

The background features a vibrant, abstract design with overlapping, wavy bands of color in shades of red, orange, yellow, green, and blue, creating a sense of motion and energy. A bright, multi-colored sunburst or starburst pattern emanates from the right side, adding to the dynamic feel.

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Let's go

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The bridge to possible

Border Gateway Protocol Fundamentals

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Cisco Webex App

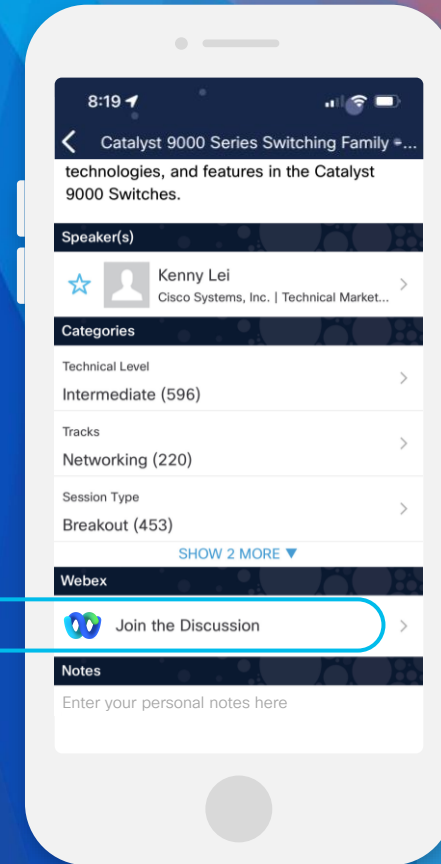
Questions?

Use Cisco Webex App to chat with the speaker after the session

How

- 1 Find this session in the Cisco Live Mobile App
- 2 Click “Join the Discussion”
- 3 Install the Webex App or go directly to the Webex space
- 4 Enter messages/questions in the Webex space

Webex spaces will be moderated by the speaker until June 9, 2023.



<https://ciscolive.ciscoevents.com/ciscolivebot/#BRKENT-1179>

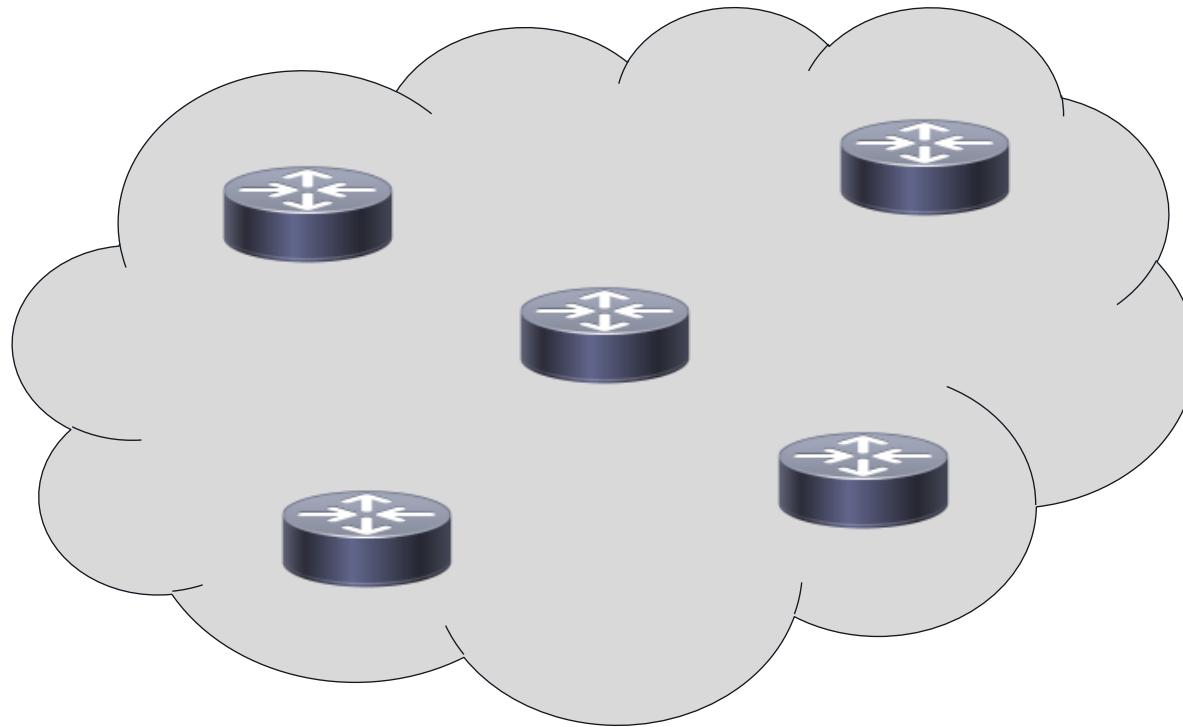
Agenda

- Why BGP?
- Messages and States
- Attributes
- Internal vs External BGP
- Best Path Selection Algorithm
- Policy Control and Traffic Engineering

Why BGP?

Autonomous System

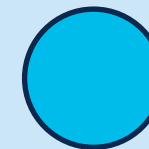
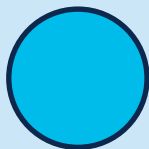
A group of one or more IP prefixes (lists of IP addresses accessible on a network) run by one or more network operators that maintain a single, clearly-defined routing policy.



BGP 2-byte ASN

RFC1105 (1989)

- Created to address 2-byte ASN depletion
- Interoperable with 2-byte ASNs (range includes 2-byte ASNs)
- 32-bit number
- 0 to 4294967295
- Additional private range 4200000000 to 4294967294



- 16-bit number
- 0 to 65535
- Private range 64512 to 65534

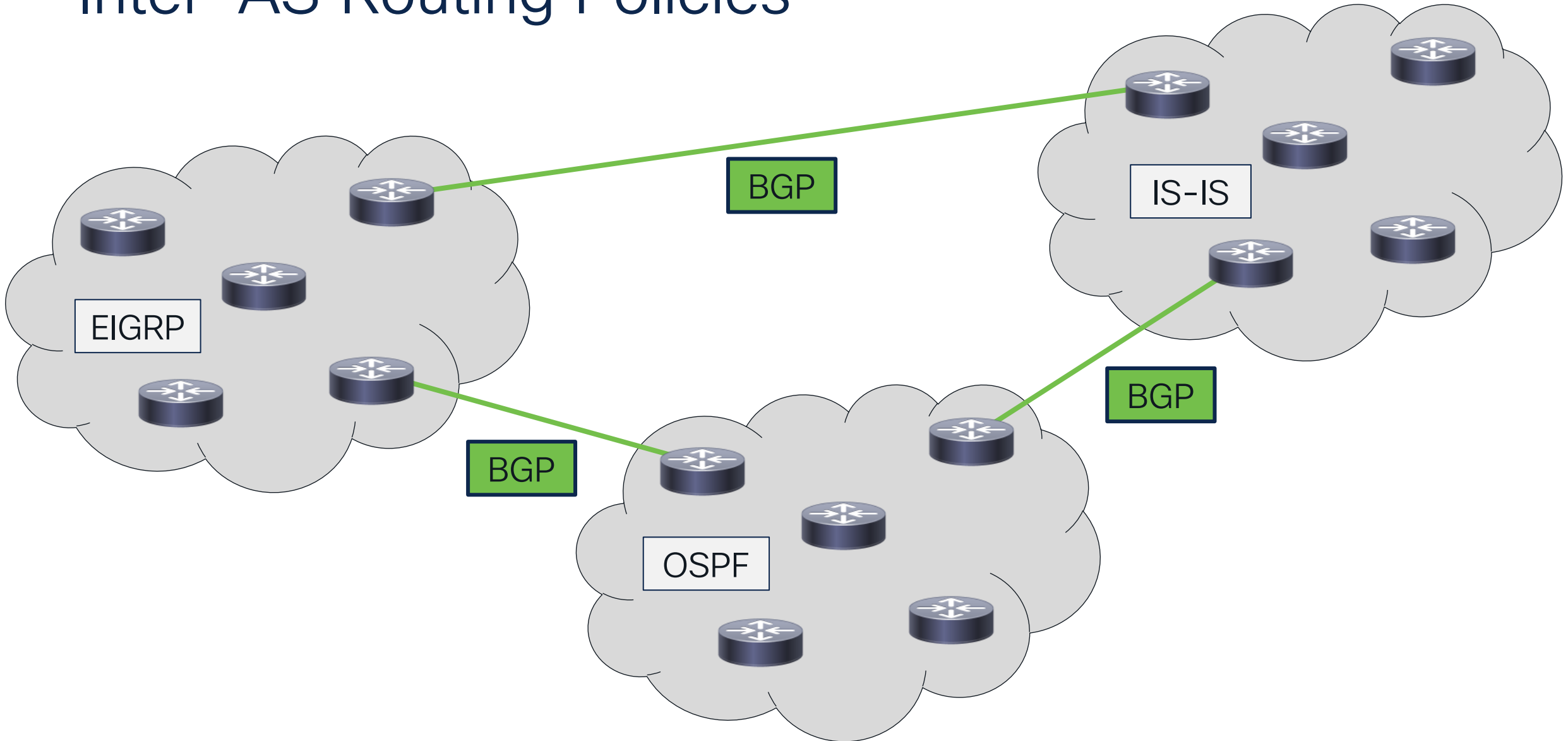
BGP 4-byte ASN

RFC4893 (2007)

Border Gateway Protocol

- Border Gateway Protocol
 - Large scale, robust and stable routing protocol designed to operate between autonomous systems
 - Based on TCP, listens on port 179
 - Fundamentally a distance vector protocol
 - Does not have the concept of a simple metric
 - Instead, uses multiple characteristics called attributes
 - Allows for strong control over advertised routes and their attributes
 - Assumes that the routing inside the autonomous system is already fully taken care of by an IGP (EIGRP, OSPF, IS-IS)

Inter-AS Routing Policies



Route Scale & Control Plane Stability

```
route-views> show bgp ipv4 unicast summary | ex never|Active|Idl
BGP router identifier 128.223.51.103, local AS number 6447
BGP table version is 2813468887, main routing table version 2813468887
Path RPKI states: 7708169 valid, 10262796 not found, 14390 invalid
962240 network entries using 238635520 bytes of memory

<Output omitted...>

BGP using 3360540172 total bytes of memory
BGP activity 71481761/70340753 prefixes, 3122764440/3095983216 paths, scan interval 60 secs

Neighbor      V      AS MsgRcvd MsgSent   TblVer  InQ OutQ Up/Down  State/PfxRcd
4.68.4.46     4      3356 5325851   83510 2813468729    12    0 3w5d      905347
12.0.1.63     4      7018 5117677   19250 2813468729   124    0 1w5d      906235

<Output omitted...>
```

BGP Stability Considerations

- Events in networks often occur in bursts
- There is always a challenge how to react
 - Reacting fast improves convergence time but may introduce churn
 - Reacting with a delay improves stability but delays convergence
- BGP favors stability
 - It delays sending updates to smoothen out the churn and to collect possibly multiple changes for a single update
 - It only advertises changes (incremental updates)

Route Scale & Control Plane Stability

```
R1# show bgp ipv4 unicast neighbors 10.1.1.2
```

```
BGP neighbor is 10.1.1.2, remote AS 65500, external link
```

```
BGP version 4, remote router ID 10.1.1.2
```

```
BGP state = Established, up for 00:48:19
```

```
Last read 00:00:14, last write 00:00:03, hold time is 180, keepalive interval is 60  
seconds
```

```
<Output omitted>
```

```
Default minimum time between advertisement runs is 30 seconds
```

```
<Output omitted>
```

Network Layer Reachability Information Exchange

Prefix/Length

```
R1(config)# router bgp 64512
R1(config-router)# address-family ?
  ipv4      Address family
  ipv6      Address family
  l2vpn     Address family
  nsap      Address family
  vpnv4     Address family
  vpnv6     Address family
```

```
route-views> show bgp all neighbors 4.68.4.46 | i family
For address family: IPv4 Unicast
  Address family IPv4 Unicast: advertised and received
  Address family IPv4 Multicast: advertised and received
For address family: IPv6 Unicast
For address family: IPv4 Multicast
  Address family IPv4 Unicast: advertised and received
  Address family IPv4 Multicast: advertised and received
For address family: L2VPN E-VPN
For address family: MVPNv4 Unicast
```

Messages

BGP Message Types

- BGP runs on top of TCP transport layer protocol which is...
 - Byte stream-oriented
 - Unicast only
 - Connection-oriented and reliable
 - Providing flow and congestion control
- The format of BGP messages partly accommodates TCP specifics
 - Message markers
 - Length indications (lots of!)

