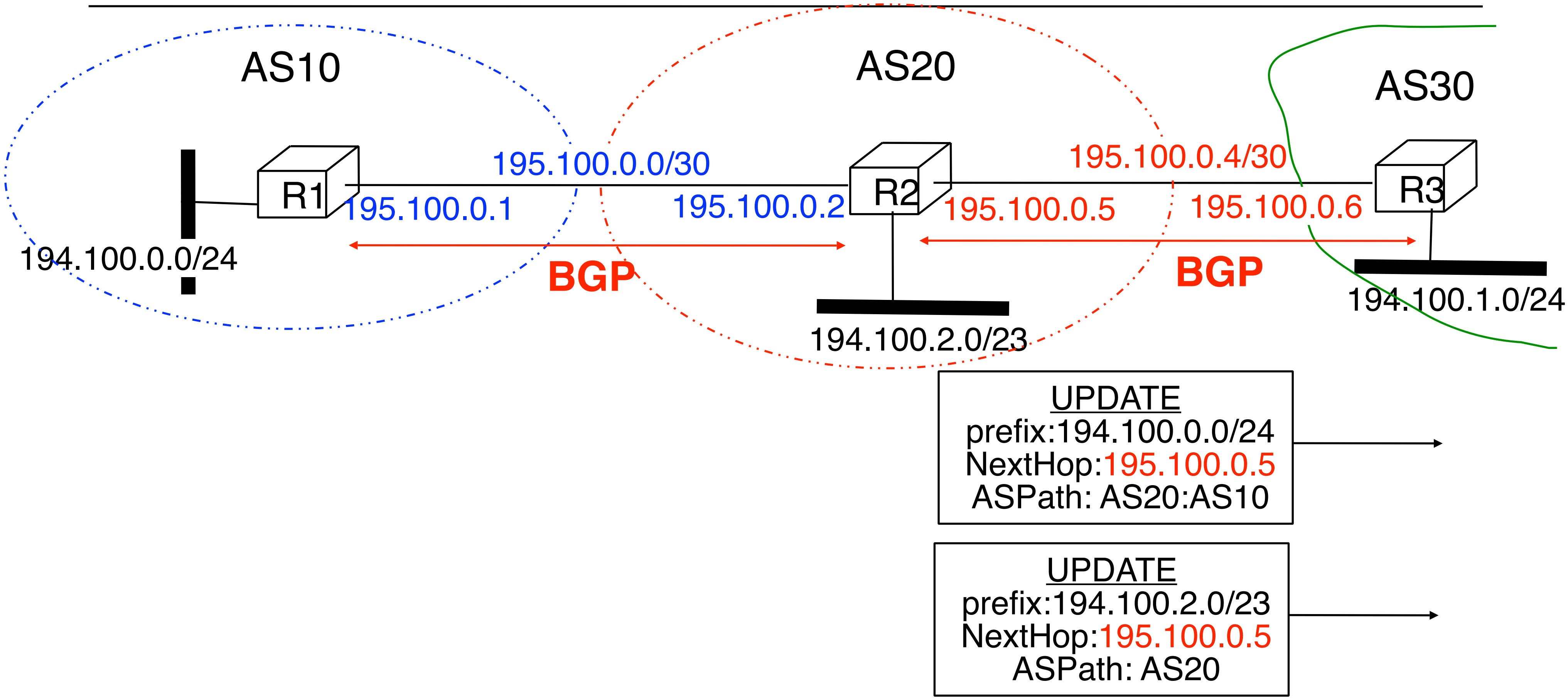
BGP and IP
A second example (2)



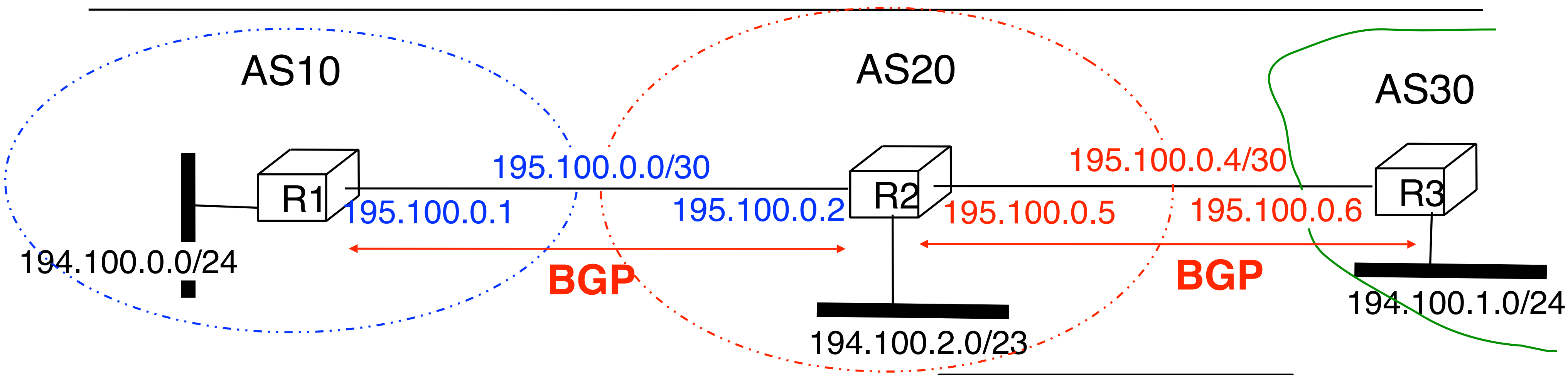
BGP and IP
A second example (2)



BGP and IP
A second example (2)



BGP and IP
A second example (2)

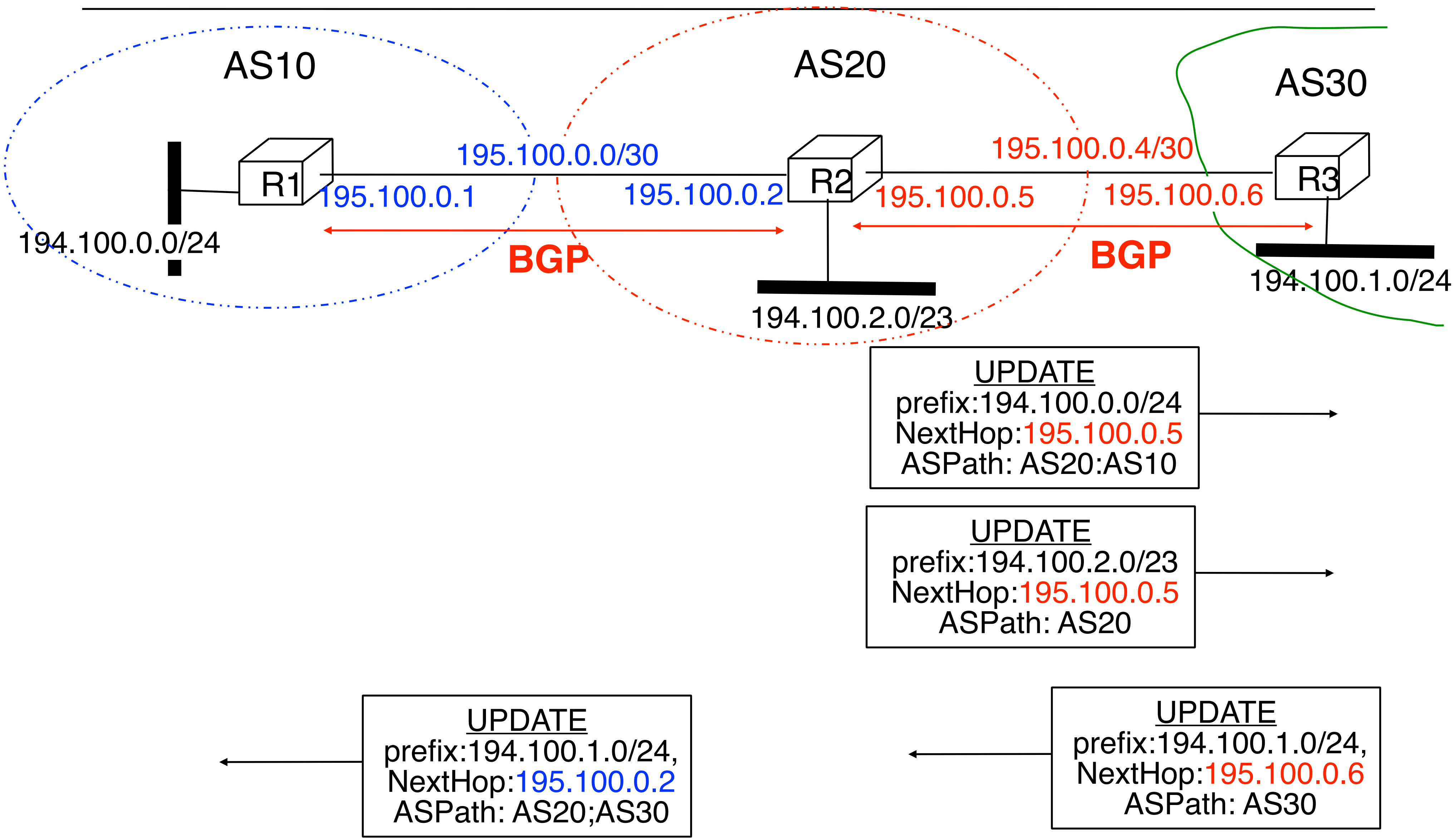


UPDATE
prefix:194.100.0.0/24
NextHop:195.100.0.5
ASPath: AS20:AS10

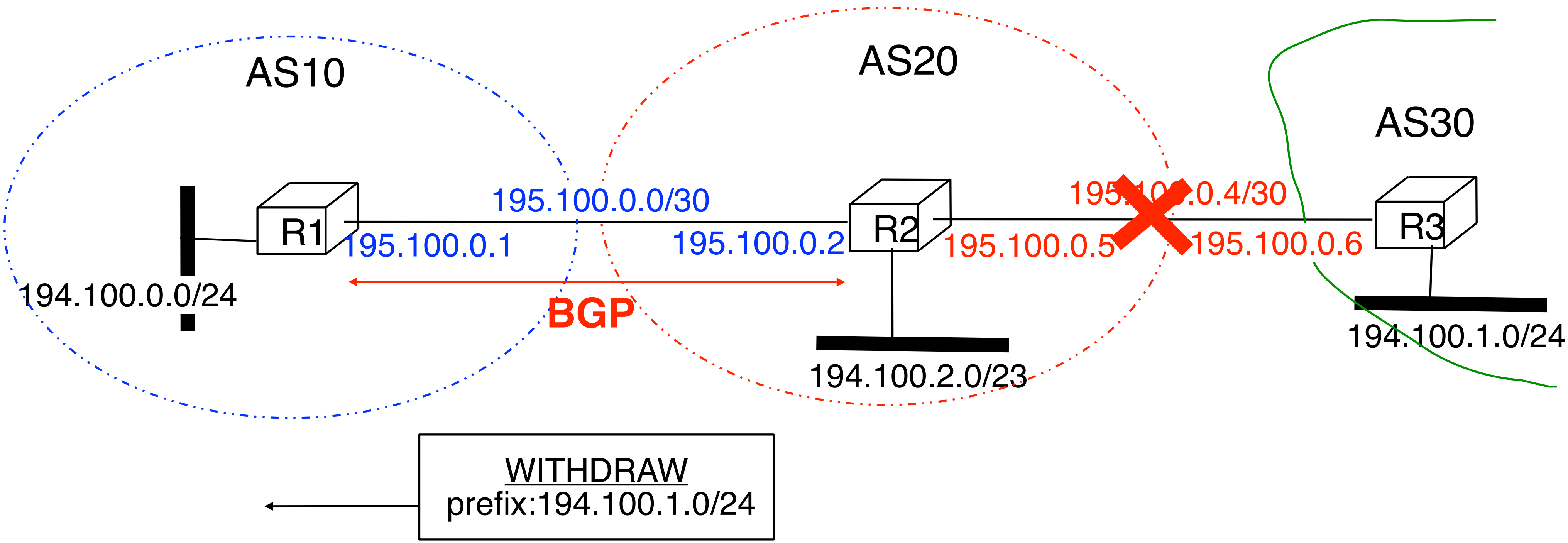
UPDATE
prefix:194.100.2.0/23
NextHop:195.100.0.5
ASPath: AS20

UPDATE
prefix:194.100.1.0/24,
NextHop:195.100.0.6
ASPath: AS30

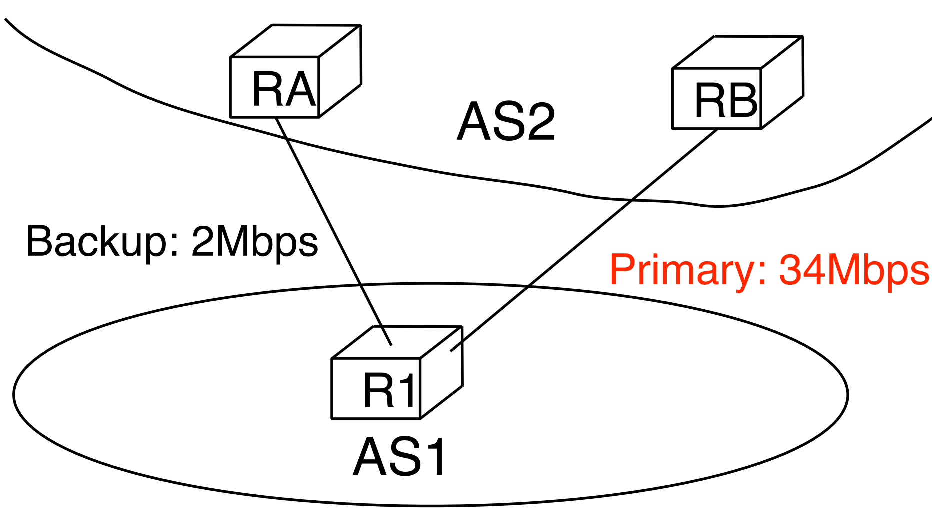
BGP and IP
A second example (2)



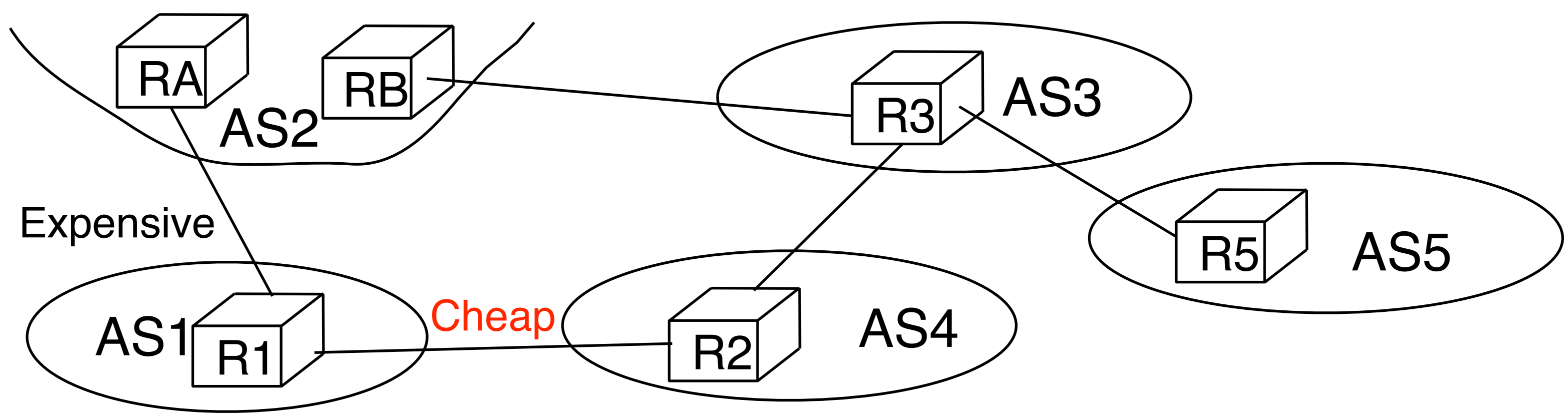
BGP and IP
A second example (3)



How to prefer some routes over others ?

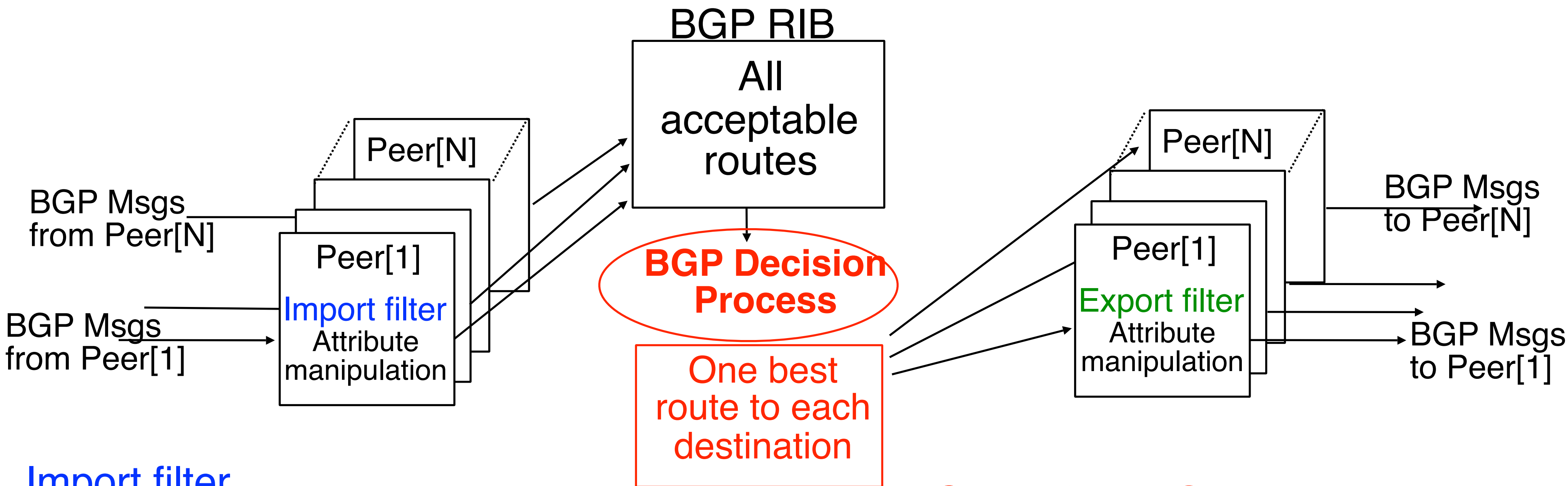


How to ensure that packets will flow on primary link ?



How to prefer cheap link over expensive link ?

How to prefer some routes over others (2) ?



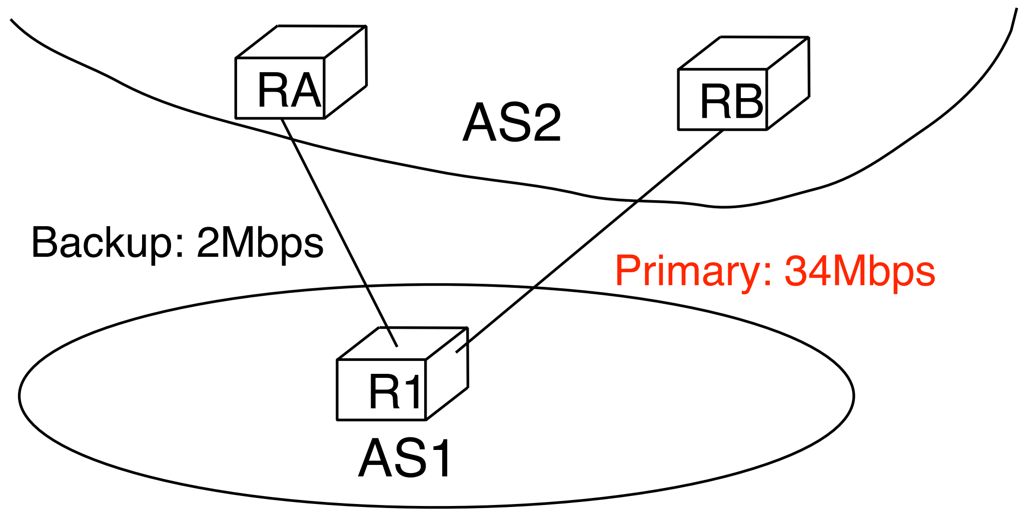
Import filter

- Selection of acceptable routes
- Addition of `local-pref` attribute inside received BGP Msg
  - Normal quality route : `local-pref`=100
  - Better than normal route :`local-pref`=200
  - Worse than normal route :`local-pref`=50

Simplified BGP Decision Process

- Select routes with highest `local-pref`
- If there are several routes, choose routes with the shortest ASPath
- If there are still several routes tie-breaking rule

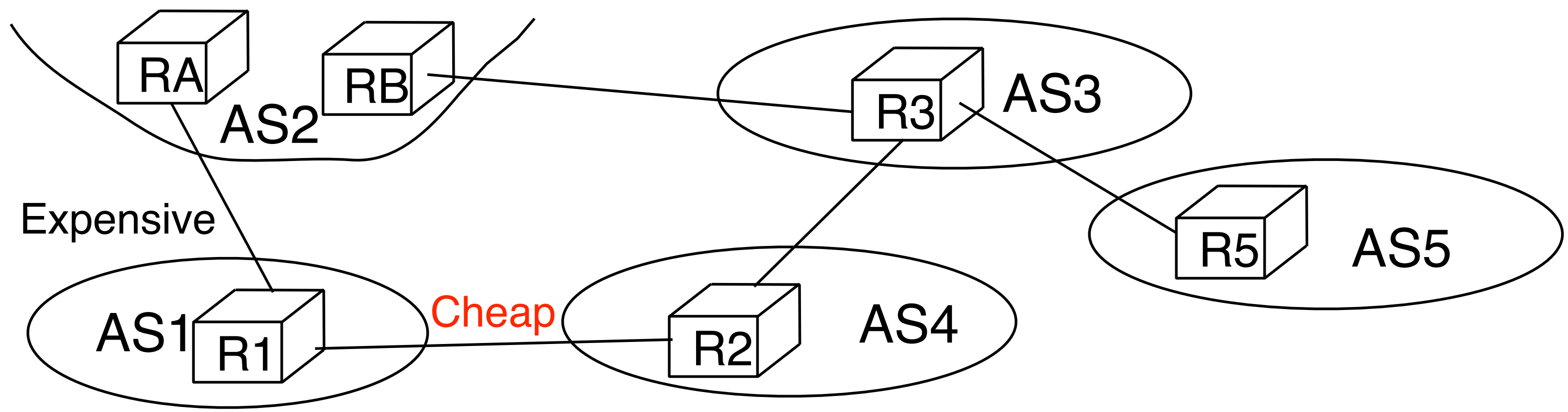
How to prefer some routes over others (3) ?



RPSL-like policy for AS1
aut-num: AS1
import: from AS2 RA at R1 set localpref=100;
from AS2 RB at R1 set localpref=200;
accept ANY
export: to AS2 RA at R1 announce AS1
to AS2 RB at R1 announce AS1

RPSL-like policy for AS2
aut-num: AS2
import: from AS1 R1 at RA set localpref=100;
from AS1 R1 at RB set localpref=200;
accept AS1
export: to AS1 R1 at RA announce ANY
to AS2 R1 at RB announce ANY

How to prefer some routes over others (4) ?



