Networking — Network layer

Three concepts

- **Naming**
  - A way to identify the source/destination
  - E.g., house address
- **Routing**
  - Finding “how to” move towards the destination
  - E.g., which airplane should the stuff go on
- **Forwarding**
  - Actually “moving” towards the destination
  - E.g., Using airplane/truck/rail

Network layer — Forwarding

Network layer — Forwarding

Lets come up with an approach? Generalize Ethernet ideas?

Network layer — Forwarding

Network layer — Forwarding

Attempt 1: Broadcast

Network layer — Forwarding

Attempt 1: Broadcast

- **Send to everybody**

Network layer — Forwarding

Attempt 1: Broadcast

- **Send to everybody**
- **Goods**

Network layer — Forwarding

Attempt 1: Broadcast

- **Send to everybody**
- **Goods**
    - Oh, well, simplicity

Network layer — Forwarding

Attempt 1: Broadcast

- **Send to everybody**
- **Goods**
    - Oh, well, simplicity
- **Not-so-goods**

Network layer — Forwarding

Attempt 1: Broadcast

- **Send to everybody**
- **Goods**
    - Oh, well, simplicity
- **Not-so-goods**
    - Oh, well, everything else

Network layer — Forwarding

Attempt 1: Broadcast

- **Send to everybody**
- **Goods**
    - Oh, well, simplicity
- **Not-so-goods**
    - Oh, well, everything else
    - Bandwidth overheads

Network layer — Forwarding

Network layer — Forwarding

Attempt 2: Time division Multiplexing

Network layer — Forwarding

Attempt 2: Time division Multiplexing

- **Each source-destination pair assigned a time slot**

Network layer — Forwarding

Attempt 2: Time division Multiplexing

- **Each source-destination pair assigned a time slot**
    - Can send data only during that slot

Network layer — Forwarding

Attempt 2: Time division Multiplexing

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Network layer — Forwarding

Attempt 2: Time division Multiplexing

- **Each source-destination pair assigned a time slot**
    - Can send data only during that slot
- **Goods**
    - No collisions

Network layer — Forwarding

Attempt 2: Time division Multiplexing

- **Each source-destination pair assigned a time slot**
    - Can send data only during that slot
- **Goods**
    - No collisions
- **Not-so-goods**

Network layer — Forwarding

Attempt 2: Time division Multiplexing

- **Each source-destination pair assigned a time slot**
    - Can send data only during that slot
- **Goods**
    - No collisions
- **Not-so-goods**
    - Underutilization of resources

Network layer — Forwarding

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)
- **Goods**

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)
- **Goods**
    - Predictable performance

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
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- **Goods**
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Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
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- **Goods**
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Network layer — Forwarding

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**
    - Transmit data using the reserved resources

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**
    - Transmit data using the reserved resources
- **Source tears down connection**

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**
    - Transmit data using the reserved resources
- **Source tears down connection**
    - Free resources for others to use

Network layer — Forwarding

Network layer — Forwarding

Circuit Switching

Network layer — Forwarding

Circuit Switching

- **Goods:**

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
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- **Not-so-goods**

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization
    - Blocked connections

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization
    - Blocked connections
    - Connection set up overheads

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization
    - Blocked connections
    - Connection set up overheads
    - Per-connection state in switches (scalability problem)

Network layer — Forwarding

Network layer — Forwarding

Attempt 4: Packet Switching

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
- **Put destination address in the header of each packet**

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
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Network layer — Forwarding

Attempt 4: Packet Switching

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- **Each device stores a “look-up table”**

Network layer — Forwarding

Attempt 4: Packet Switching

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    - Whats the next hop towards the destination?

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
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- **Each device stores a "look-up table"**
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- **Destination receives the packet(s)**

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
- **Put destination address in the header of each packet**
    - Just like shipping stuff
- **Each device stores a "look-up table"**
    - Whats the next hop towards the destination?
- **Destination receives the packet(s)**
    - And reconstructs the message

Network layer — Forwarding

Network layer — Forwarding

Packet Switched forwarding

Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**

Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**
- **Each router has a “look-up table” (forwarding information base)**

Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**
- **Each router has a “look-up table” (forwarding information base)**
    - What should be stored in this table?

Network layer — Forwarding

Packet Switched forwarding

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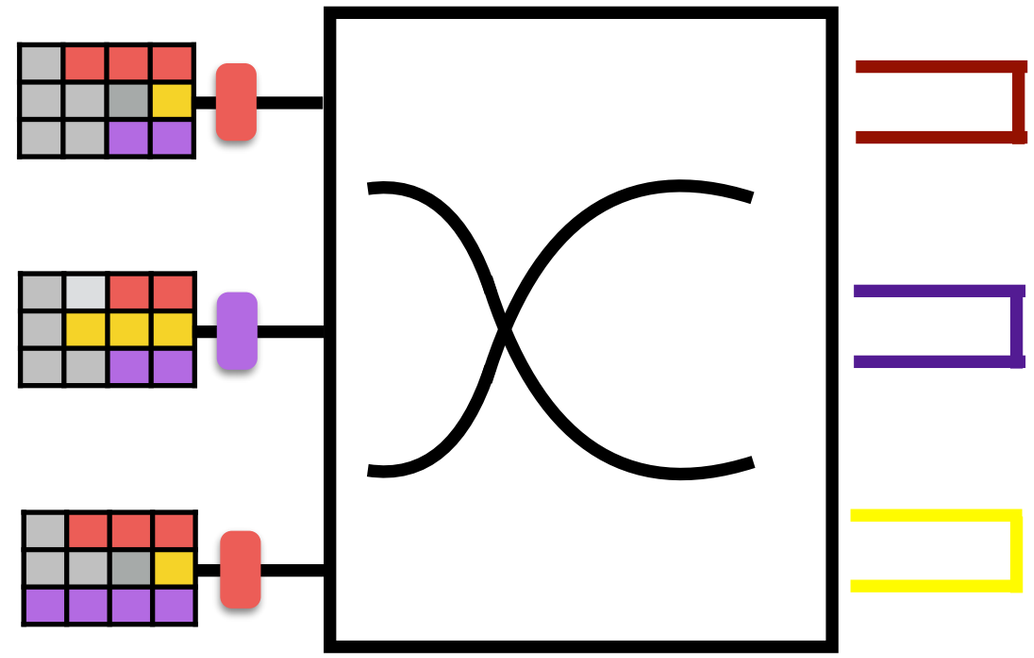
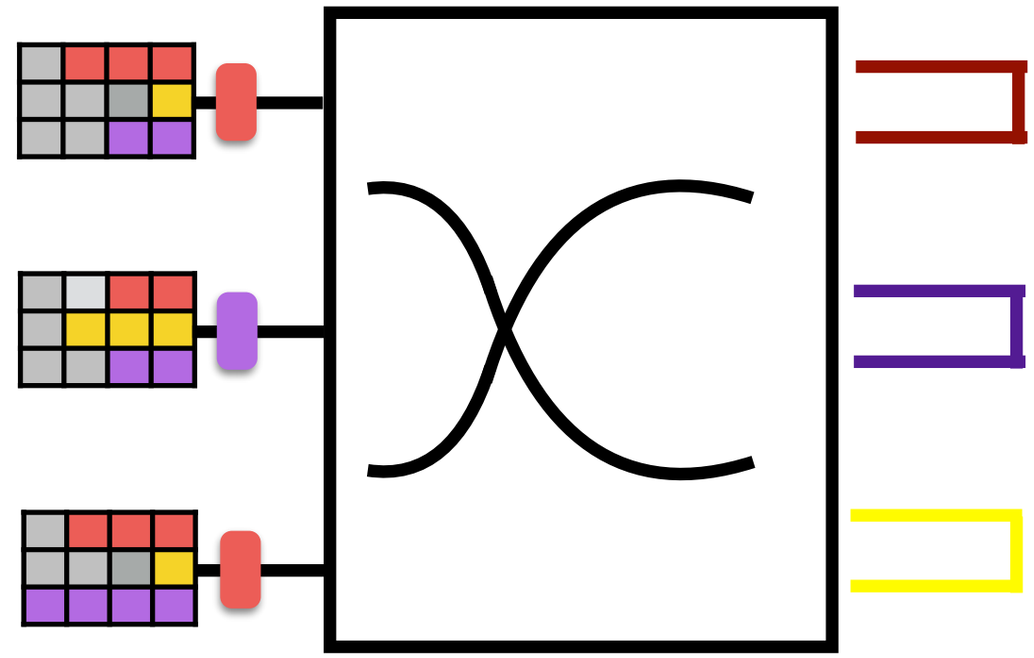