BGP Message Types

- BGPv4 uses (only) 5 message types
 - OPEN
 - UPDATE
 - NOTIFICATION
 - KEEPALIVE
 - ROUTE-REFRESH (not part of initial BGPv4 RFC 1654 specification, brought in through RFC 2918 and nearly universally supported)

BGP OPEN Message

- BGP speakers use OPEN to advertise their configuration and capabilities once their TCP session comes up
 - Version advertisement
 - Autonomous System Number advertisement
 - Hold Time advertisement/negotiation
 - BGP Router ID advertisement
 - Optional Capabilities advertisement/negotiation
- If the peer advertises an incompatible configuration, the peering is terminated, and the TCP session closed

BGP OPEN Message

Border Gateway Protocol - OPEN Message

Marker: ff

Length: 57

Type: OPEN Message (1)

Version: 4

My AS: 64512

Hold Time: 180

BGP Identifier: 10.255.255.1

Optional Parameters Length: 28

- Optional Parameters

▸ Optional Parameter: Capability

▸ Optional Parameter: Capability

▸ Optional Parameter: Capability

▸ Optional Parameter: Capability

- Optional Parameter: Capability

Parameter Type: Capability (2)

Parameter Length: 6

▸ Capability: Support for 4-octet AS number capability



Select BGP Capability Codes for OPEN Message

<https://www.iana.org/assignments/capability-codes/capability-codes.xhtml#capability-codes-2>

Value	Name	RFC
1	Multiprotocol Extensions for BGP-4	2858
2	Route Refresh Capability for BGP-4	2918
3	Outbound Route Filtering Capability	5291
5	Extended Next Hop Encoding	8950
6	BGP Extended Message	8654
7	BGPsec Capability	8205
8	Multiple Labels Capability	8277
9	BGP Role	9234
64	Graceful Restart Capability	4724
65	Support for 4-octet AS number capability	6793
69	ADD-PATH Capability	7911
70	Enhanced Route Refresh Capability	7313

BGP NOTIFICATION Message

- The NOTIFICATION message is sent out by a peer who detected an unrecoverable condition and needs to terminate the peering
- After sending out a NOTIFICATION, the sender closes the session
- The NOTIFICATION contents are useful for diagnostics

Border Gateway Protocol - NOTIFICATION Message

Marker: ff

Length: 21

Type: NOTIFICATION Message (3)

Major error Code: Cease (6)

Minor error Code (Cease): Administratively Shutdown (2)



Select BGP Error Codes for NOTIFICATION

<https://www.iana.org/assignments/bgp-parameters/bgp-parameters.xhtml#bgp-parameters-3>

Value	Name	RFC
1	Message Header Error	4271
2	OPEN Message Error	4271
3	UPDATE Message Error	4271
4	Hold Timer Expired	4271
5	Finite State Machine Error	4271
6	Cease	4271
7	ROUTE-REFRESH Message Error	7313



Select BGP Error Subcodes

<https://www.iana.org/assignments/bgp-parameters/bgp-parameters.xhtml#bgp-parameters-3>

Message Header Error Subcodes		
Value	Name	RFC
0	Unspecific	EID 4493
1	Connection Not Synchronized	4271
2	Bad Message Length	4271
3	Bad Message Type	4271

OPEN Message Error Subcodes		
Value	Name	RFC
0	Unspecific	EID 4493
1	Unsupported Version Number	4271
2	Bad Peer AS	4271
3	Bad BGP Identifier	4271
4	Unsupported Optional Parameter	4271
6	Unacceptable Hold Time	4271
7	Unsupported Capability	4271
11	Role Mismatch	9234



Select BGP Error Subcodes

<https://www.iana.org/assignments/bgp-parameters/bgp-parameters.xhtml#bgp-parameters-3>

UPDATE Message Error Subcodes		
Value	Name	RFC
0	Unspecific	EID 4493
1	Malformed Attribute List	4271
2	Unrecognized Well-known Attribute	4271
3	Missing Well-known Attribute	4271
4	Attribute Flags Error	4271
5	Attribute Length Error	4271
6	Invalid ORIGIN Attribute	4271
8	Invalid NEXT_HOP Attribute	4271
9	Optional Attribute Error	4271
10	Invalid Network Field	4271
11	Malformed AS_PATH Attribute	4271

Finite State Machine Error Subcodes		
Value	Name	RFC
0	Unspecified Error	6608
1	Receive Unexpected Message in OpenSent State	6608
2	Receive Unexpected Message in OpenCofirm State	6608
3	Receive Unexpected Message in Established State	6608



Select BGP Error Subcodes

<https://www.iana.org/assignments/bgp-parameters/bgp-parameters.xhtml#bgp-parameters-3>

Cease Subcodes		
Value	Name	RFC
1	Max Number of Prefixes Reached	4486
2	Administrative Shutdown	4486
3	Peer De-configured	4486
4	Administrative Reset	4486
5	Connection Rejected	4486
6	Other Configuration Change	4486
7	Connection Collision Resolution	4486
8	Out of Resources	4486
9	Hard Reset	8538
10	BFD Down	9384

ROUTE-REFRESH Message Error Subcodes		
Value	Name	RFC
0	Reserved	7313
1	Invalid Message Length	7313

BGP KEEPALIVE Message

- Instead of relying on TCP keepalives, BGP uses the KEEPALIVE message to periodically announce a speaker's liveness
- KEEPALIVE is sent...
 - Immediately after receiving an agreeable OPEN message from peer
 - Periodically, with the period being one third of Hold Time by default

Border Gateway Protocol - KEEPALIVE Message

Marker: ff

Length: 19

Type: KEEPALIVE Message (4)

BGP ROUTE-REFRESH Message

- Original BGP specification did not specify means to ask a peer to resend prefixes to us
 - This is necessary when the inbound route policy changes
 - Vendors worked around this deficiency by storing aside a separate unfiltered copy of all routes from the peer (“Soft Reconfiguration”)
- RFC 2918 brought the ROUTE-REFRESH message allowing to ask a peer to resend all routes of any particular address family

Border Gateway Protocol - ROUTE-REFRESH Message

Marker: ff

Length: 23

Type: ROUTE-REFRESH Message (5)

Address family identifier (AFI): IPv4 (1)

Subtype: Normal route refresh request [RFC2918] with/without ORF [RFC5291] (0)

Subsequent address family identifier (SAFI): Unicast (1)

BGP UPDATE Message

- The UPDATE message is the workhorse of BGP
 - Advertises reachable NLRI's along with their attributes
 - Withdraws unreachable NLRI's
- The format of the UPDATE message targets maximum efficiency
 - The path attributes are included only once, followed by the list of all NLRI's that share them
 - Every NLRI contains only the network prefix (and padding bits to a whole octet if needed)

BGP Update Message – New/Updated Routes

Border Gateway Protocol - UPDATE Message

Marker: ffffffffffffffffffffffffffffffffff

Length: 67

Type: UPDATE Message (2)

Withdrawn Routes Length: 0

Total Path Attribute Length: 28

- Path attributes

▸ Path Attribute - ORIGIN: IGP

▸ Path Attribute - AS_PATH: empty

▸ Path Attribute - NEXT_HOP: 10.255.255.1

▸ Path Attribute - MULTI_EXIT_DISC: 1234

▸ Path Attribute - LOCAL_PREF: 100

- Network Layer Reachability Information (NLRI)

▸ 192.168.0.0/24

▸ 192.168.1.0/24

▸ 192.168.2.0/24

▸ 192.168.3.0/24

BGP Update Message – Withdrawn Routes

```
Border Gateway Protocol - UPDATE Message
Marker: ffffffffffffffffffffffffffffffffffffffff
Length: 27
Type: UPDATE Message (2)
Withdrawn Routes Length: 4
- Withdrawn Routes
  ▸ 192.168.3.0/24
Total Path Attribute Length: 0
```


States

Active, Idle, Connect

1174	17:39:50.701103	10.1.1.2	10.1.1.1	TCP	60	52565 → 179	[SYN] Seq=0 Win=16384
1175	17:39:50.724304	10.1.1.1	10.1.1.2	TCP	60	179 → 52565	[SYN, ACK] Seq=0 Ack=
1176	17:39:50.761402	10.1.1.2	10.1.1.1	TCP	60	52565 → 179	[ACK] Seq=1 Ack=1 Win=16384
> Frame 1174: 60 bytes on wire (480 bits), 60 bytes captured (480 bits) on interface -, id 0							
> Ethernet II, Src: ca:02:9f:44:00:00 (ca:02:9f:44:00:00), Dst: ca:01:5f:3a:00:00 (ca:01:5f:3a:00:00)							
> Internet Protocol Version 4, Src: 10.1.1.2, Dst: 10.1.1.1							
✓ Transmission Control Protocol, Src Port: 52565, Dst Port: 179, Seq: 0, Len: 0							
Source Port: 52565							
Destination Port: 179							
[Stream index: 4]							
[Conversation completeness: Incomplete, DATA (15)]							
[TCP Segment Len: 0]							
Sequence Number: 0 (relative sequence number)							
Sequence Number (raw): 3742606240							
[Next Sequence Number: 1 (relative sequence number)]							
Acknowledgment Number: 0							
Acknowledgment number (raw): 0							
0110 = Header Length: 24 bytes (6)							
> Flags: 0x002 (SYN)							
Window: 16384							
[Calculated window size: 16384]							
Checksum: 0xf164 [unverified]							
[Checksum Status: Unverified]							
Urgent Pointer: 0							
> Options: (4 bytes), Maximum segment size							
> [Timestamps]							

Open Sent & Open Confirmed

1177	17:39:50.792164	10.1.1.2	10.1.1.1	BGP	112	OPEN Message
1178	17:39:50.815234	10.1.1.1	10.1.1.2	BGP	112	OPEN Message
1179	17:39:50.815297	10.1.1.1	10.1.1.2	BGP	73	KEEPALIVE Message
1180	17:39:50.873147	10.1.1.2	10.1.1.1	BGP	73	KEEPALIVE Message

- > Frame 1177: 112 bytes on wire (896 bits), 112 bytes captured (896 bits) on interface -, id 0
- > Ethernet II, Src: ca:02:9f:44:00:00 (ca:02:9f:44:00:00), Dst: ca:01:5f:3a:00:00 (ca:01:5f:3a:00:00)
- > Internet Protocol Version 4, Src: 10.1.1.2, Dst: 10.1.1.1
- > Transmission Control Protocol, Src Port: 52565, Dst Port: 179, Seq: 1, Ack: 1, Len: 58
- ✓ Border Gateway Protocol – OPEN Message
 - Marker: ffffffffffffffffffffffffffffffffff
 - Length: 58
 - Type: OPEN Message (1)
 - Version: 4
 - My AS: 65500
 - Hold Time: 180
 - BGP Identifier: 10.1.1.2
 - Optional Parameters Length: 29
 - ✓ Optional Parameters
 - ✓ Optional Parameter: Capability
 - Parameter Type: Capability (2)
 - Parameter Length: 6
 - > Capability: Multiprotocol extensions capability
 - ✓ Optional Parameter: Capability
 - Parameter Type: Capability (2)
 - Parameter Length: 2
 - > Capability: Route refresh capability (Cisco)
 - ✓ Optional Parameter: Capability
 - Parameter Type: Capability (2)
 - Parameter Length: 2
 - > Capability: Route refresh capability

Established

```
R1# show bgp ipv4 unicast summary
```

```
BGP router identifier 10.1.1.1, local AS number 64512
```

```
BGP table version is 1, main routing table version 1
```

Neighbor	V	AS	MsgRcvd	MsgSent	TblVer	InQ	OutQ	Up/Down	State/PfxRcd
10.1.1.2	4	65500	15	15	1	0	0	00:10:49	0

Attributes

BGP Attributes

- An attribute is an additional piece of information accompanying an advertised NLRI
- BGP uses attributes in multiple ways
 - Prevents routing loops
 - Performs best path selection
 - Filters or sorts routes
 - ... and many more
- Basic BGP specification recognizes only a handful of attributes
 - Several new have been added over time for various applications and uses

BGP Attribute Types

- **Well-known:** Every BGP implementation must support it
 - **Well-known** mandatory: Must always be included with a NLRI
 - **Well-known** discretionary: May be included with a NLRI as needed
- **Optional:** BGP implementations do not need to support it
 - **Optional** transitive: When advertising a learned NLRI, keep the attribute with the NLRI even if not recognized
 - **Optional** non-transitive: When advertising a learned NLRI, remove the attribute from the NLRI if not recognized

Note: All well-known attributes are transitive

BGP Attributes

- Well-known mandatory:

