Lab 10. Single-Area OSPF

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Credit to naich

Slide: https://tg.pe/nYE

Purpose

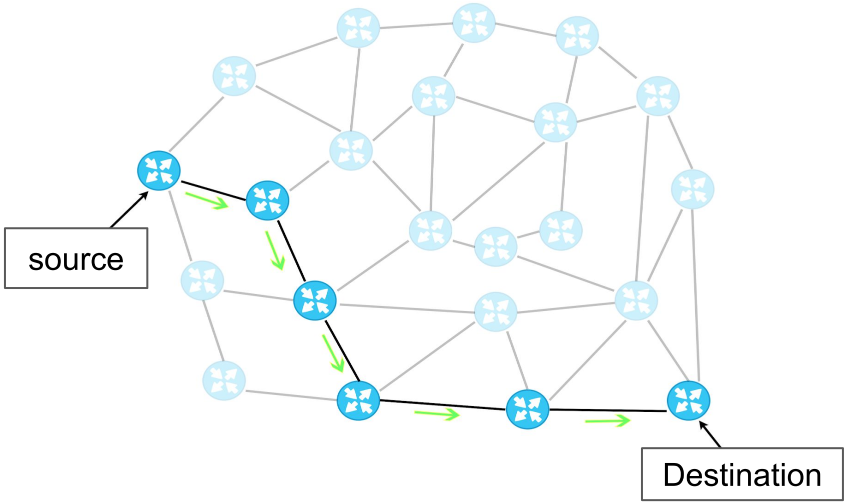
- We have already learned about routing, static routing, and RIPv2.
- OSPF is a scalable, efficient, flexible, open standard routing algorithm.
- It's common to use OSPF for dynamic routing in modern network systems.

Video Record

It will be uploaded after class

Destination-based Routing

- A basic routing mode for IPv4 packets.
- Each router determines a proper **next-hop** for a packet.
- Based only on the destination address found in the packet.



How do routers learn next-hop from?

- Static routing
  - Manually configured into the routing table.
  - It must be reconfigured whenever the network topology changes.
- **Dynamic** routing
  - **Automatically** learned through dynamic routing protocols.
  - Two major classes: Distance-Vector routing and Link-State routing.

IGP v.s. EGP

- Interior Gateway Protocol v.s. Exterior Gateway Protocol
- Autonomous System (AS)
- **Inside** an AS v.s. **Between** AS's
- Scenario: inside NYCU v.s. exchange with NTHU

Distance-Vector v.s. Link-State

	RIP (Distance-Vector)	OSPF (Link-State)
Send	Routing Table	Link State Advertisement (LSA)
Metric	Hop Count	Route Cost
Sending Range	Only Neighbors	Whole Topology

Link-State Routing Protocol

- Every routing node …
  a. constructs a **map** of the connectivity to the network.
  b. calculates the best logical path (**next-hop**) to every possible destination.
  c. generate **routing rules** from best paths.
- Example: OSPF (**O**pen **S**hortest **P**ath **F**irst), IS-IS (**I**ntermediate **S**ystem to **I**ntermediate **S**ystem)

OSPF vs IS-IS (supplementary)

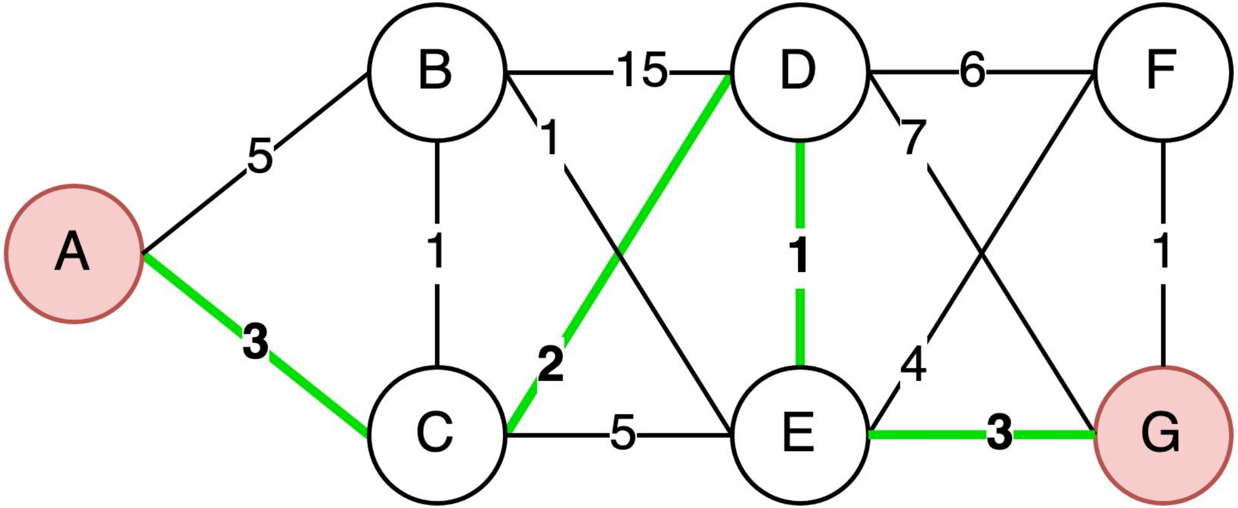
- Layer 3 (Network Layer) vs Layer 2 (Data-link Layer)
  - OSPF: IP protocol number: 89 (0x59), based on IP.
  - IS-IS: EtherType: 0xFEFE/0x00FE/etc., based on Layer 2 protocol.
- Area 0 as backbone vs. Level 1 and Level 2
  - OSPF: Any area must be connected to area 0.
  - IS-IS: routers can be L1, L1/L2, or L2. It’s more flexible.

How OSPF Perform Link-State Routing

- Establish adjacency with neighbor.
- Synchronize **L**ink **S**tate **A**dvertisement (LSA) between routers.
- Store **L**ink-**S**tate **D**ata**b**ase (LSDB) in routers.
- Calculate the shortest path using the Dijkstra algorithm.
- Put the best path into the routing table.

💭 Background: Shortest Path First

- Calculated by Dijkstra algorithm.



A	0	(A)
B	4	(A - B)
C	3	(A - C)
D	5	(A - C - D)
E	6	(A - C - D - E)
F	10	(A - C - D - E - F)
G	9	(A - C - D - E - G)

Open Shortest Path First (OSPF)

- A link-state routing protocol defined in RFC 2328
- Based on Dijkstra's (Shortest Path) Algorithm.
- Every router **receives the whole topology** and then computes its own routes.
- Widely used in large networks.

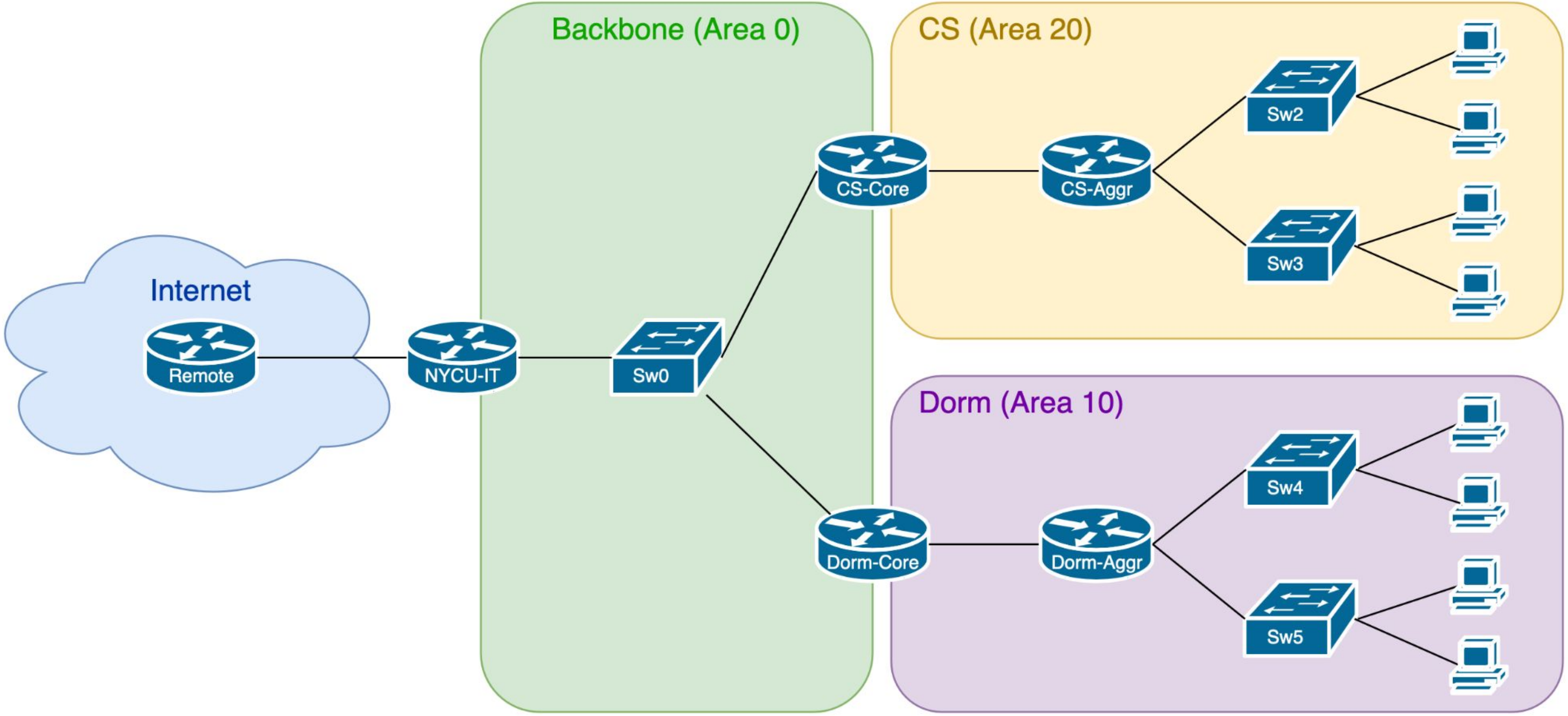
OSPFv3 (supplementary)