Network layer — Forwarding

Packet Switched forwarding

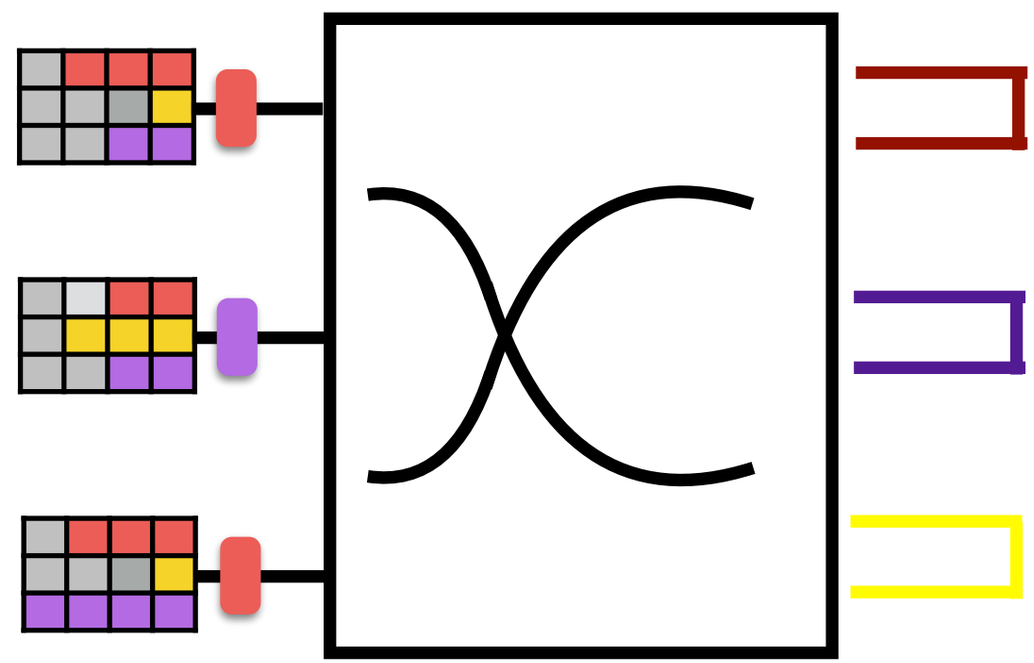
- **Hop-by-hop forwarding**
- **Each router has a "look-up table" (forwarding information base)**
    - What should be stored in this table?
    - Prefix-based forwarding **(longest-prefix matching)**



Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**
- **Each router has a "look-up table" (forwarding information base)**
    - What should be stored in this table?
    - Prefix-based forwarding **(longest-prefix matching)**
    - Maps **prefixes** to the next-hop



Network layer — Forwarding

Network layer — Forwarding

Packet Switching

Network layer — Forwarding

Packet Switching

- **Goods:**

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem
    - No per-connection state

Network layer — Forwarding

Packet Switching

- **Goods:**
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        - A source can send more if others don’t use resources
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Network layer — Forwarding

Packet Switching

- **Goods:**
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Network layer — Forwarding

Packet Switching

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    - Packet header overhead

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem
    - No per-connection state
    - No set-up cost
- **Not-so-goods:**
    - Packet header overhead
    - Network failures become a problem