RPSL policy for AS1
aut-num: AS1
import: from AS2 RA at R1 set localpref=100;
from AS4 R2 at R1 set localpref=200;
accept ANY
export: to AS2 RA at R1 announce AS1
to AS4 R2 at R1 announce AS1

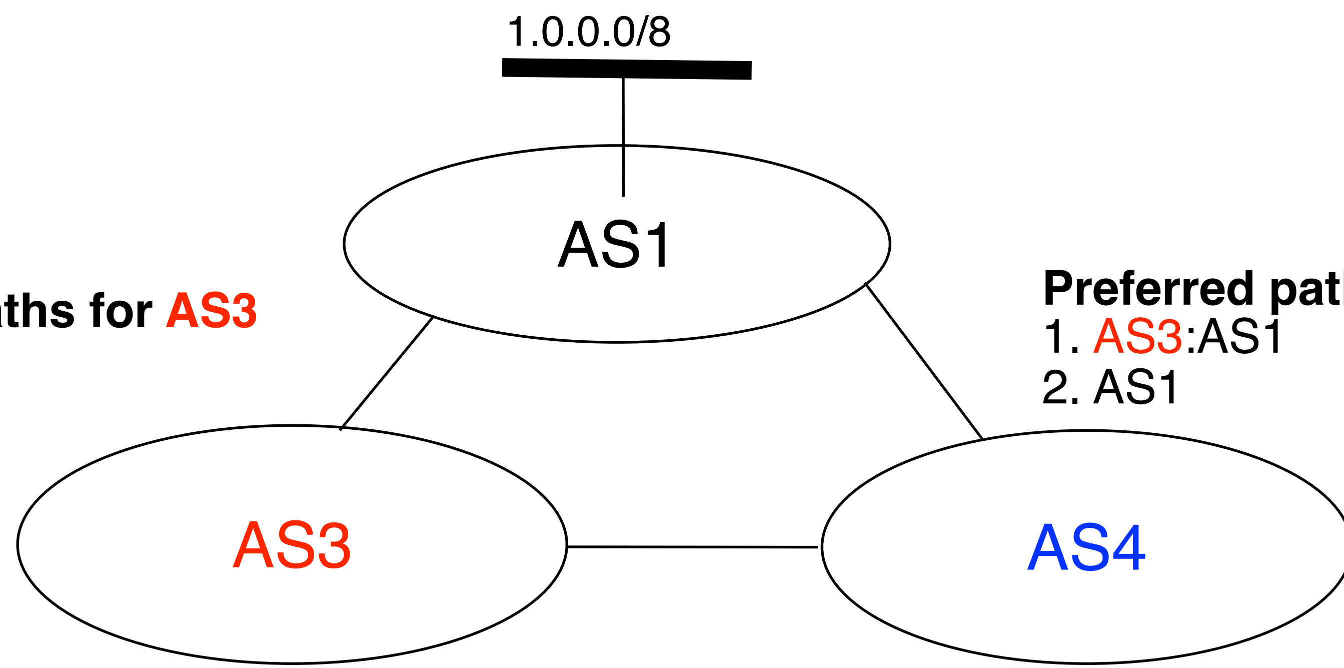
AS1 will prefer to send packets over the cheap link
But the flow of the packets destined to AS1 will depend on the routing policy of the other domains

Limitations of `local-pref`

In theory

- Each domain is free to define its order of preference for the routes learned from external peers

Preferred paths for AS3
1. AS4:AS1
2. AS1

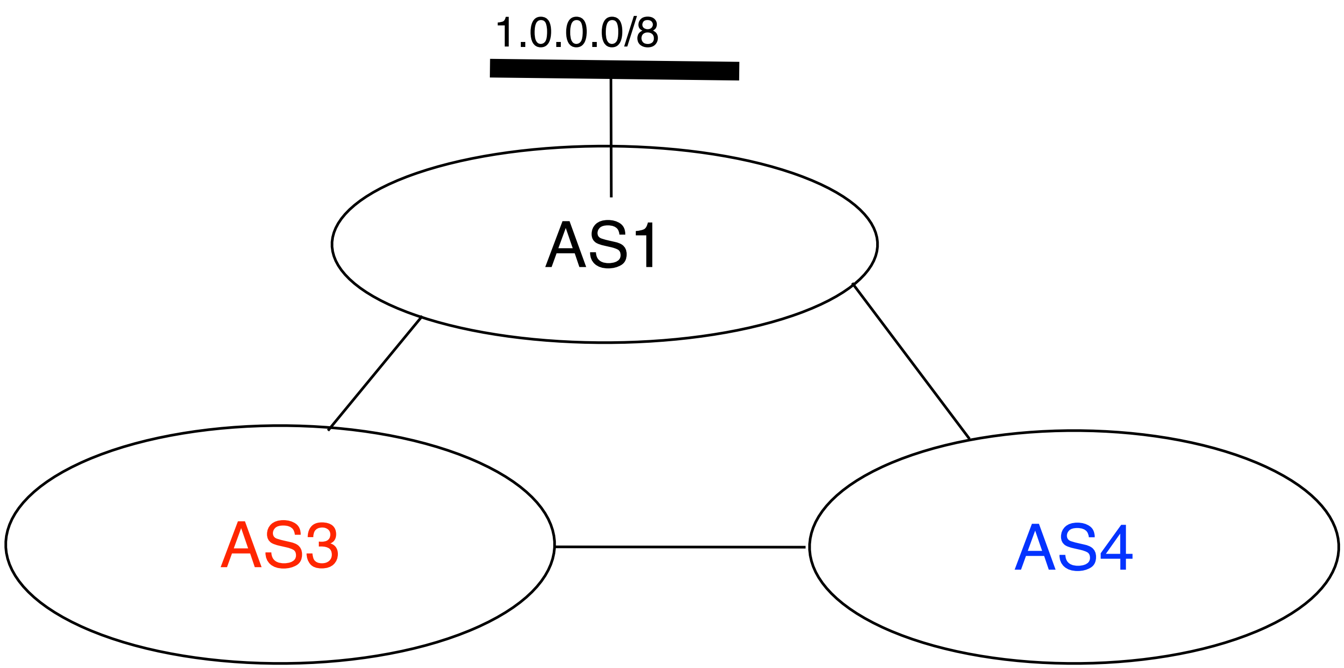


Preferred paths for AS4
1. AS3:AS1
2. AS1

How to reach 1.0.0.0/8 from AS3 and AS4 ?

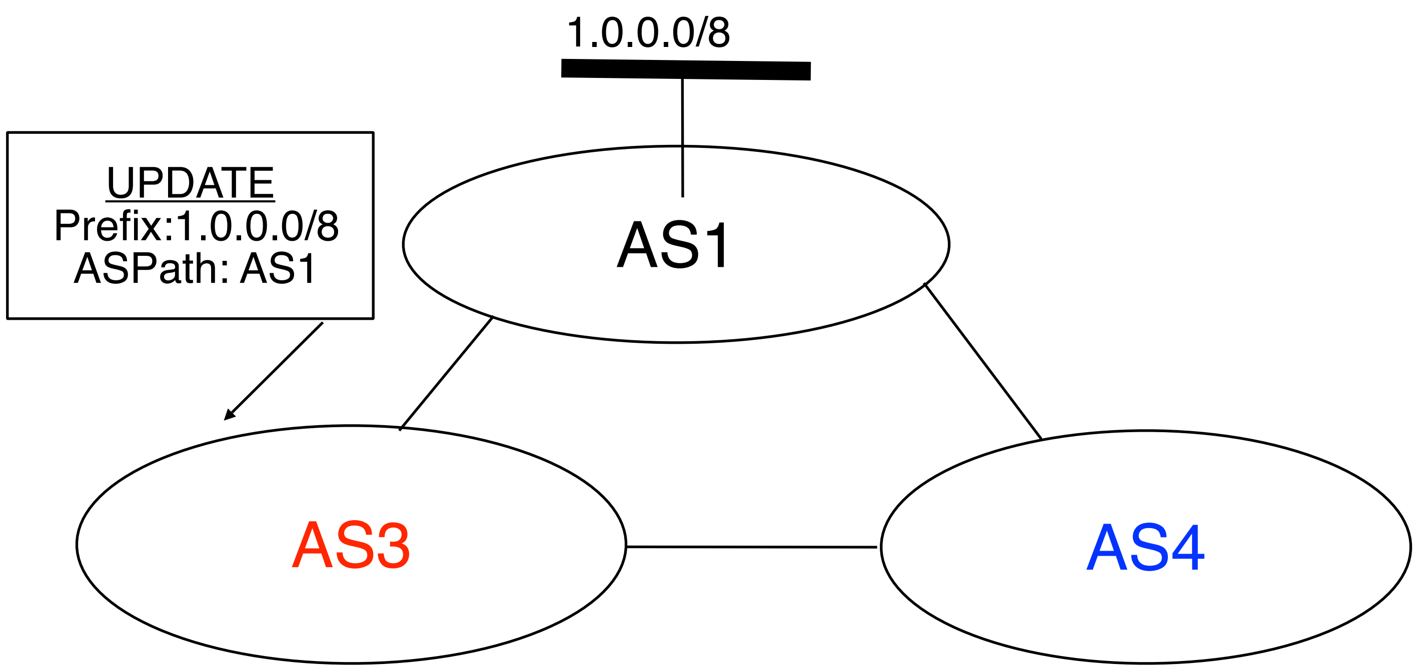
Limitations of `local-pref` (2)

AS1 sends its UPDATE messages ...



Limitations of `local-pref` (2)

AS1 sends its UPDATE messages ...

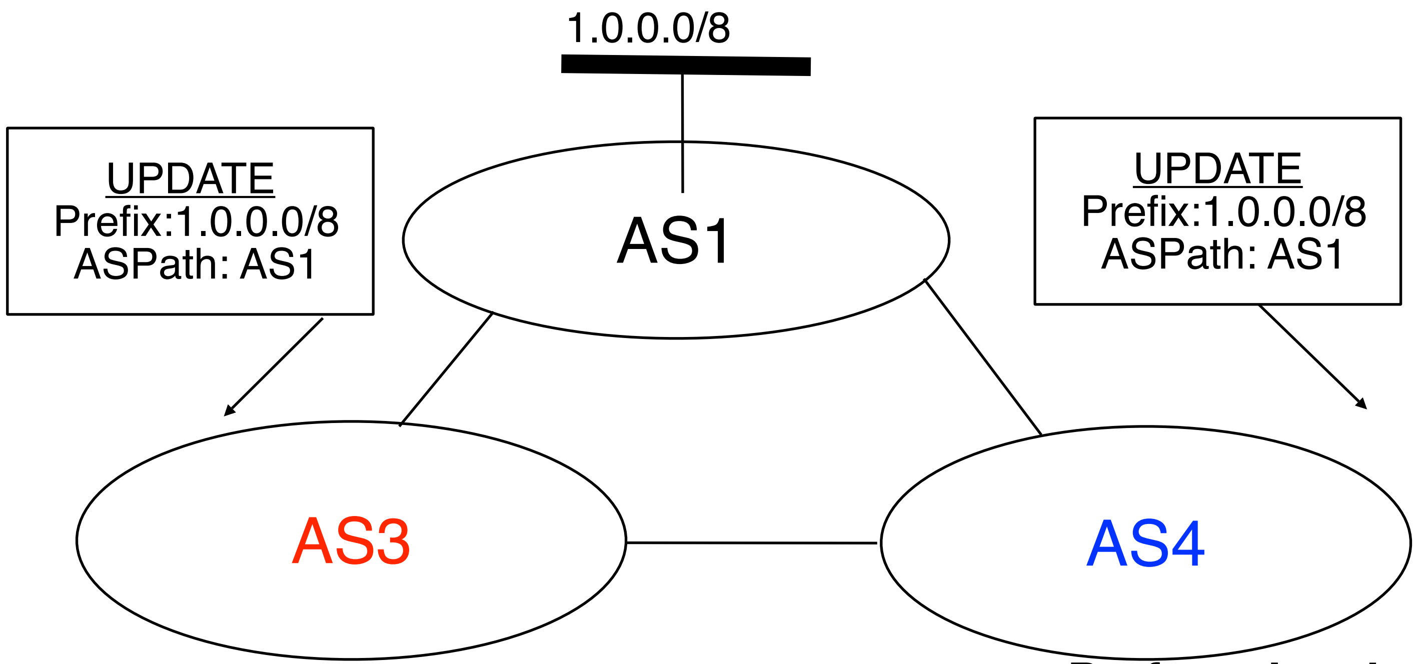


Preferred paths for AS3
1. AS4:AS1
2. AS1

Routing table for AS3
1.0.0.0/8 ASPath: AS1 (best)

Limitations of `local-pref` (2)

AS1 sends its UPDATE messages ...



Preferred paths for AS3
1. AS4:AS1
2. AS1

Preferred paths for AS4
1. AS3:AS1
2. AS1

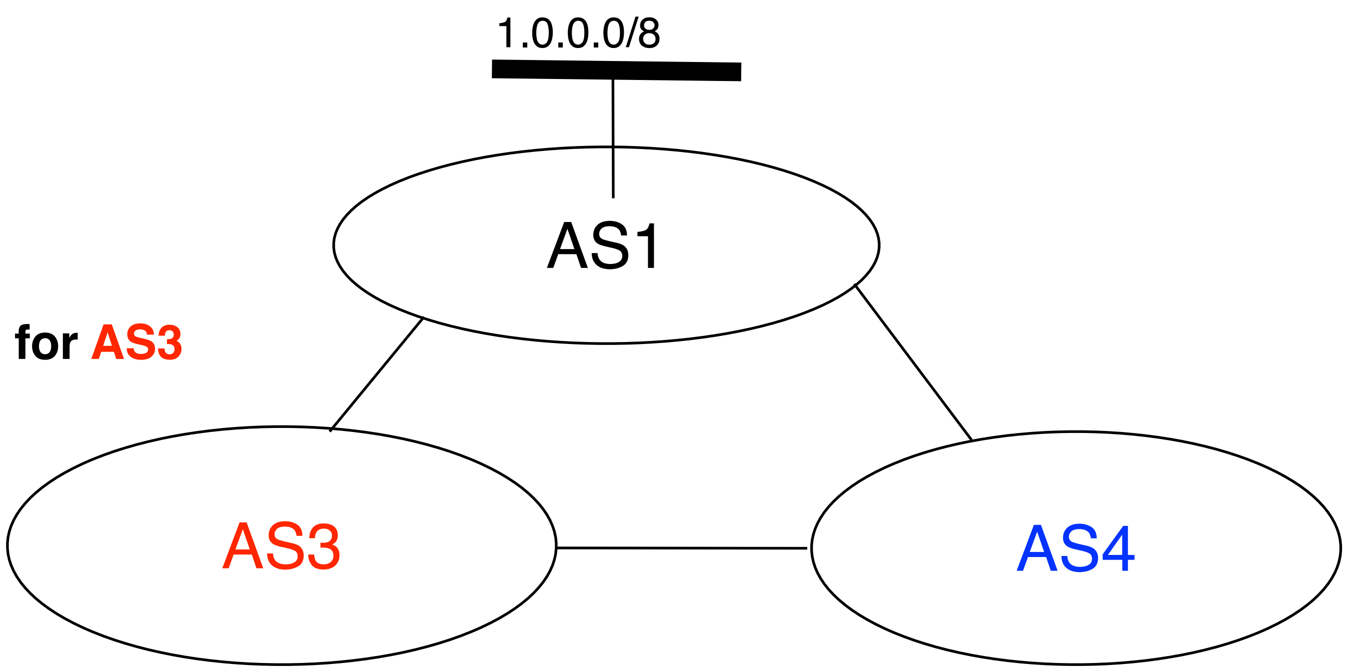
Routing table for AS3
1.0.0.0/8 ASPath: AS1 (best)

Routing table for AS4
1.0.0.0/8 ASPath: AS1 (best)

Limitations of `local-pref` (3)

First possibility

AS3 sends its UPDATE first...



Preferred paths for AS3

1. AS4:AS1
2. AS1

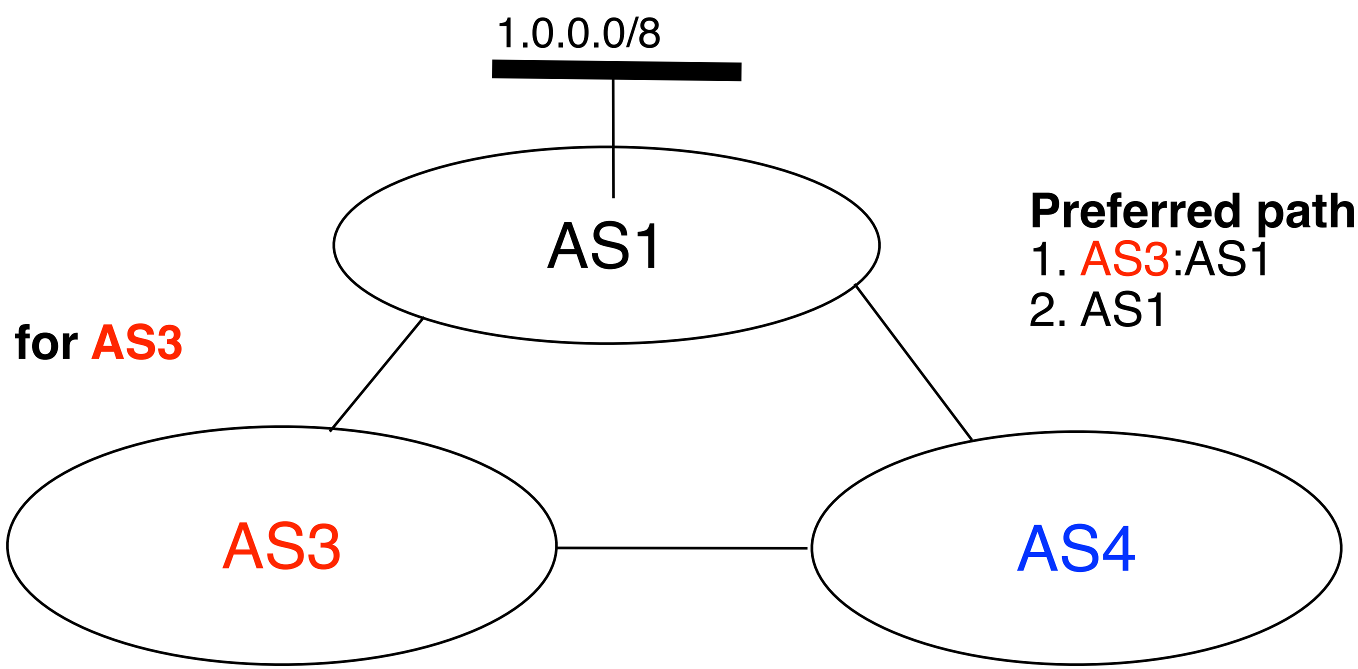
Routing table for AS3

1.0.0.0/8 ASPath: AS1 (best)

Limitations of `local-pref` (3)

First possibility

AS3 sends its UPDATE first...



Preferred paths for AS4
1. AS3:AS1
2. AS1

Preferred paths for AS3
1. AS4:AS1
2. AS1

Routing table for AS3
1.0.0.0/8 ASPath: AS1 (best)

UPDATE
Prefix:1.0.0.0/8
ASPath: AS3:AS1

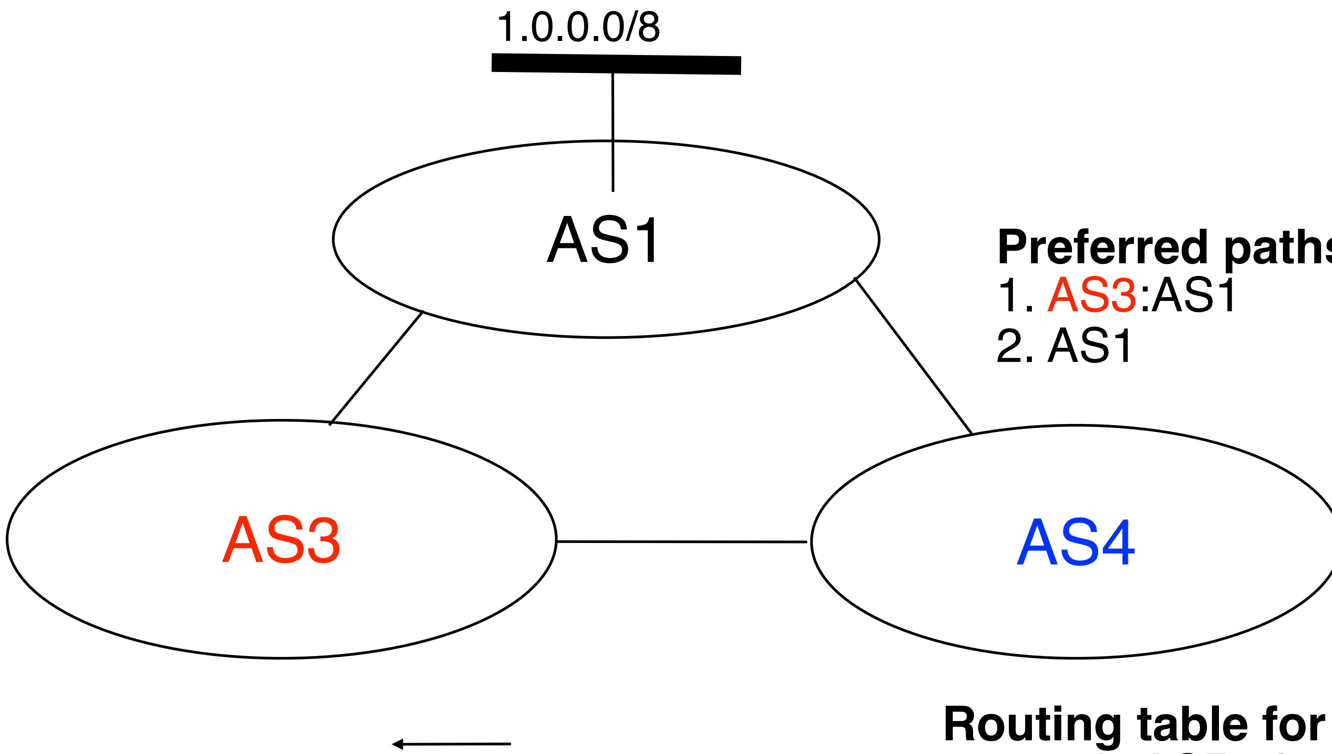
Routing table for AS4
1.0.0.0/8 ASPath: AS1
1.0.0.0/8 ASPath:AS3:AS1 (best)

Stable route assignment

Limitations of `local-pref` (4)

Second possibility

AS4 sends its UPDATE first...



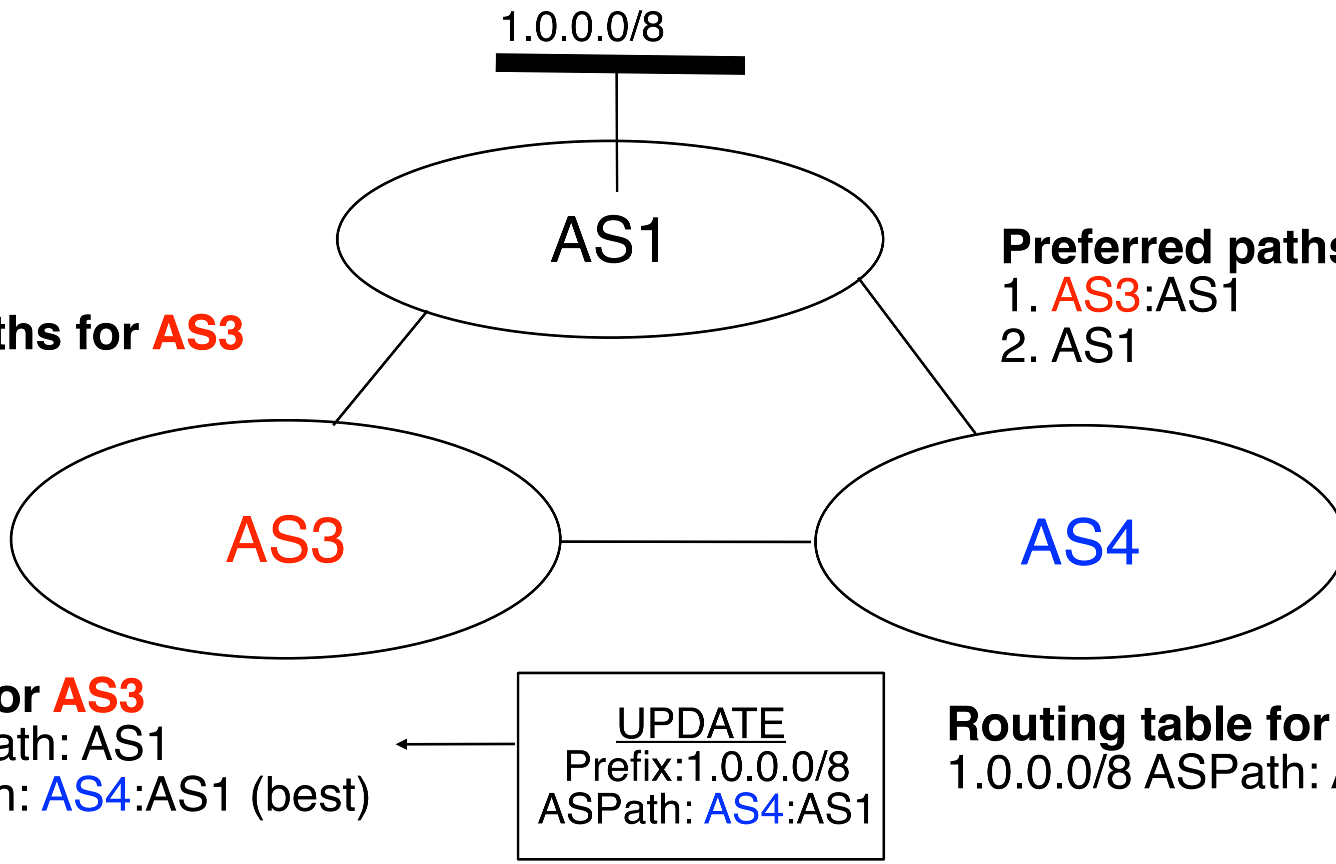
Preferred paths for AS4
1. AS3:AS1
2. AS1

Routing table for AS4
1.0.0.0/8 ASPath: AS1 (best)

Limitations of `local-pref` (4)

Second possibility

AS4 sends its UPDATE first...



Preferred paths for AS3
1. AS4:AS1
2. AS1

Preferred paths for AS4
1. AS3:AS1
2. AS1

Routing table for AS3
1.0.0.0/8 ASPath: AS1
1.0.0.0/8 ASPath: AS4:AS1 (best)

Routing table for AS4
1.0.0.0/8 ASPath: AS1 (best)

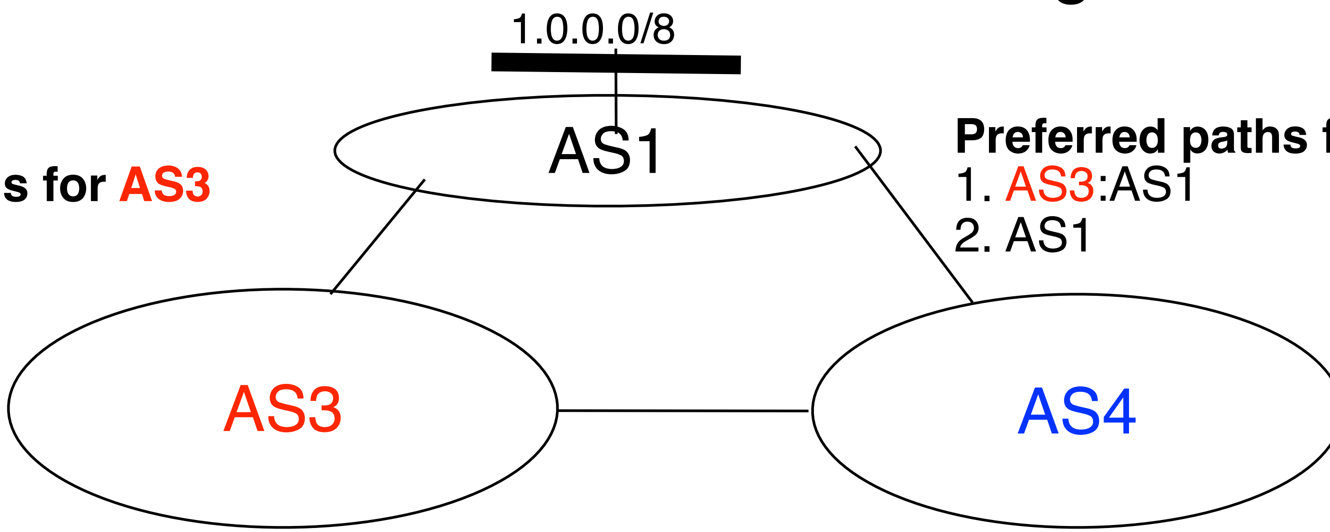
Another (but different) stable route assignment

Limitations of `local-pref` (5)

Third possibility

AS3 and AS4 send their UPDATE together...