- Defined in [RFC 5340] (was RFC 2740)
- Support IPv6
- Use IPsec instead of MD5 for Authn
- Multicast address is `FF02::5` and `FF02::6` (OSPFv2: `224.0.0.5` and `.6`)

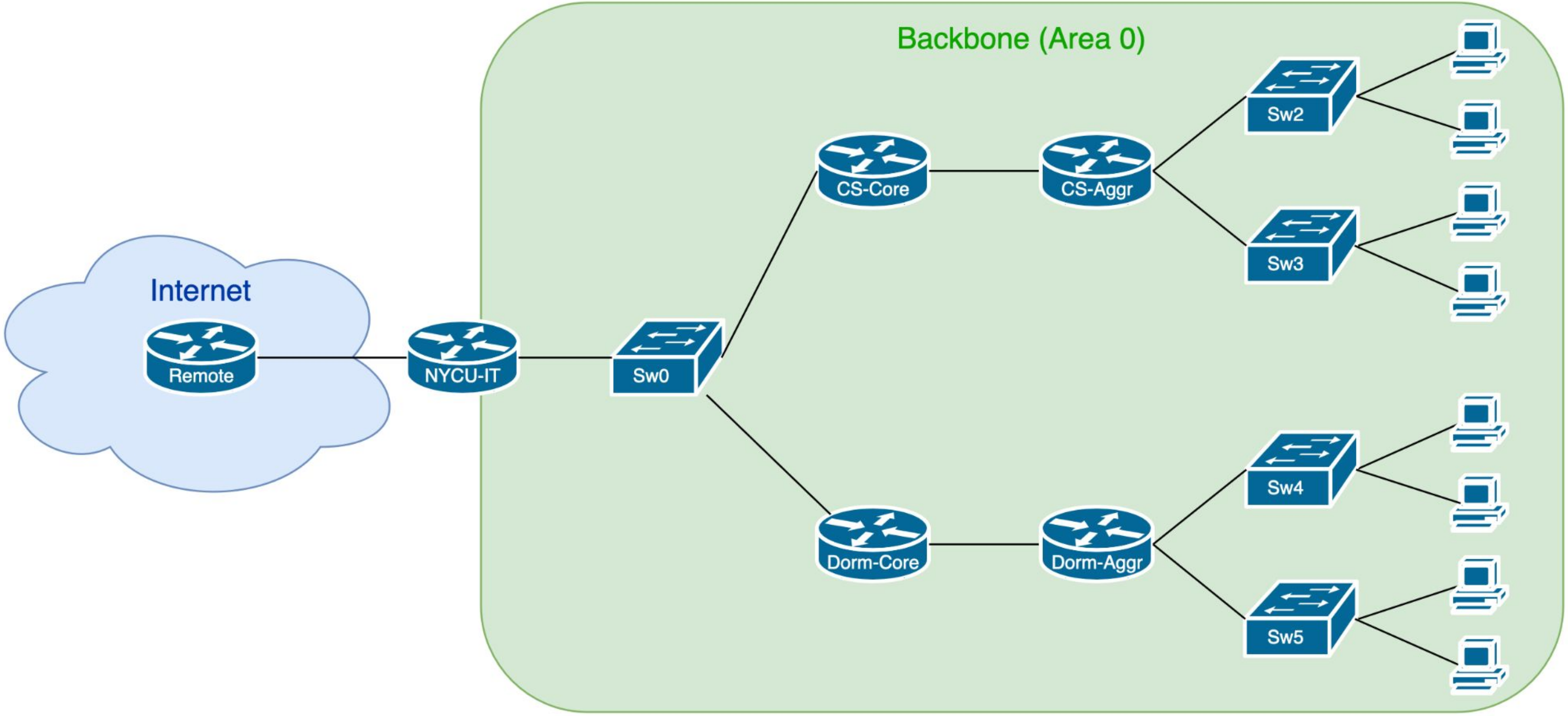
RFC 9454 Update to OSPF Terminology (supplementary)

- For politically correct
- Changed “Master/Slave” to "Leader/Follower"
- “Master (MS) bit" is renamed to "Leader (L) bit" in the Database Description.
- Drafted: 2022 February
- Published: 2023 August

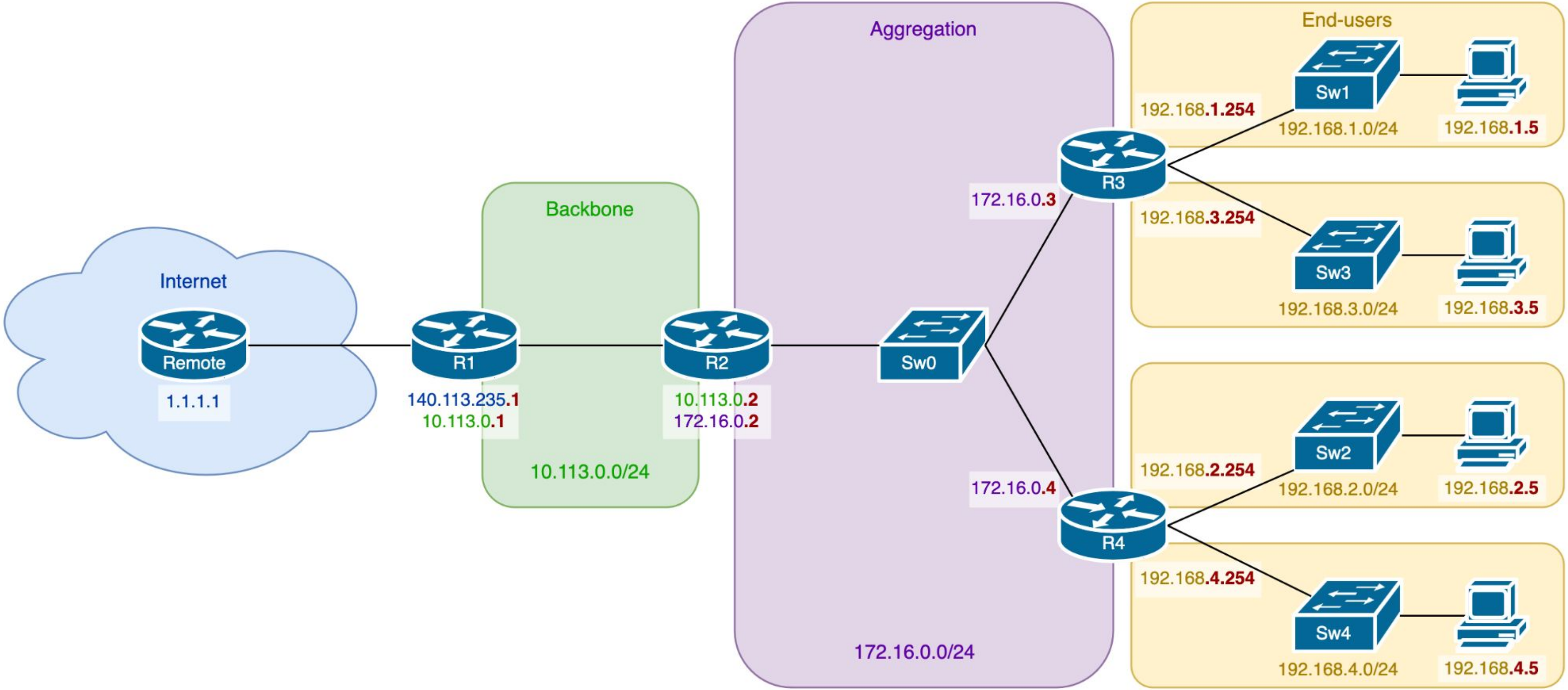
Multi-Area OSPF



Single-Area OSPF



Topology (Lab10-OSPF.pkt)



What is `127.0.0.1`?

- All computers use this address as their own.
- Try to `ping 127.0.0.1` on your device.
- The **`localhost`** domain name usually resolves to `127.0.0.1` address.
- Cannot reach others using this address.
- The address block `127.0.0.0/8` is assigned as the **loopback** network.

Loopback Interface

- An **always-up** interface which you can assign an IP address (Layer 3).
- It has no MAC address, just a virtual interface.
- Usually used in management, or protocols like OSPF, BGP, and NTP.