Networking — Network layer

Three concepts

- **Naming**
    - A way to identify the source/destination
    - E.g., house address
- **Routing**
    - Finding “how to” move towards the destination
    - E.g., which airplane should the stuff go on
- **Forwarding**
    - Actually “moving” towards the destination
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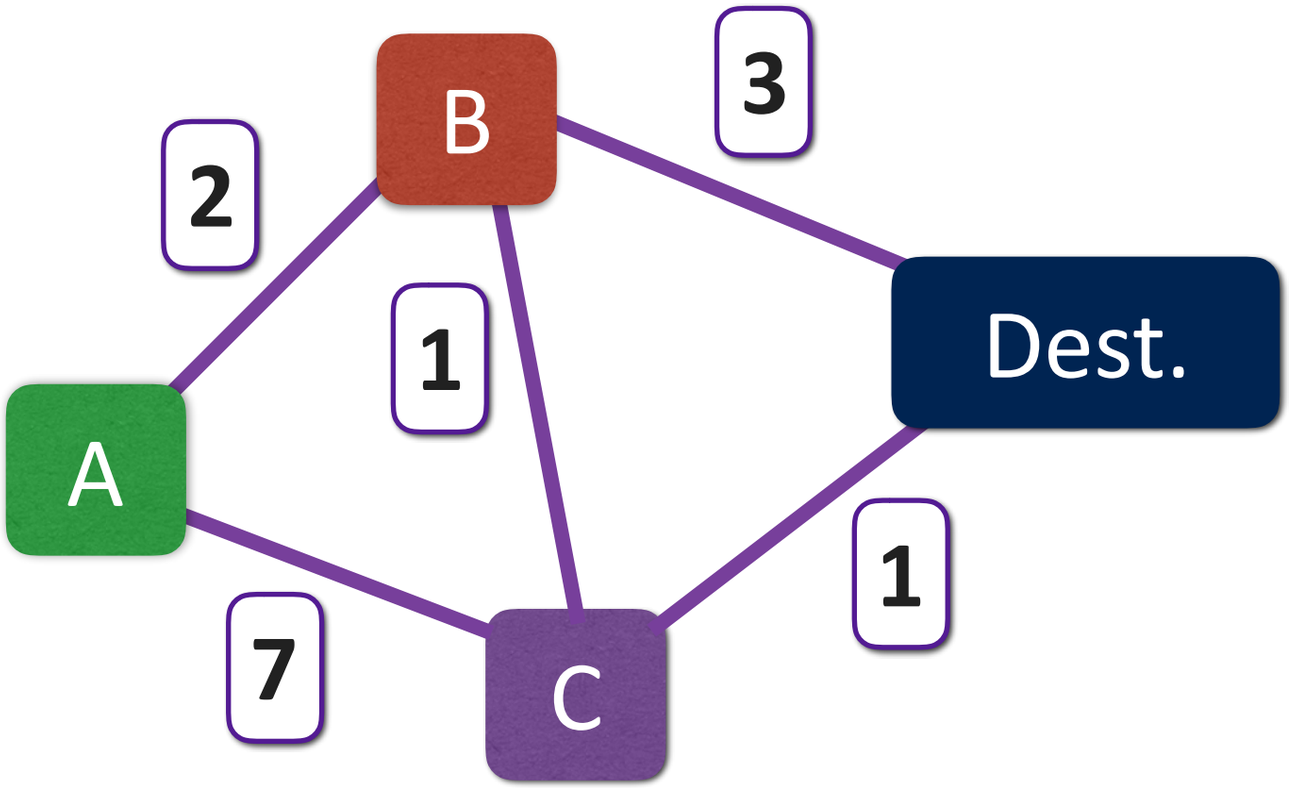
Network layer — Example