Preferred paths for AS3
1. AS4:AS1
2. AS1

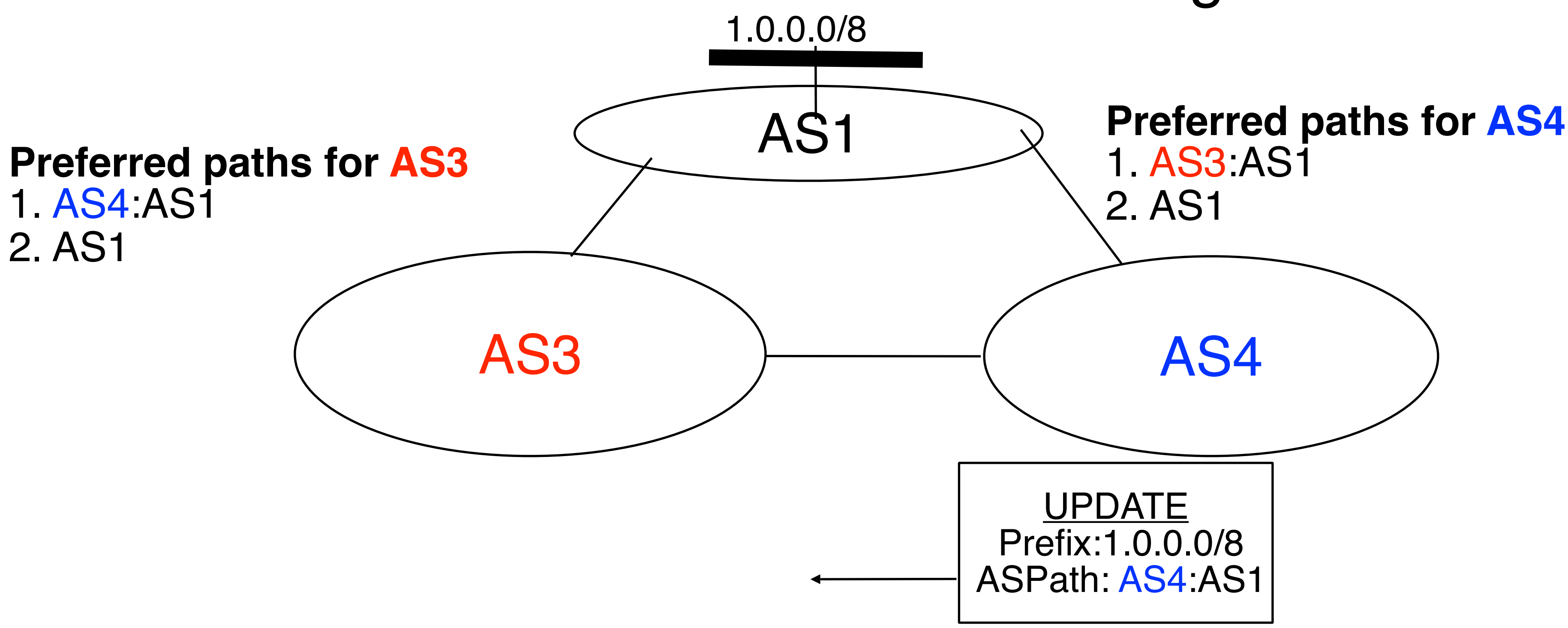


Preferred paths for AS4
1. AS3:AS1
2. AS1

Limitations of `local-pref` (5)

Third possibility

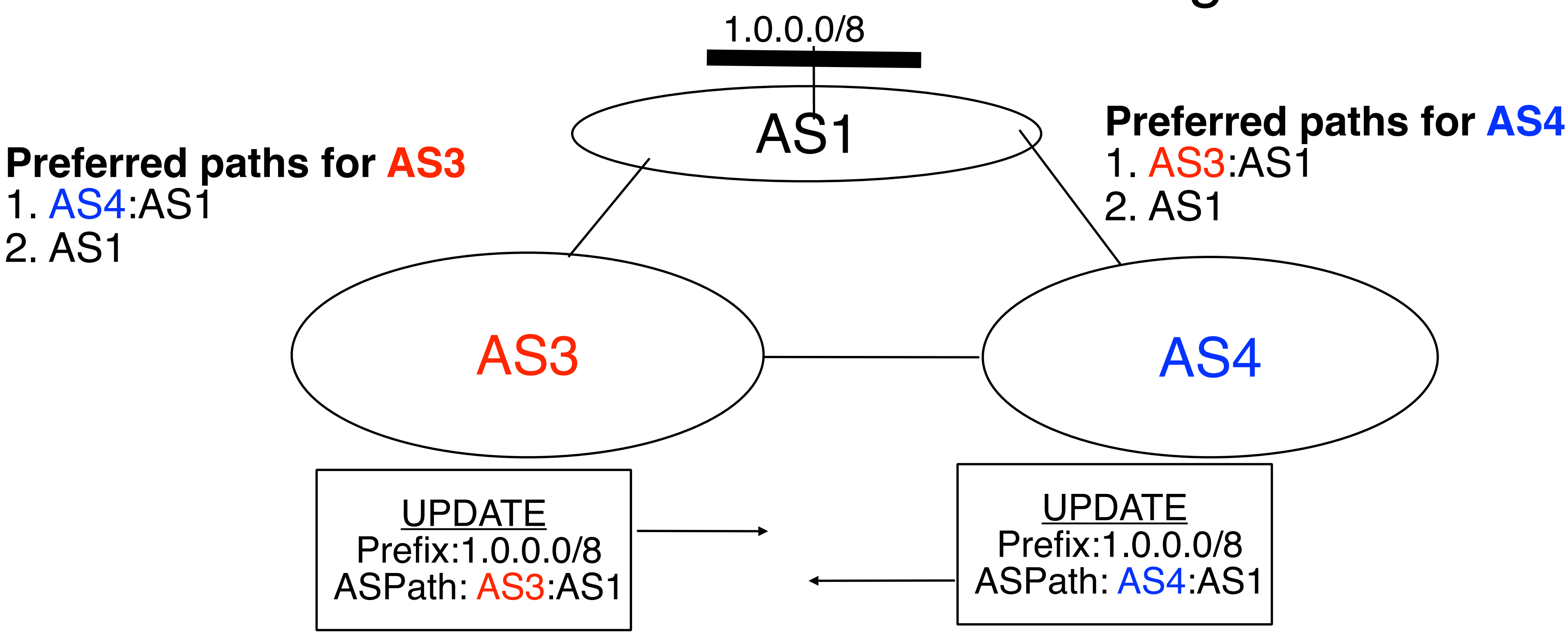
AS3 and AS4 send their UPDATE together...



Limitations of `local-pref` (5)

Third possibility

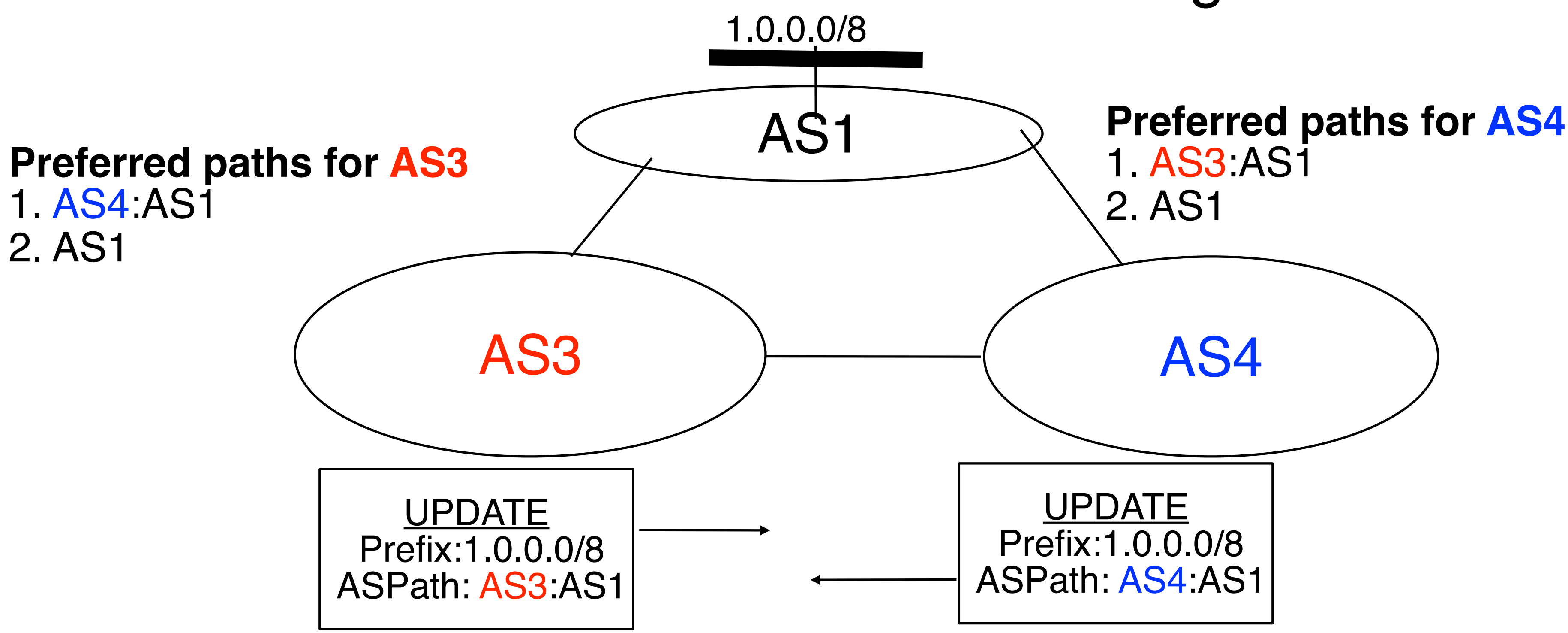
AS3 and AS4 send their UPDATE together...



Limitations of `local-pref` (5)

Third possibility

AS3 and AS4 send their UPDATE together...



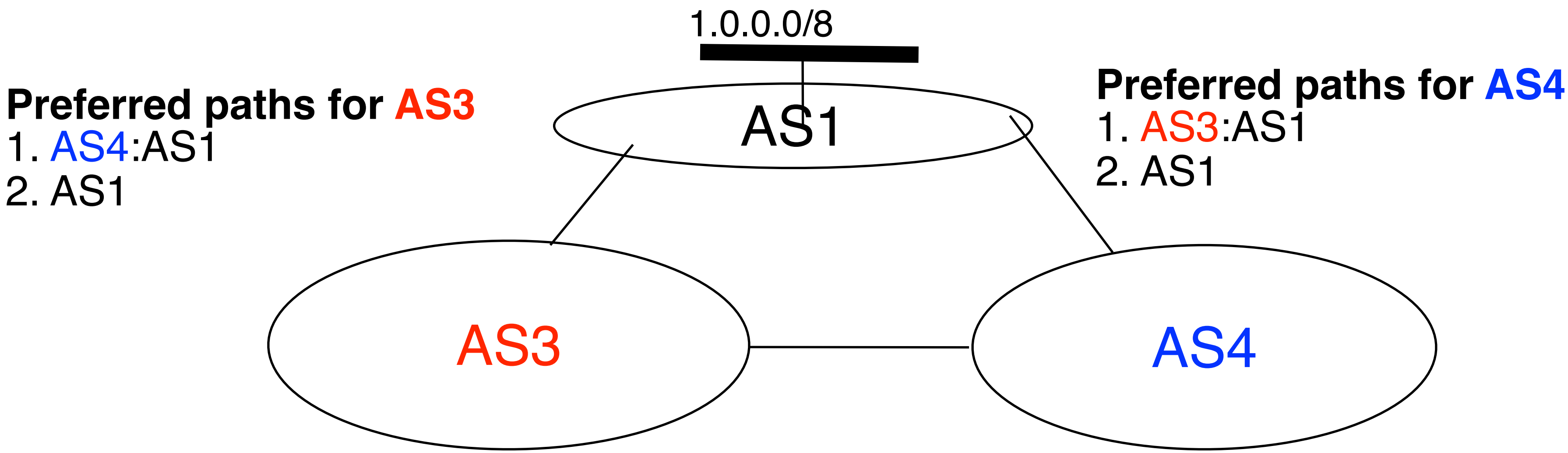
AS3 prefers the indirect path and will thus send withdraw since the chosen best path is via AS4

AS4 prefers the indirect path and will thus send withdraw since the chosen best path is via AS3

Limitations of `local-pref` (6)

Third possibility (cont.)

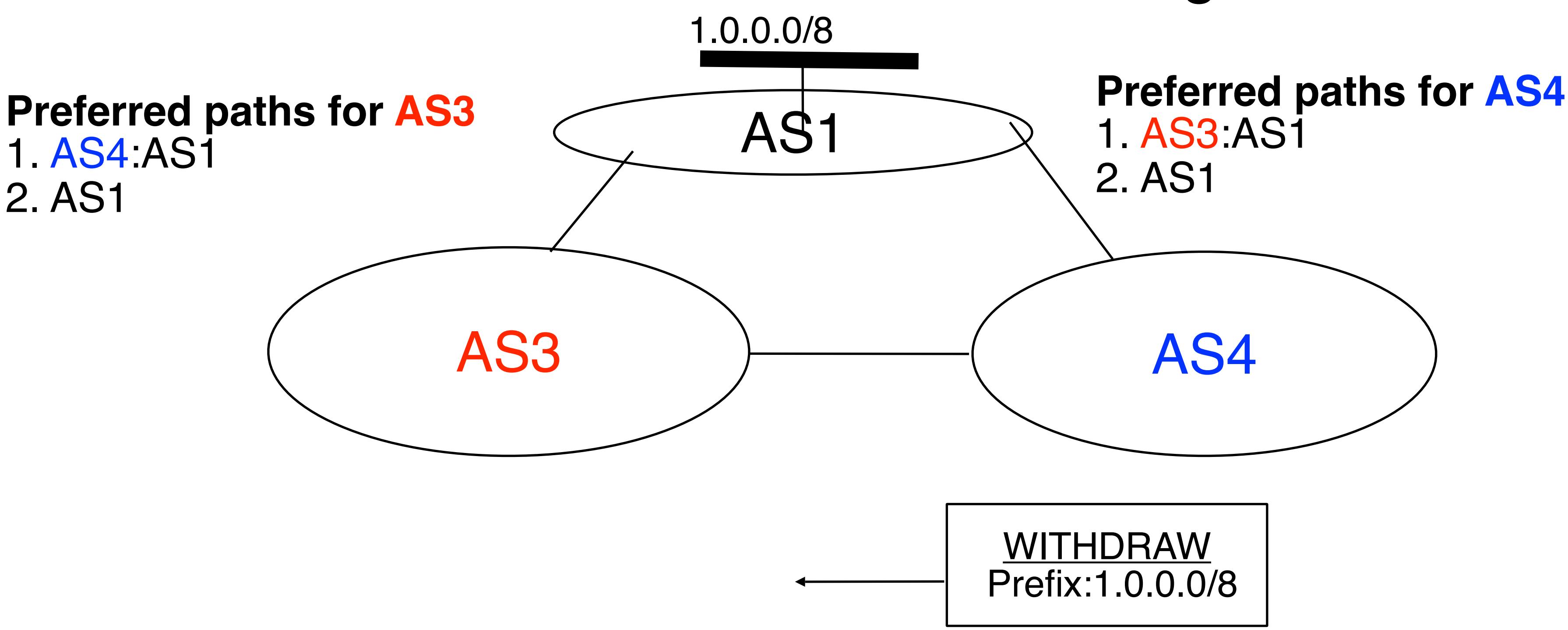
AS3 and AS4 send their UPDATE together...



Limitations of `local-pref` (6)

Third possibility (cont.)

AS3 and AS4 send their UPDATE together...



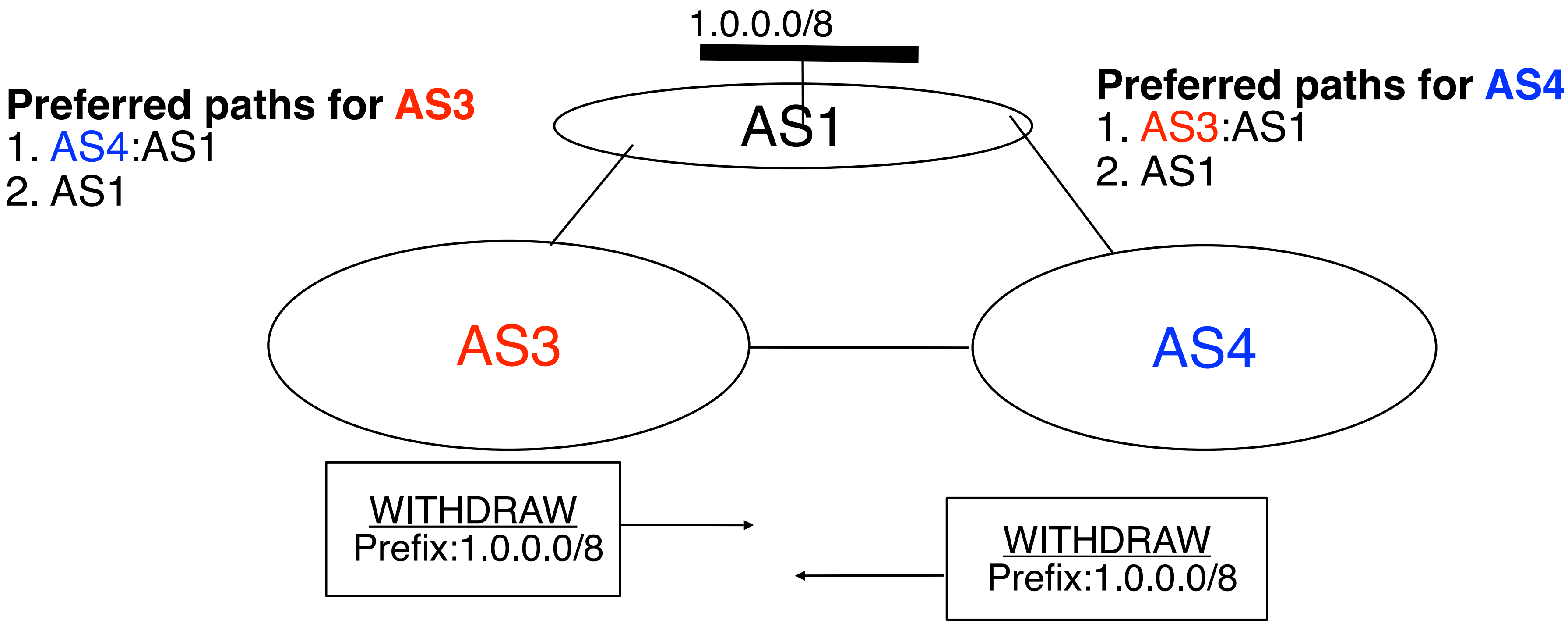
AS3 learns that the indirect route is not available anymore

AS3 will reannounce its direct route...

Limitations of `local-pref` (6)

Third possibility (cont.)

AS3 and AS4 send their UPDATE together...



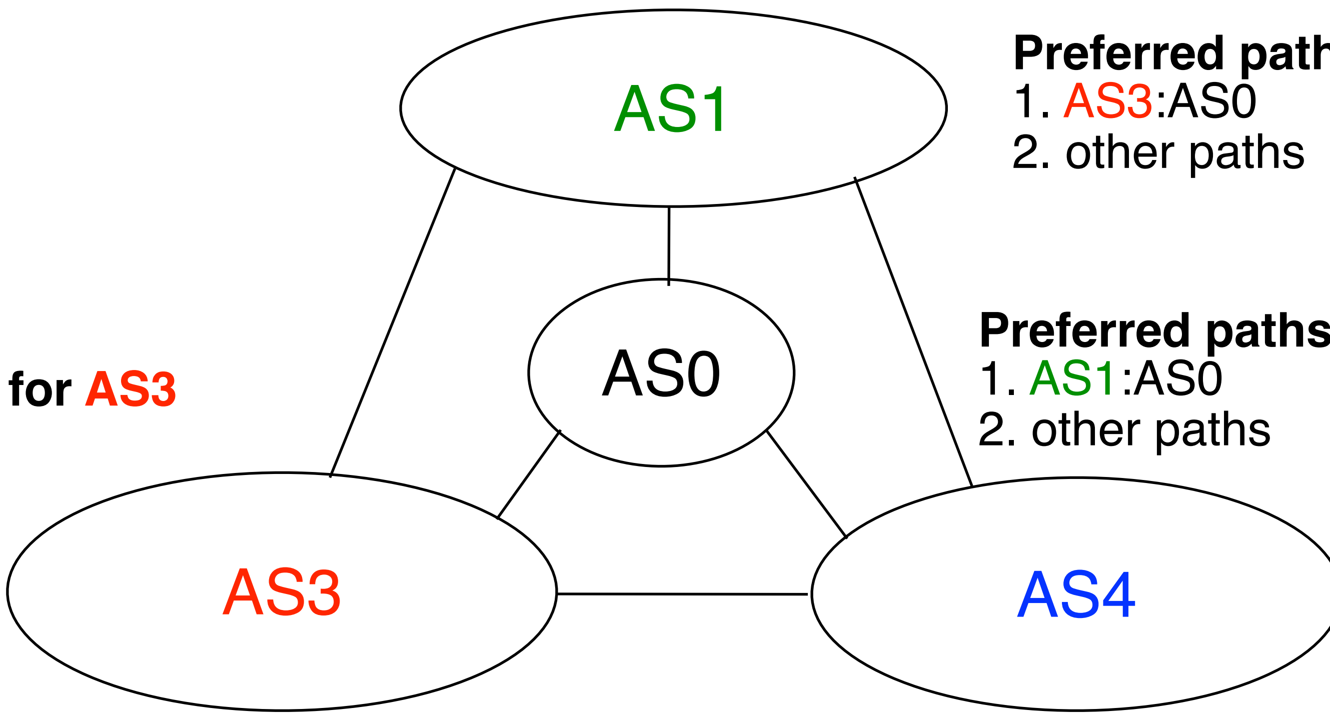
AS3 learns that the indirect route is not available anymore
- AS3 will reannounce its direct route...

AS4 learns that the indirect route is not available anymore
- AS4 will reannounce its direct route...

More limitations of `local-pref`

Unfortunately, interdomain routing may not converge at all in some cases...

Preferred paths for AS1
1. AS3:AS0
2. other paths



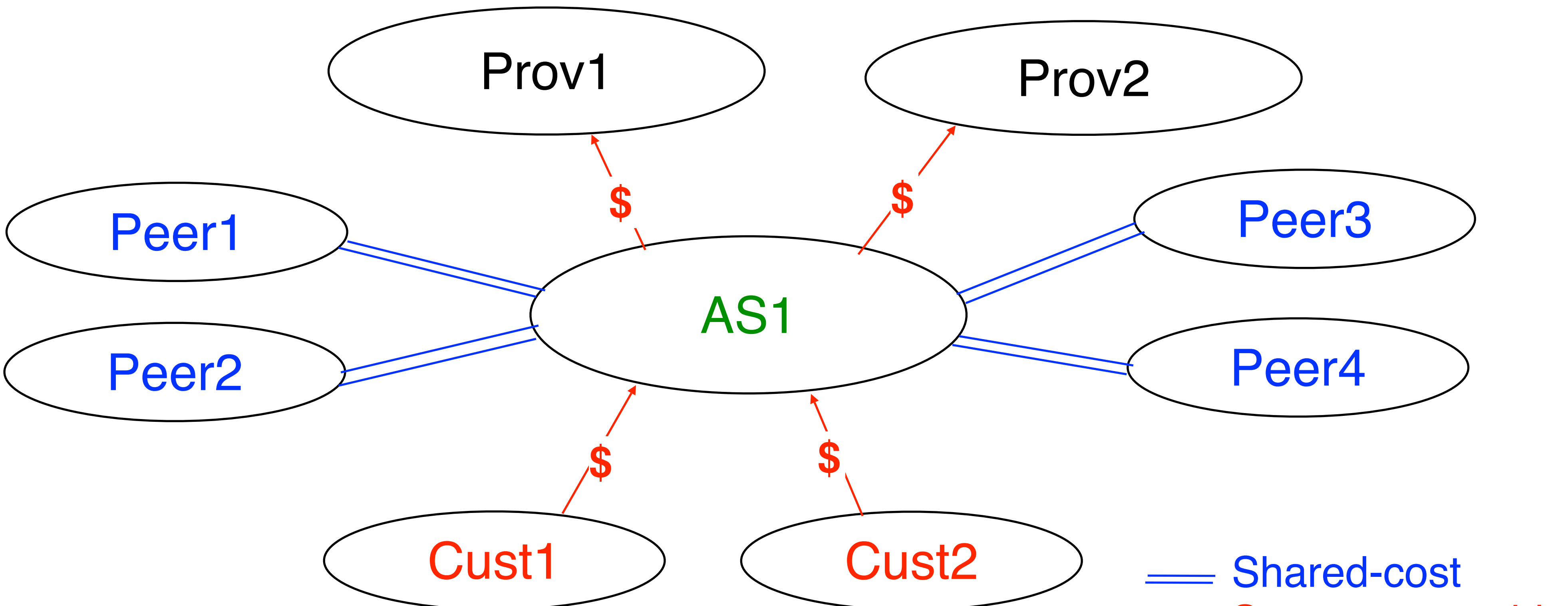
Preferred paths for AS4
1. AS1:AS0
2. other paths

Preferred paths for AS3
1. AS4:AS0
2. other paths

How to reach a destination inside AS0 in this case ?