※ OSPF (Open Shortest Path First), BGP (Border Gateway Protocol), NTP (Network Time Protocol)

Set Management IP Address for R1:

```
R1(config)# interface loopback 0
R1(config-if)# ip address 140.113.0.1 255.255.255.255
```

Router OSPF Configuration Mode

Enable OSPF in R1

```
R1(config)# router ospf 42
R1(config-router)#
```

Process ID

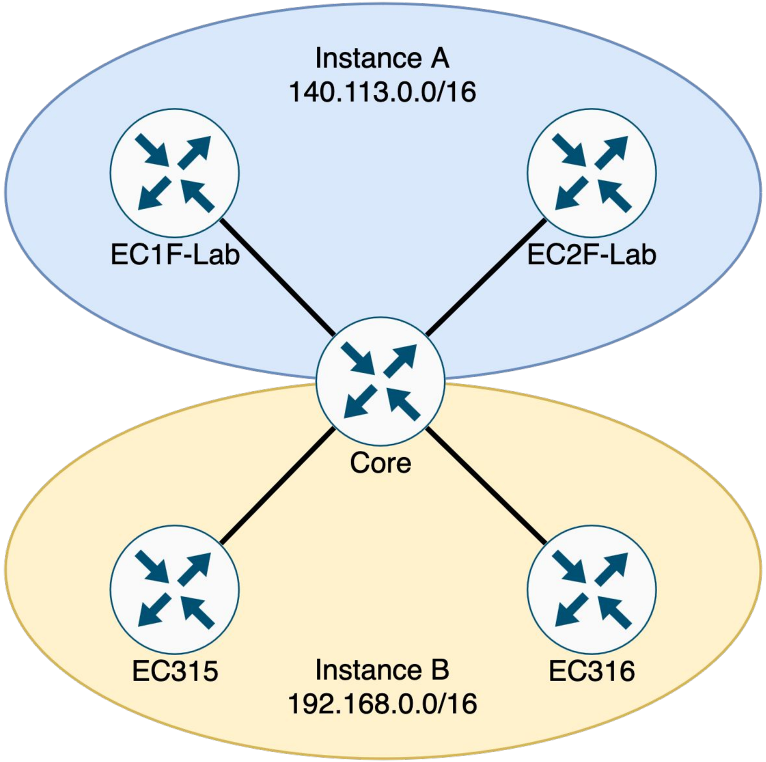
- The Process ID value is **locally significant**.
- A router can have several OSPF processes.

Multi-instance OSPF (supplementary)

- Each process owns its instance.
- Each instance owns its database.
- A single process is sufficient for simple topology.

```
Core(config)# router ospf 113
Core(config-router)#
```

```
Core(config)# router ospf 192
Core(config-router)#
```



Router ID

- To participate in an OSPF domain, a router needs a Router ID
- A **32-bit value**, expressed as an IPv4 address
- The Router ID is used by the OSPF-enabled router to:
    - Uniquely identify the router
    - Participate in the election of the DR/BDR (Backup / Designated Router)
- The Router ID is selected in the following order:
    a. Manually configure the `router-id` property.
    b. The highest IPv4 address of any **loopback** interface.
    c. The highest **active** IPv4 address of any of its **physical** interfaces.

Check the Router ID of R1

```
R1# show ip protocols
Routing Protocol is "ospf 42"
  Outgoing update filter list for all interfaces is not set
  Incoming update filter list for all interfaces is not set
  Router ID 140.113.0.1
  Number of areas in this router is 0. 0 normal 0 stub 0 nssa
  [...]
```

Since we didn't set the `router-id` for R1, it will take the loopback address automatically.

Enable OSPF for R2

```
R2(config)# router ospf 42
R2(config-router)# router-id 140.113.0.2
```

```
R2# show ip protocols  ! Check Router ID
Routing Protocol is "ospf 42"
  Outgoing update filter list for all interfaces is not set
  Incoming update filter list for all interfaces is not set
  Router ID 140.113.0.2
  [...]
```

The manually configured `router-id` will have top priority.

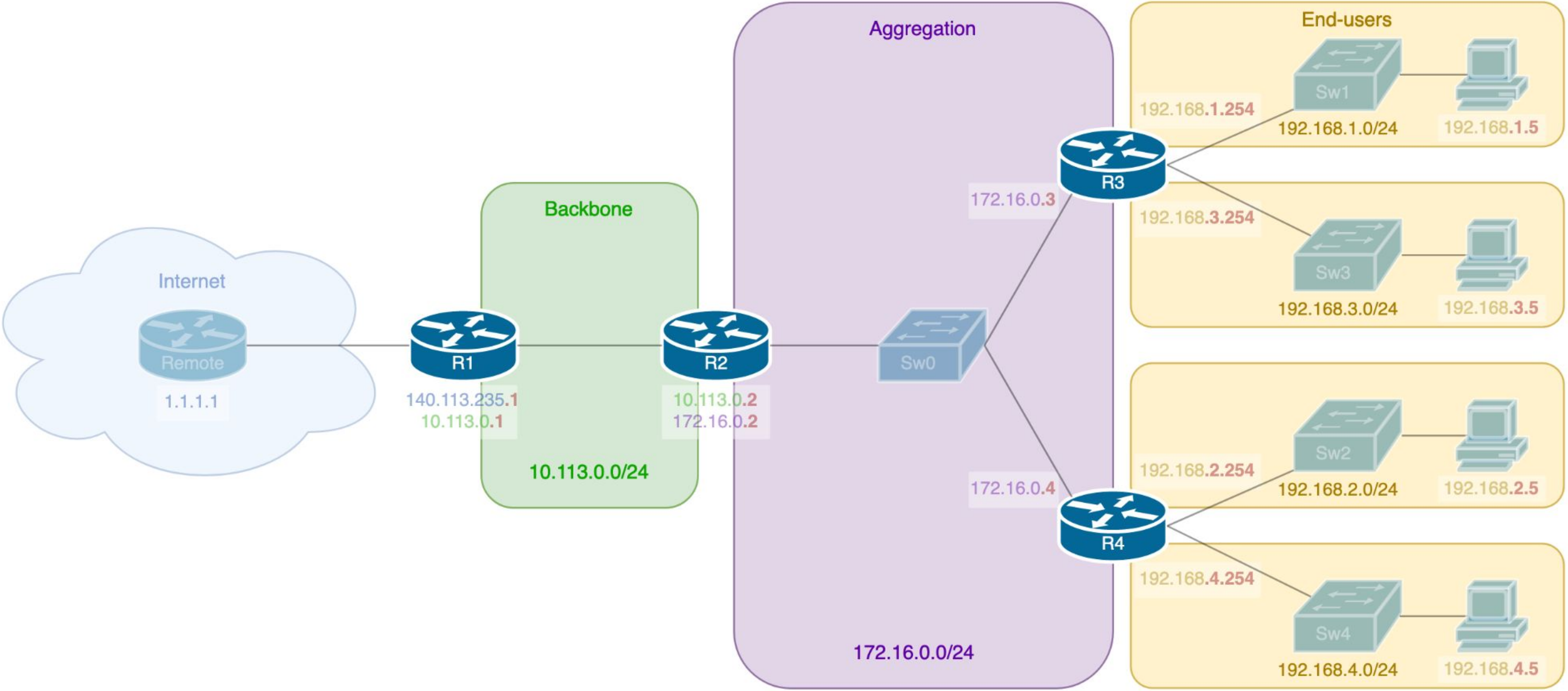
Enable OSPF for R3/R4

```
R3(config)# router ospf 42
R3(config-router)#
```

```
R3# show ip protocols  ! Check Router ID
Routing Protocol is "ospf 42"
  Outgoing update filter list for all interfaces is not set
  Incoming update filter list for all interfaces is not set
  Router ID 192.168.3.254
  [...]
```

The highest IP address will be the Router ID. What will be the Router ID for R4?

Advertise Network



Advertise Network #1: Global Config

```
R2(config)# router ospf 42
R2(config-router)# network 10.113.0.0 0.0.0.255 area 0
R2(config-router)# network 172.16.0.0 255.255.255.0 area 0
```

- The IP address must appear on the router interface for advertising
- The wildcard should be the reverse of the subnet mask.
- If we enter the subnet mask instead, it will be converted to a wildcard before stored to the `running-config`.

Advertise Network #2: Per-interface Config

```
R2(config)# interface GigabitEthernet 0/0
R2(config-if)# ip ospf 42 area 0
```

```
R2(config)# interface GigabitEthernet 0/1
R2(config-if)# ip ospf 42 area 0
```

- We can also specify the network on the interface.
- It has higher priority than specified in Router OSPF Configuration Mode.
- Question: Why we don’t need to specify an IP address?

Advertising Networks for R1/R3/R4

```
R1(config)# router ospf 42
R1(config-router)# network 10.113.0.0 0.0.0.255 area 0
```

```
R3(config)# router ospf 42
R3(config-router)# network 172.16.0.0 0.0.0.255 area 0
R3(config-router)# network 192.168.1.0 0.0.0.255 area 0
R3(config-router)# network 192.168.3.0 0.0.0.255 area 0
```

```
R4(config)# router ospf 42
R4(config-router)# network 172.16.0.0 0.0.0.255 area 0
R4(config-router)# network 192.168.2.0 0.0.0.255 area 0
R4(config-router)# network 192.168.4.0 0.0.0.255 area 0
```

Verify OSPF Neighbor

```
R2# show ip ospf neighbor

Neighbor ID     Pri State           Dead Time  Address        Interface
192.168.3.254     1 FULL/BDR        00:00:36   172.16.0.3     Gi0/0
192.168.4.254     1 FULL/DROTHER    00:00:36   172.16.0.4     Gi0/0
140.113.0.1       1 FULL/BDR        00:00:36   10.113.0.1     Gi0/1
```

- R2 has 3 neighbors (R3, R4, R1) as the above output.
- Checkpoint: R1 should have 1 neighbor, and R3/R4 should have 2 neighbors.