- AS_PATH
- NEXT_HOP
- ORIGIN

- Well-known discretionary

- LOCAL_PREF
- ATOMIC_AGGREGATE

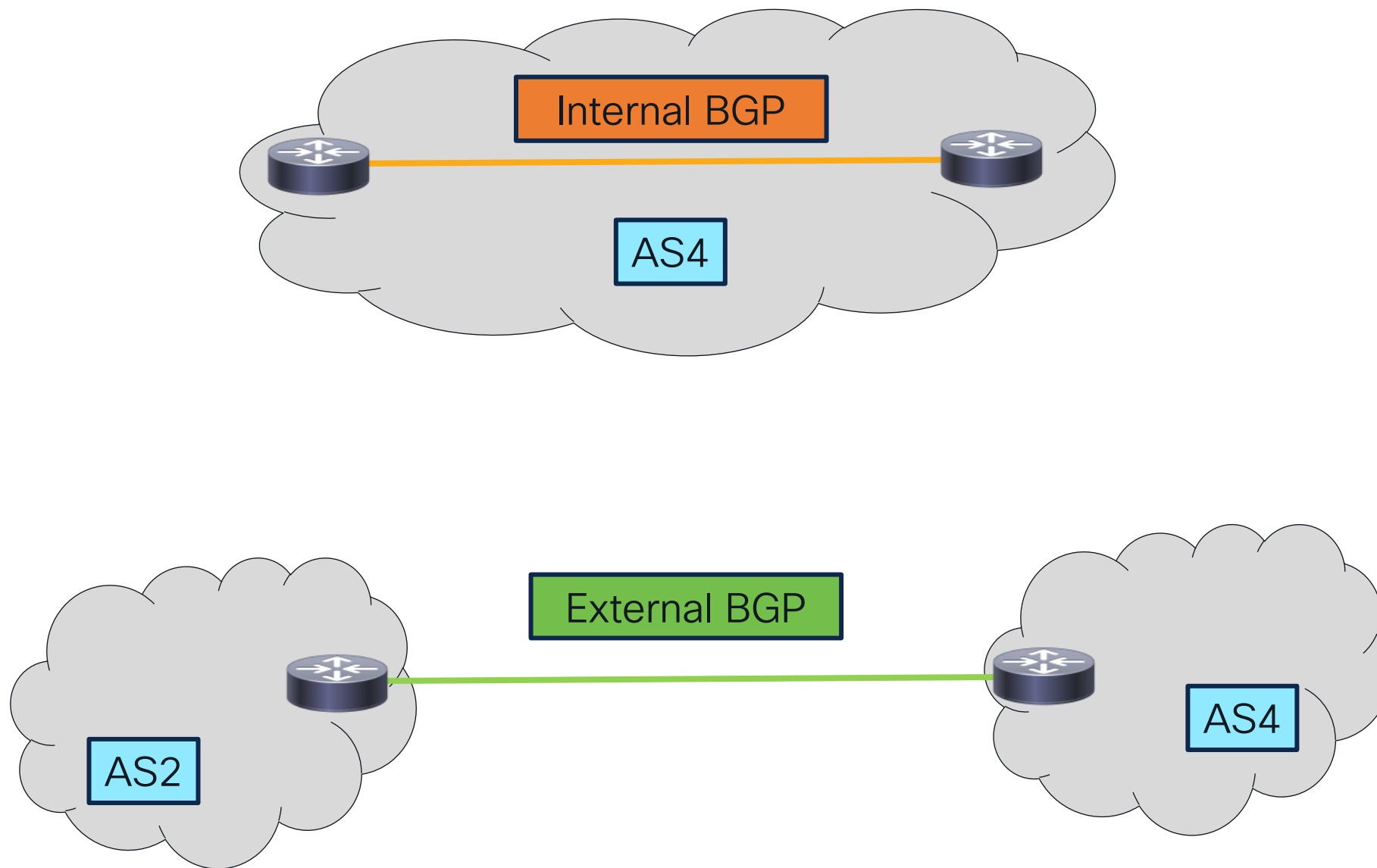
- Optional transitive

- AGGREGATOR
- COMMUNITIES
- EXTENDED_COMMUNITIES

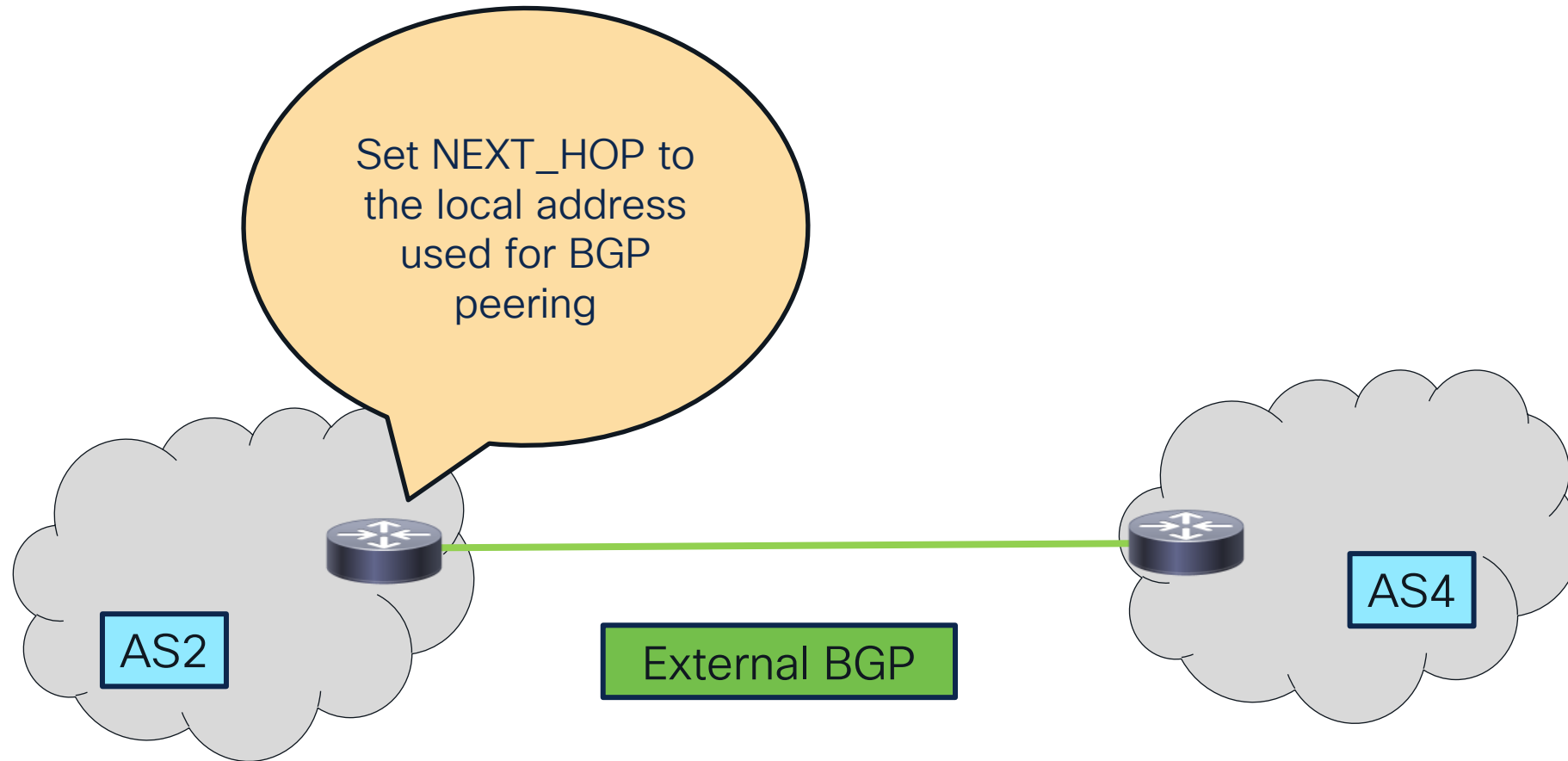
- Optional non-transitive

- MULTI_EXIT_DISC
- CLUSTER_LIST

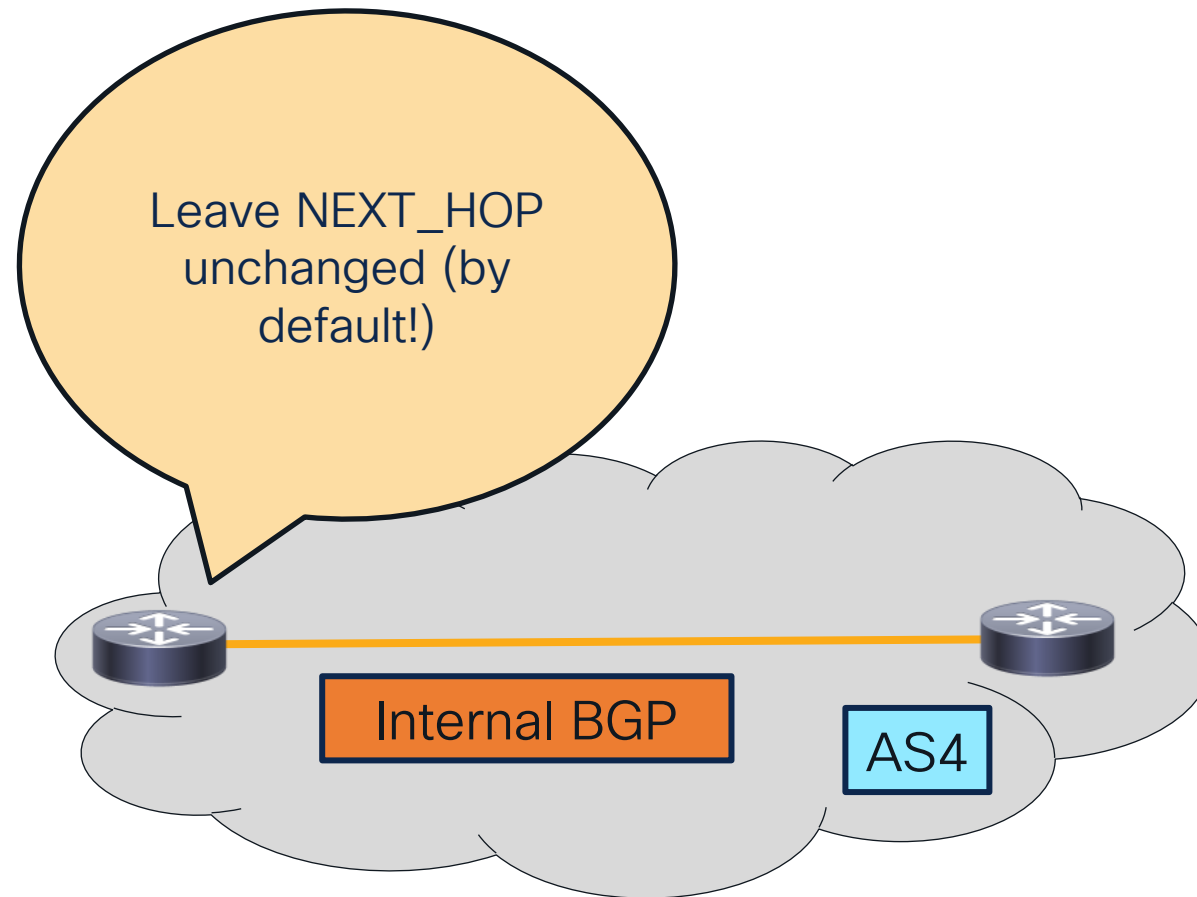
Internal vs External BGP



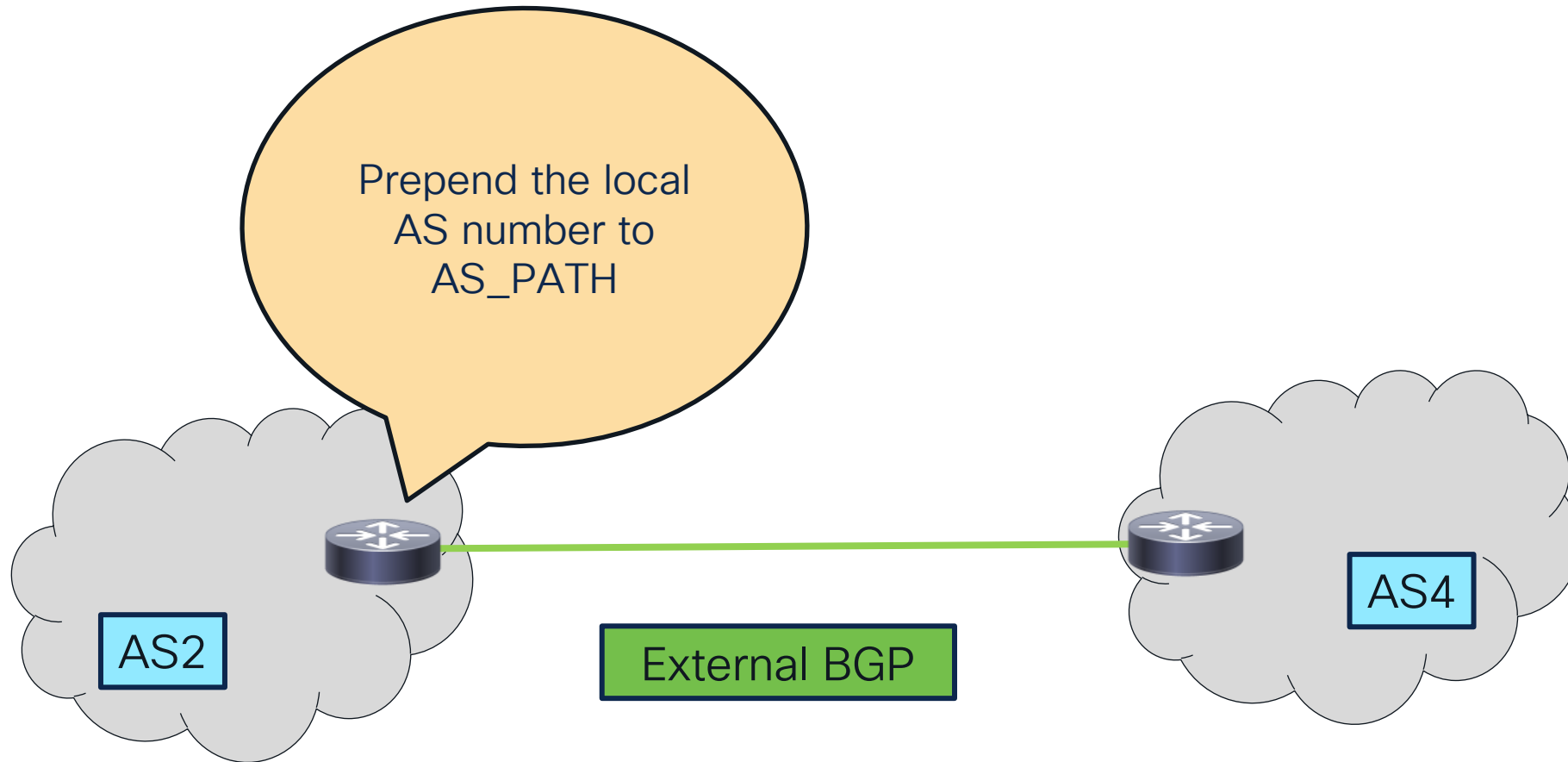
NEXT_HOP in eBGP



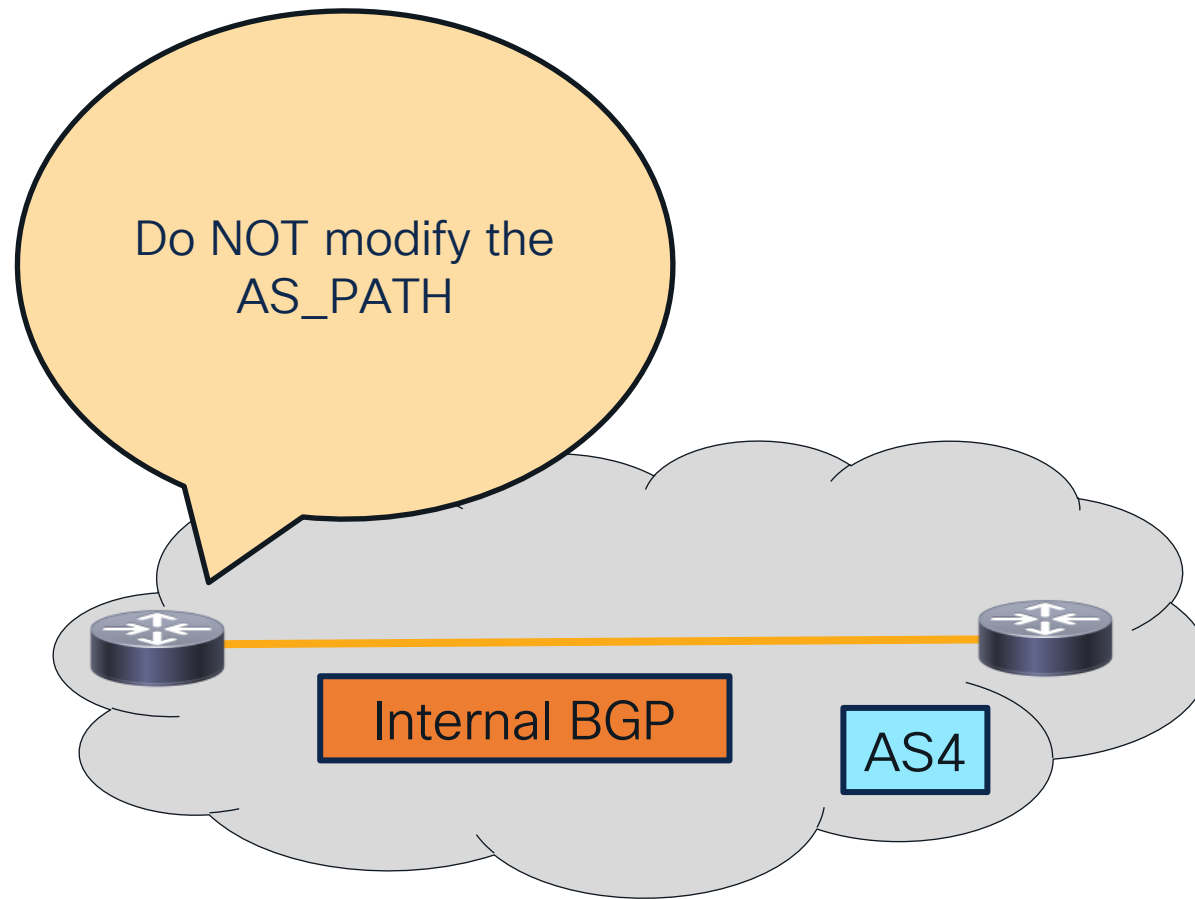
NEXT_HOP in iBGP



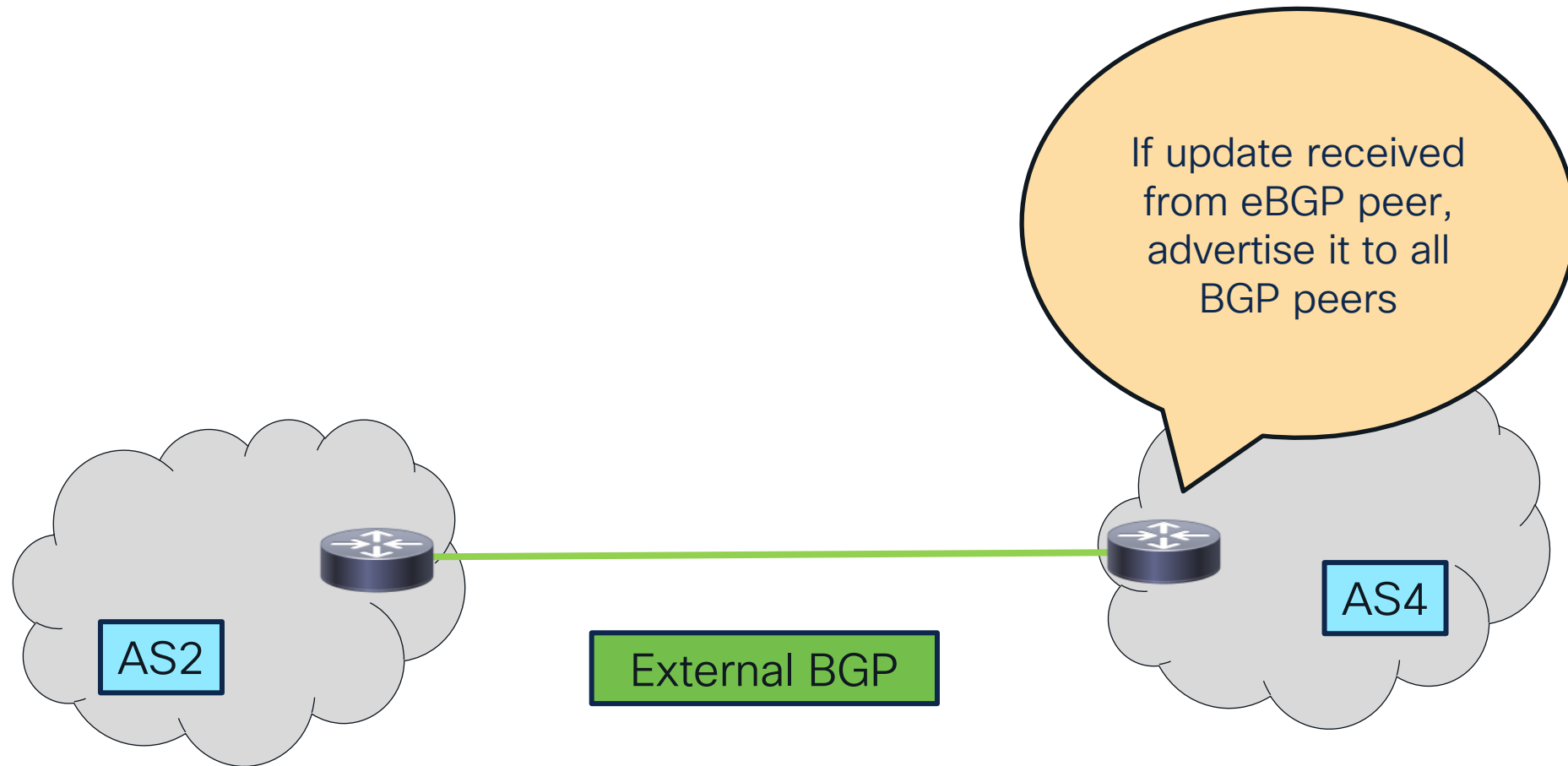
AS_PATH in eBGP



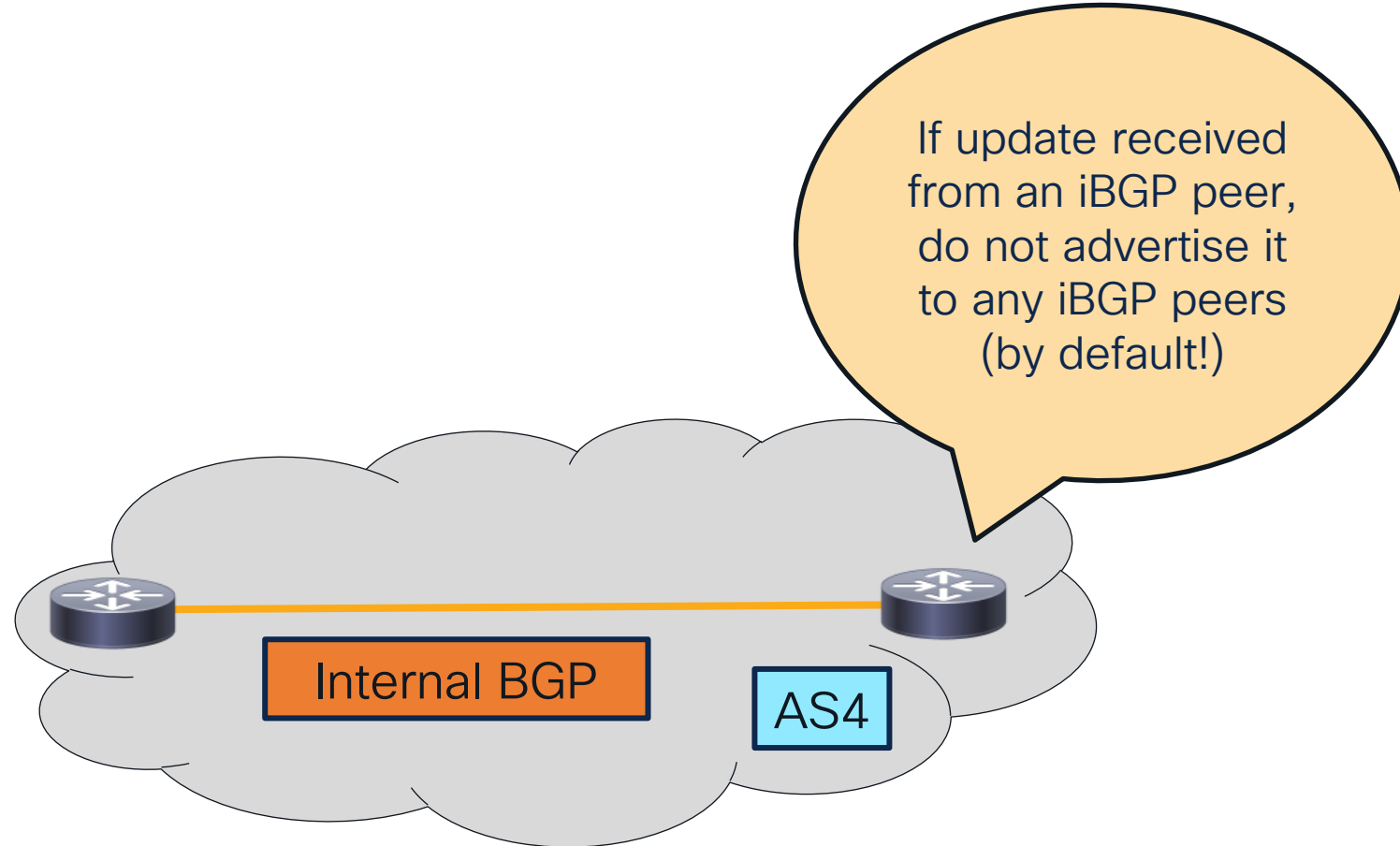
AS_PATH in iBGP



Updates in eBGP



Updates in iBGP





eBGP/iBGP Attribute Handling Summary

	Internal	External
Scope	Within AS	Between AS's
NEXT_HOP	Unchanged (default)	Changed to local address used to establish eBGP session
AS_PATH	Unchanged	Local AS inserted at the beginning of the AS_PATH list
Update	From iBGP not sent to iBGP (default)	From any sent to eBGP From eBGP sent to iBGP

Best Path Selection Algorithm

Best Path Selection in BGP

- BGP observes multiple constraints when selecting the best path
 - Loop-free
 - Shortest in terms of the number of ASes to traverse
 - Most likely to hit the true destination
 - Leaving the local autonomous system as quickly as possible (if needed)
 - ... but not updated unnecessarily if changed only insignificantly
 - ... and always with the possibility for the admin to override the selection
- BGP rules for best path selection aim to select exactly one best path per NLRI – to be both used locally and advertised to peers

10,000 Miles View at BGP Best Path Selection

- BGP speaker needs to decide on the best path for an NLRI if it learns about multiple options (variants) on how to reach it
- For every learned NLRI:
 - Select the first variant in the database as the **best one**
 - If there are more variants, go through them one by one, and compare the **current best one** to the **entry at hand**, and pick the new best one
 - The **new best one** may be the **current one** (no change), or the **entry at hand**
 - Finish when all variants have been inspected

Before Getting to the Nitty Gritty...