`local-pref` and economical relationships

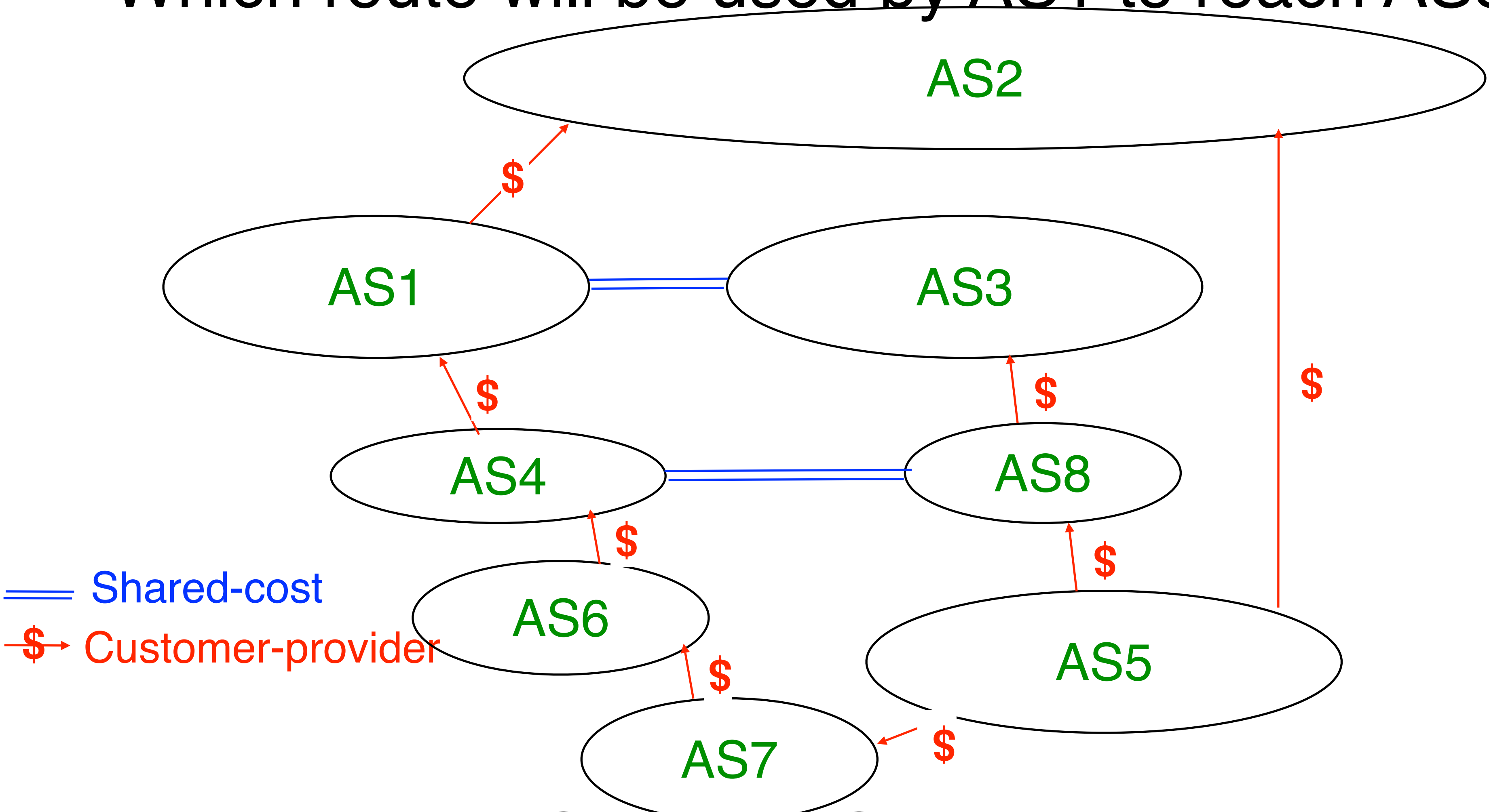
In practice, `local-pref` is often used to enforce economical relationships



Local-pref values used by AS1
> 1000 for the routes received from a Customer
500 – 999 for the routes learned from a Peer
< 500 for the routes learned from a Provider

Consequence of this utilisation of `local-pref`

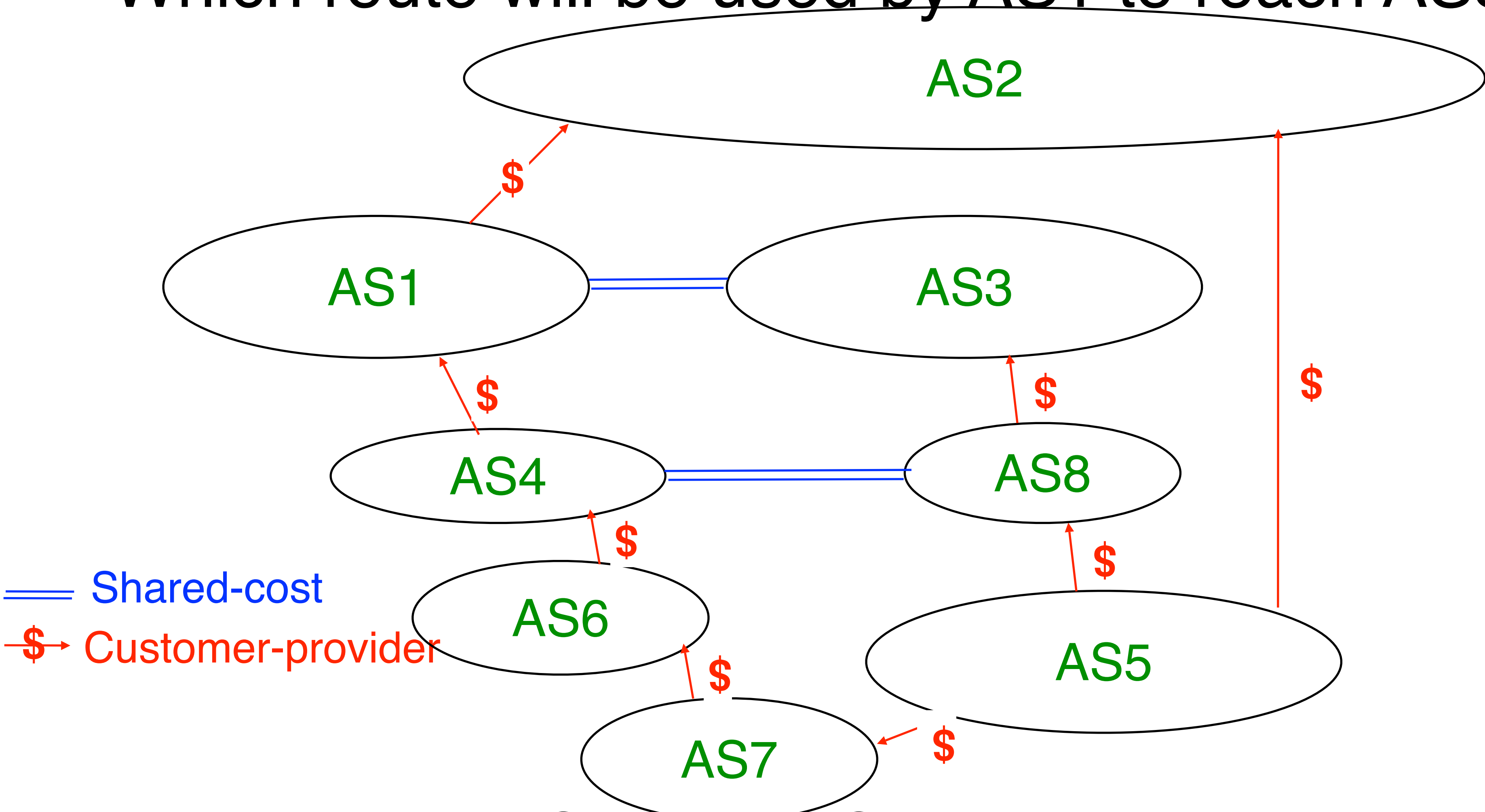
Which route will be used by AS1 to reach AS5 ?



and how will AS5 reach AS1 ?

Consequence of this utilisation of `local-pref`

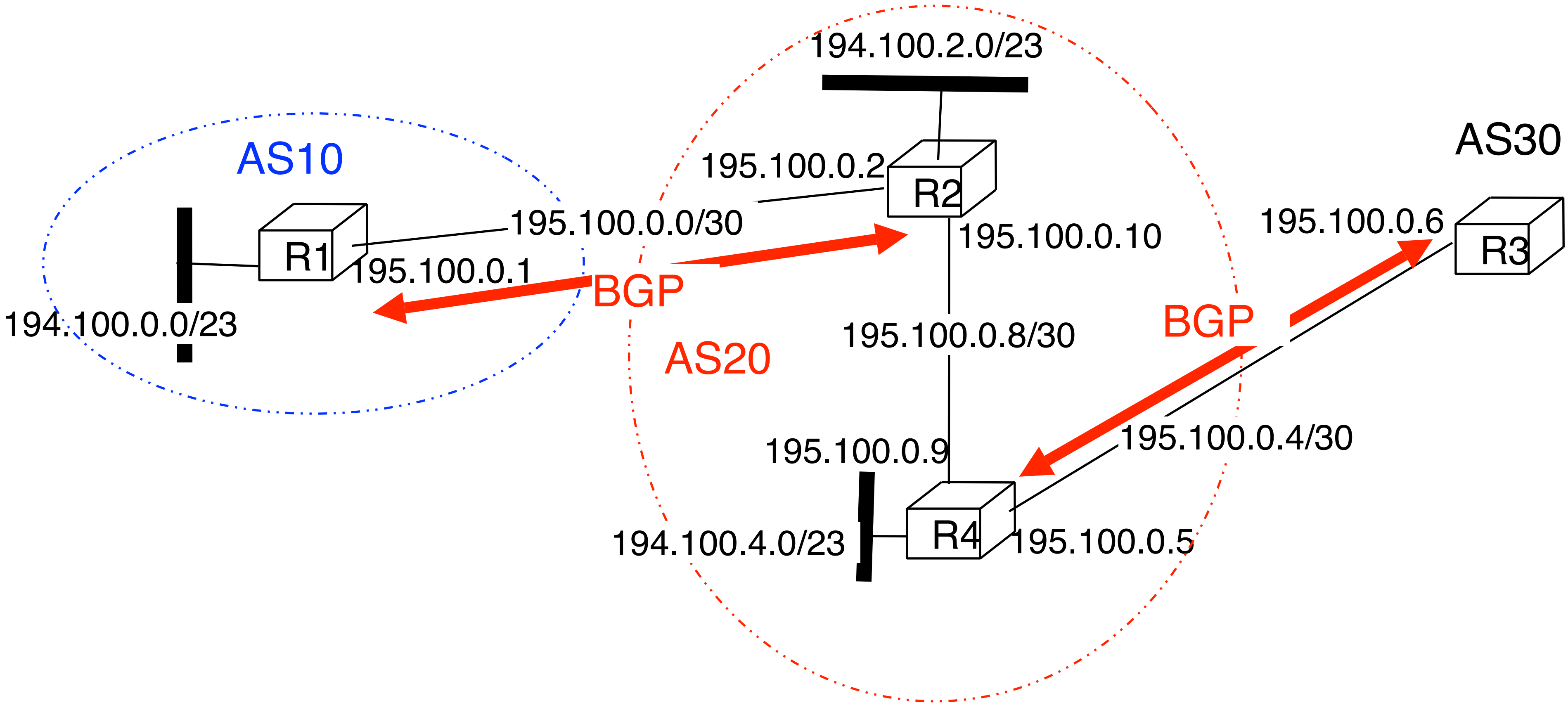
Which route will be used by AS1 to reach AS5 ?



and how will AS5 reach AS1 ?

Internet paths are often asymmetrical

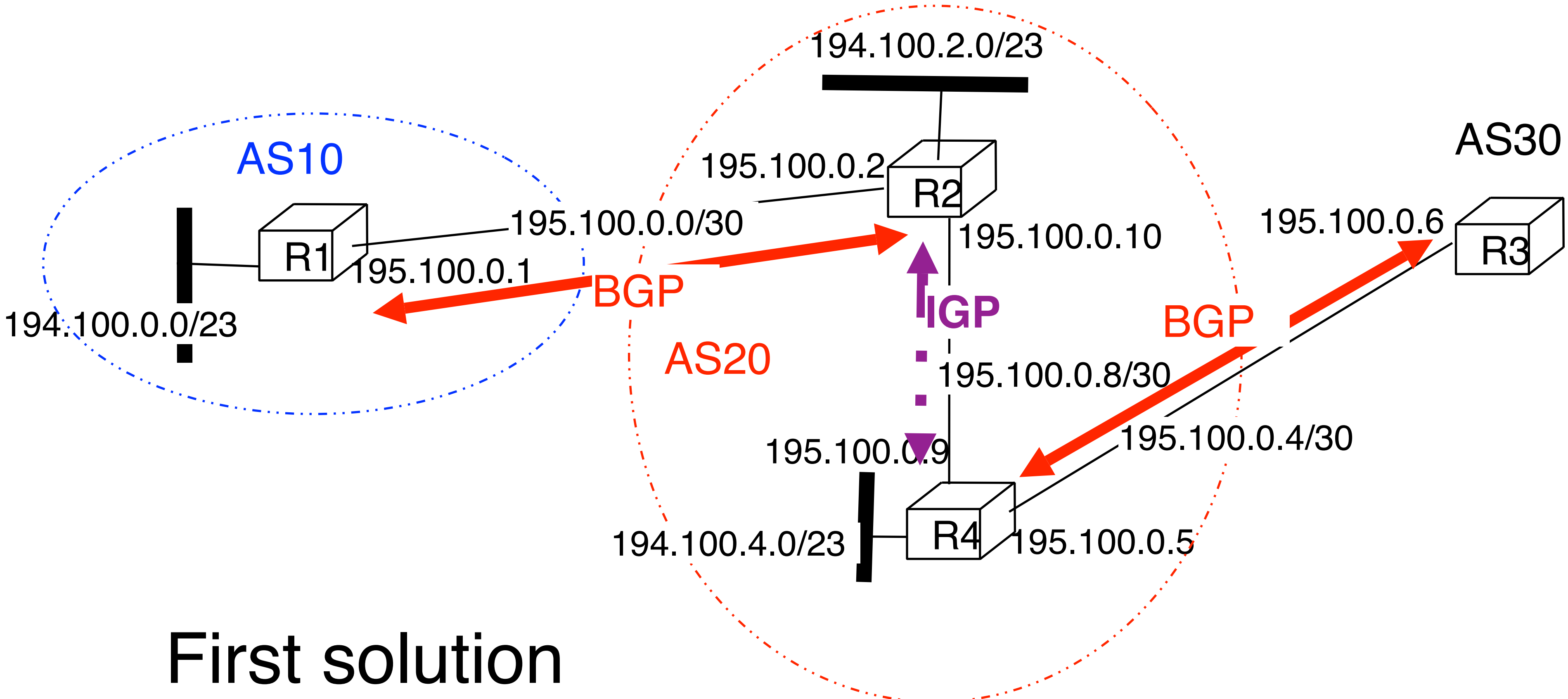
BGP and IP
Second example



Problem

How can R2 (resp. R4) advertise to R4 (resp. R2) the routes learned from AS10 (resp. AS30) ?

BGP and IP
Second example (2)



First solution

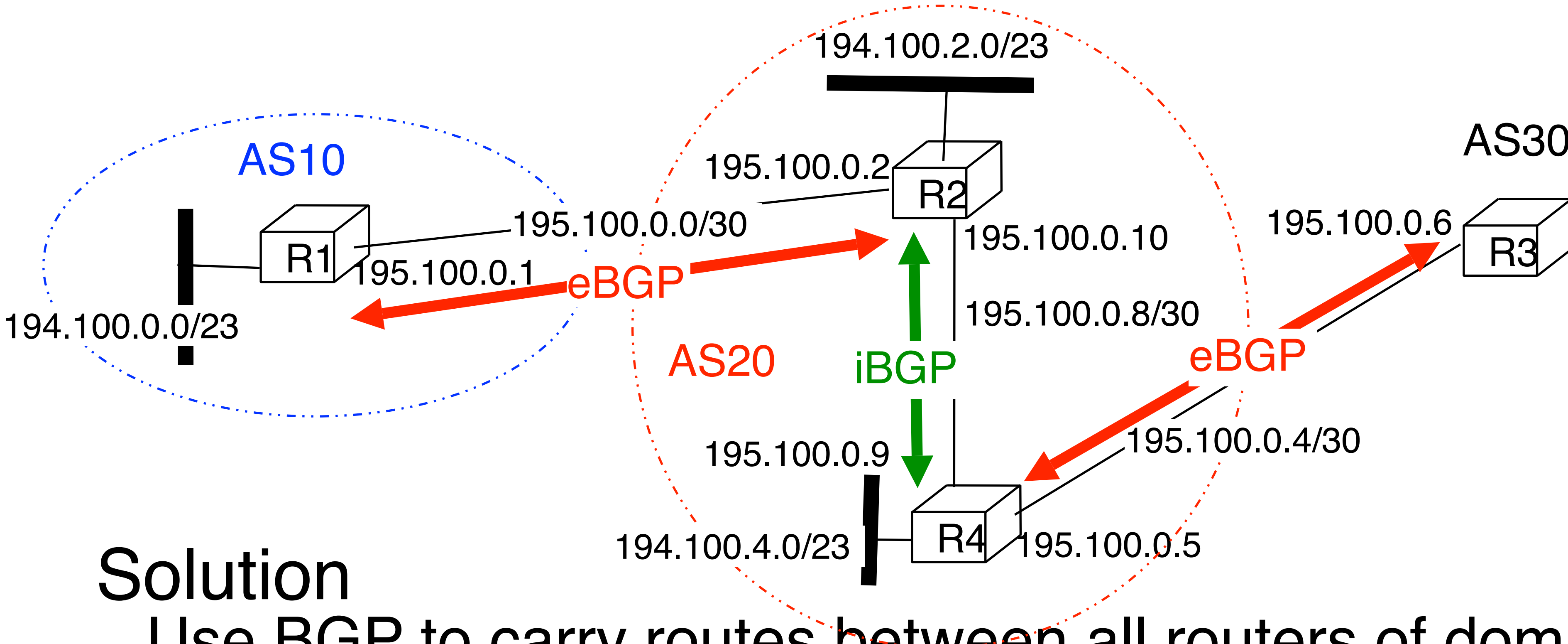
Use IGP (OSPF/ISIS,RIP) to carry BGP routes

Drawbacks

IGP may not be able to support so many routes

IGP does not carry BGP attributes like ASPath !

iBGP and eBGP



Solution

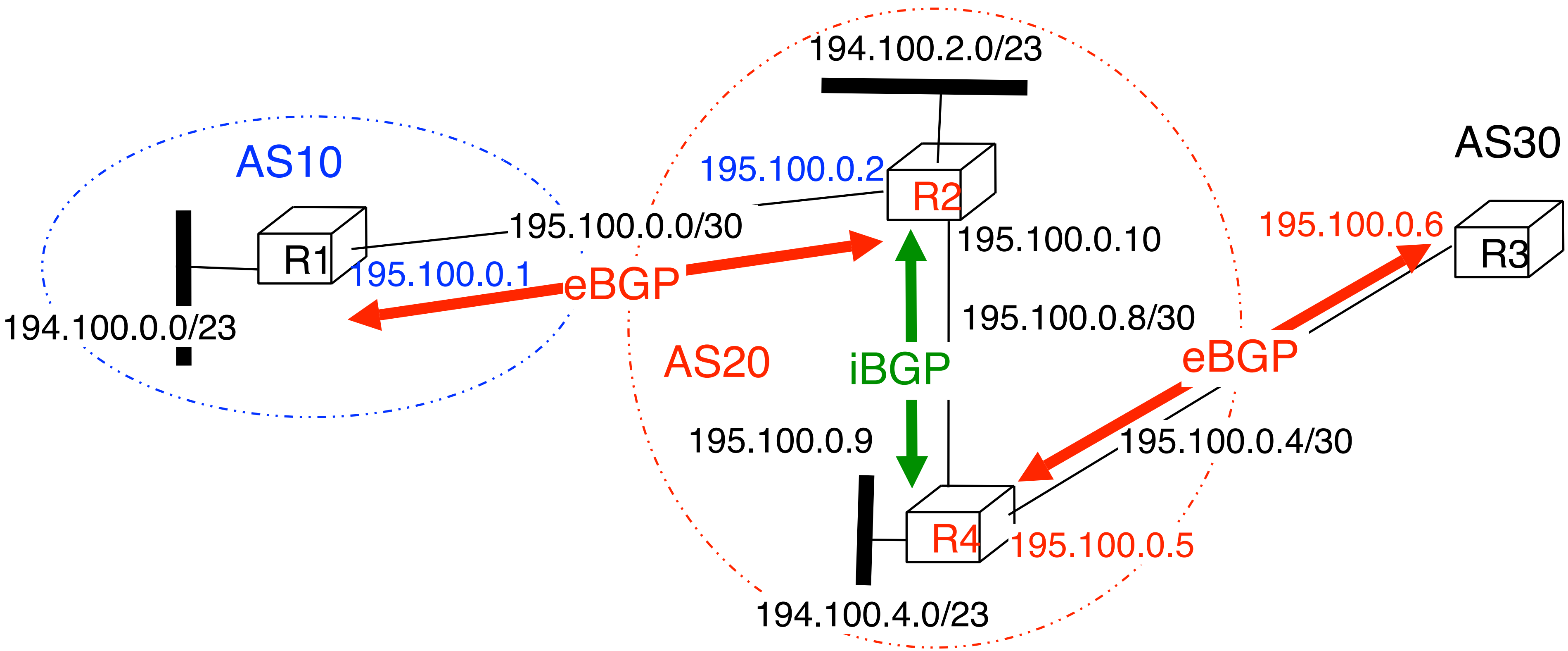
- Use BGP to carry routes between all routers of domain
  - Two different types of BGP sessions
  - eBGP between routers belonging to different ASes
  - iBGP between each pair of routers belonging to the same AS
    - Each BGP router inside ASx maintains an iBGP session with all other BGP routers of ASx (full iBGP mesh)
    - Note that the iBGP sessions do not necessarily follow physical topology

iBGP versus eBGP

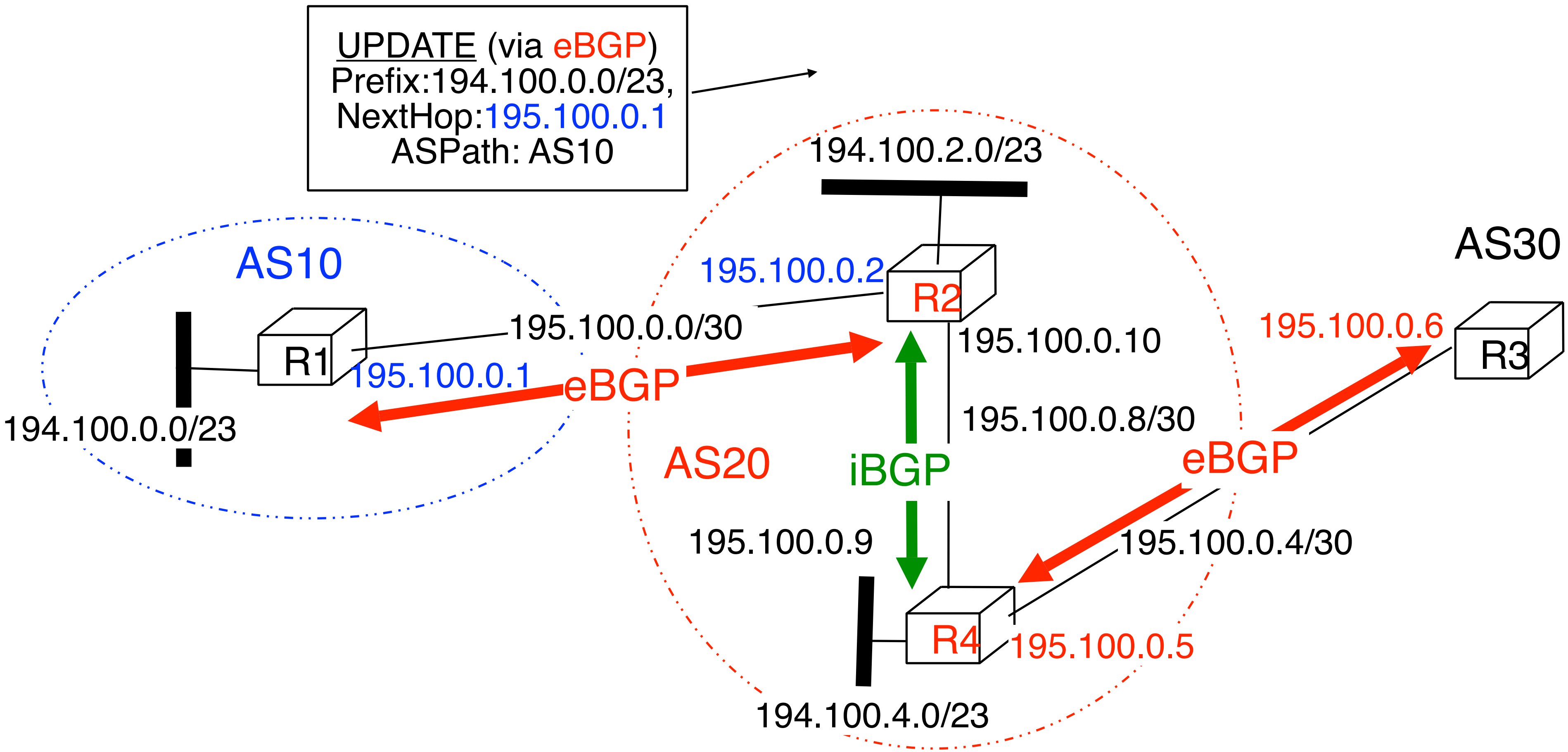
Differences between iBGP and eBGP

- `local-pref` attribute is only carried inside messages sent over iBGP session
- Over an eBGP session, a router only advertises its best route towards each destination
  - Usually, import and export filters are defined for each eBGP session
- Over an iBGP session, a router advertises only its best routes learned over eBGP sessions
  - A route learned over an iBGP session is *never* advertised over another iBGP session
  - Usually, no filter is applied on iBGP sessions