Reload OSPF Process

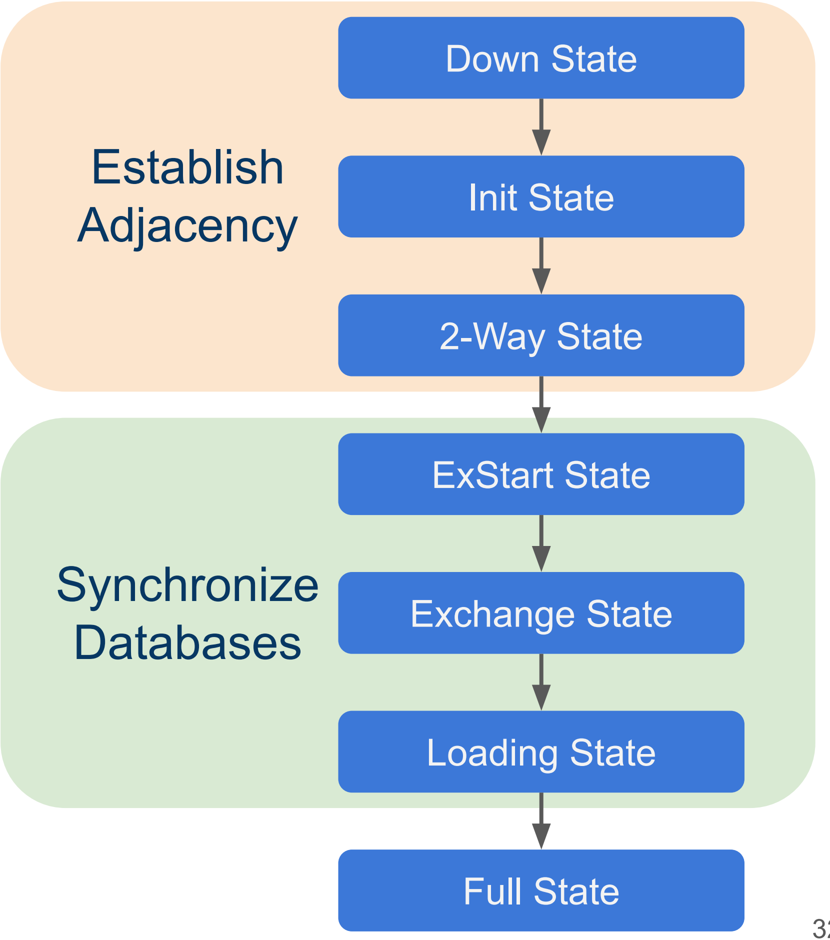
```
R2# clear ip ospf process
Reset ALL OSPF processes? [no]: yes

%OSPF-5-ADJCHG: Process 42, Nbr 192.168.3.254 on GigabitEthernet0/0
from FULL to DOWN, Neighbor Down: Adjacency forced to reset
```

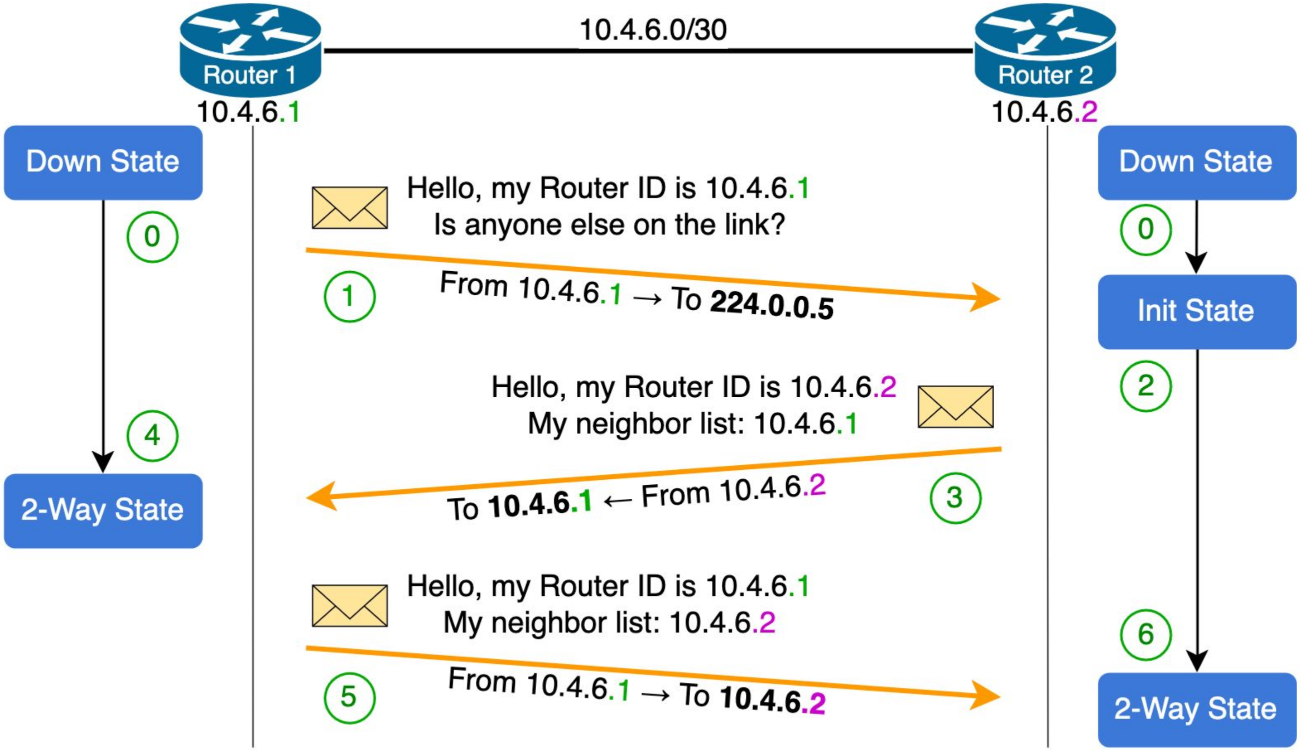
- To update the Router ID, we must reboot the router or reload the ospf process.
- If something weird happens, try to reload or reboot.
- We might reload the ospf process for all routers and see how it establishes a neighbor.

Neighbor States

- The OSPF neighbor adjacency begins from **Down State**.
- Maybe it ends in the **2-Way State**, as we will cover later.
- Usually, it will reach **Full State**.

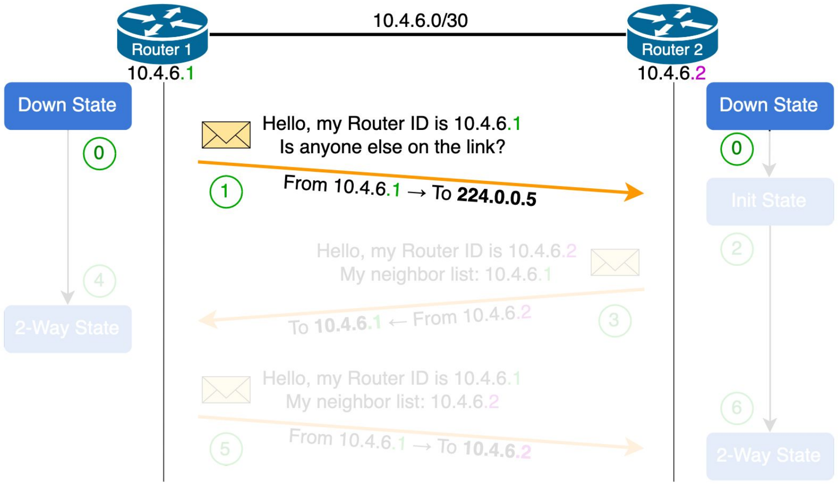


Establish Adjacencies



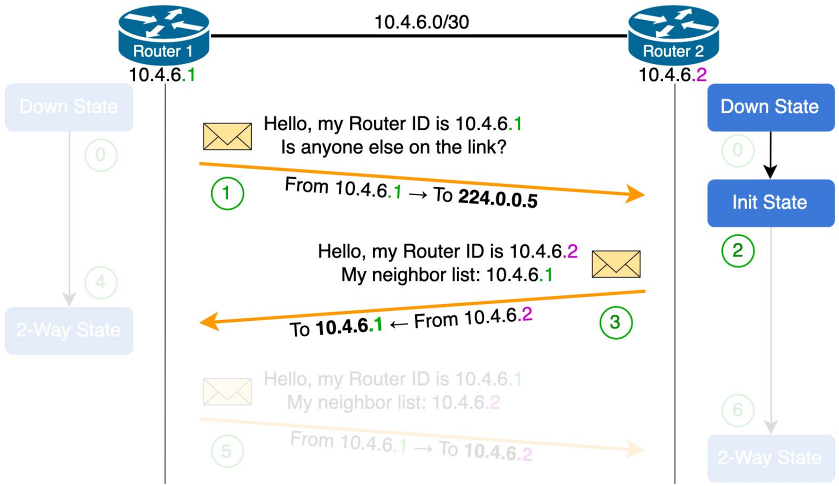
Down State (1/4)

- The initial OSPF state. Not received Hello packets from the neighbor yet.
- Will send Hello packets to `ospf-all` on all OSPF-enabled interfaces.