- Before diving into the BGP best path algorithm steps, keep in mind:
 - For every NLRI, BGP always compares the current best path to a variant in its database (injected locally or learned from peers)
 - The best path is both used locally (if it makes sense) and advertised to other peers, subject to the advertisement rules and policies
- In upcoming slides, the diagrams demonstrate typical scenarios but are not exhaustive



Router performing the best path selection



Generic router (unspecific)



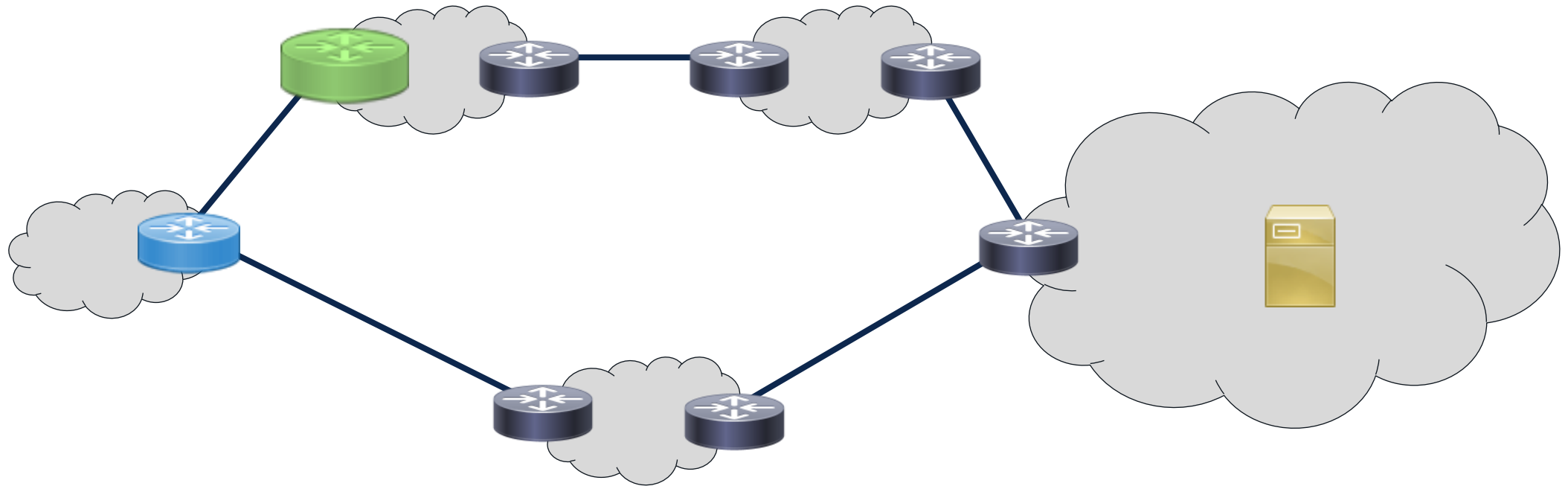
The resulting next hop



Destination (NLRI)

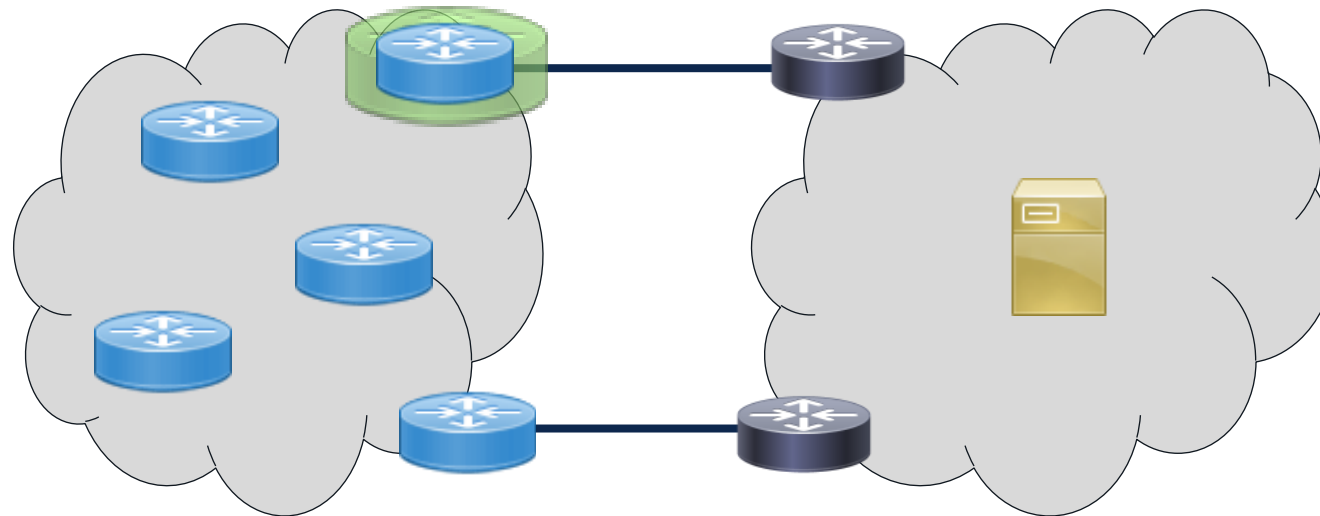
The logic behind BGP best path selection (1)

- Step 1: Prefer the path with the higher WEIGHT
 - Rationale: Always have means to **override** the path choice **locally**
 - Note: This is an override rule



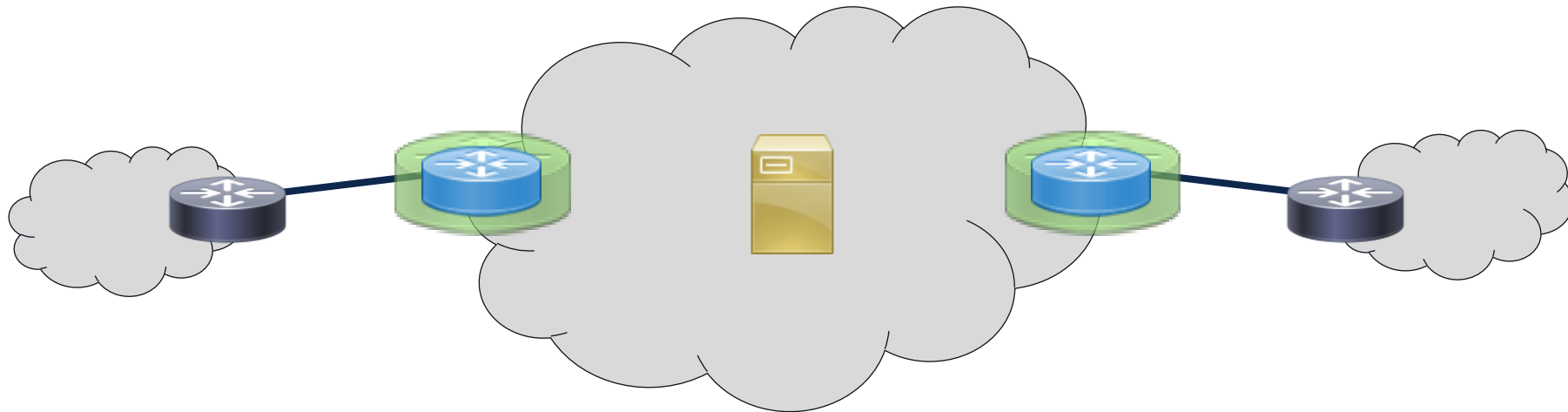
The logic behind BGP best path selection (2)

- Step 2: Prefer the path with the higher LOCAL_PREF
 - Rationale: Have means to **override** the best path **for the entire AS from a single exit point**
 - Note: This is an override rule



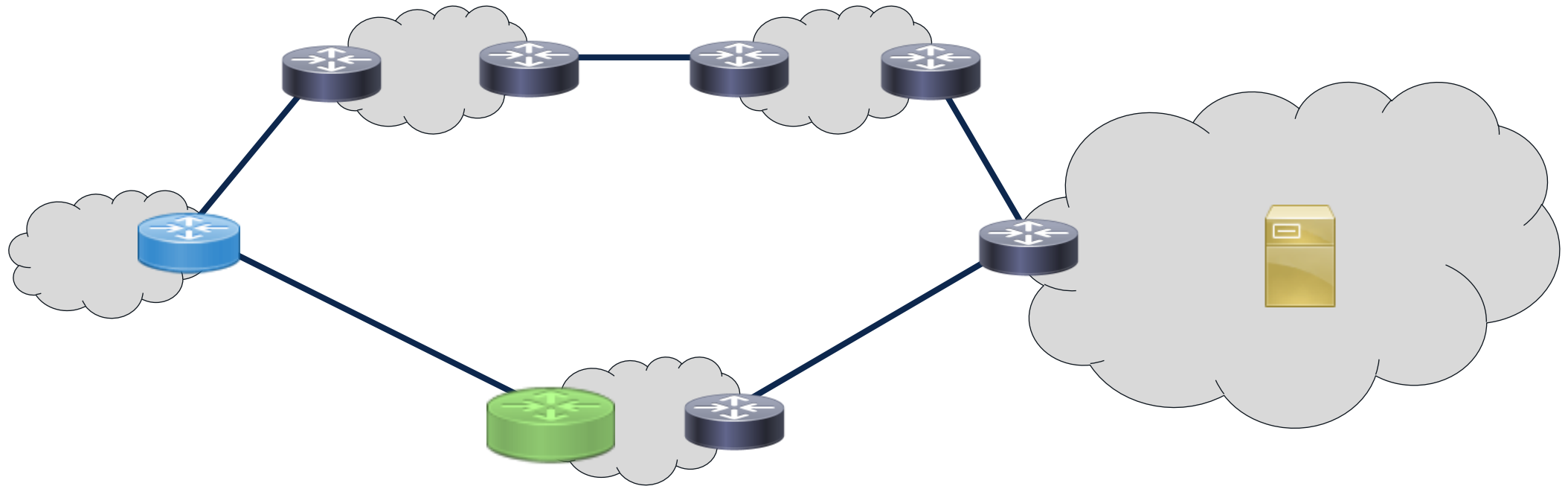
The logic behind BGP best path selection (3)

- Step 3: Prefer the locally originated path (network, redistribution, aggregation)
 - Rationale: I get a chance to **speak on behalf of my own local AS**
 - Note: The best route is not just for me to use but also to advertise to **others** so that **they know**



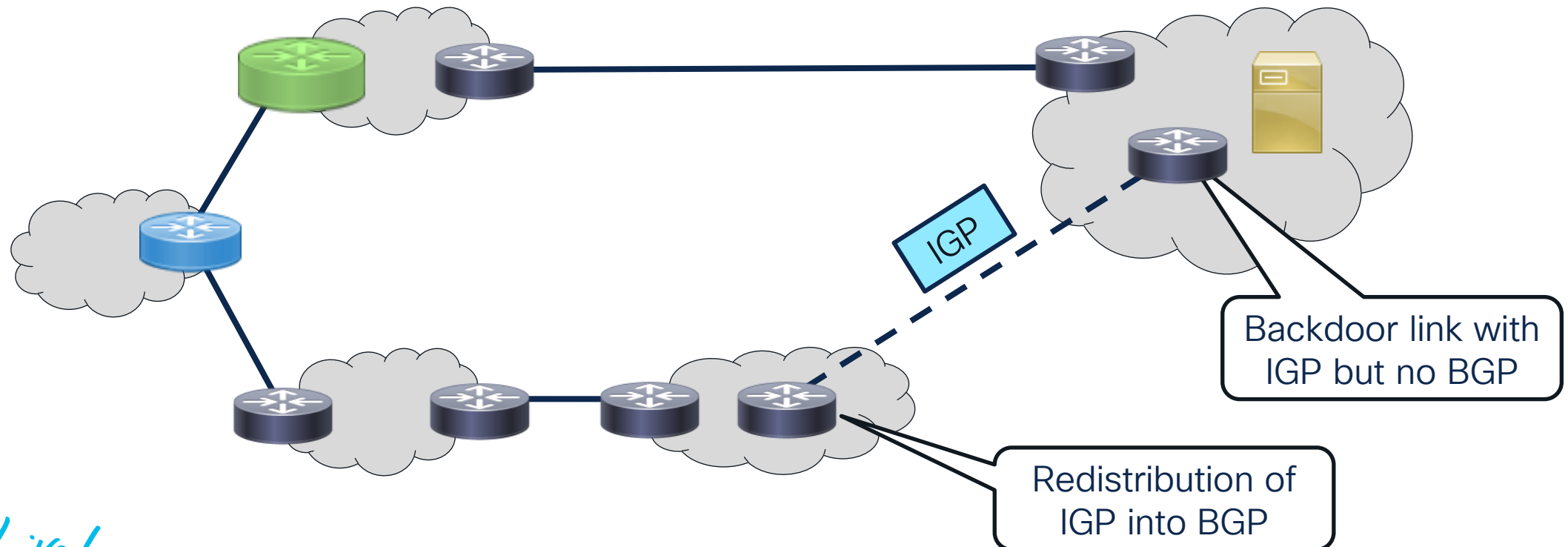
The logic behind BGP best path selection (4)

- Step 4: Prefer the path with the shortest AS_PATH / AS4_PATH
 - Rationale: Traverse the **least amount of autonomous systems**



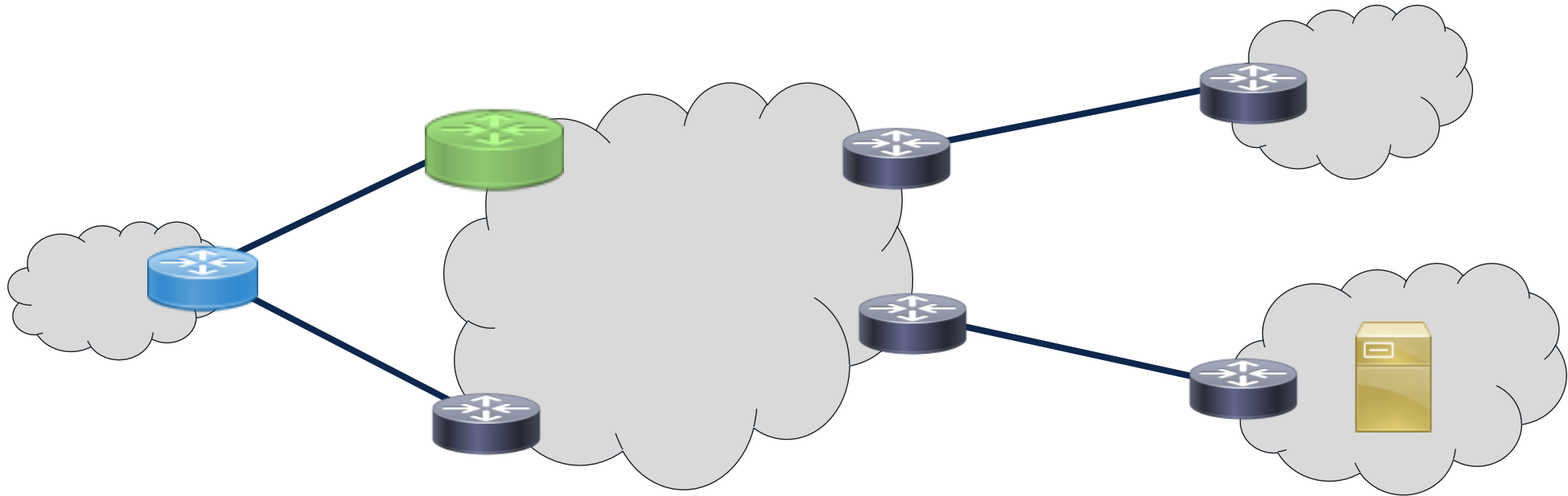
The logic behind BGP best path selection (5)