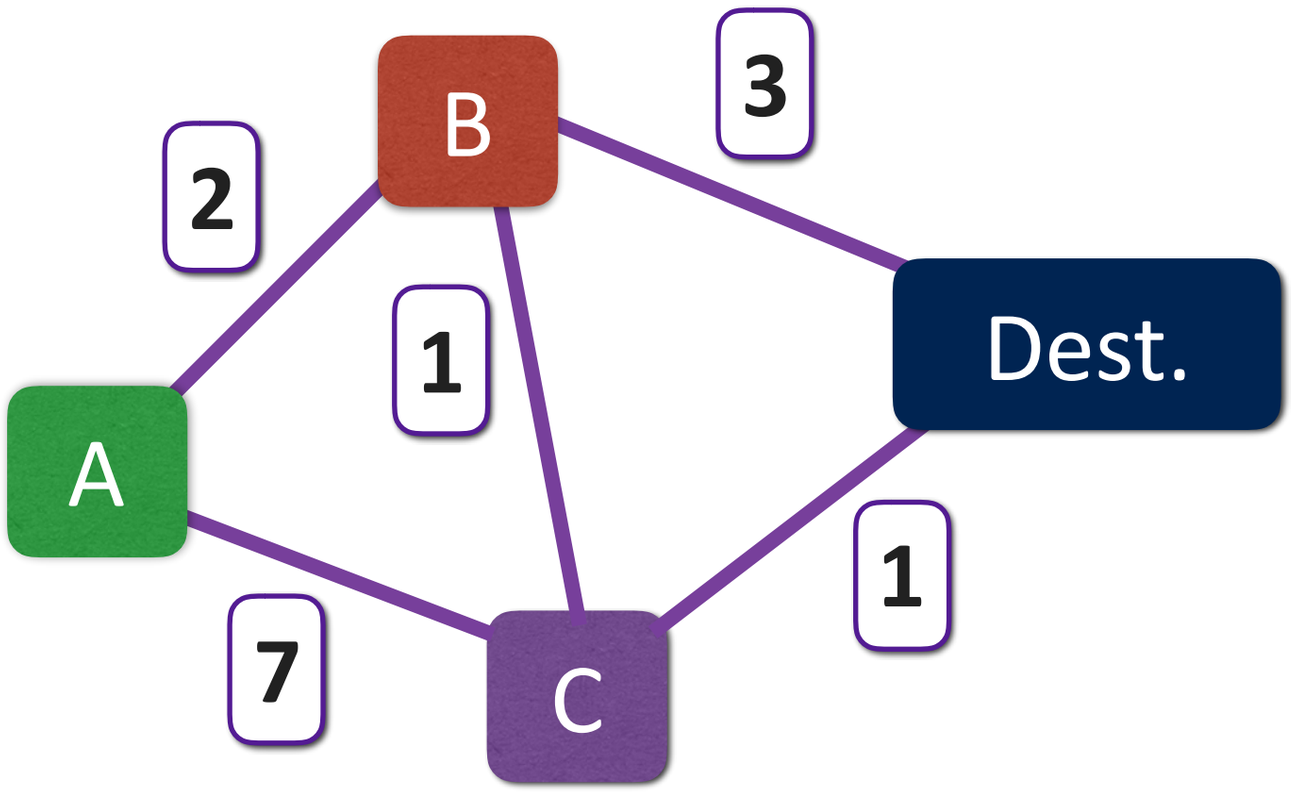


Network layer — Routing

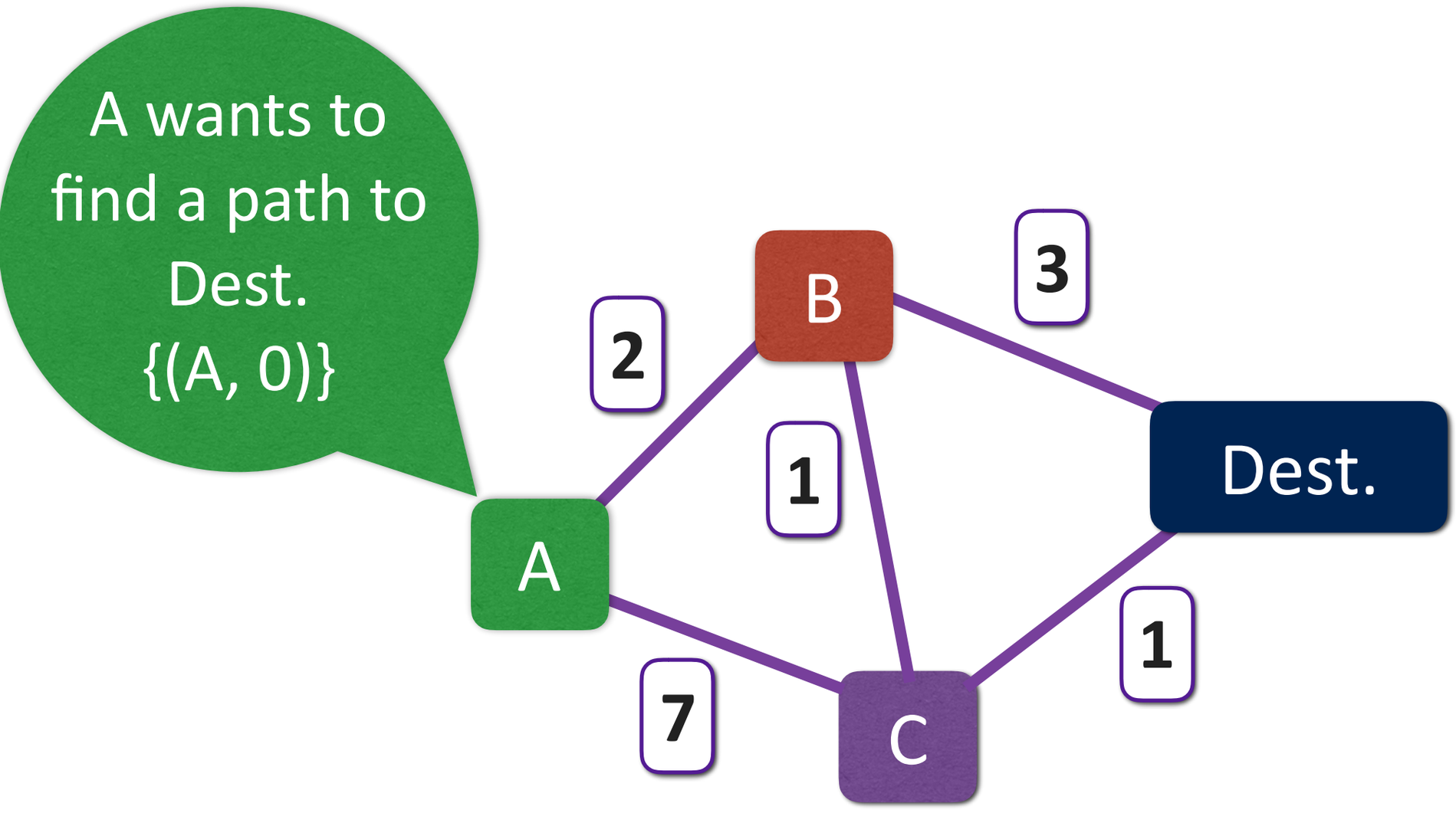
Network layer — Routing

Lets come up with a routing scheme

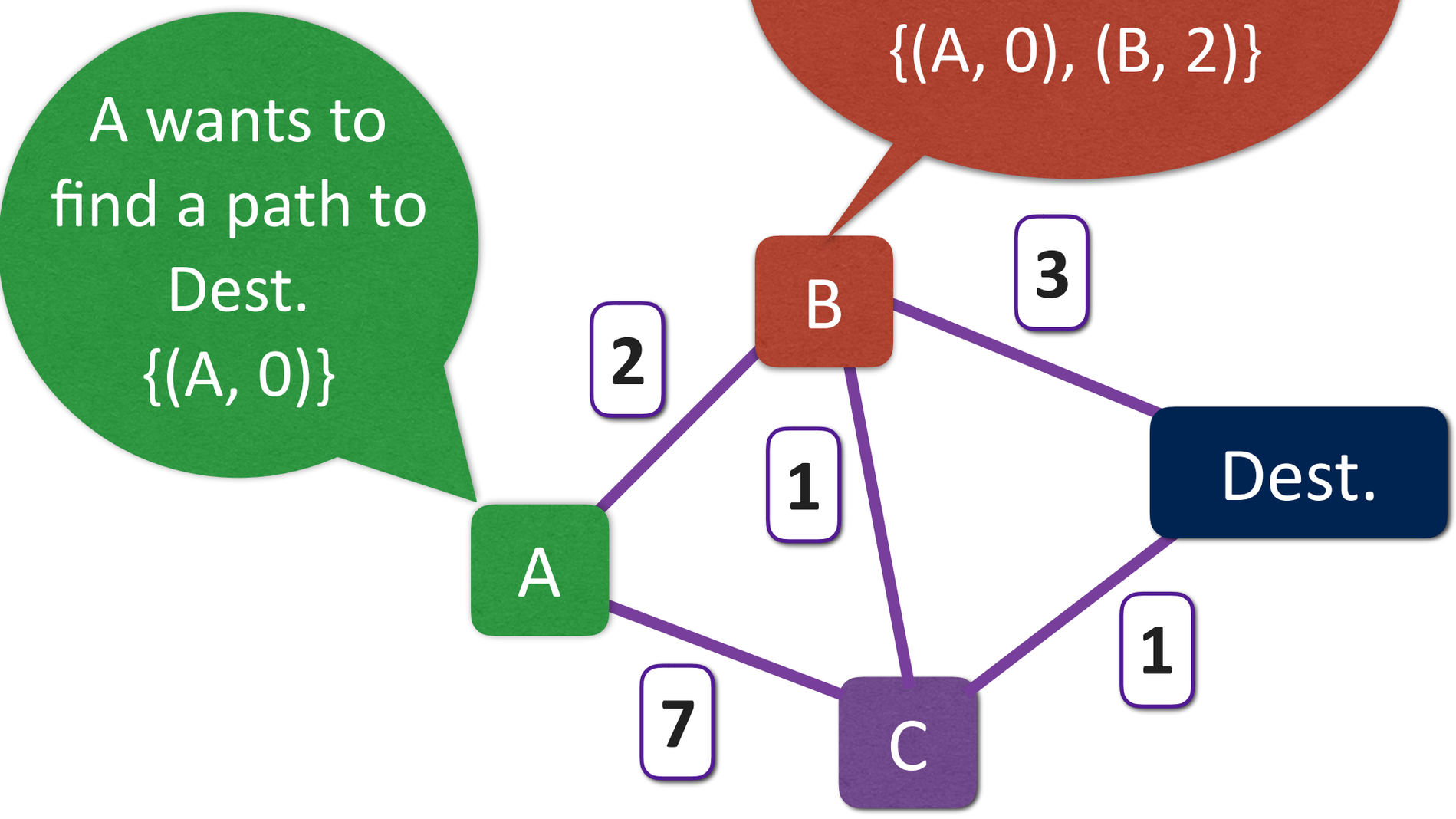
Network layer — Routing