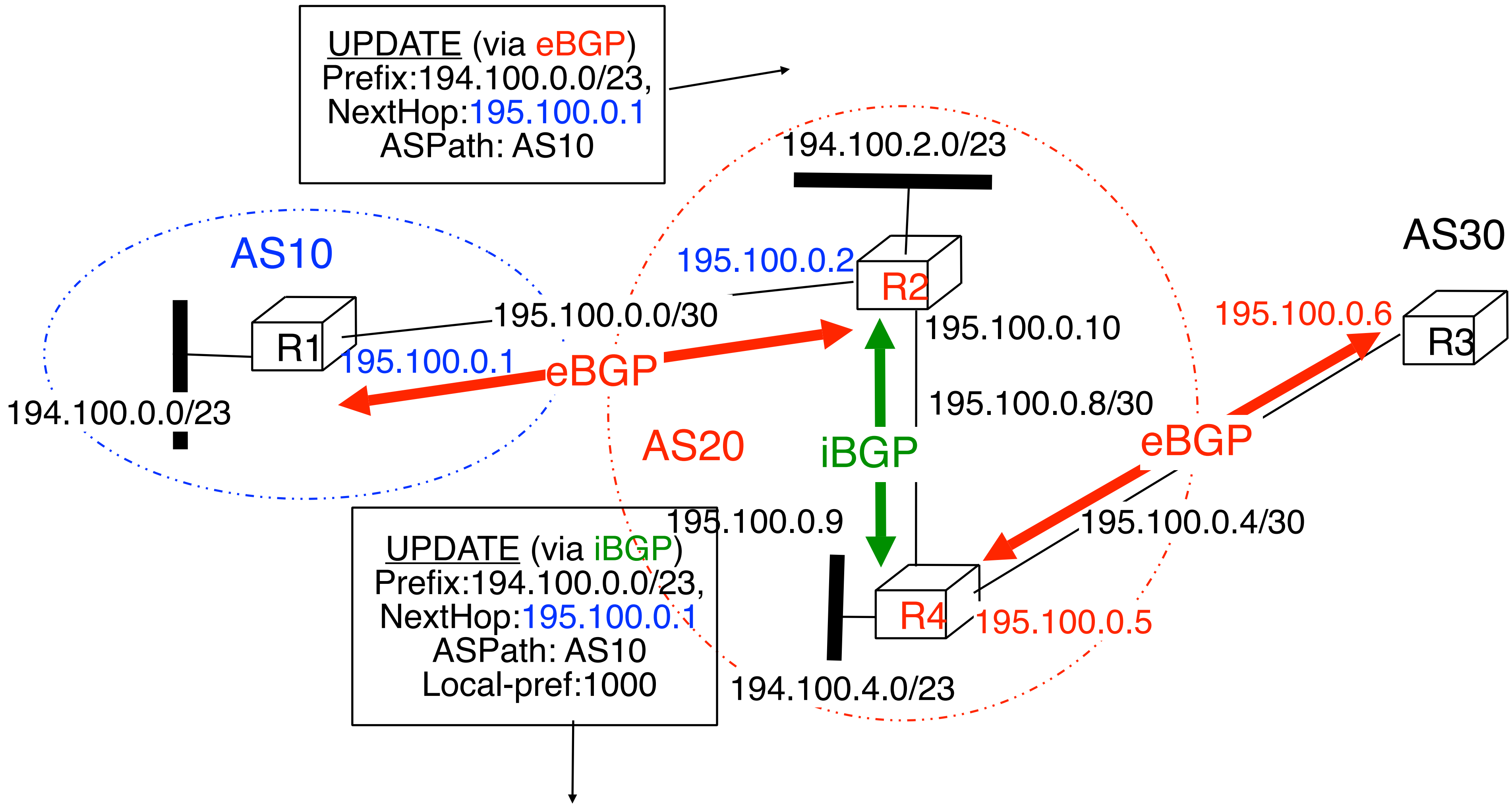
iBGP and eBGP : Example



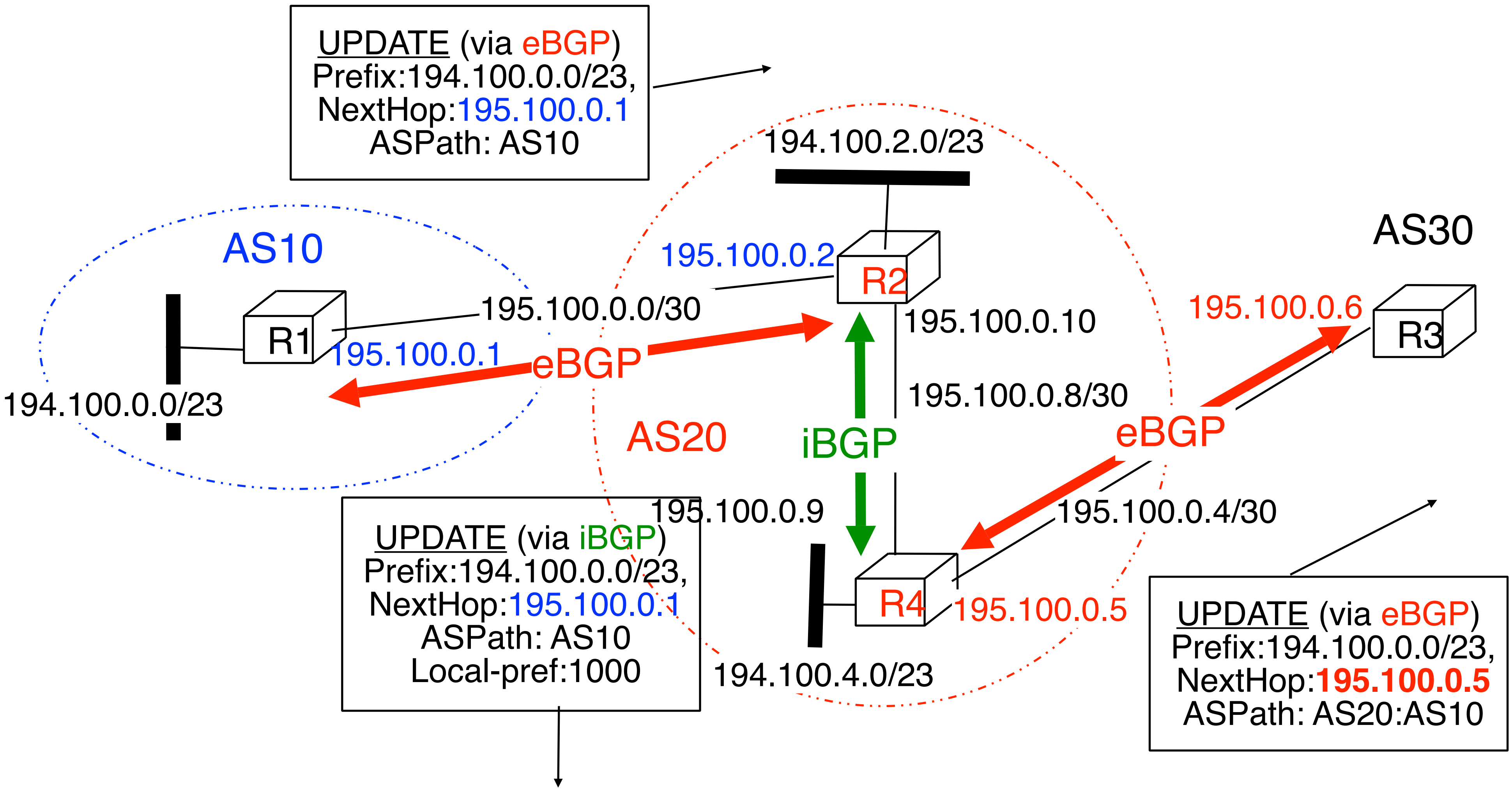
iBGP and eBGP : Example



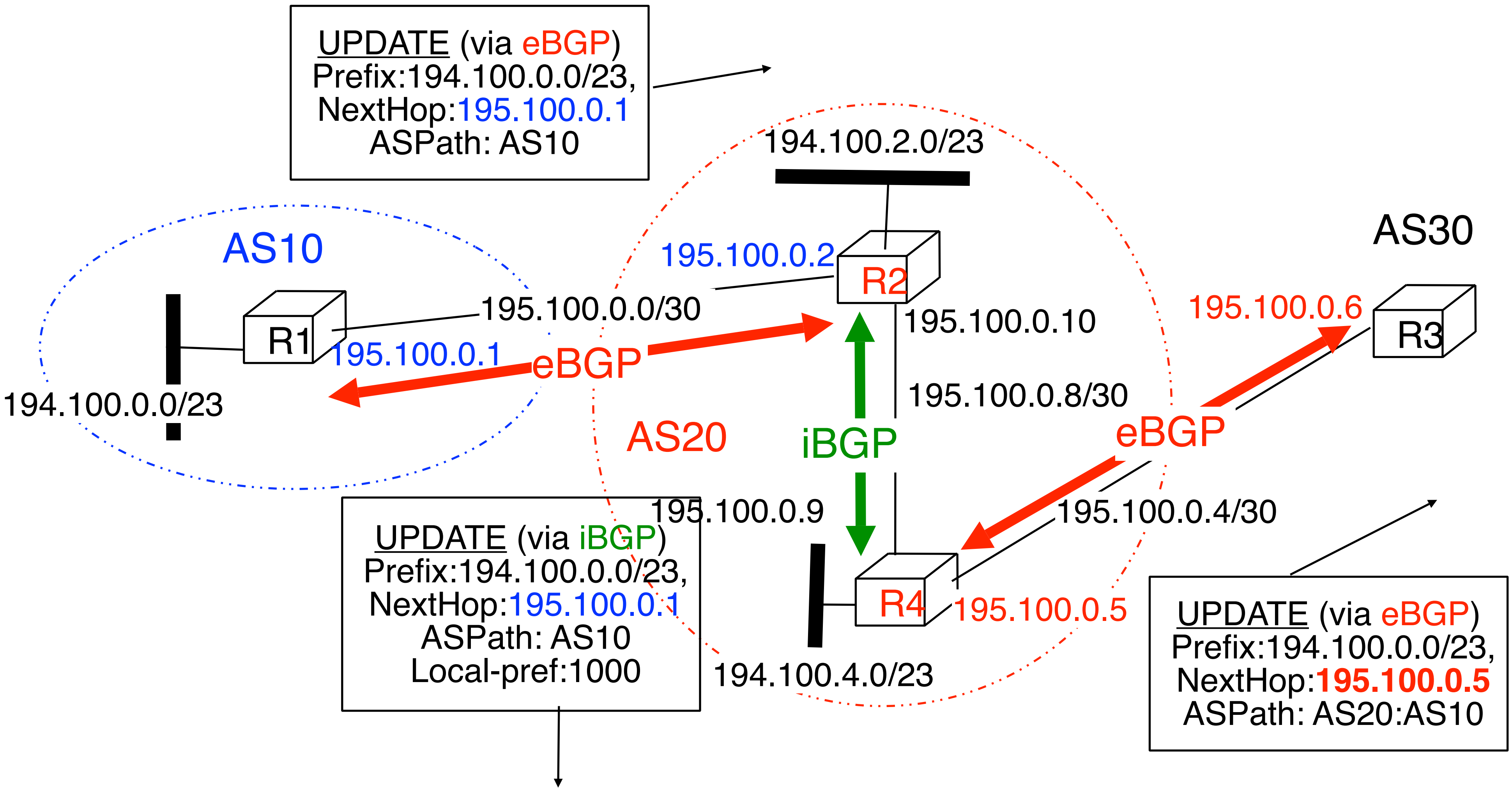
iBGP and eBGP : Example



iBGP and eBGP : Example

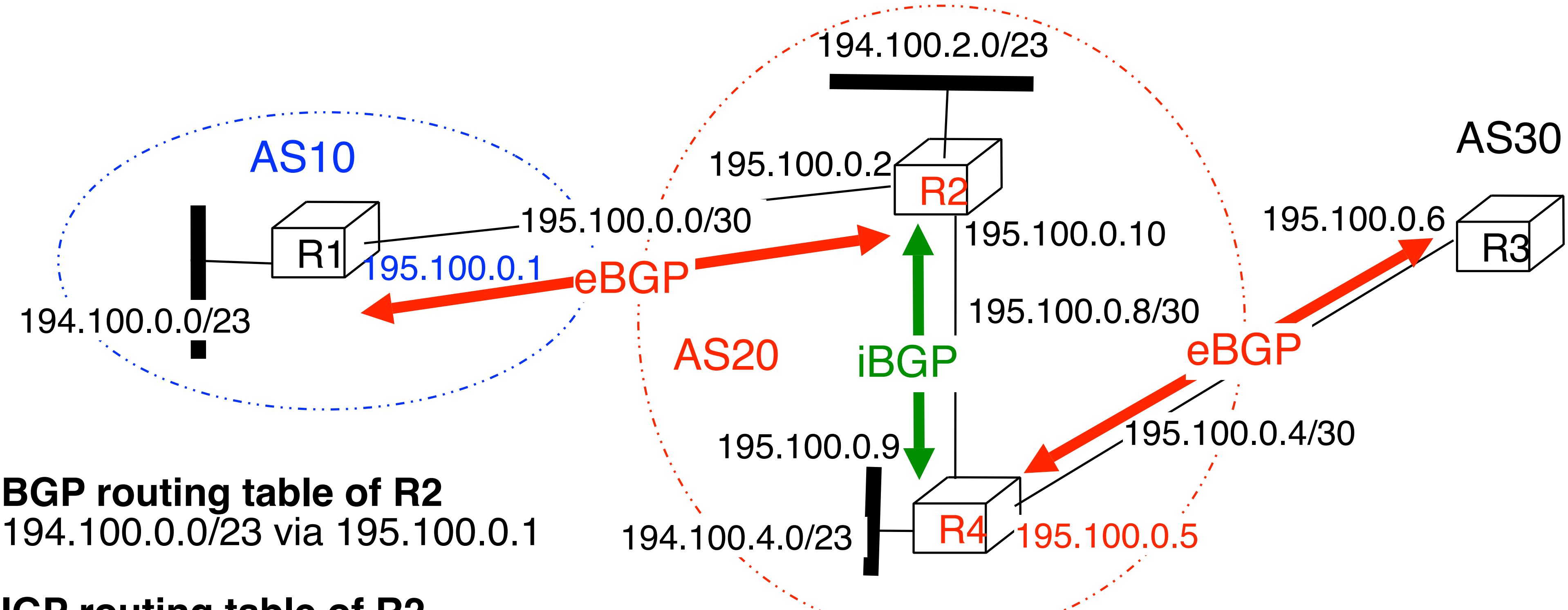


iBGP and eBGP : Example



Note that the next-hop and the AS-Path of BGP update messages are only updated when sent over an eBGP session

iBGP and eBGP Packet Forwarding



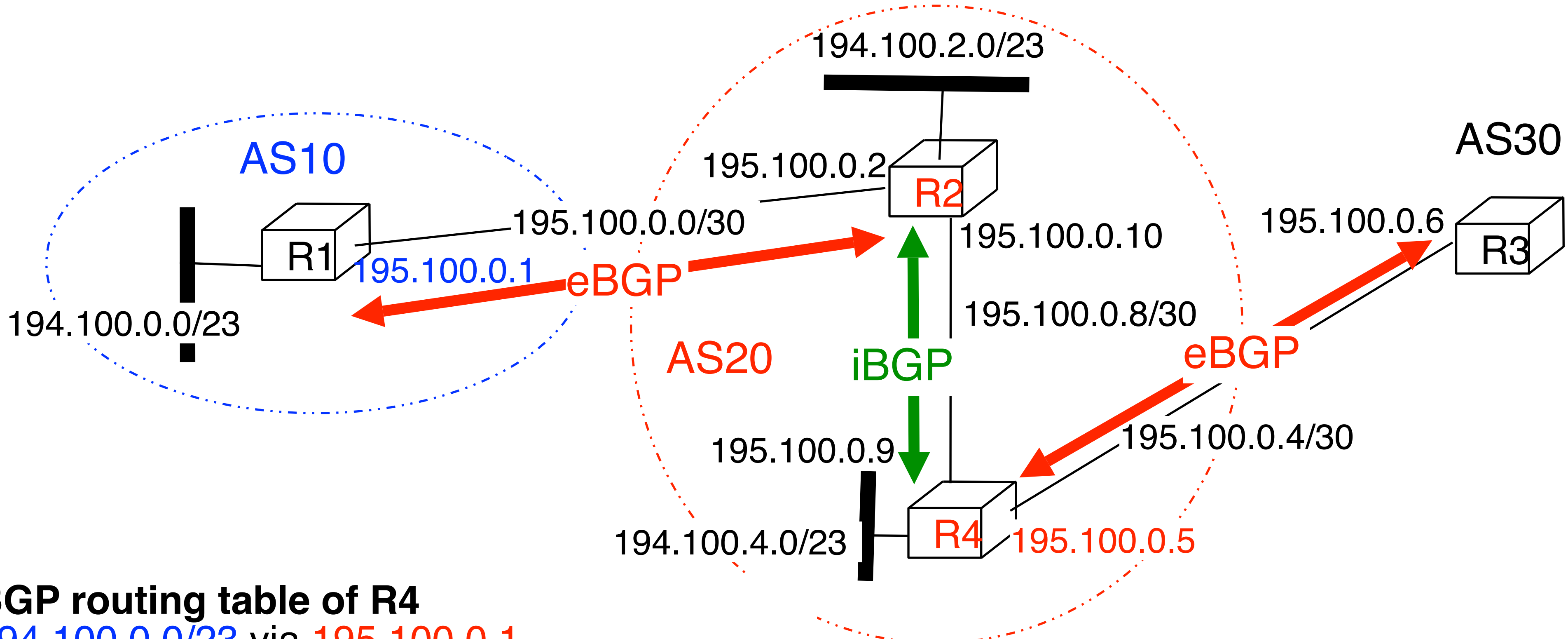
BGP routing table of R2
194.100.0.0/23 via 195.100.0.1

IGP routing table of R2
195.100.0.0/30 West
195.100.0.4/30 via 195.100.0.9
195.100.0.8/30 South
194.100.0.4/23 via 195.100.0.9
194.100.2.0/23 North

BGP routing table of R4
194.100.0.0/23 via 195.100.0.1

IGP routing table of R4
195.100.0.0/30 via 195.100.0.10
195.100.0.4/30 East
195.100.0.8/30 North
194.100.2.0/23 via 195.100.0.10
194.100.0.4/23 West

iBGP and eBGP Packet Forwarding (2)

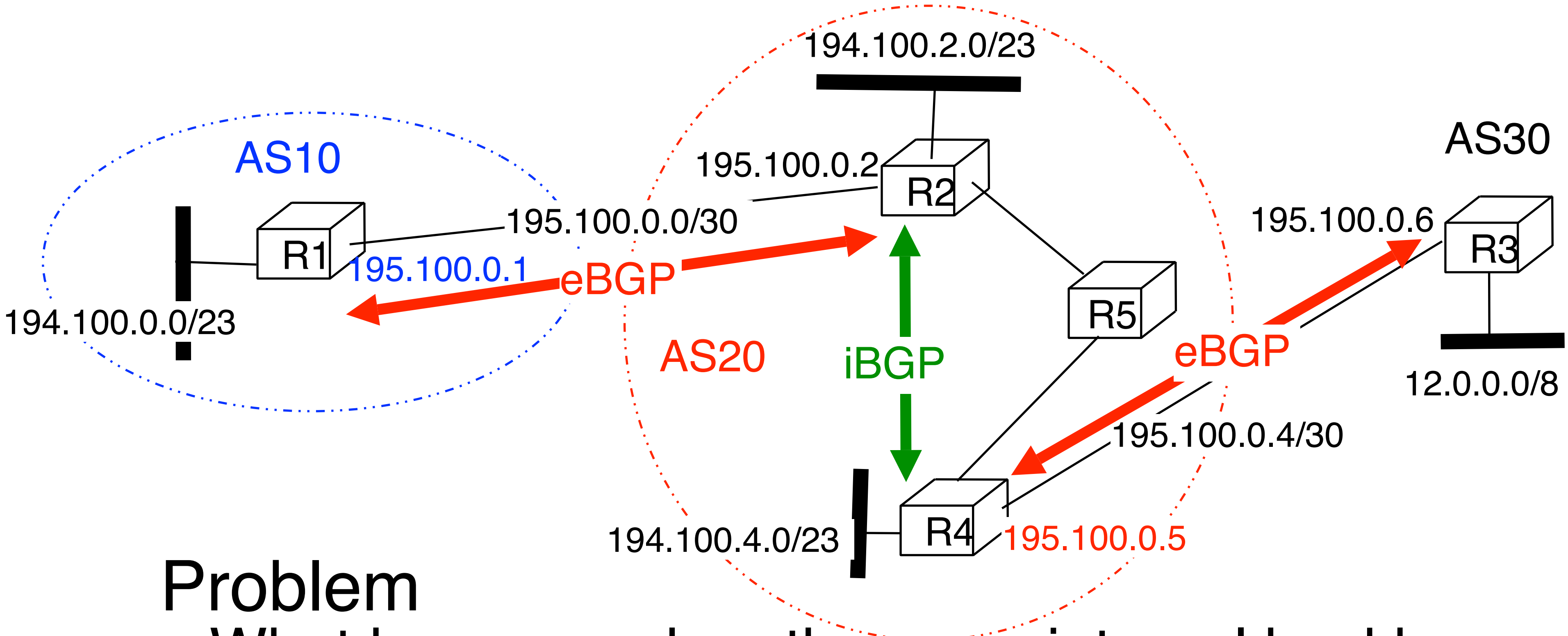


BGP routing table of R4
194.100.0.0/23 via 195.100.0.1

IGP routing table of R4
195.100.0.0/30 via **195.100.0.10**
195.100.0.4/30 East
195.100.0.8/30 North
194.100.2.0/23 via 195.100.0.10
194.100.4.0/23 West

Forwarding of R4
194.100.0.0/23 via **195.100.0.10**
195.100.0.0/30 via 195.100.0.10
195.100.0.4/30 East
195.100.0.8/30 North
194.100.2.0/23 via 195.100.0.10
194.100.4.0/23 West

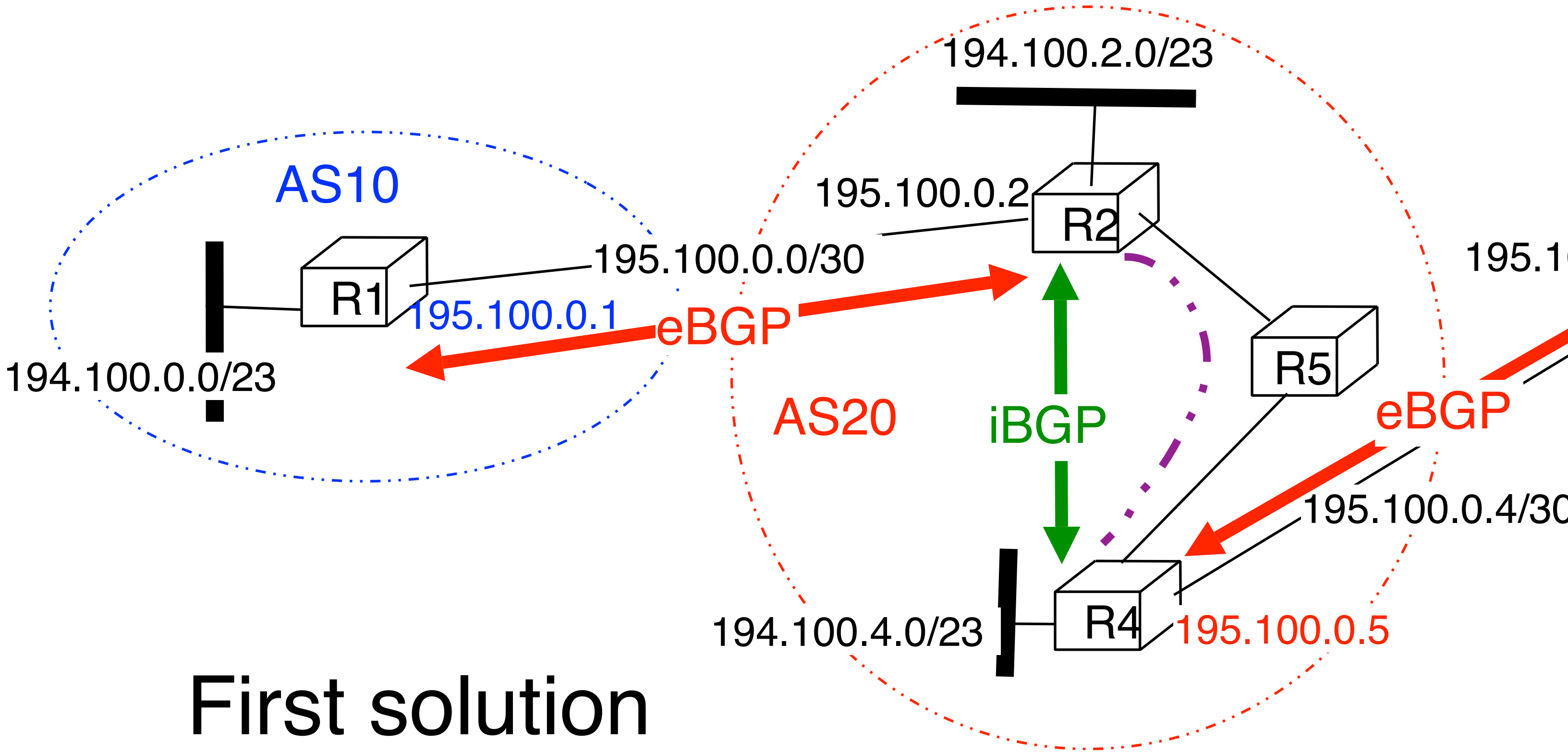
Using non-BGP routers



Problem

- What happens when there are internal backbone routers between BGP routers inside an AS ?
  - iBGP session between BGP routers is easily established when IGP is running since iBGP runs over TCP connection
  - How to populate the routing table of the backbone routers to ensure that they will be able to route any IP packet ?