- Step 5: Prefer the path with the lower ORIGIN code
 - Rationale: Take the *most trustworthy* path
 - Note: IGP is lower than EGP, EGP is lower than Incomplete



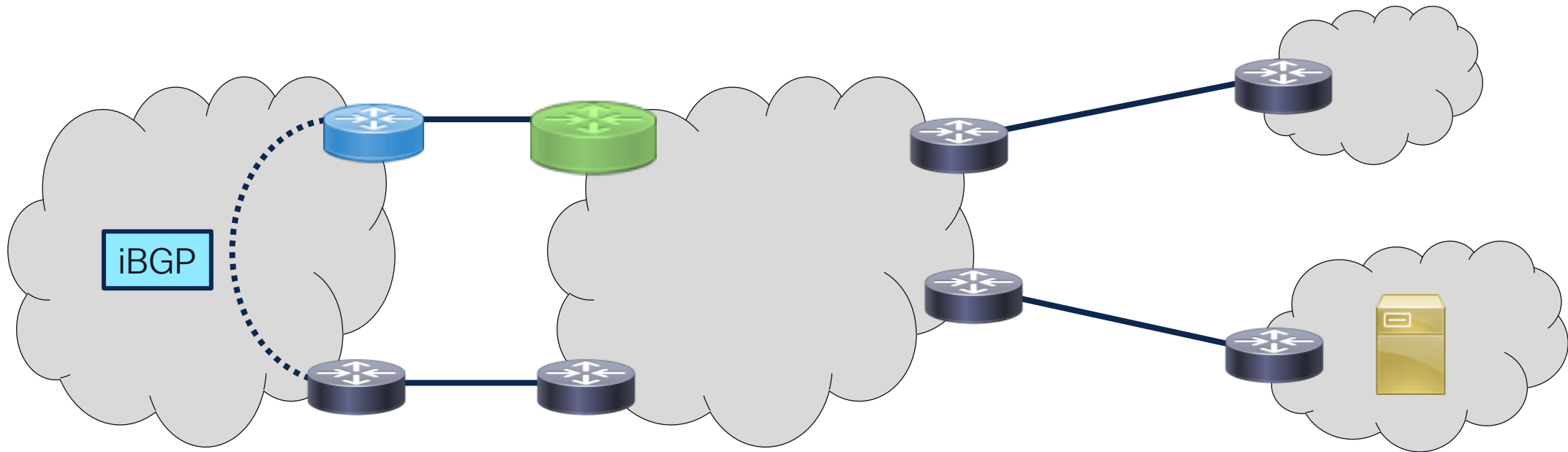
The logic behind BGP best path selection (6)

- Step 6: Prefer the path with the lower MULTI_EXIT_DISC
 - Rationale: Respect the *preferred path hint* indicated by the neighbor AS



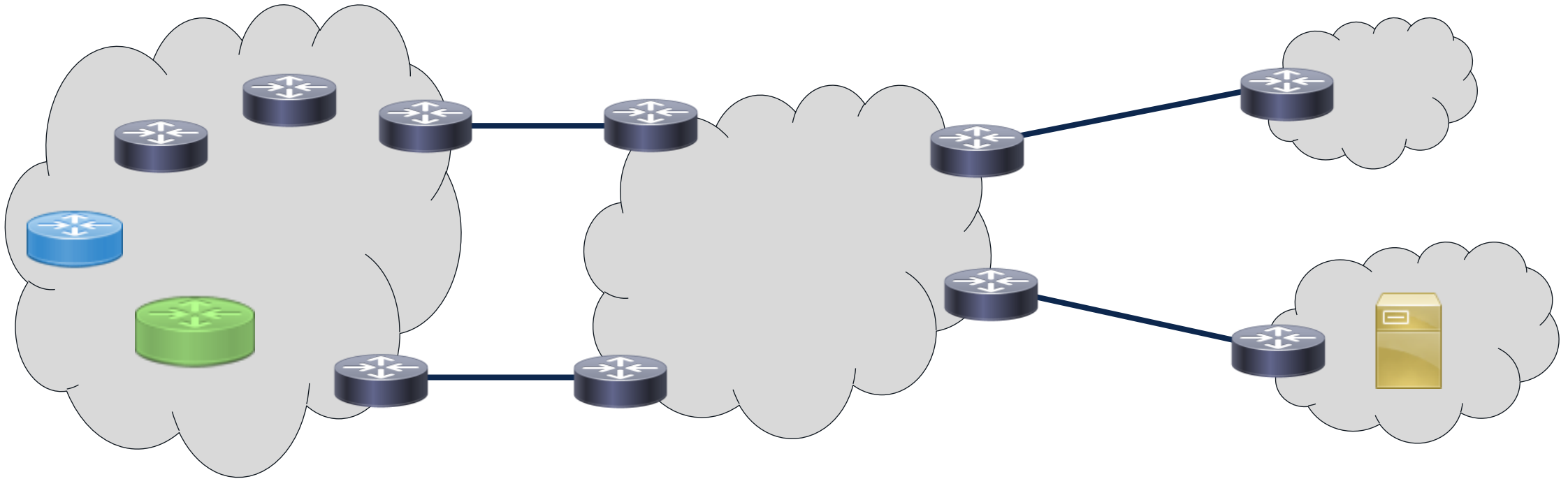
The logic behind BGP best path selection (7)

- Step 7: Prefer eBGP-learned path over iBGP-learned one
 - Rationale: If you need to *leave* the local AS, *leave right away if you can*



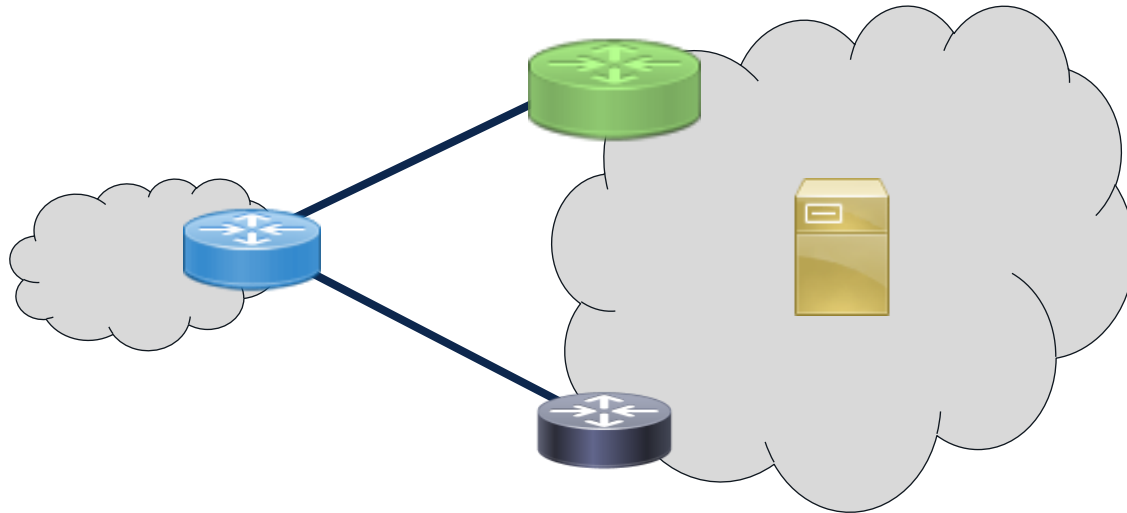
The logic behind BGP best path selection (8)

- Step 8: Prefer the path with the lower IGP metric to the next hop
 - Rationale: If you need to *traverse* the local AS but *can't leave* right away, just *take the shortest path toward the exit*



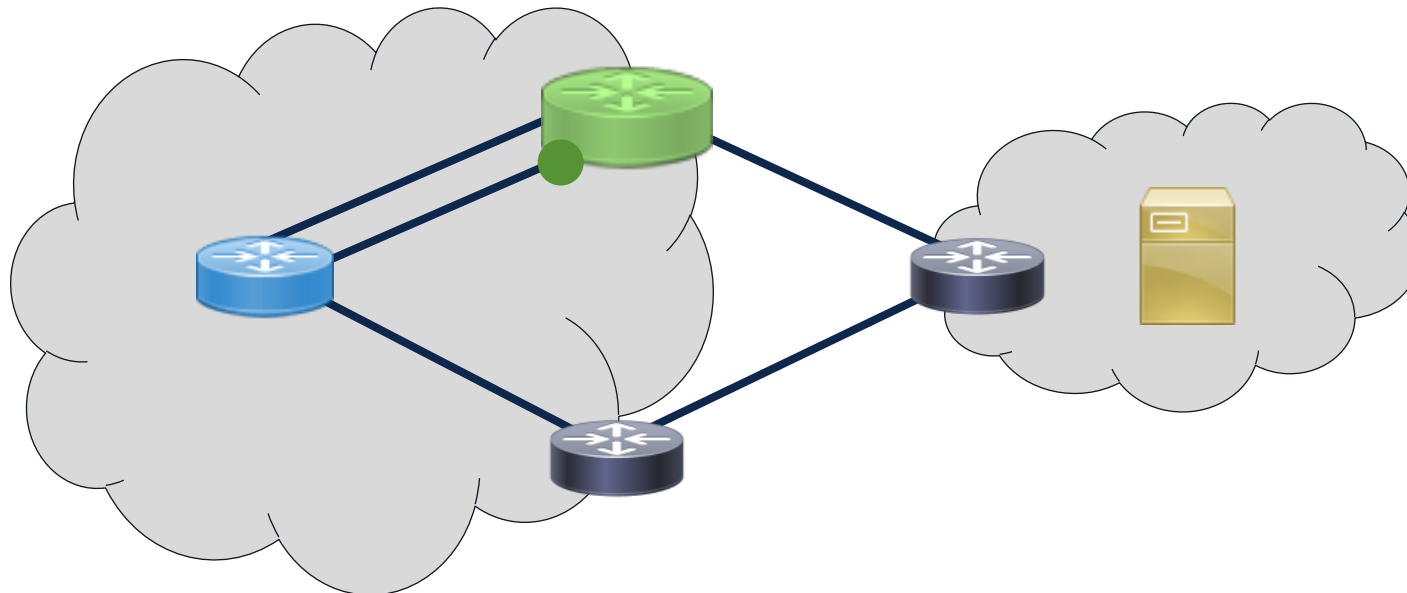
The logic behind BGP best path selection (9)

- Step 9: If both paths are learned via eBGP, prefer the older one
 - Rationale: The eBGP paths are, by this point, **effectively equal** – so **don't bother** updating anything



The logic behind BGP best path selection (10-12)

- Steps 10-12: Prefer the path learned from the BGP peer with the lower Router ID, **then** with the shorter CLUSTER_LIST, **then** from the BGP peer with the lower peering IP address
 - Rationale: Technical tiebreakers to arrive at *exactly one best path*





BGP Best Path Selection Algorithm

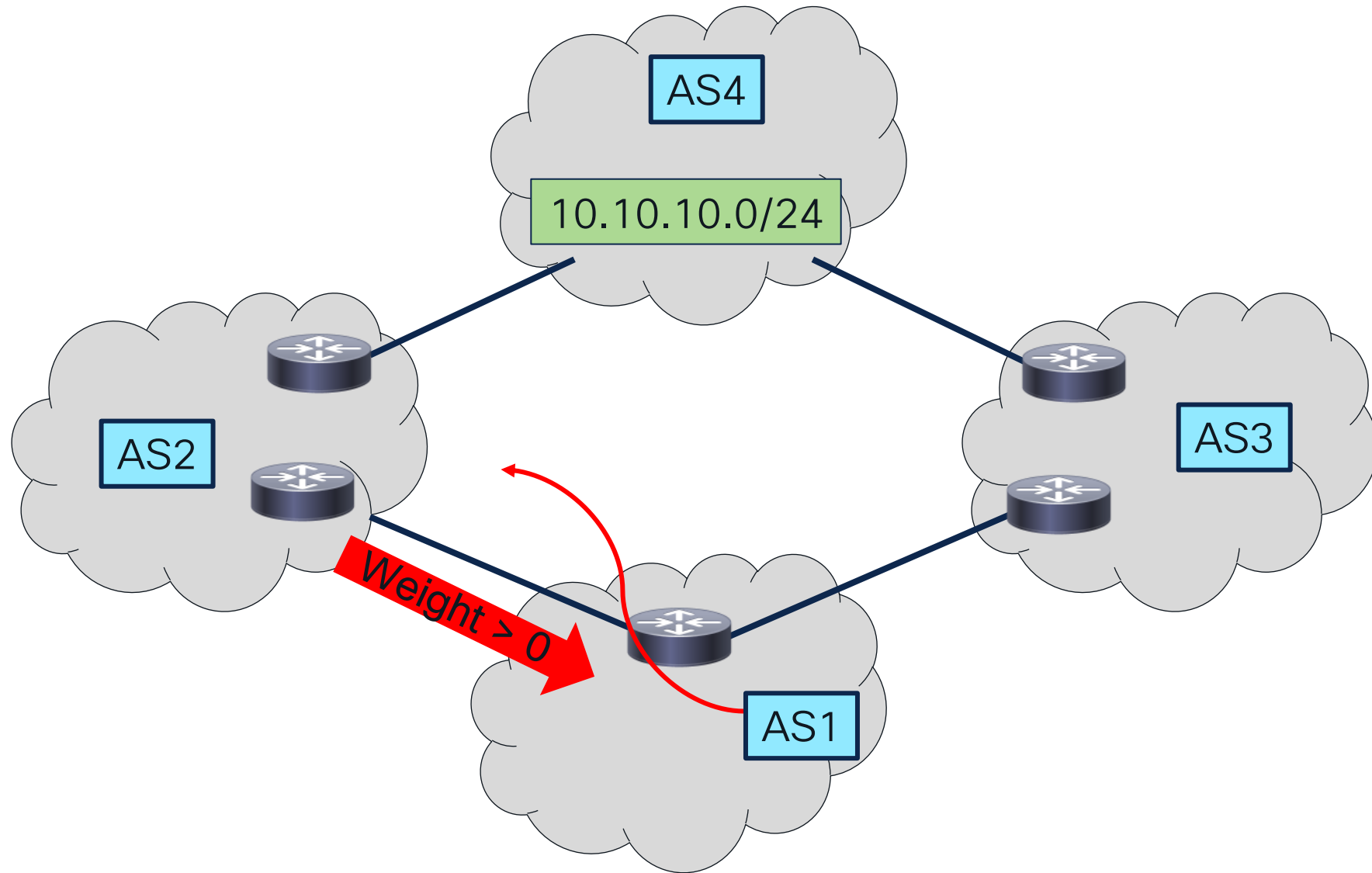
<https://www.cisco.com/c/en/us/support/docs/ip/border-gateway-protocol-bgp/13753-25.html>