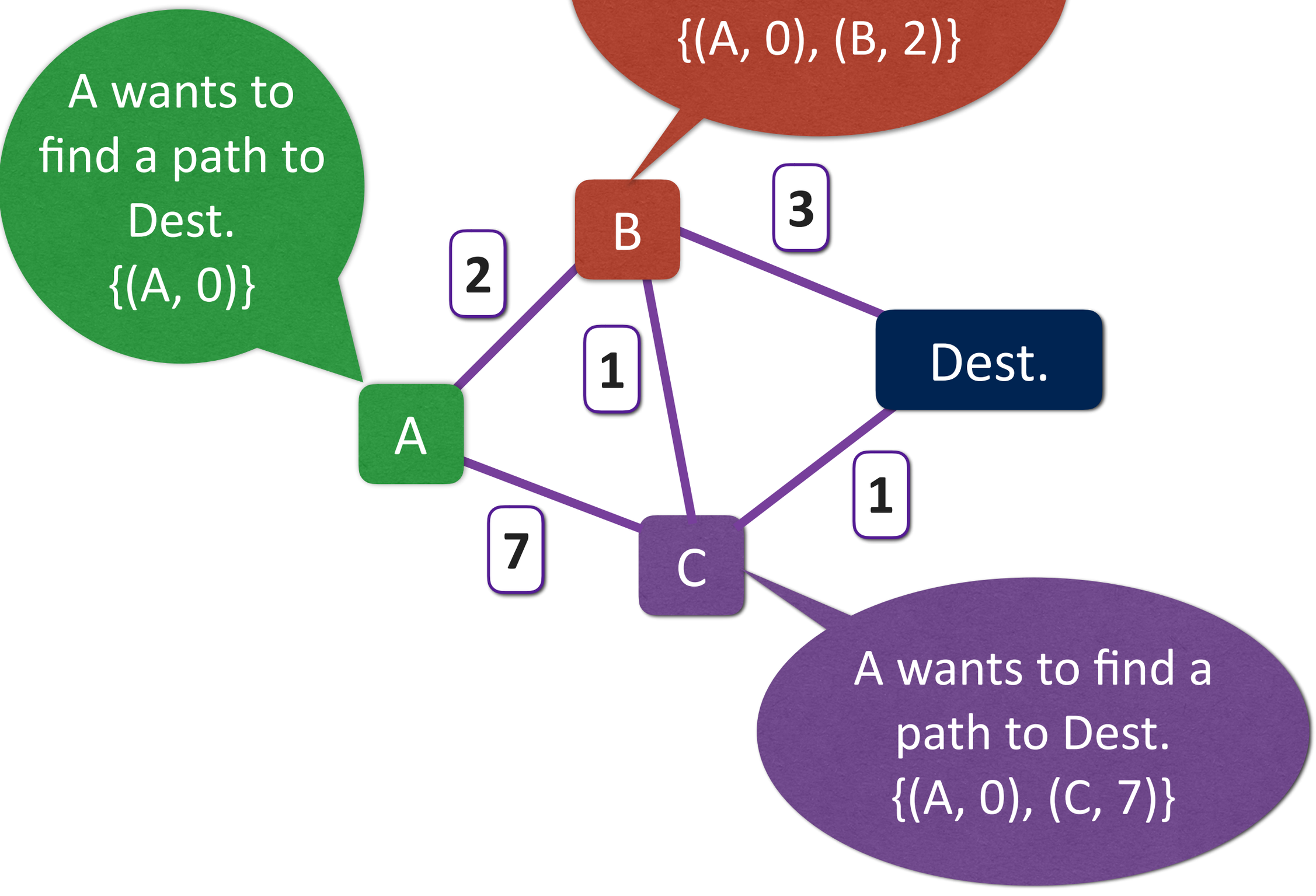
Network layer — Routing



Network layer — Routing



Network layer — Routing



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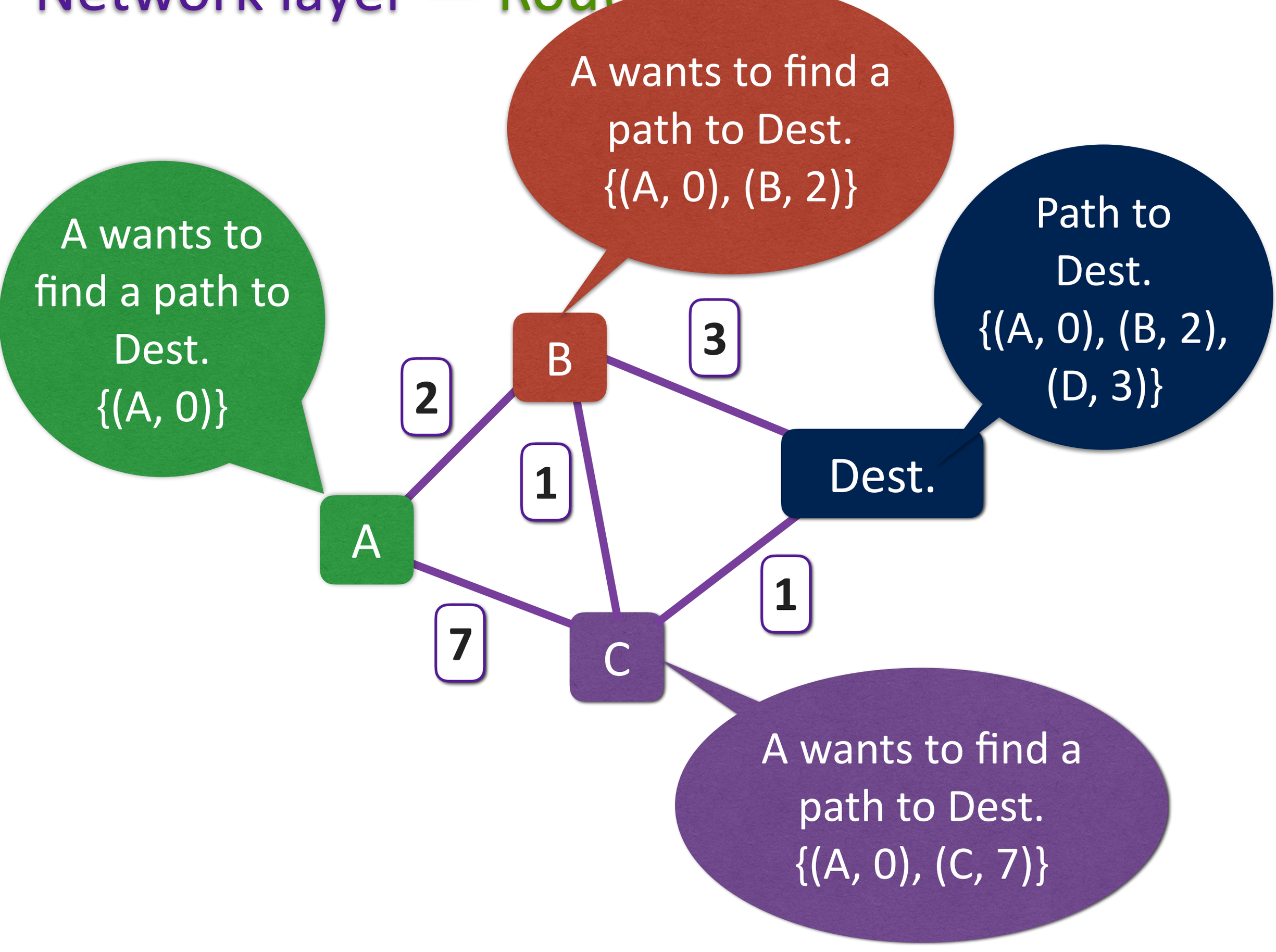