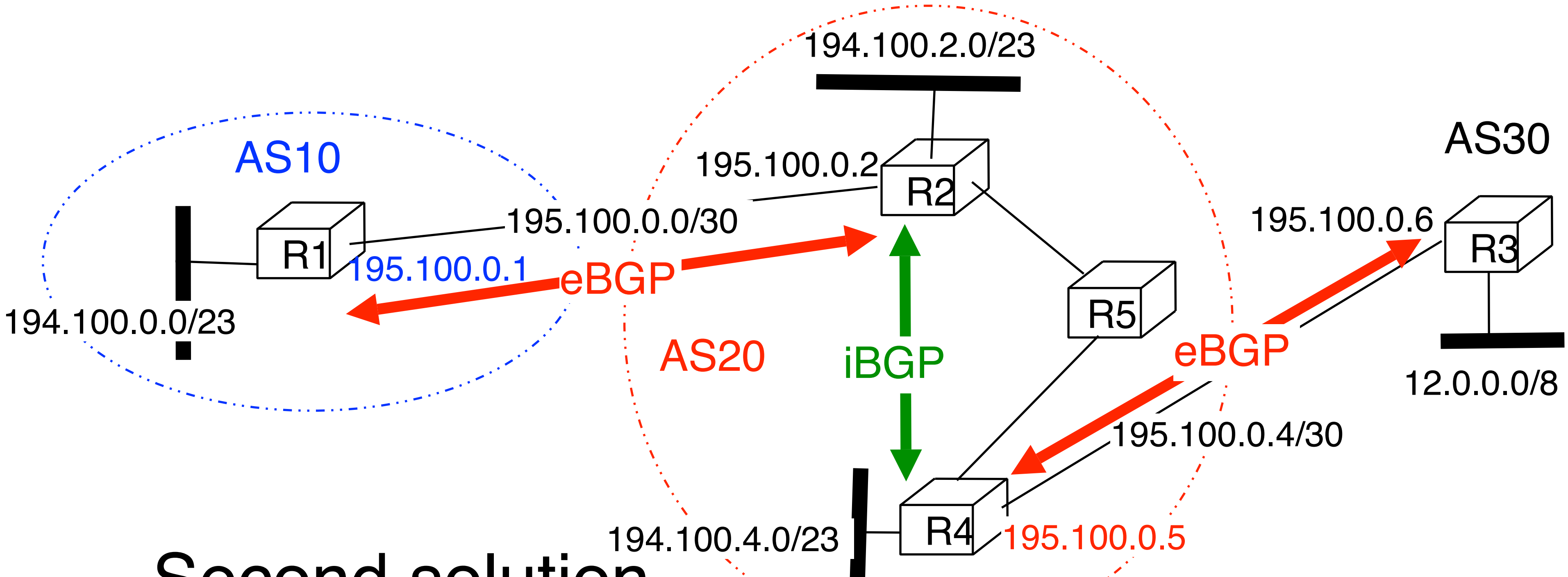
Using non-BGP routers (2)



First solution

- Use tunnels between BGP routers to encapsulate interdomain packets
  - GRE tunnel
    - Needs static configuration and be careful with MTU issues
  - MPLS tunnel
    - Can be dynamically established in MPLS enabled backbone

Using non-BGP routers (3)



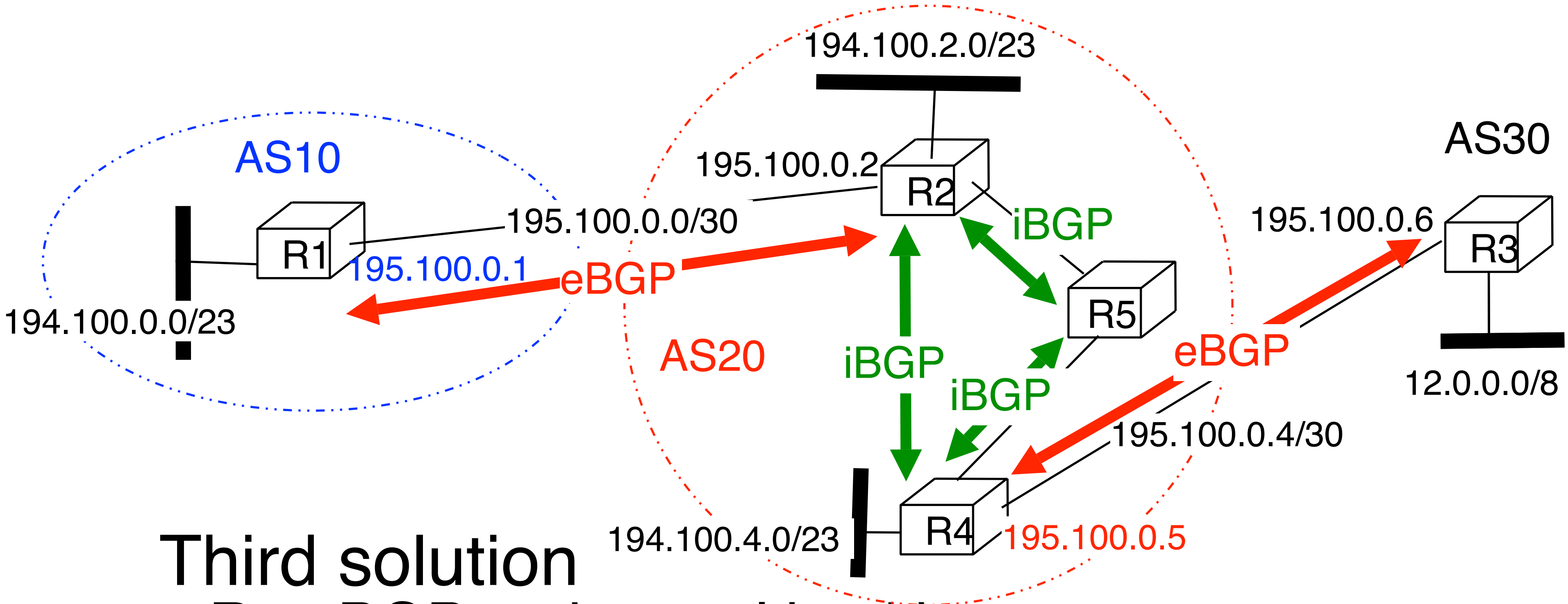
Second solution

Use IGP (OSPF/IS-IS - RIP) to redistribute interdomain routes to internal backbone routers

Drawbacks

- Size of BGP tables may completely overload the IGP
- Make sure that BGP routes learned by R2 and injected inside IGP will not be re-injected inside BGP by R4 !

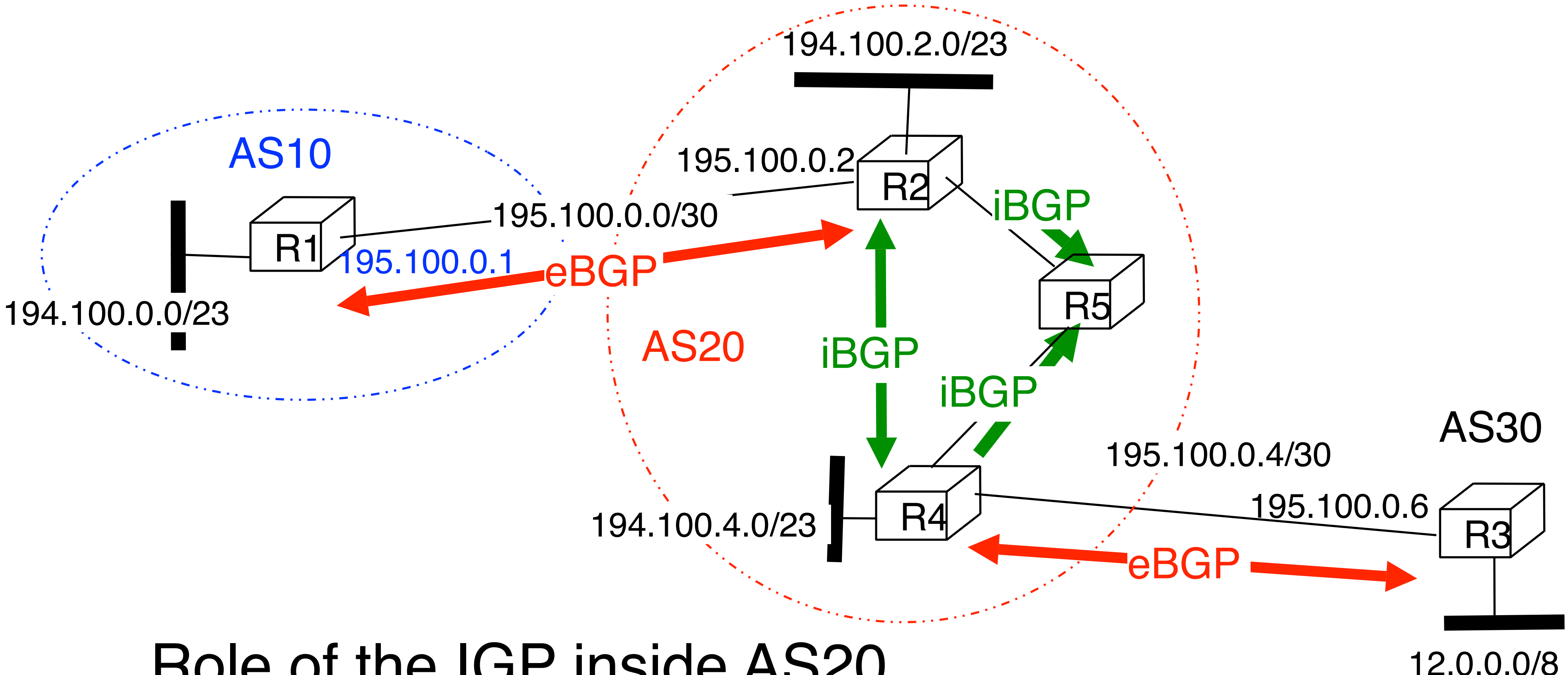
Using non-BGP routers (4)



Third solution

- Run BGP on internal backbone routers
- Internal backbone routers need to participate in iBGP full mesh
  - Internal backbone routers receive BGP routes via iBGP but never advertise any routes
    - Remember : a route learned over an iBGP session is never advertised over another iBGP session

The roles of IGP and BGP

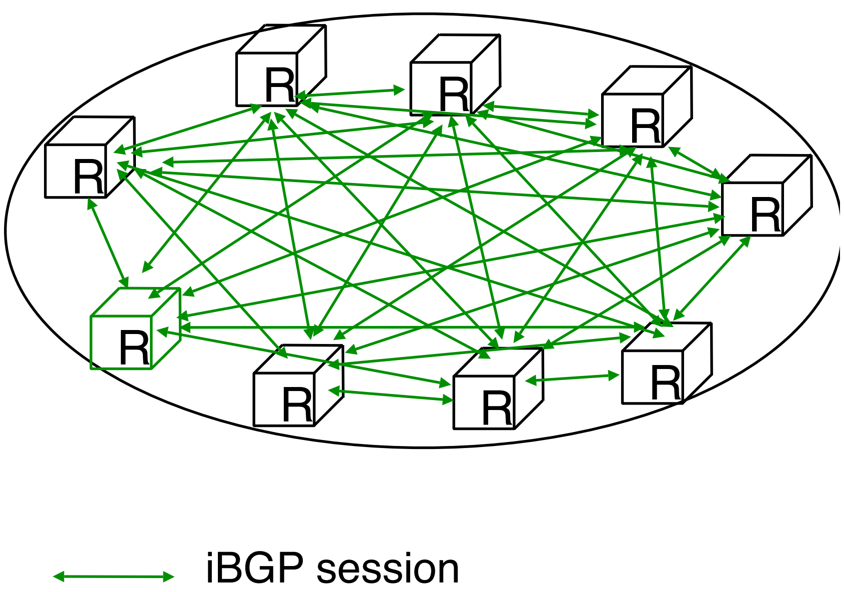


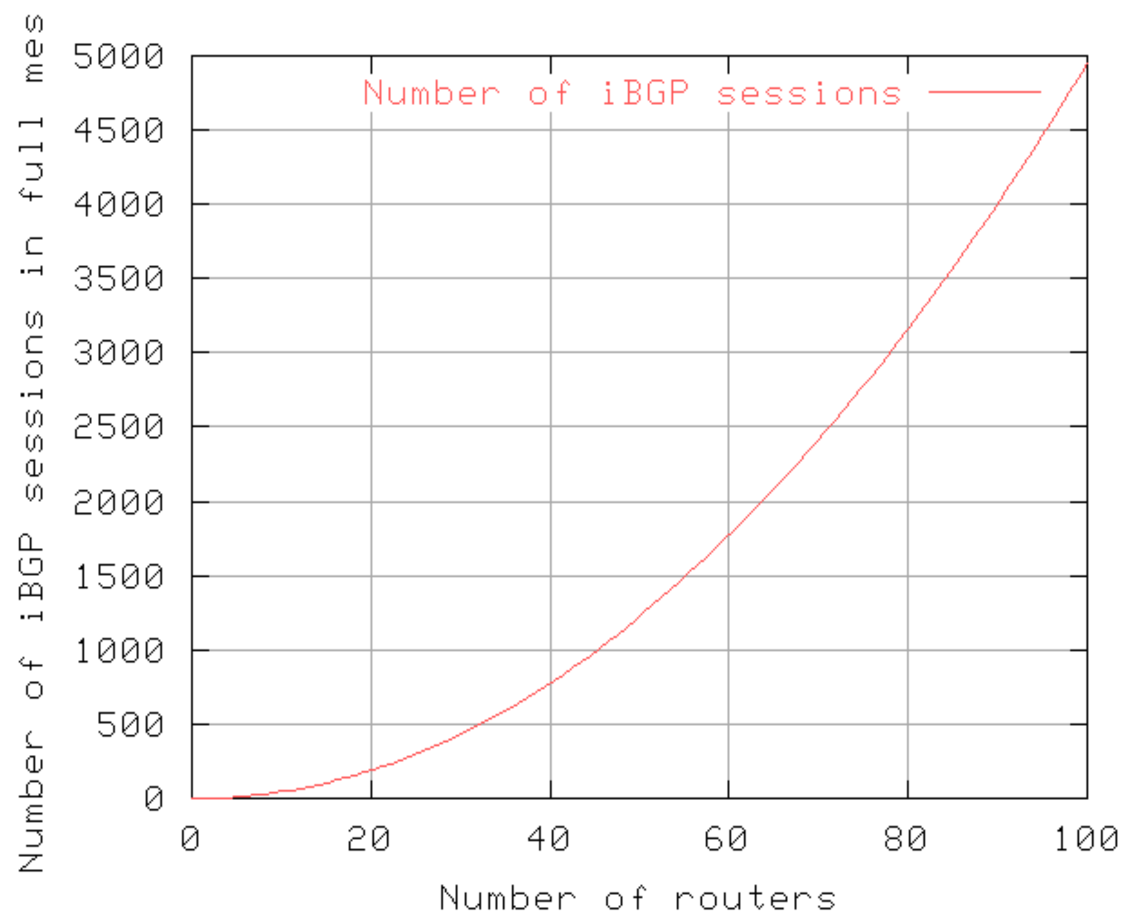
- Role of the IGP inside AS20
  - Distribute internal topology and internal addresses R2-R4-R5)
- Role of BGP inside AS20
  - Distribute the routes towards external destinations
  - IGP must run to allow BGP routers to establish iBGP sessions

The iBGP full mesh

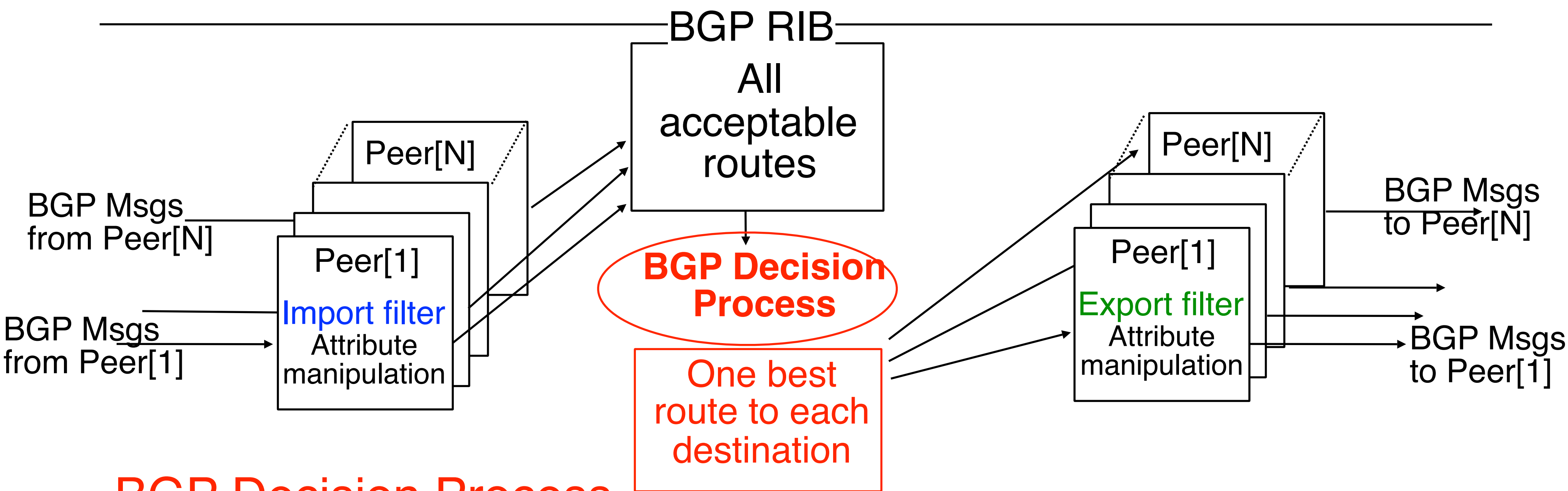
Drawback

N*(N-1)/2 iBGP sessions for N routers





The BGP decision process



BGP Decision Process

Ignore routes with unreachable nexthop

Prefer routes with highest local-pref

Prefer routes with shortest ASPath

Prefer routes with smallest MED

Prefer routes learned via eBGP over routes learned via iBGP

Prefer routes with closest next-hop

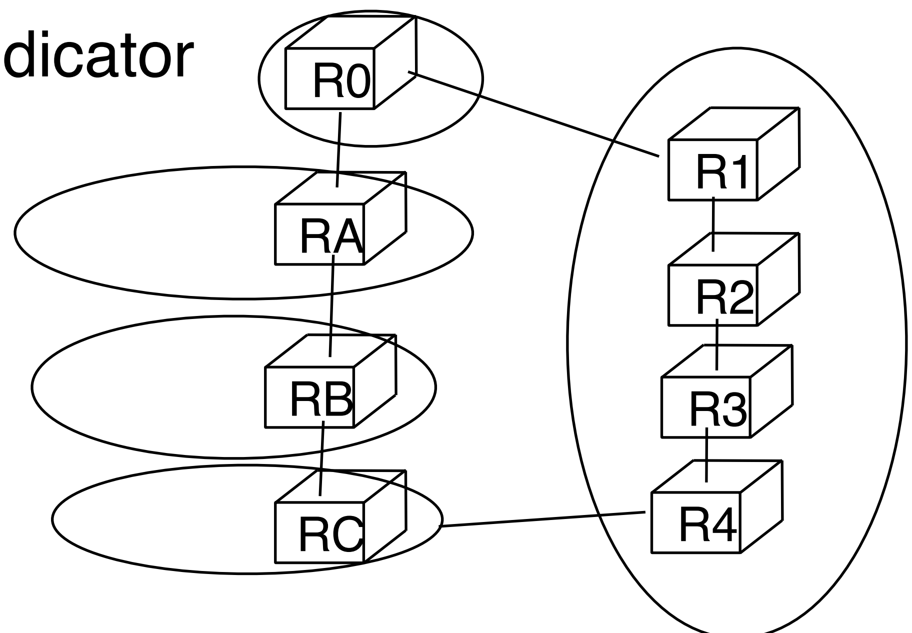
Tie breaking rules

- Prefer Routes learned from router with lowest router id

The shortest `AS-Path` step in the BGP decision process

Motivation

- BGP does not contain a real " metric"
- Use length of AS-Path as an indication of the quality of routes
  - Not always a good indicator

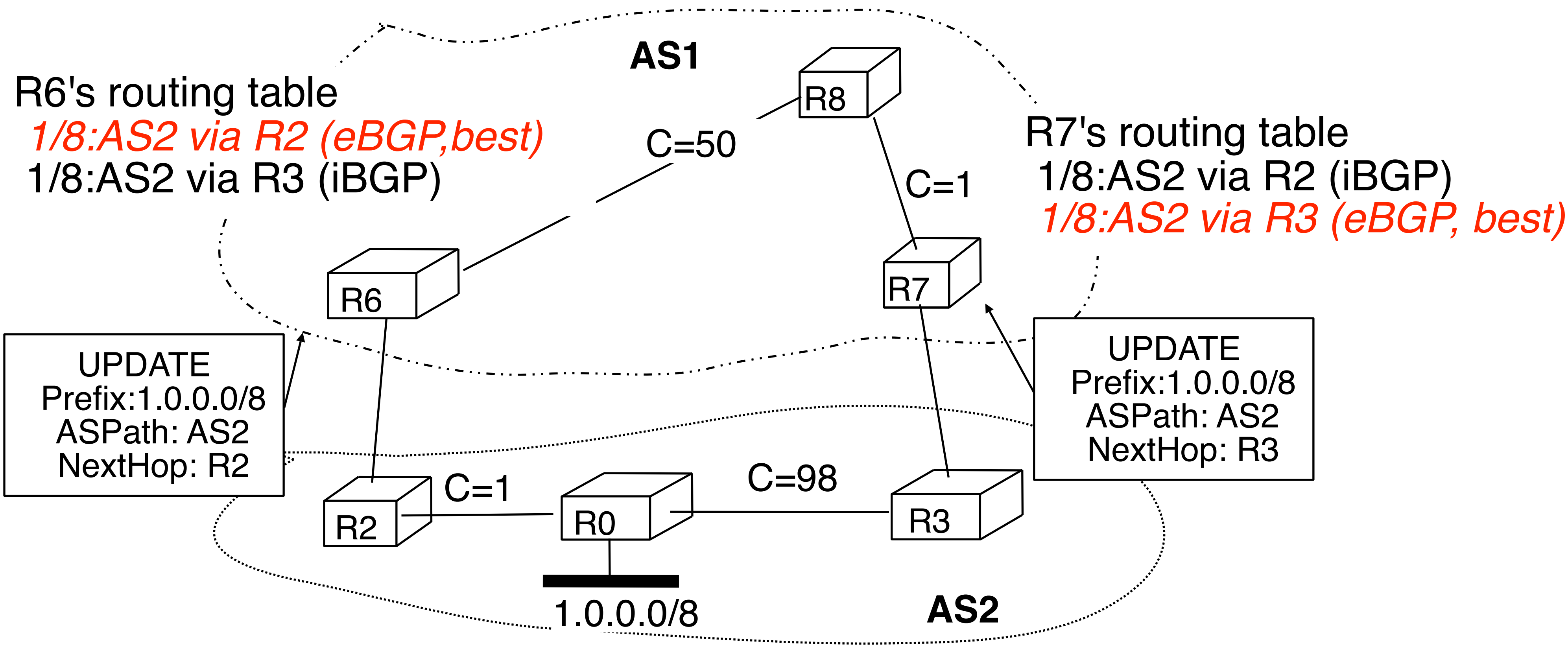


Consequence

- Internet paths tend to be short, 3-5 AS hops
- Many paths converge at Tier-1 ISPs and those ISPs carry lots of traffic