BGP Best Path Selection Algorithm as Implemented on Cisco Devices

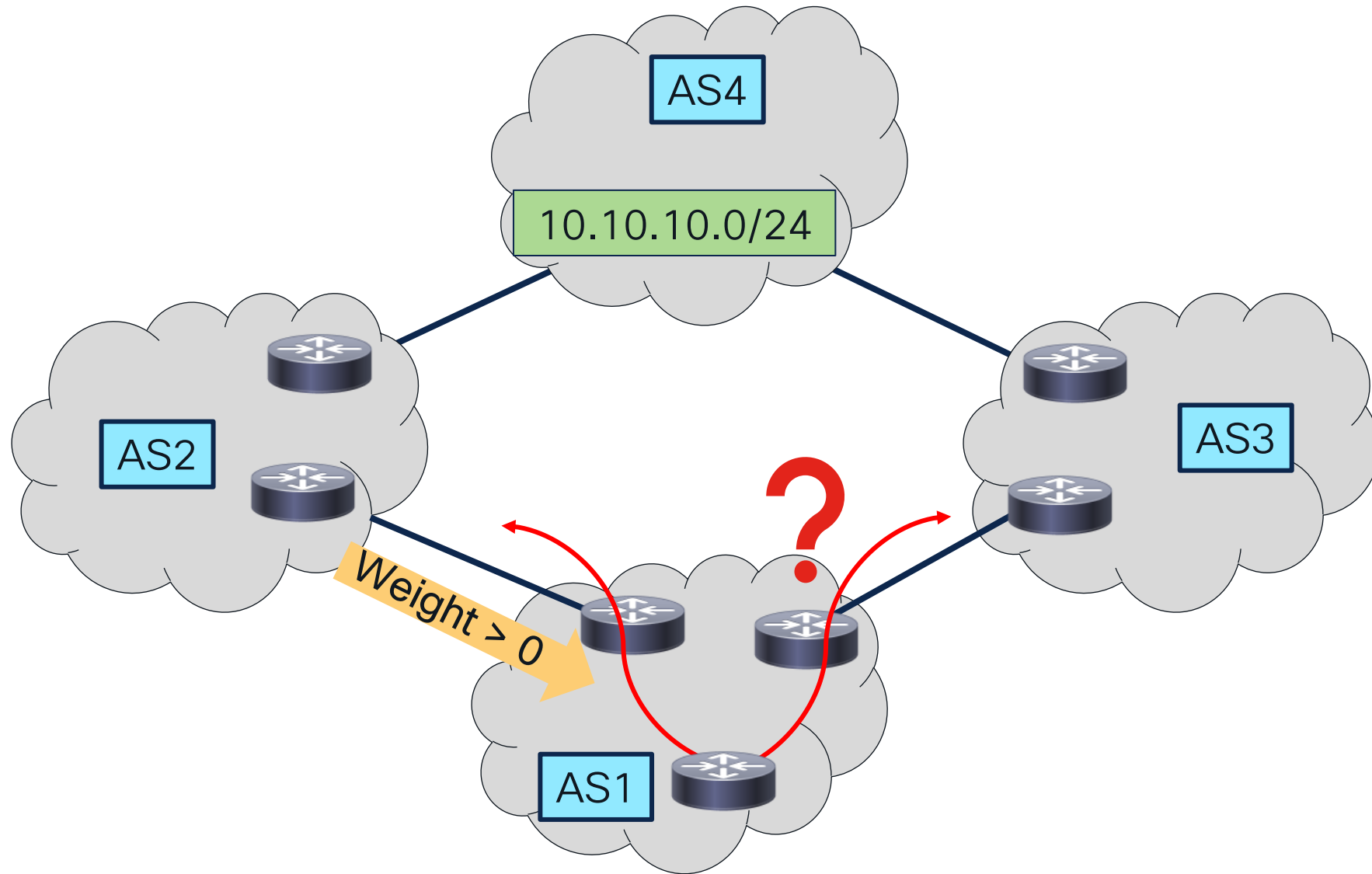
1. Highest WEIGHT	7. eBGP-learned route over iBGP-learned one
2. Highest LOCAL_PREF	8. Lowest IGP metric to the next hop
3. Locally originated (injected) route	9. Oldest eBGP-learned route
4. Shortest AS_PATH / AS4_PATH	10. Lowest BGP peer's Router ID
5. Lowest ORIGIN code	11. Shortest CLUSTER_LIST
6. Lowest MULTI_EXIT_DISC	12. Lowest BGP peer's address