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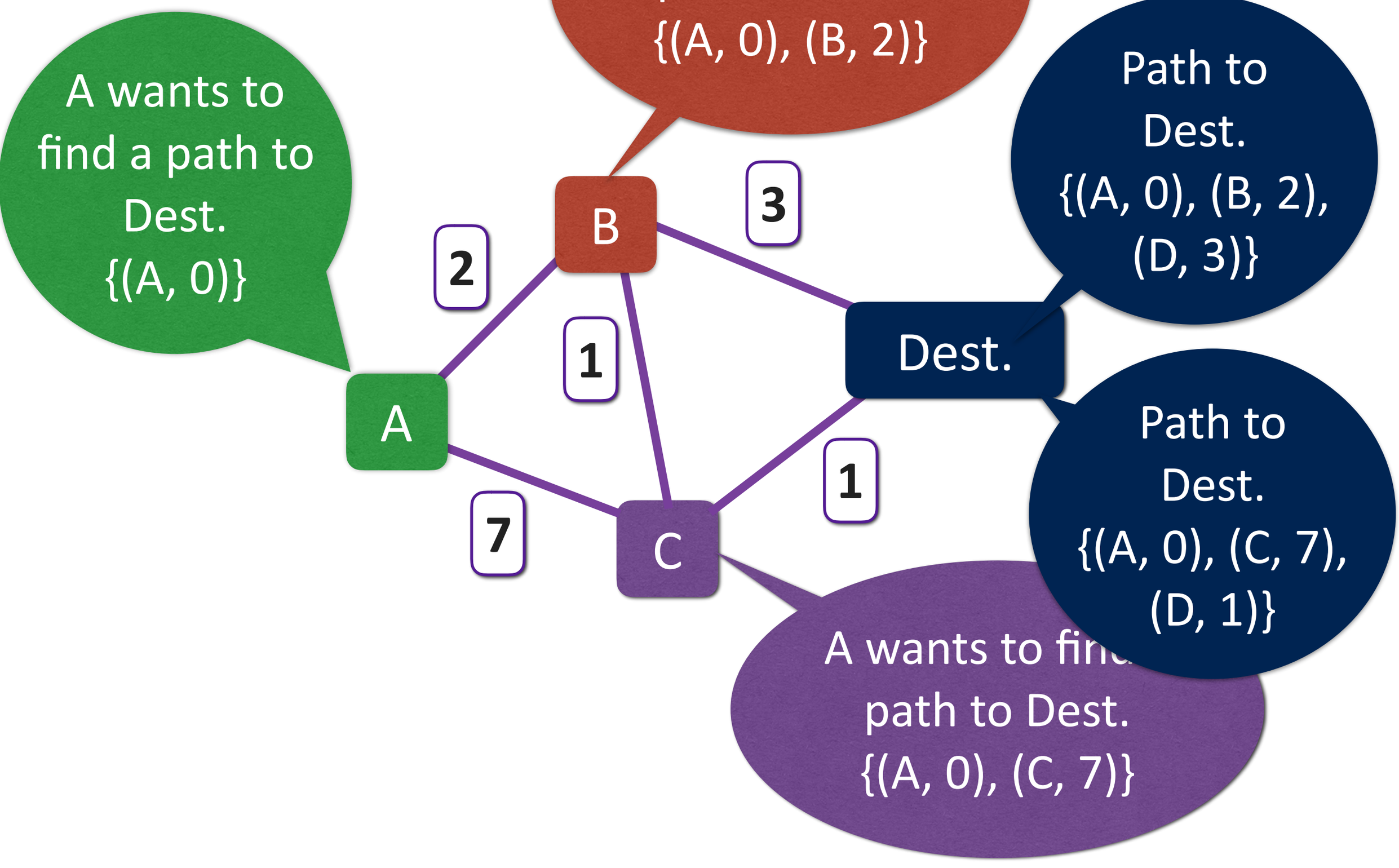