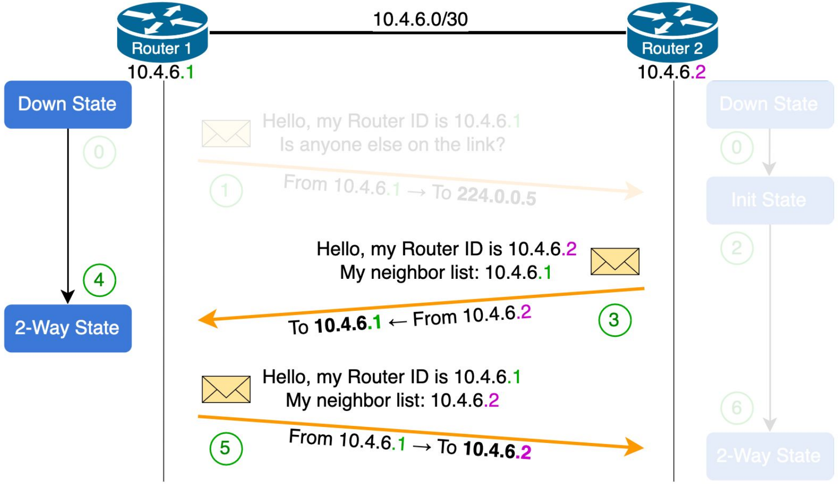
Init State (2/4)

- Received Hello packet, but “the neighbor” doesn’t seem to know me.
- Will send a Hello packet to let “the neighbor” know my Router ID.



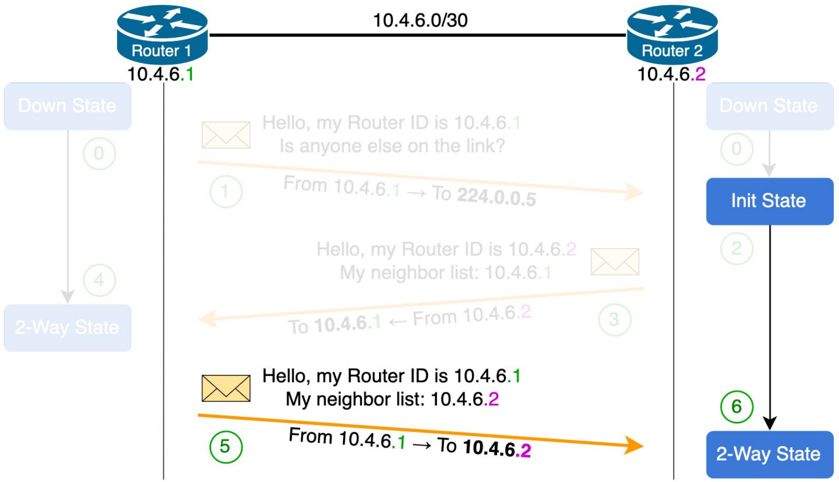
2-Way State (3/4)

- Received a Hello packet with my Router ID listed in the Hello packet.
- Will send a Hello packet to let “the neighbor” also finish the handshake.



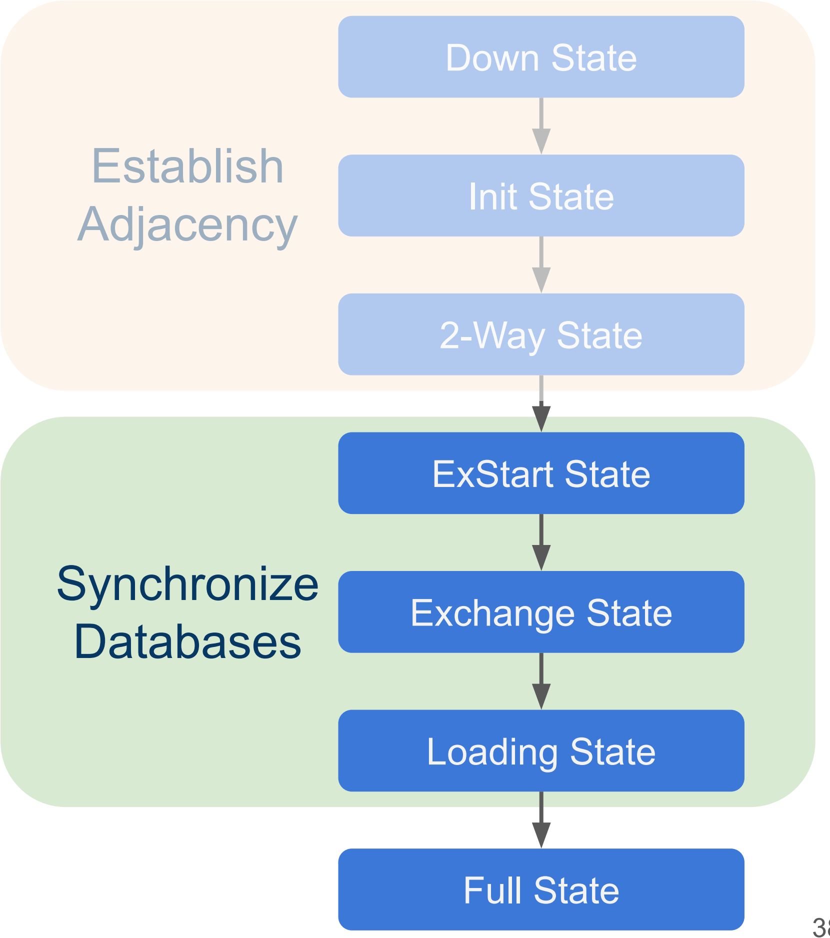
Adjacency Established (4/4)

- Both routers reached the 2-Way State.
- Ready for negotiation about exchanging roles.



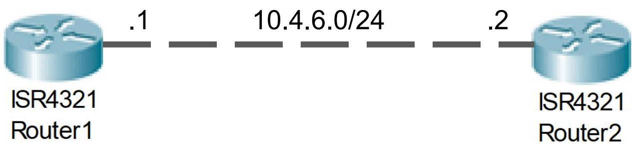
Neighbor States

- After the 2-Way State, the router will transit to the ExStart State.
- When master negotiation is done, router will enter the Exchange State and exchange the metadata (DBD).
- If the metadata is synced, enter the Loading State and continue to request the real data (LSR).
- Reach the Full State when received all data.



ExStart State (supplementary)

- After the 2-Way State, routers are ready to synchronize the database.
  - Four types of OSPF packets are used during this process.
- In the ExStart State, routers will send empty DBD packets periodically.
  - The router with the higher Router ID will be the master during the Exchange State.

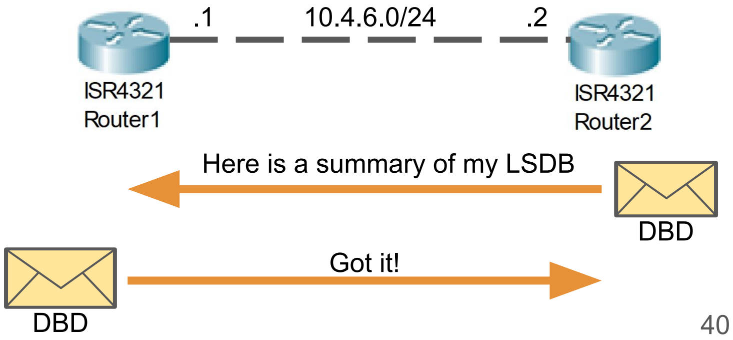


R2 has the highest Router ID,
so it will send the DBD packet first

Exchange State (supplementary)

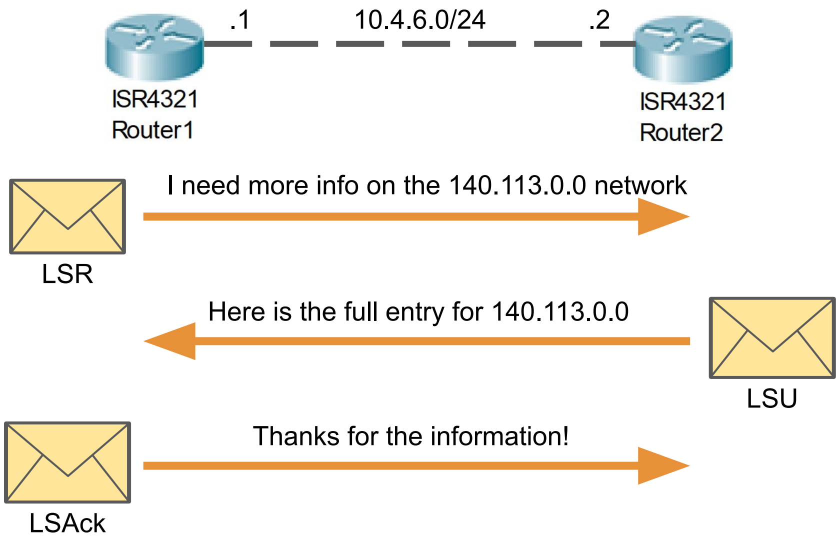
The master will send the summary of the Link-State Database (LSDB) by DBD.