Policy Control and Traffic Engineering

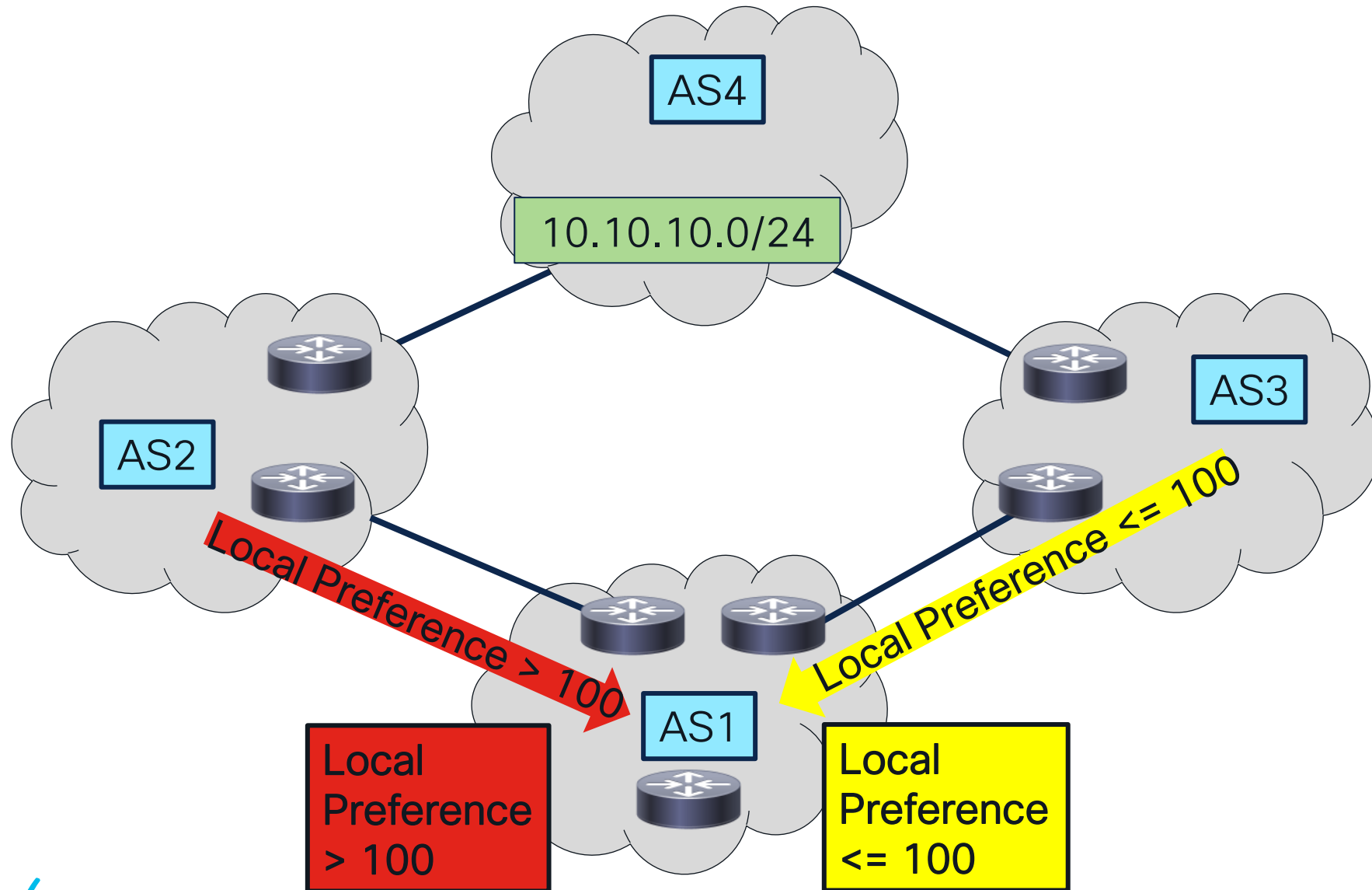
Outbound Traffic - Weight



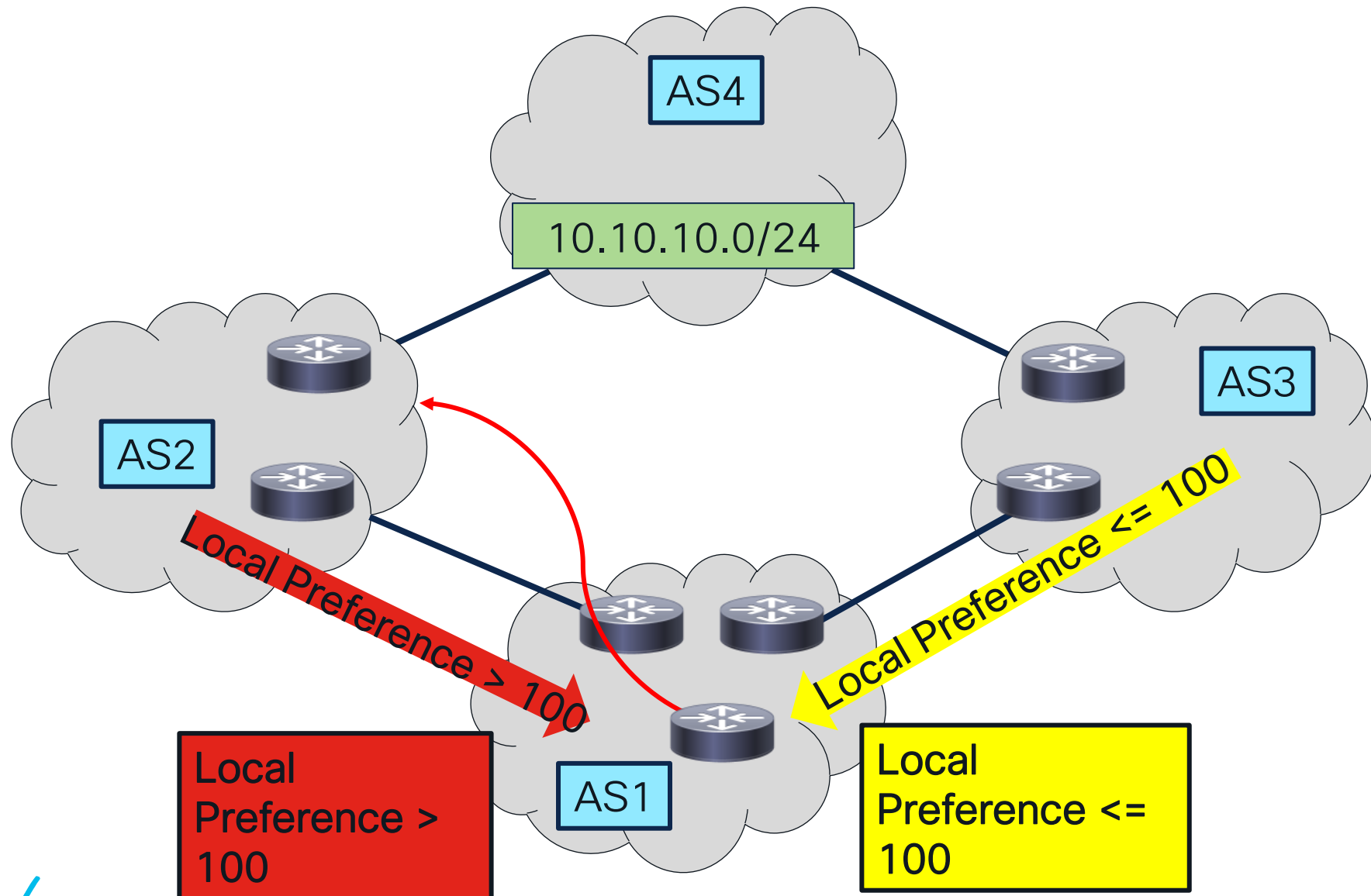
Outbound Traffic - Weight



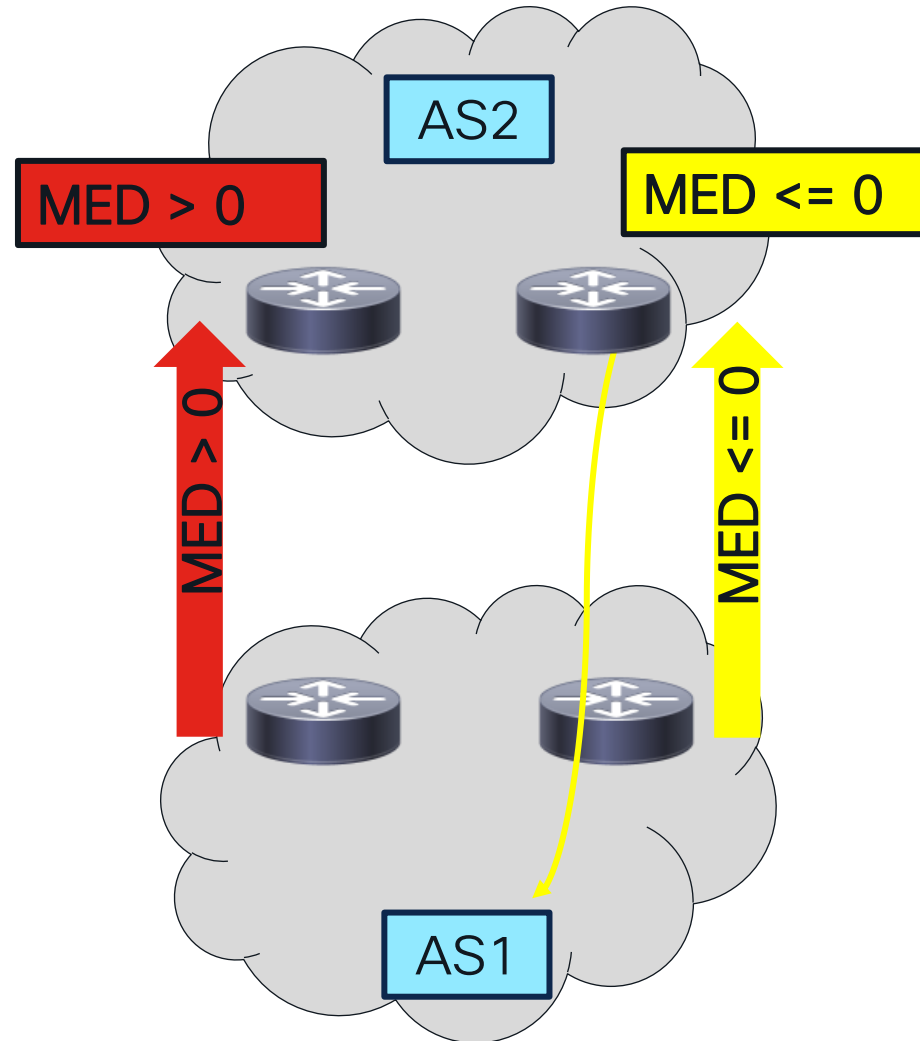
Outbound Traffic – LOCAL_PREF



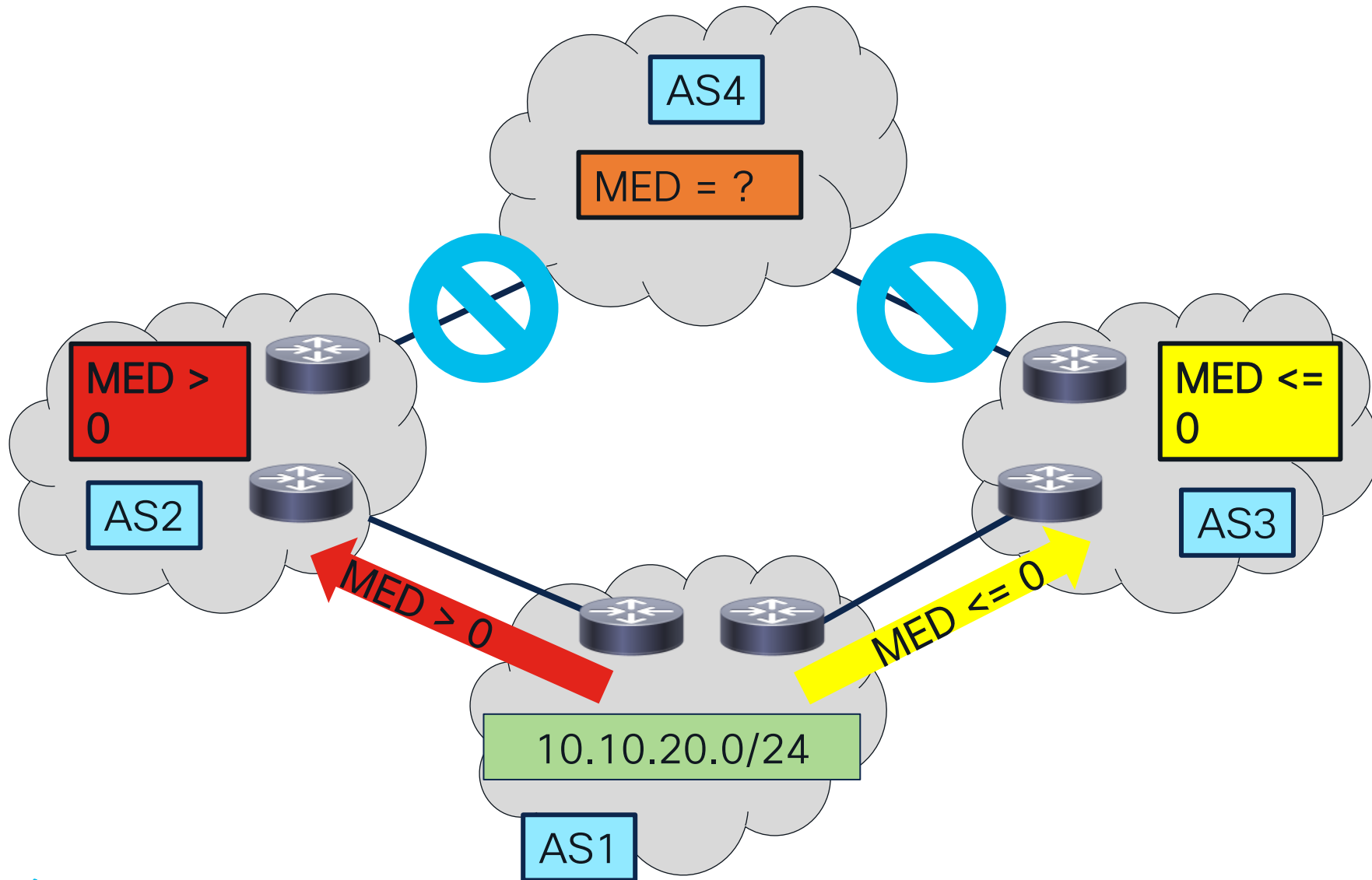
Outbound Traffic - LOCAL_PREF



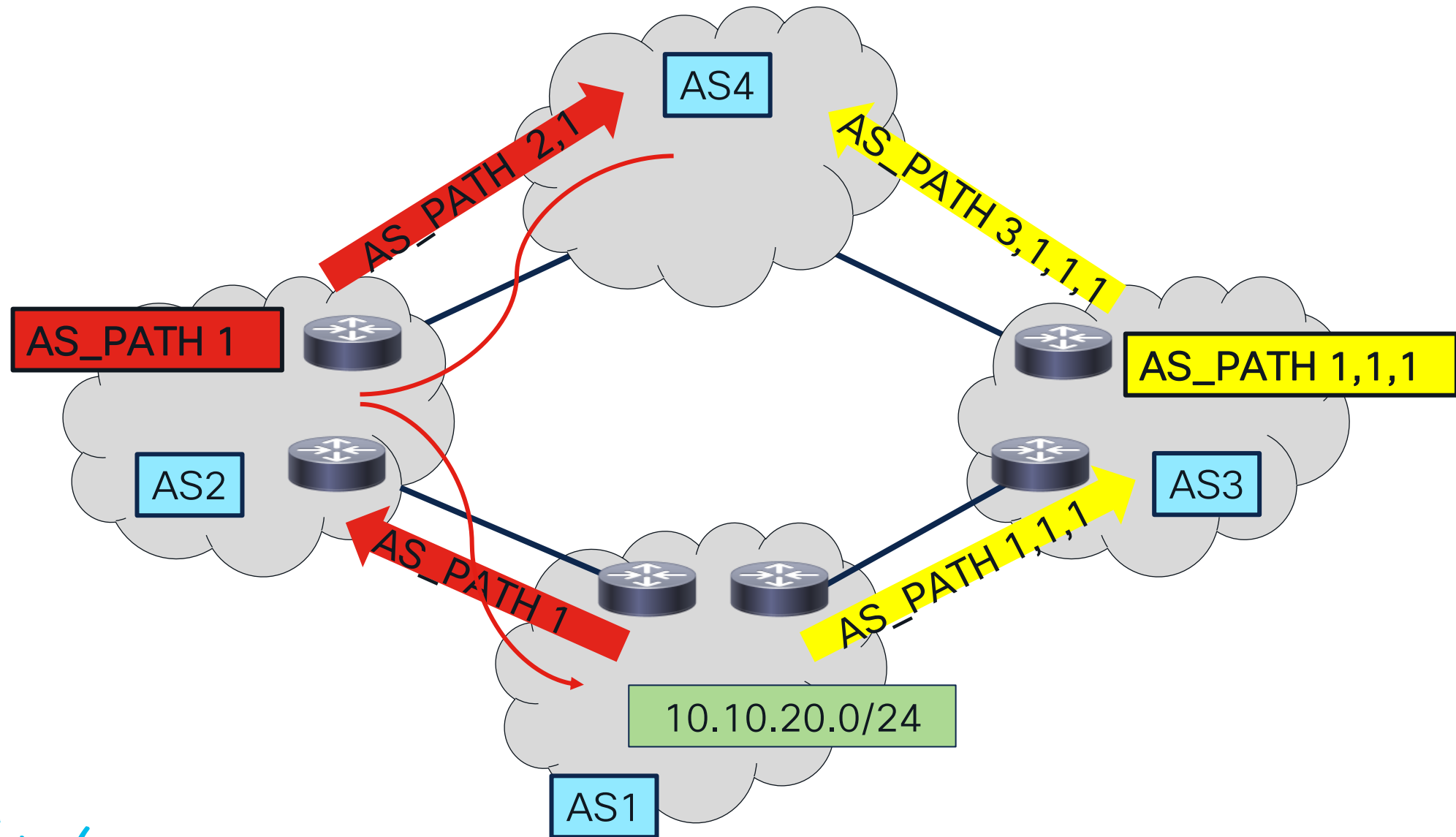
Inbound Traffic – MULTI_EXIT_DISC



Inbound Traffic – MULTI_EXIT_DISC



Inbound Traffic - AS_PATH



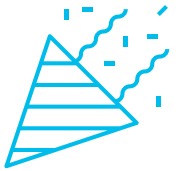
Concluding Remarks

- BGPv4 is ~30 years old but its core is still the same
 - A credit to its well-thought design
- BGP is a world on its own – where to learn more?
 - Cisco Press textbooks
 - Cisco Communities, Cisco Learning Network
 - IETF RFCs
 - Wireshark
 - Hands-on experience is key

“Like a fine wine, BGP only gets better with age.”

Anonymous

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The bridge to possible

Thank you

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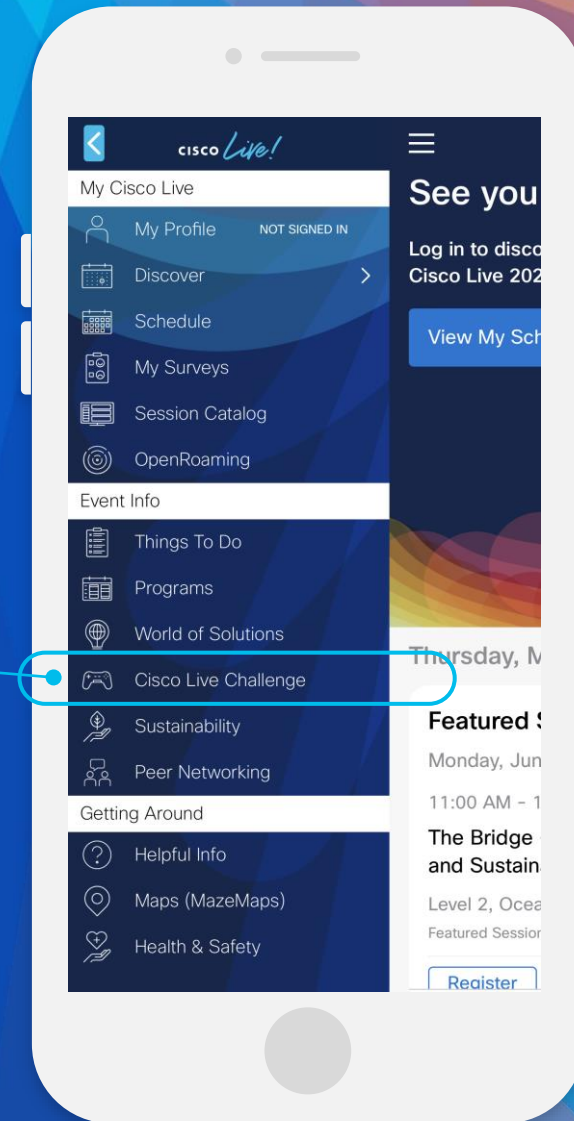
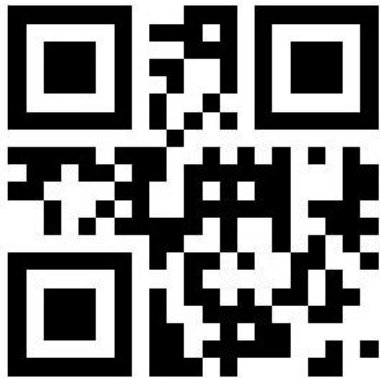
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The background is a vibrant, abstract graphic. It features a central bright white light source from which numerous colorful rays emanate, creating a sunburst or starburst effect. The rays transition through a spectrum of colors including yellow, orange, red, and various shades of blue and green. Overlaid on this are large, soft-edged, overlapping shapes in warm tones like orange, red, and yellow, which resemble stylized clouds or waves. The overall composition is dynamic and energetic.

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