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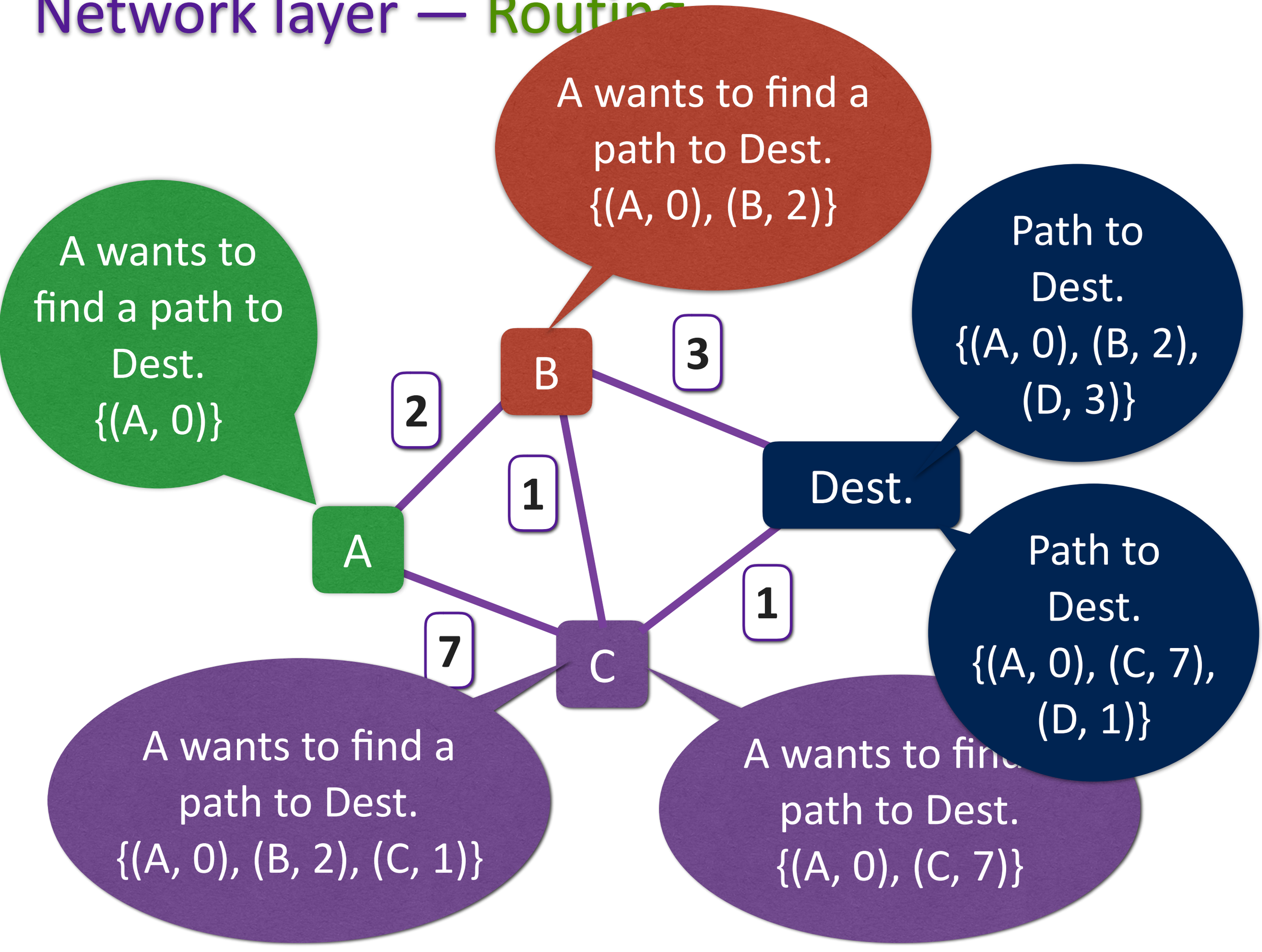
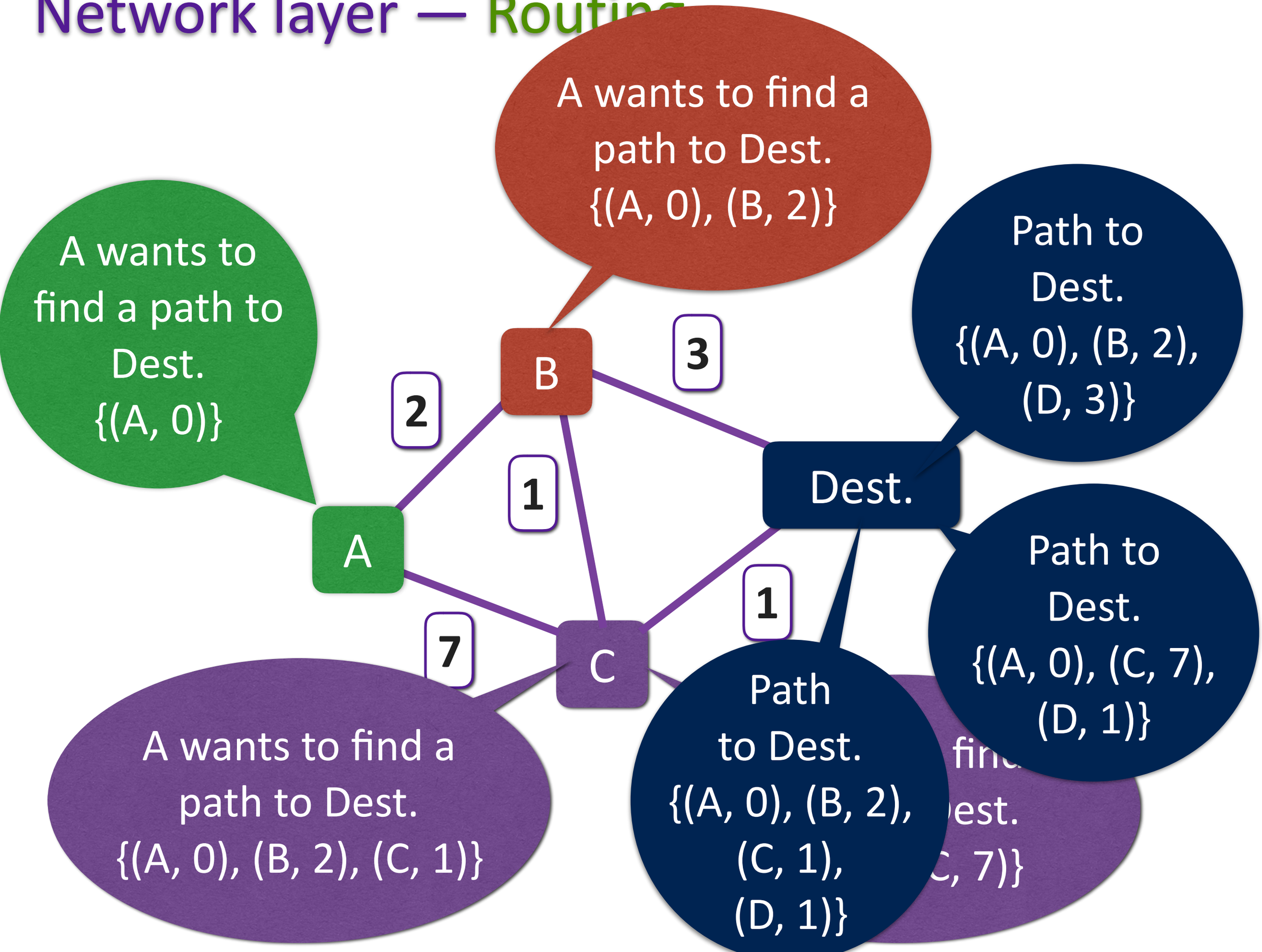


Network layer — Routing



Network layer — Routing

Network layer — Routing

Attempt 1: Dynamic Source Routing

Network layer — Routing

Attempt 1: Dynamic Source Routing

- **Broadcast a Route Request Packet for destination d**

Network layer — Routing

Attempt 1: Dynamic Source Routing

- **Broadcast a Route Request Packet for destination d**
    - Put source ID in the packet header

Network layer — Routing

Attempt 1: Dynamic Source Routing

- **Broadcast a Route Request Packet for destination d**
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- **At each router**

Network layer — Routing

Attempt 1: Dynamic Source Routing

- **Broadcast a Route Request Packet for destination d**
    - Put source ID in the packet header
- **At each router**
    - If a path not known to the destination

Network layer — Routing

Attempt 1: Dynamic Source Routing

- **Broadcast a Route Request Packet for destination d**
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- **At each router**
    - If a path not known to the destination
        - Put its {ID, cost} in the packet header

Network layer — Routing

Attempt 1: Dynamic Source Routing

- **Broadcast a Route Request Packet for destination d**
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- **At each router**
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Network layer — Routing

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Network layer — Routing

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- Else
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Network layer — Routing