- The packet includes information about entry headers that appear in the router's database.
- The entries can be about a link or a network.
- Each entry header includes information about:
    - Sequence number: used to determine the freshness of the router's database entry
    - Address of the advertising router
    - Link type
    - Link's cost



Loading State (supplementary)

- When it receives all the DBD packets, the router transits to the Loading State.



Full State (supplementary)

- After all LSRs have been satisfied for a given router, the adjacent routers are considered synchronized and in a Full State.
- As long as the neighboring routers continue receiving Hello packets, the routing entry in the transmitted entries remains in the topology database.
- After the topological databases are synchronized, updates (LSU) are sent only to neighbors.

📝 Quiz: Neighbor Discovery

- How does OSPF discover neighbors?
- Which IP address is used?
- Hint: Unicast / **Multicast** / Broadcast / Anycast

⌛ Break time

- We learned: What OSPF is, OSPF States, How to establish neighbor
- Next section: LSA Types, Designated router, Advanced settings

What is LSA?

- **L**ink **S**tate **A**dvertisement
  - Individually, LSAs act as database records and provide specific OSPF network details.
- An LSDB (**L**ink **S**tate **D**ata**b**ase) contains LSAs.
  - In combination, LSAs describe the entire topology of an OSPF network/area.
- There are 11 different LSA types.
  - Type 1 - 2: Single-Area
  - Type 3 - 5: Multi-Area
  - Type 6: Multicast (deprecated)
  - Type 7: Multi-Area (Not-So-Stubby Area)
  - Type 8 - 11: OSPFv3 (for IPv6)

LSA Type 1 (1/2)

#	Name	Sender	Receiver	Information
Type 1	Router LSA	Any OSPF Router	All other routers in the same area	Link / Network information
Type 2	Network LSA	DR	All other routers in the same area	List of routers that DR connects with
Type 3	Summary LSA	ABR	All routers in the different area	Network information of other areas
Type 4	Summary ASBR LSA	ABR	All routers in OSPF routing domain	Information of ASBR
Type 5	AS External Link	ASBR	All routers in OSPF routing domain	External network
Type 7	NSSA External LSA	ASBR	All the routers in the NSSA	External network

LSA Type 1 (2/2)

- All routers advertise their directly connected OSPF-enabled links and forward their network information to OSPF neighbors.
  - Type 1 LSA contains a list of directly connected interfaces, link types, neighbors, and link states.
- Flooded only within the area in which the LSA Type 1 messages originated.

Verify LSA Type 1 (1/2)

All routers advertise in their area about all the networks they know.

```
R1# show ip ospf 42 database router
         OSPF Router with ID (140.113.0.1) (Process ID 42)
               Router Link States (Area 0)
LS Type: Router Links
Link State ID: 140.113.0.1
Advertising Router: 140.113.0.1
[...]
Number of Links: 1
```

Verify LSA Type 1 (2/2)

Try it on every router!

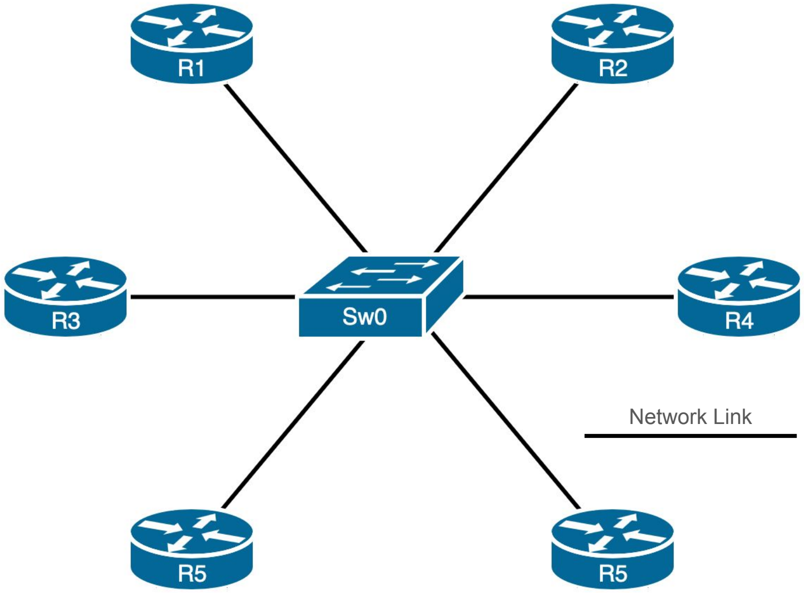
```
R2# show ip ospf 42 database router
[...]

R3# show ip ospf 42 database router
[...]

R4# show ip ospf 42 database router
[...]
```

Multi-Access Network

- When multiple routers are connected to one access network.
- The multicast Hello packet will be sent to all the other routers.

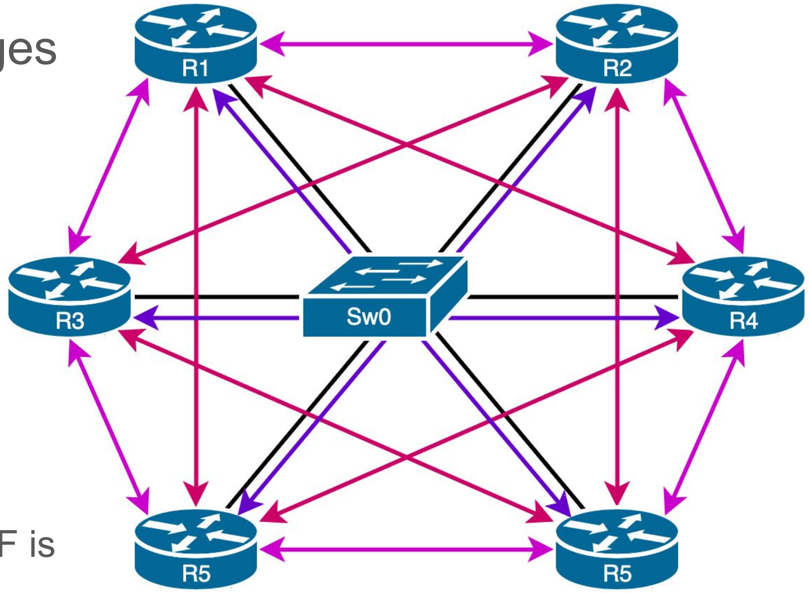


Device count: 6 routers
Number of links: 6

Network without Designated Router

Multi-access networks can create two challenges for OSPF regarding the flooding of Updates:

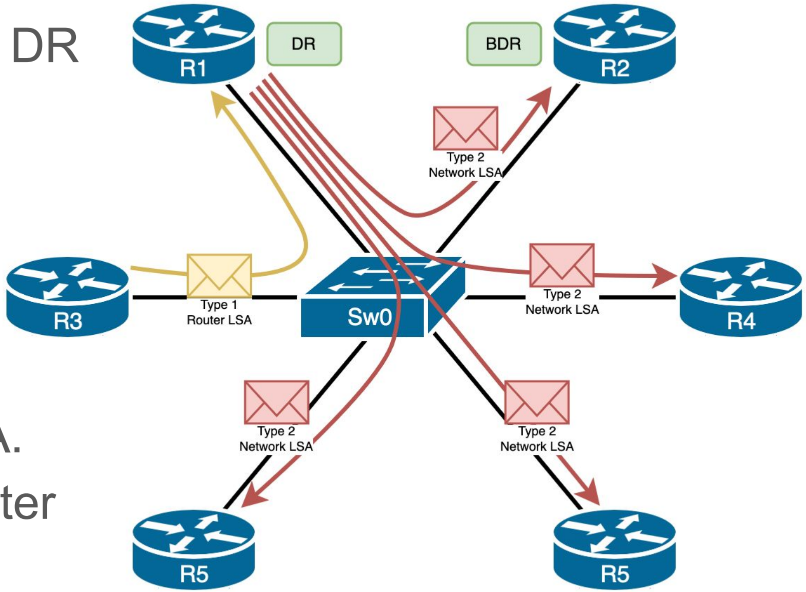
- Creation of multiple adjacencies
  - Ethernet networks could interconnect many OSPF routers over a common link.
  - Creating adjacencies with every router is unnecessary and undesirable.
- Extensive flooding of updates
  - Link-state routers flood their LSU any time OSPF is initialized, or when there is a change in the topology. This flooding can become excessive.



Device count: 6 routers
Number of adjacencies: 6 * (6 - 1) / 2 = 15

Designated Router

- On multi-access networks, OSPF elects a DR to be the collection and distribution point.
  - To manage the number of adjacencies and the flooding of updates.
  - A Backup Designated Router (BDR) is also elected in case the DR fails.
  - All other routers become DROTHERs.
- The DR is only used to propagate the LSA.
- Routers will still use the best next-hop router for forwarding network traffic.



Election Process of Designated Router

- The OSPF DR election decision is based on **priority** and **Router ID**
- The router with the **highest** interface **priority** is the DR.
  - Priority could be any number between **0 – 255**.
  - If the priority is set to 0, the router is **not** capable of becoming the **DR**.
  - The **default** priority of interfaces is 1
- If the interface priorities are equal, then the router with the **highest** Router ID is elected the DR.
- The election is **non-preemptive**
  - It is possible that a router with a lower Router ID becomes the DR
  - Shut down the OSPF process on **all routers**, and then re-enable the OSPF process, to force a new DR/BDR election

Backup Designated Router (BDR)

- The BDR election decision is basically the same as the DR election.
  - BDR would be the one with the highest priority among all DROTHERs.
- If the DR fails, the BDR is automatically promoted to DR.
  - After a BDR is **promoted** to DR, a new BDR election occurs, and the **DROTHER** with the higher priority or Router ID is elected as the **new BDR**.