The prefer eBGP over iBGP step in the BGP decision process

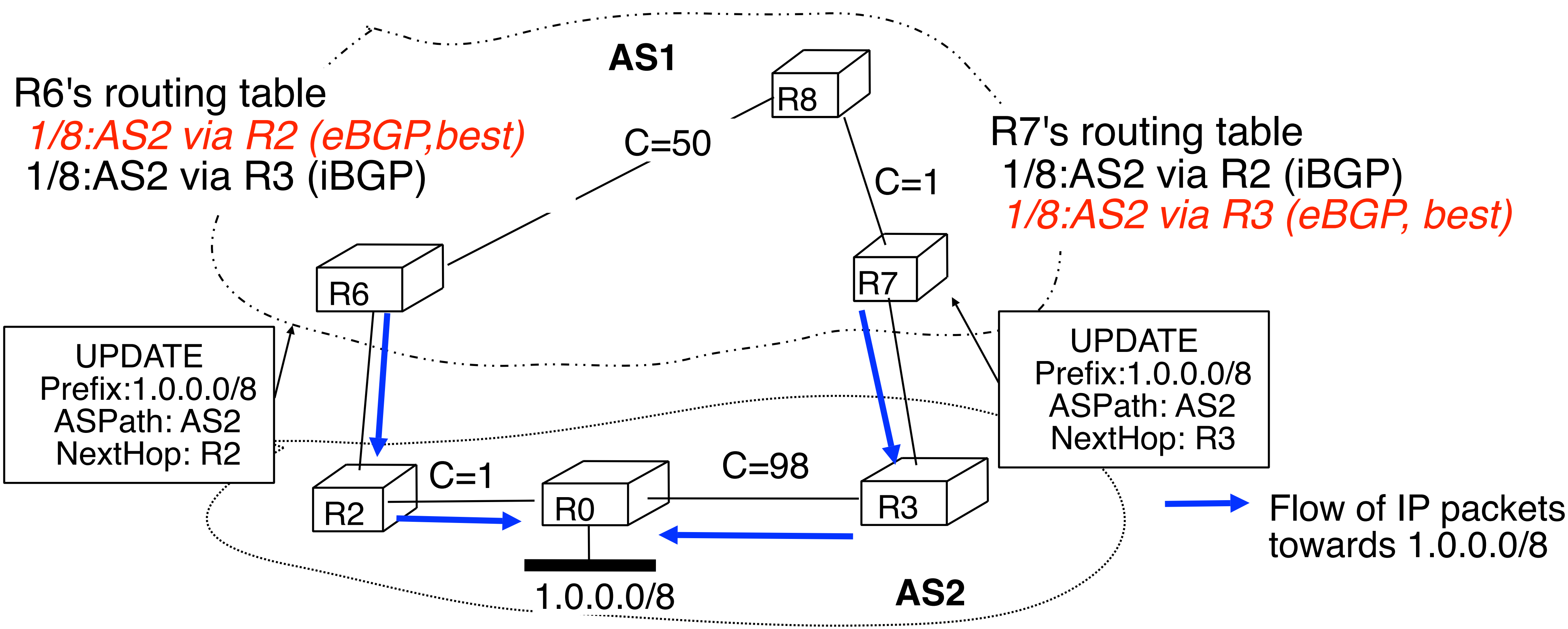
- Motivation : hot potato routing
  - A router should try to get rid of packets sent to external domains as soon as possible



The prefer eBGP over iBGP step in the BGP decision process

Motivation : hot potato routing

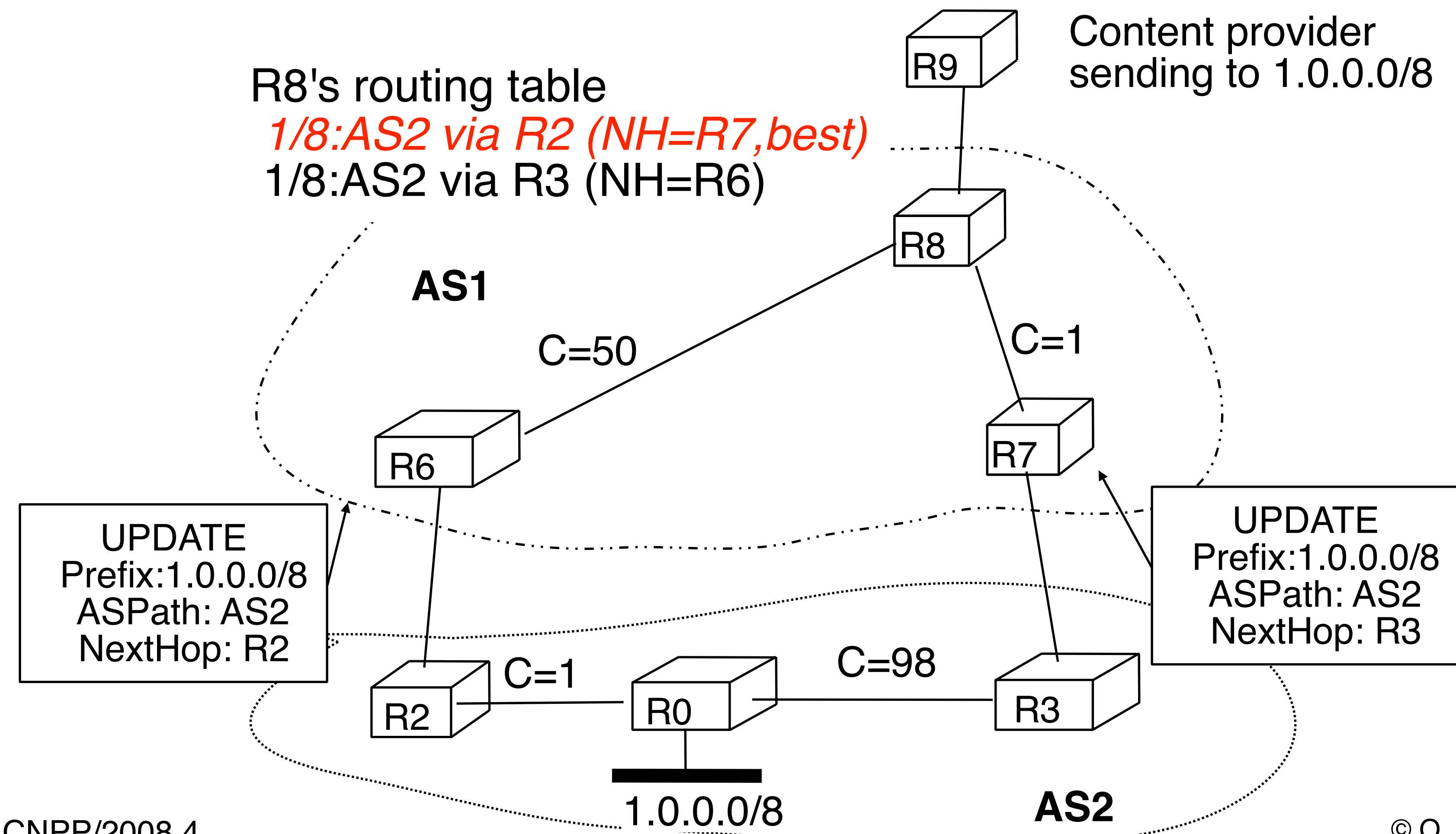
A router should try to get rid of packets sent to external domains as soon as possible



The closest `nexthop` step in the BGP decision process

Motivation : hot potato routing

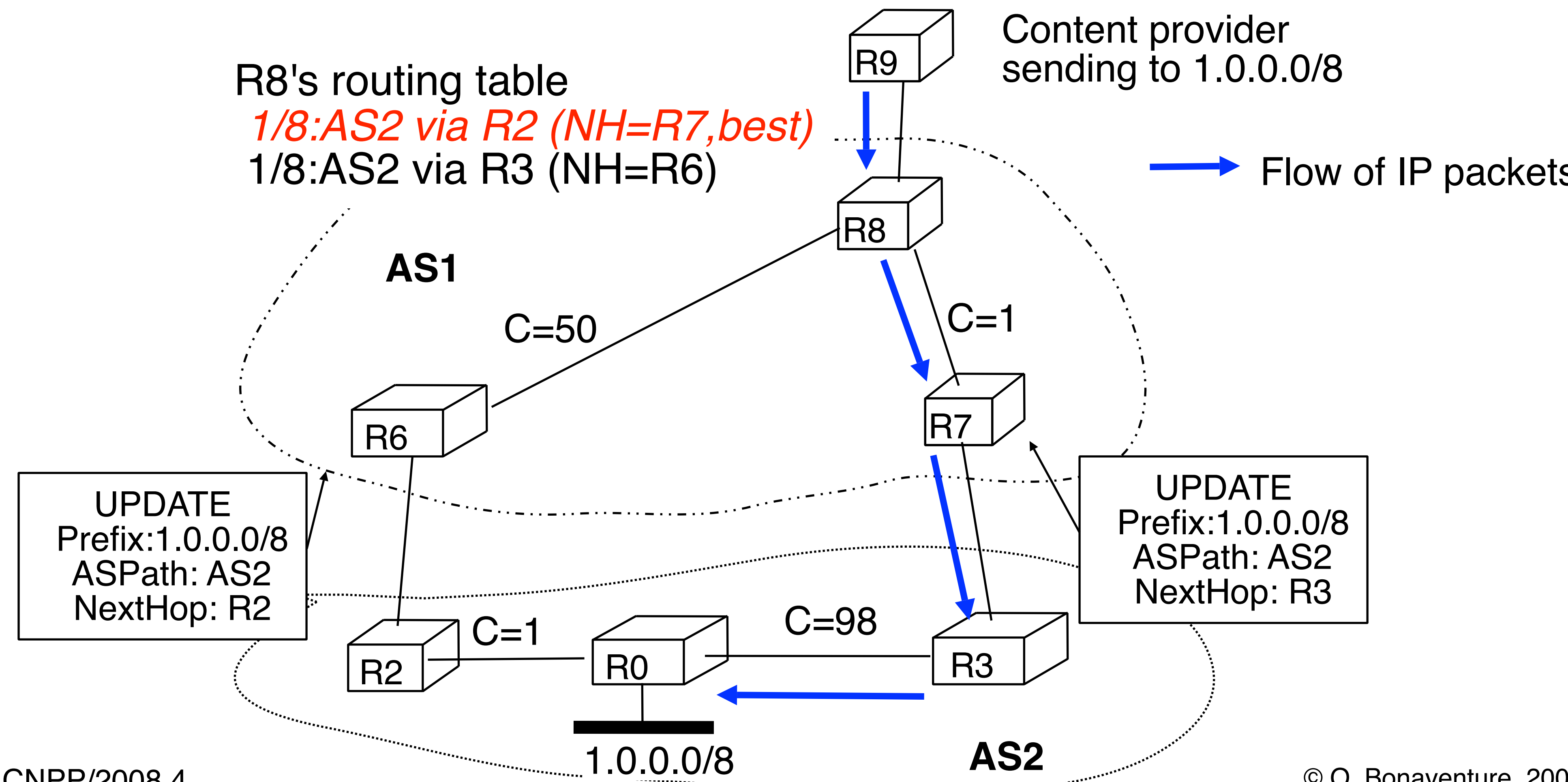
A router should try to get rid of packets sent to external domains as soon as possible



The closest `nexthop` step in the BGP decision process

Motivation : hot potato routing

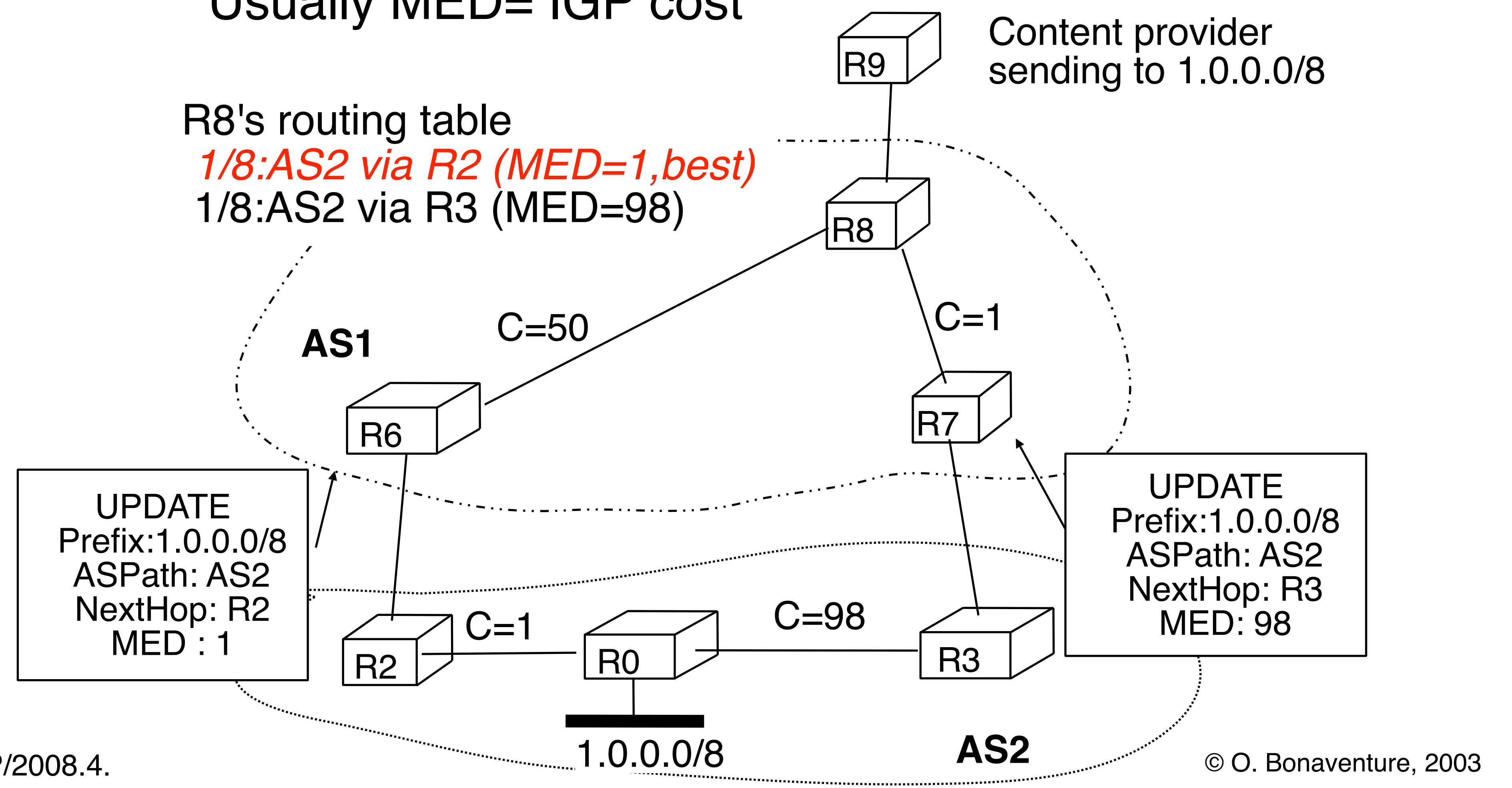
A router should try to get rid of packets sent to external domains as soon as possible



The lowest MED step in the BGP decision process

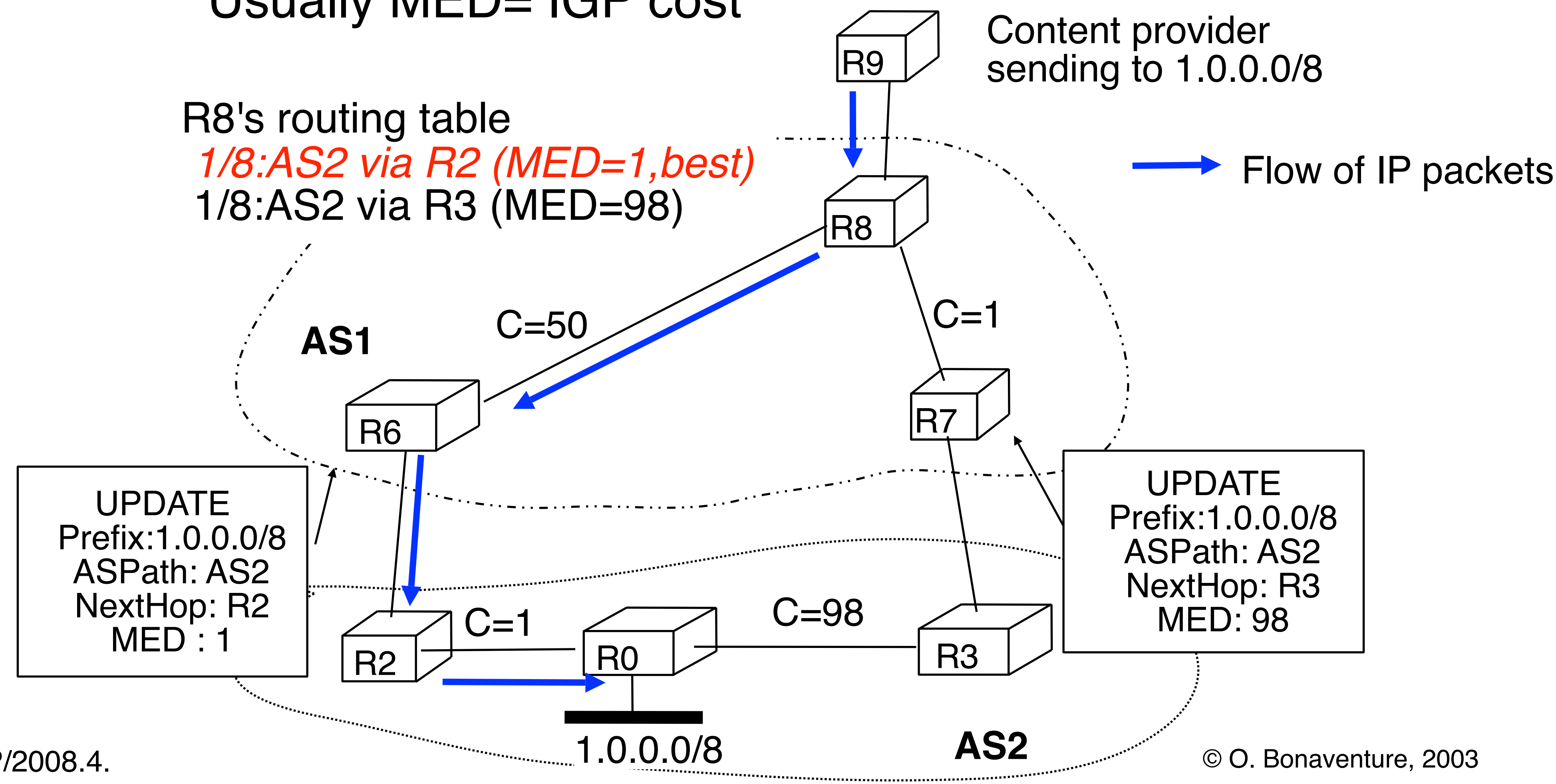
Motivation : cold potato routing

- In a multi-connected AS, indicate which entry border router is closest to the advertised prefix
  - Usually MED= IGP cost



The lowest `MED` step in the BGP decision process

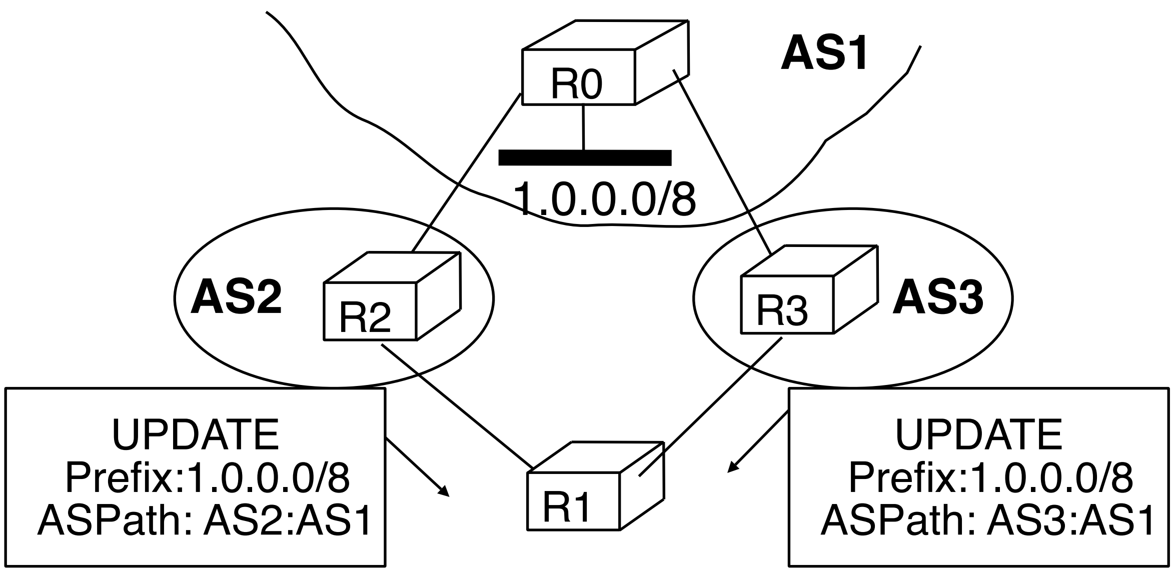
- Motivation : cold potato routing
  - In a multi-connected AS, indicate which entry border router is closest to the advertised prefix
    - Usually MED= IGP cost



The lowest router id step in the BGP decision process

Motivation

- A router must be able to determine *one* best route towards each destination prefix
  - A router may receive several routes with comparable attributes towards one destination



Consequence

- A router with a low IP address will be preferred

Allocation of IP addresses

- How to allocate IP addresses
- First solution
  - Objective : Ensure that IP addresses are unique
  - Rule used by registries
    - Any organisation can be allocated a unique IP subnet on a FCFS basis
  - Size of the allocated subnet : three classes
    - Class A : subnet with 8 bits mask
    - Class B : subnet with 16 bits mask
    - Class C : subnet with 24 bits mask
  - Drawbacks
    - Too rigid
      - Class A is too large for most networks and Class C too small
        - address waste !
    - Difficult to aggregate prefixes

Allocation of IP addresses (2)

CIDR

Goals

1. Ensure that IP addresses are unique
2. Allow BGP routers to advertise aggregated prefixes

Rules used by registries

- Only Internet Service Providers (and large companies) can obtain IP subnets
  - Size of allocated subnet is function of current and expected number of customers
- An organisation willing to be connected to the Internet must obtain IP addresses from its ISP

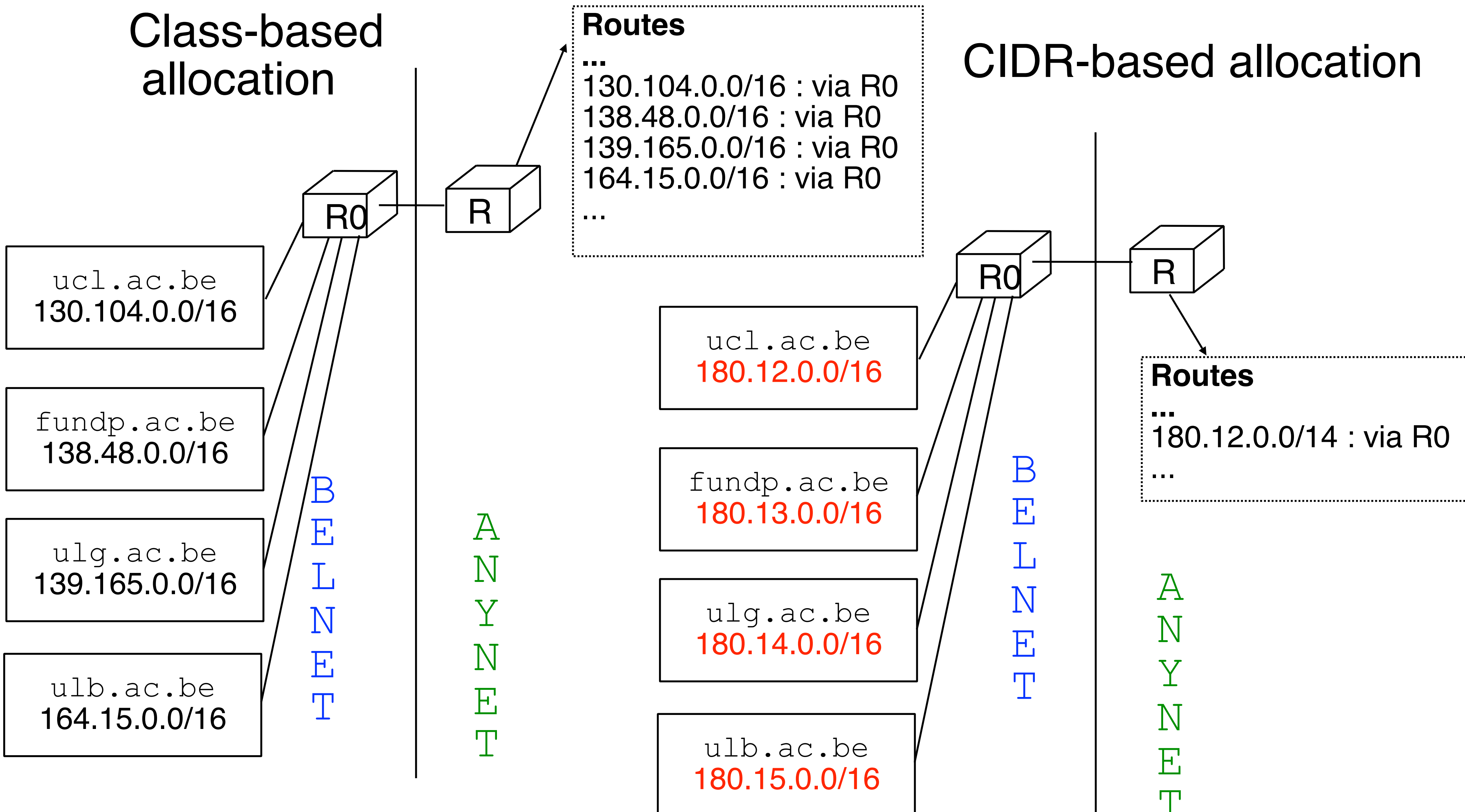
Advantage

- Improved aggregation of addresses

Drawback

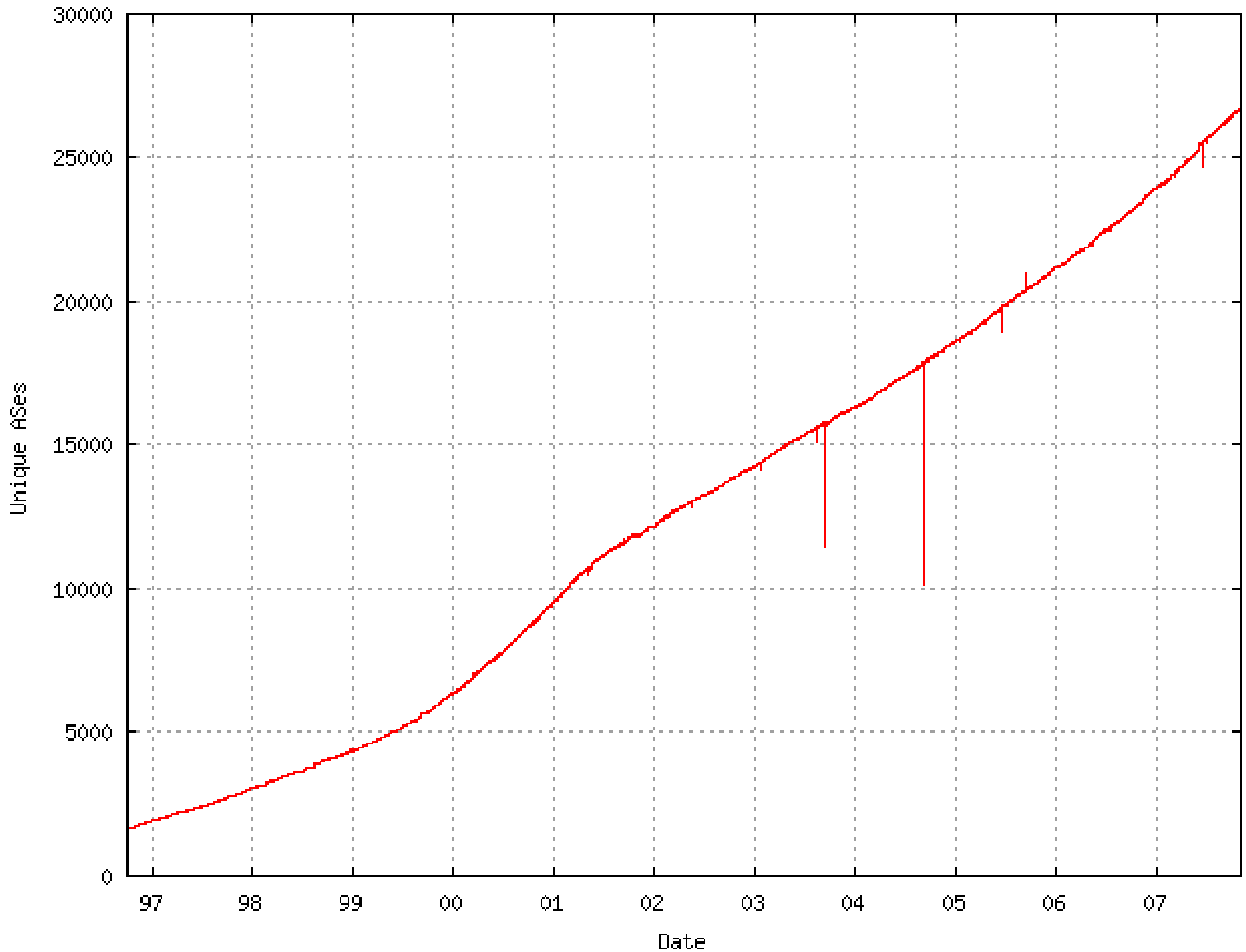
- If a company switches from one provider to another, it will need to renumber its IP network - a real pain !