Configure interface priority

```
R4(config)# interface GigabitEthernet 0/0
R4(config-if)# ip ospf priority 255
R4(config-if)# end
```

Verify OSPF Neighbor

```
R3# show ip ospf neighbor


Neighbor ID     Pri  State            Dead Time   Address        Interface
140.113.0.2       1  FULL/DROTHER     00:00:36    172.16.0.2     Gi0/0
192.168.4.254     1  FULL/DR          00:00:36    172.16.0.4     Gi0/0
```

- R4 has the highest Router ID.
- Note that DR is non-preemptive.
- save and reboot

LSA Type 2 (1/2)

#	Name	Sender	Receiver	Information
Type 1	Router LSA	Any OSPF Router	All other routers in the same area	Link / Network information
Type 2	Network LSA	DR	All other routers in the same area	List of routers that DR connects with
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Type 5	AS External Link	ASBR	All routers in OSPF routing domain	External network
Type 7	NSSA External LSA	ASBR	All the routers in the NSSA	External network

LSA Type 2 (2/2)

- Only exists for networks where there is a DR elected.
- Contains the Router ID and IP address of DR.
  - Along with the Router ID of all other routers in the multi-access segment.
  - Type 2 LSA is created for every multi-access network in the area.
  - To give other routers information about multi-access networks within the same area.
- The DR floods Type 2 LSAs only within the area in which they originated.
  - Type 2 LSAs are not forwarded outside of an area.
- Link State ID for a network LSA is the IP interface address of the DR that advertises it.

Verify LSA Type 2 (1/2)

```
R1# show ip ospf 42 database network
    OSPF Router with ID (140.113.0.1) (Process ID 42)
          Net Link States (Area 0)
LS Type: Network Links
Link State ID: 10.113.0.2  (address of Designated Router)
Advertising Router: 140.113.0.2
Network Mask: /24
      Attached Router: 140.113.0.1
      Attached Router: 140.113.0.2


[...]
```

Link 1: R1 and R2

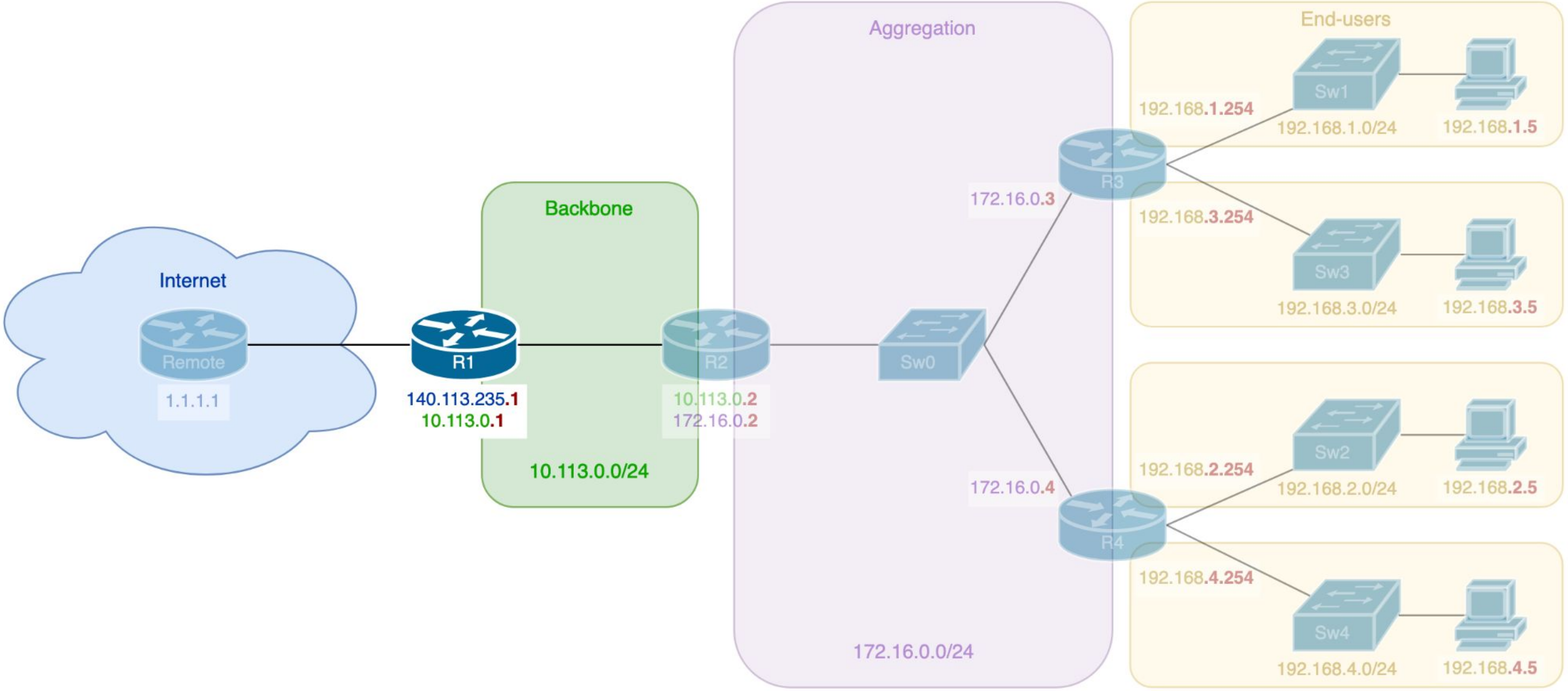
Verify LSA Type 2 (2/2)

```
[...]

LS Type: Network Links
Link State ID: 172.16.0.4   (address of Designated Router)
Advertising Router: 192.168.4.254
Network Mask: /24
      Attached Router: 140.113.0.2
      Attached Router: 192.168.3.254
      Attached Router: 192.168.4.254
```

Link 2: R2, R3, R4

Default Route



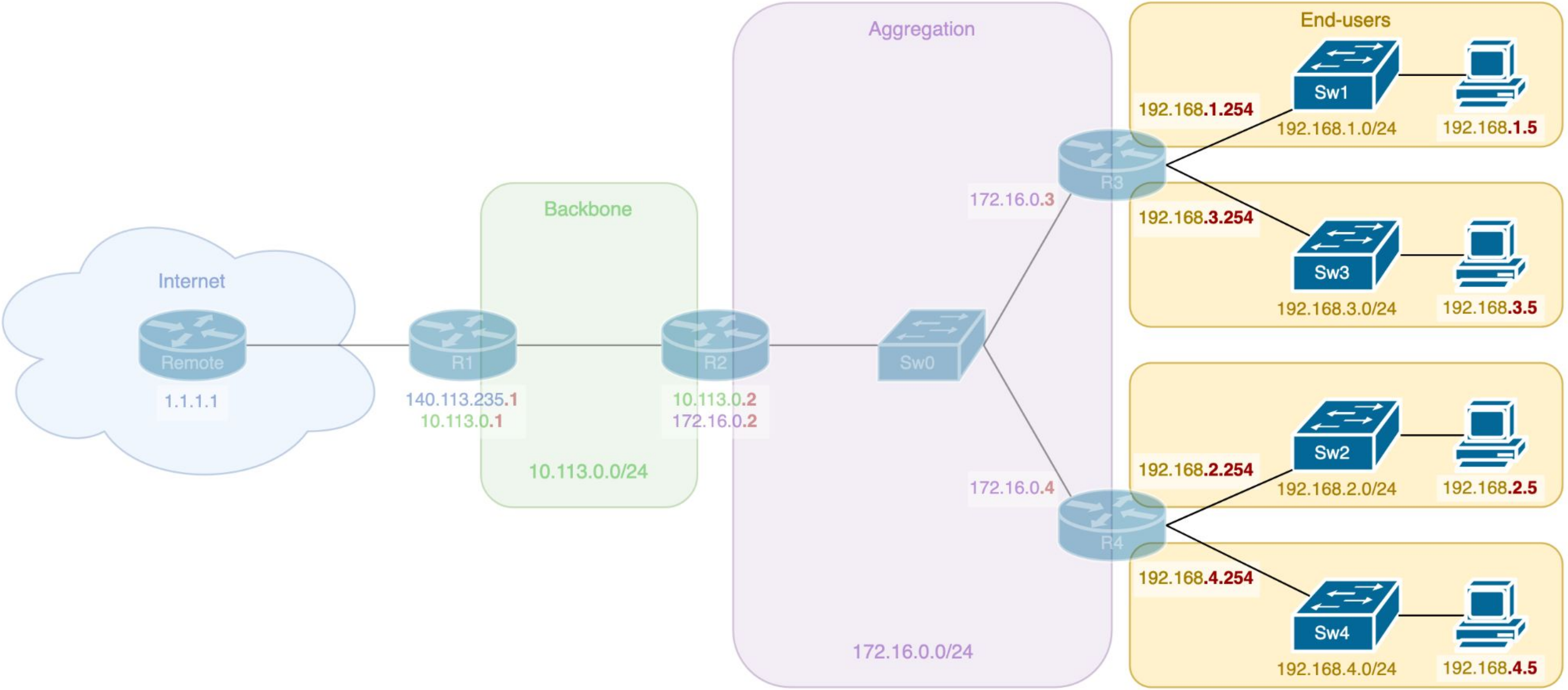
Propagating Default Route

- A router can propagate a **default route** to other routers with OSPF
- For the board router located between the OSPF routing domain and the external network.

Configure Propagating Default Static Route

```
R1(config)# ip route 0.0.0.0 0.0.0.0 GigabitEthernet 0/0
R1(config)# router ospf 42
R1(config-router)# default-information originate
R1(config-router)# end
```

Edge Devices



Passive Interfaces

- Prevent the transmission of routing messages through a specific interface.
  - For security and save the bandwidth.
- All interfaces can be made passive by default.
  - Interfaces that should not be passive can be manually enabled.

Method #1: Configure passive interfaces

```
R3(config-router)# passive-interface GigabitEthernet 0/1
R3(config-router)# passive-interface GigabitEthernet 0/2
```

Method #2: Made passive by default

```
R3(config-router)# passive-interface default
R3(config-router)# no passive-interface GigabitEthernet 0/0
```

Recap: Routing Table

Source	Destination network		AD		Metric		Next-hop	Timestamp	Outgoing interface
D	140.113.235.0/24	[	110	/	2	] via	10.0.1.24,	00:00:42,	Gi0/24

- **Route source**: how the route was learned
- **Destination network**: the destination of the packets
- **Administrative distance (AD)**
  - the trustworthiness of the route source
  - the lower value, the more preferred route source
- **Metric**
  - the value assigned to reach the remote network
  - the lower value, the more preferred route
- **Next-hop**: where the router should send to
- **Route timestamp**: after the route was learned
- **Outgoing interface**: the exit interface to forward packets

OSPF Metric

- The metric (cost) would be higher for low bandwidth links.
- `metric = max(1, ref_bw / if_bw)`
- A lower metric indicates a better path.

Interface Type	Reference Bandwidth in bps		Default Bandwidth in bps	Cost
10 Gigabit Ethernet 10 Gbps	100,000,000	÷	10,000,000,000	1
Gigabit Ethernet 1 Gbps	100,000,000	÷	1,000,000,000	1
Fast Ethernet 100 Mbps	100,000,000	÷	100,000,000	1
Ethernet 10 Mbps	100,000,000	÷	10,000,000	10
Serial 1.544 Mbps	100,000,000	÷	1,544,000	64
Serial 128 kbps	100,000,000	÷	128,000	781
Serial 64 kbps	100,000,000	÷	64,000	1562

Same Cost due to reference bandwidth

Adjusting the Reference Bandwidth

- OSPF uses a reference bandwidth of **100 Mbps** for any links.
    - **Too low** in a modern network environment.
- Changing the reference bandwidth does not actually affect the **bandwidth.**
    - Simply **affects** the **calculation** used to determine the metric.
- The reference bandwidth must be configured **on every router** in the OSPF **domain.**

Configure Reference Bandwidth to 10 Gbps

```
R2(config)# router ospf 42
R2(config-router)# auto-cost reference-bandwidth 10000
```

Bandwidth in **Mbps**

Default Interface Bandwidth Value

- All interfaces have default bandwidth values assigned to them.
- Administrators can modify the bandwidth value on each interface.
- The bandwidth value should reflect the actual speed of the link.
- This value does not affect the actual speed or capacity of the link.

Configure Interface Bandwidth to 100 Mbps

```
R2(config)# int GigaEthernet 0/1
R2(config-if)# bandwidth 100000
```

Bandwidth in **Kbps**

Manually Setting the OSPF Cost

- Administrators can **also** manually modify the **cost** of each interface.
- Useful in **multi-vendor** environments.
  - Non-Cisco routers may use a metric other than bandwidth to calculate the costs.
- Both the `bandwidth` and the `ip ospf cost` command in interface config mode achieve the same result.
- It's recommended to use `ip ospf cost` method in most case.

```
R2(config)# interface GigabitEthernet 0/1
R2(config-if)# ip ospf cost 100
```

OSPF Accumulates Costs

The cost of an OSPF route is the **accumulated value** from one router to the destination network.

```
R2# show ip route 192.168.1.5
Routing entry for 192.168.1.0/24
Known via "ospf 42", distance 110, metric 101, type intra area
  Last update from 172.16.0.3 on GigabitEthernet0/0, 00:00:20 ago
  Routing Descriptor Blocks:
  * 172.16.0.3, from 192.168.3.254, 00:00:20 ago, via GigabitEthernet0/0
      Route metric is 101, traffic share count is 1
```

Also try it on R1, what’s the difference?

OSPF Messages Encapsulation

Ethernet Header	IP Header	OSPF Header	**OSPF Packet Data**

- Ethernet Frame Header (L2. Data link layer)
  - Destination MAC address: **01:00:5E:00:00:05** (ALL) or **01:00:5E:00:00:06** (DR/BDR)
- IPv4 Packet Header (L3. Network layer)
  - Destination IP address (multicast): **224.0.0.5** or **224.0.0.6**
  - Protocol number: OSPF (89)
- OSPF Header (L7. Application layer)
  - Includes OSPF Packet Type, Router ID, Area ID, etc.
- **OSPF Packet Data**

OSPF Packet Types

OSPF uses the following packets to establish and maintain neighbor adjacencies and exchange routing updates.

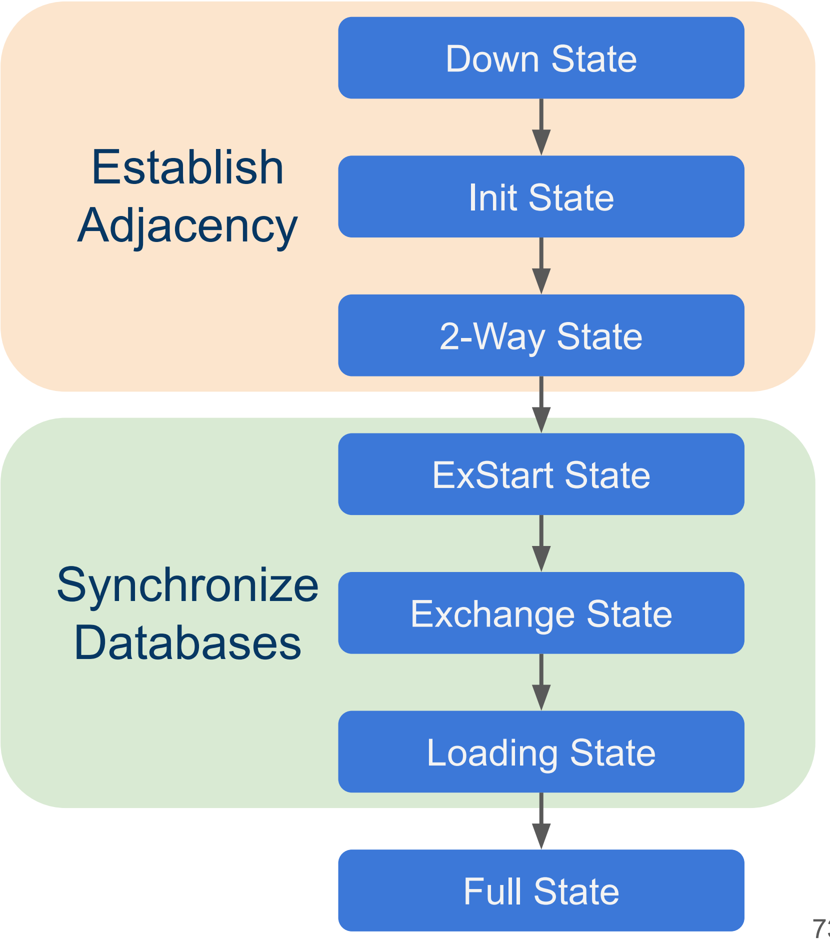
- Type 1. Hello packet
  - Used to establish and maintain adjacency with other OSPF routers.
- Type 2. Database Description (DBD) packet
  - Contains the summary of the Link State info in the router database.
- Type 3. Link State Request (LSR) packet
  - When there are missing entries in the DBD, routers request details by sending an LSR.
- Type 4. Link State Update (LSU) packet
  - Used to reply to LSR and to announce new information.
- Type 5. Link State Acknowledgment (LSAck) packet
  - Used to confirm receipt of the LSU.

LSA Types

#	Name	Sender	Receiver	Information
Type 1	Router LSA	Any OSPF Router	All other routers in the same area	Link / Network information
Type 2	Network LSA	DR	All other routers in the same area	List of routers that DR connects with
Type 3	Summary LSA	ABR	All routers in the different area	Network information of other areas
Type 4	Summary ASBR LSA	ABR	All routers in OSPF routing domain	Information of ASBR
Type 5	AS External Link	ASBR	All routers in OSPF routing domain	External network
Type 7	NSSA External LSA	ASBR	All the routers in the NSSA	External network

Neighbor States

- Hello Packet vs. Link State Packet
- How OSPF transmits “LSA” data.
- OSPF Packet Types vs. LSA Types



Thanks

- Reference: RFC 2328 (OSPF)
- Thanks to ChatGPT for clarifying concepts.
- Next Week: Multi-Area OSPF