Allocation of IP addresses (3)



Internet evolution

Number of Autonomous Systems

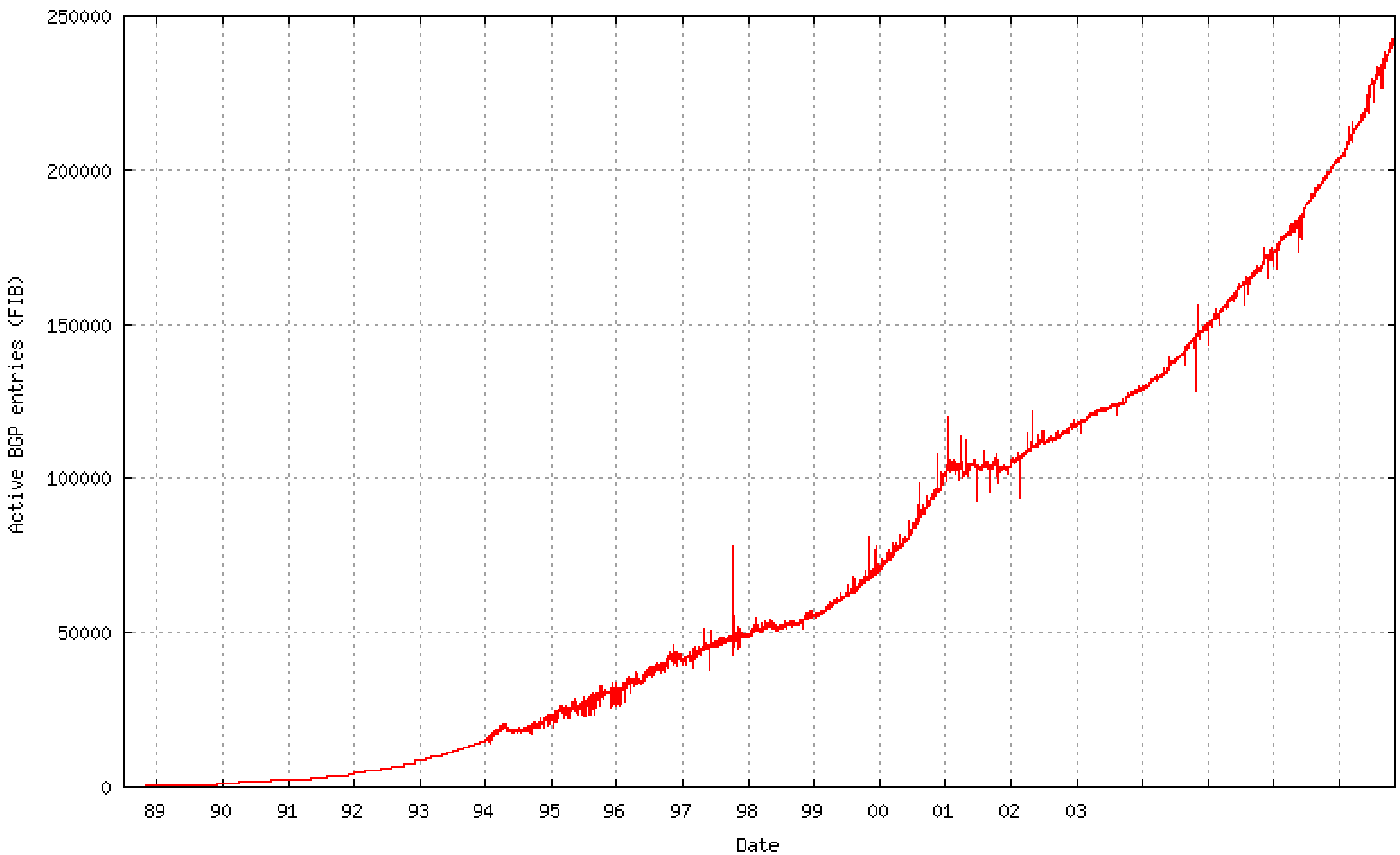


Source : http://bgp.potaroo.net

Internet evolution (2)

Size of the BGP routing tables

Number of IPv4 prefixes in default-free routers



Source : http://bgp.potaroo.net

Internet evolution (2)

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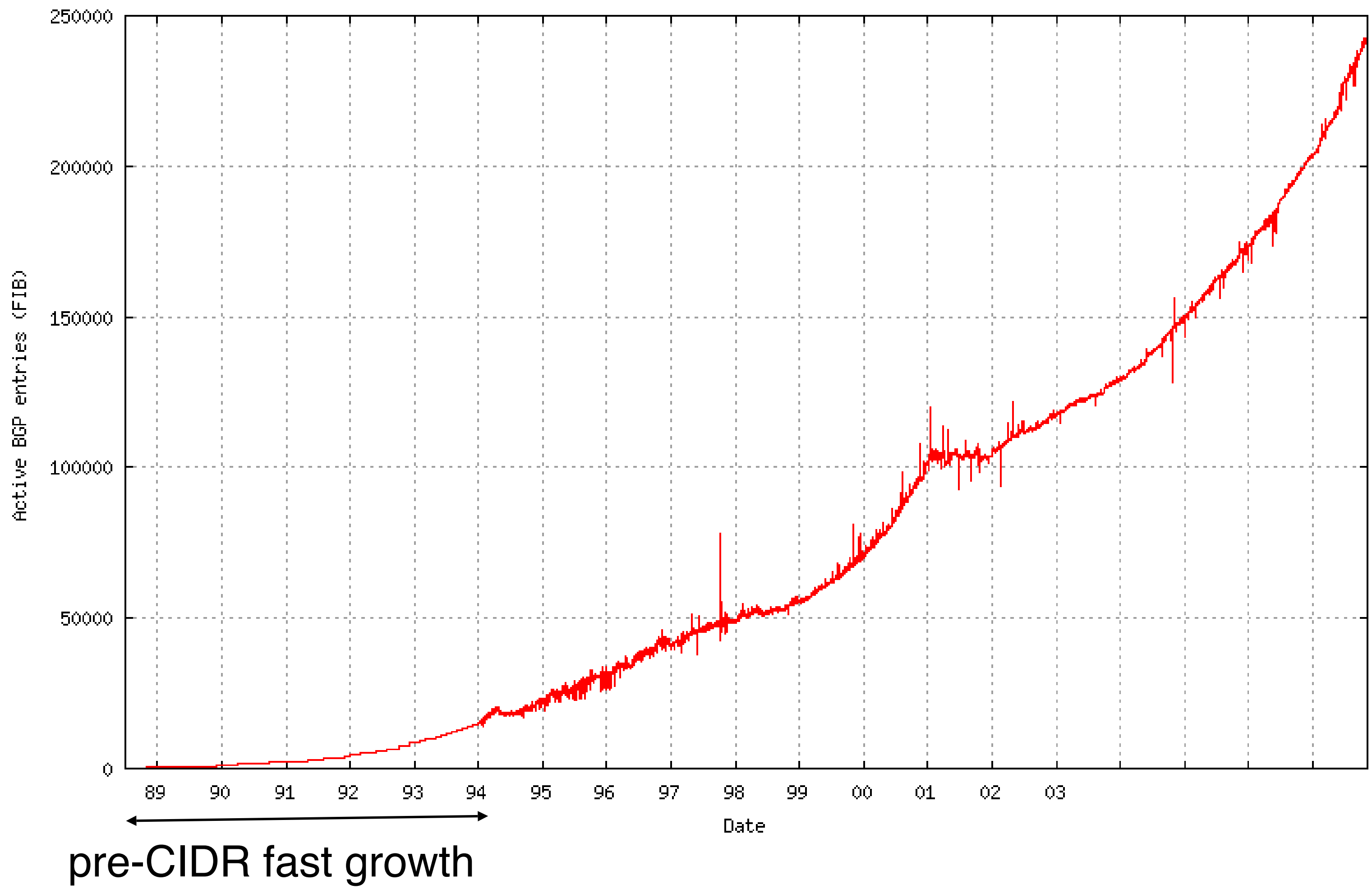

Source : http://bgp.potaroo.net

Internet evolution (2)

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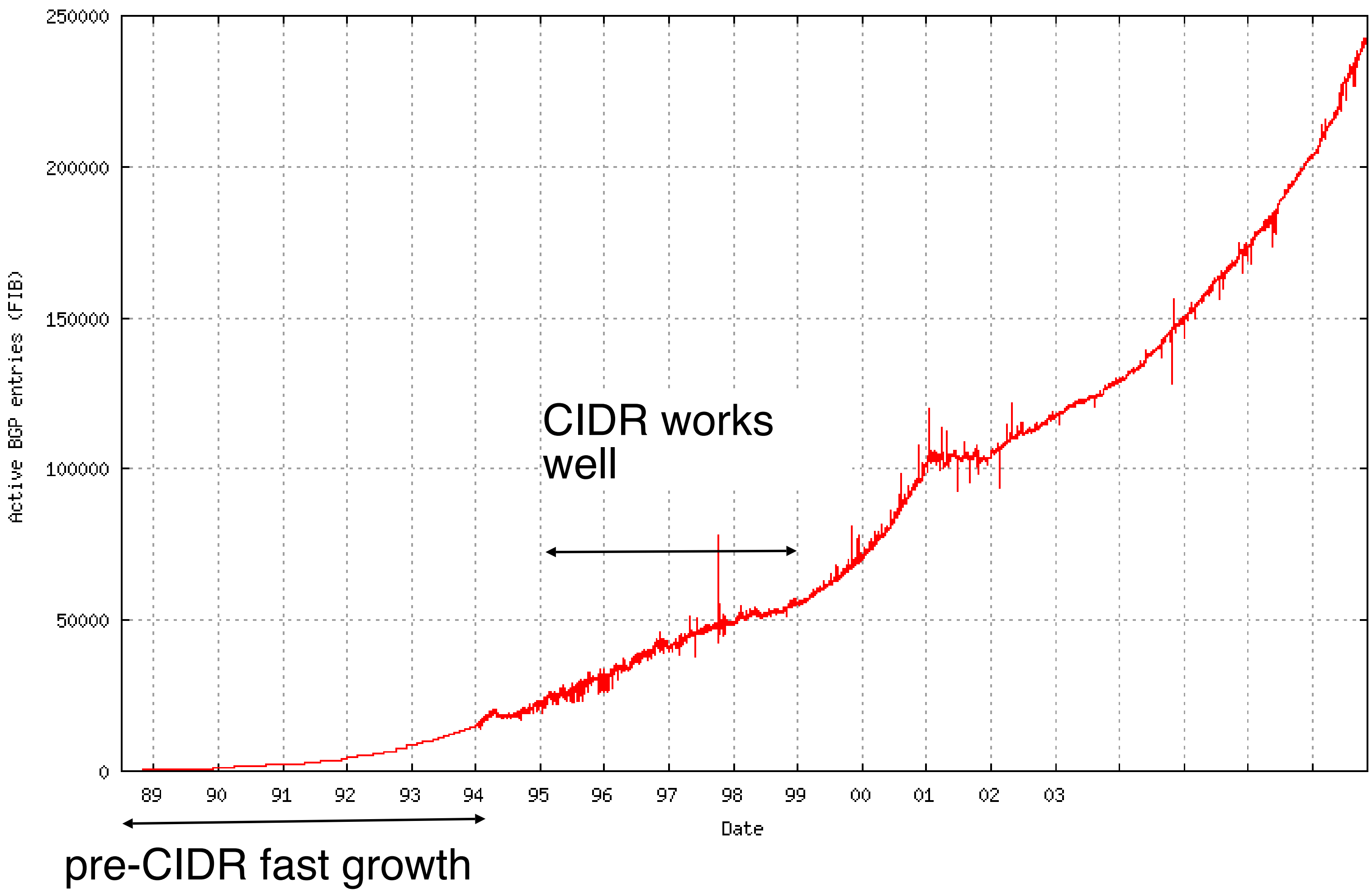

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Internet evolution (2)

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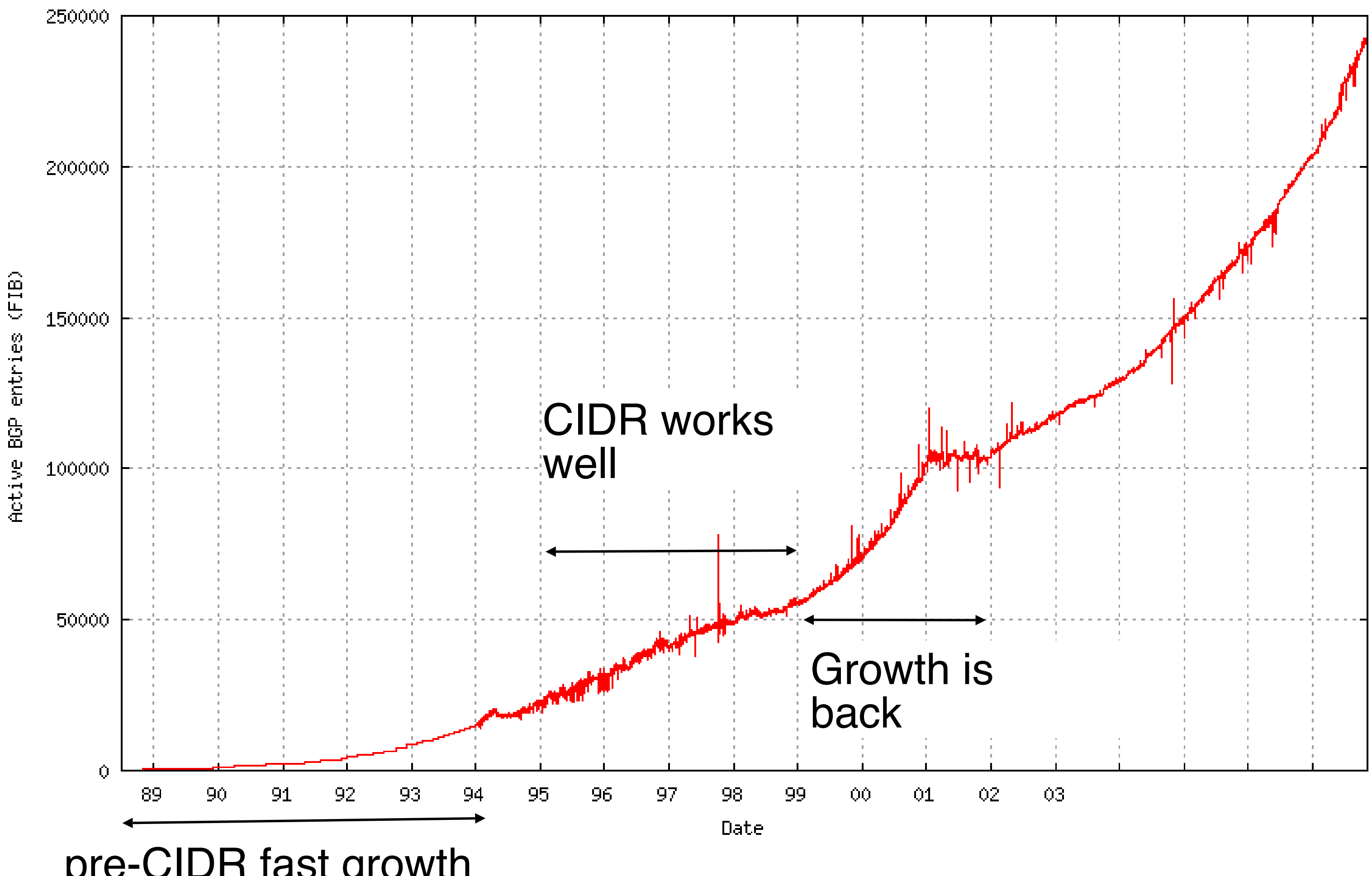

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Internet evolution (2)

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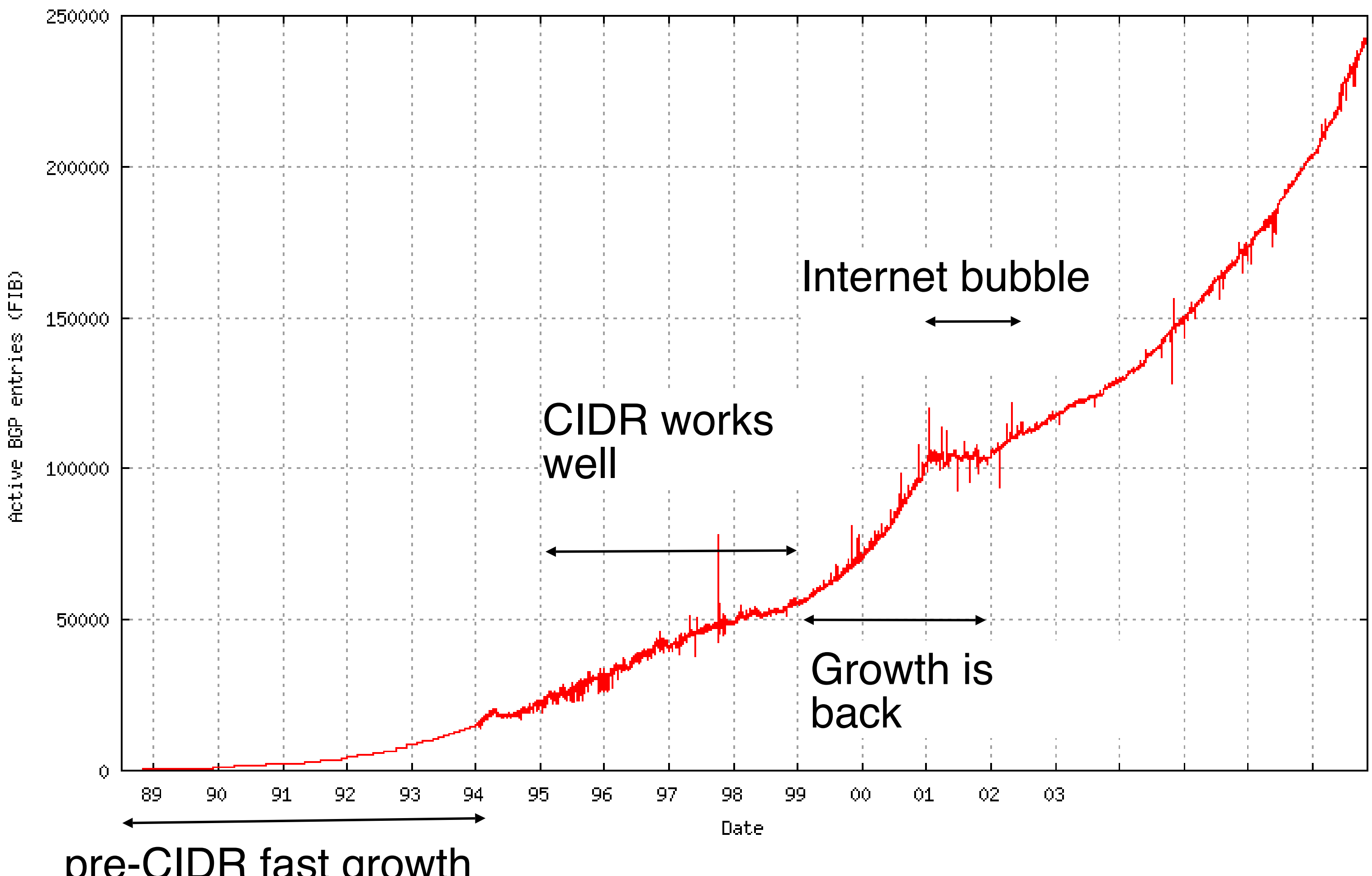

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Internet evolution (2)

Size of the BGP routing tables

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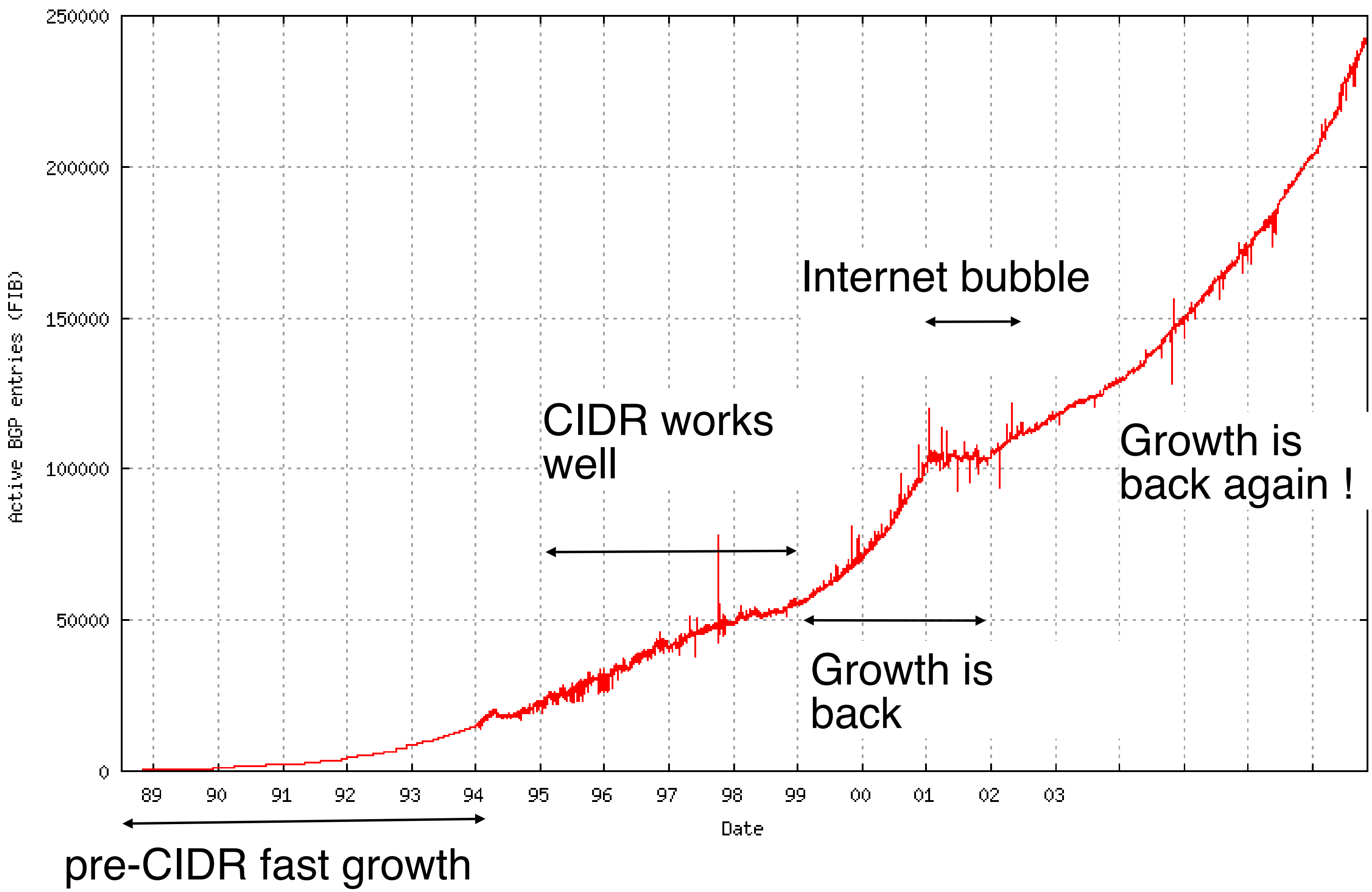

Source : http://bgp.potaroo.net