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Network layer — Routing

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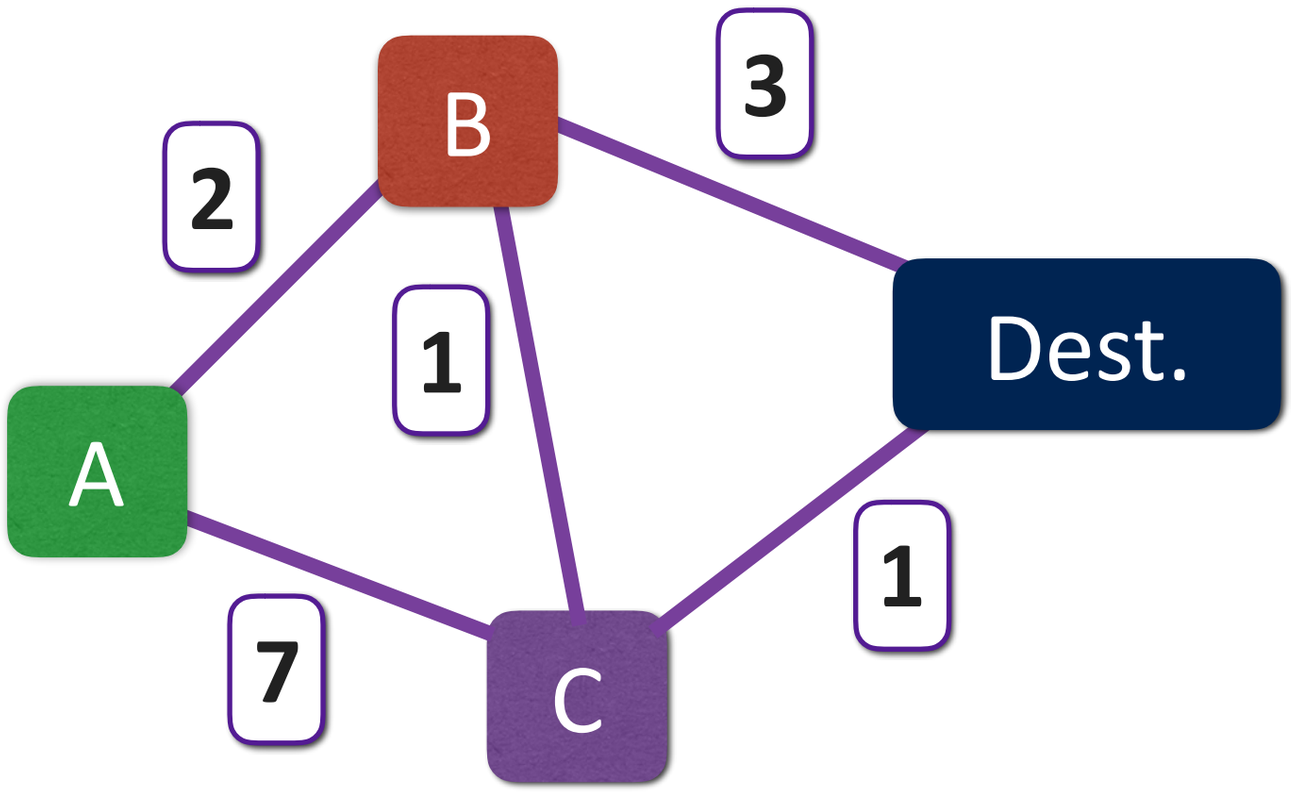
- **Challenge?**

Network layer — Routing



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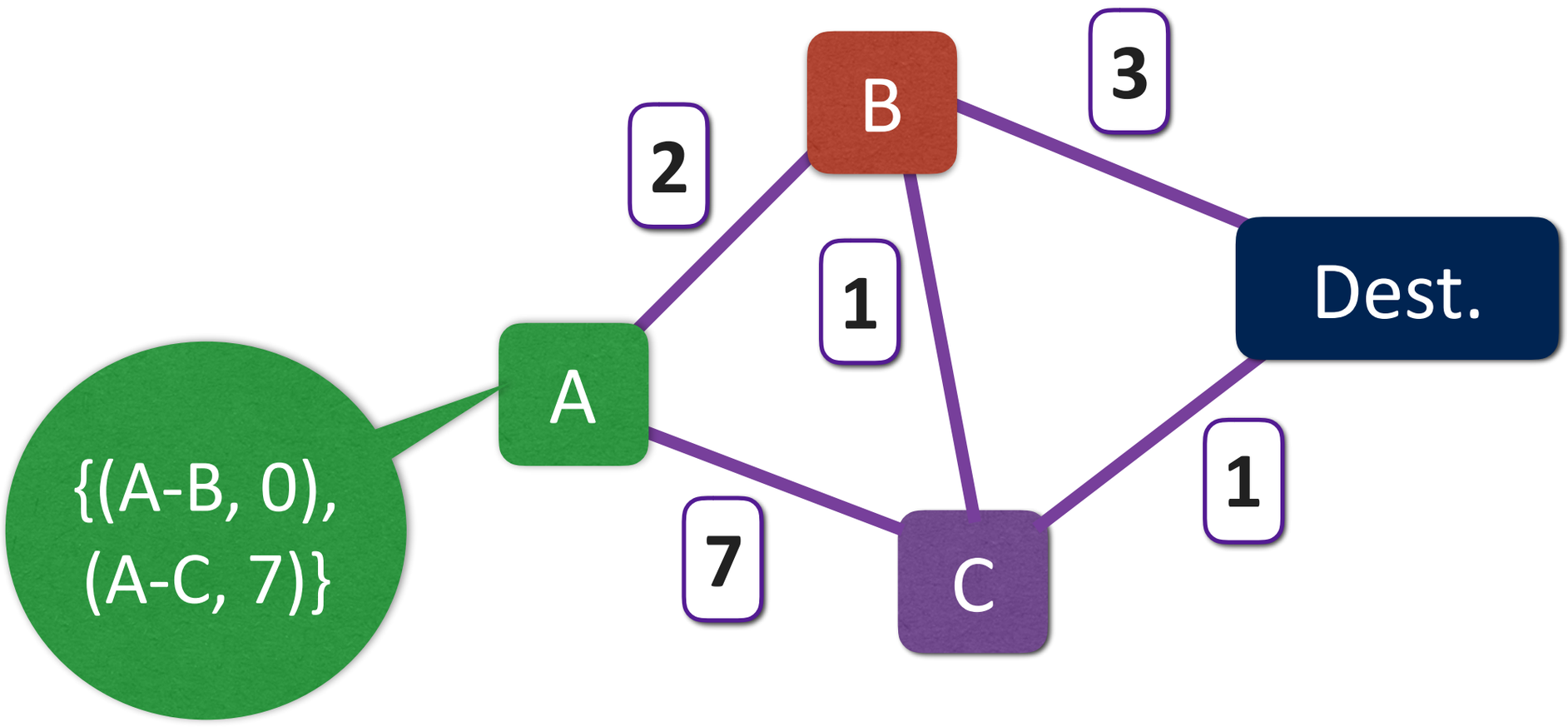

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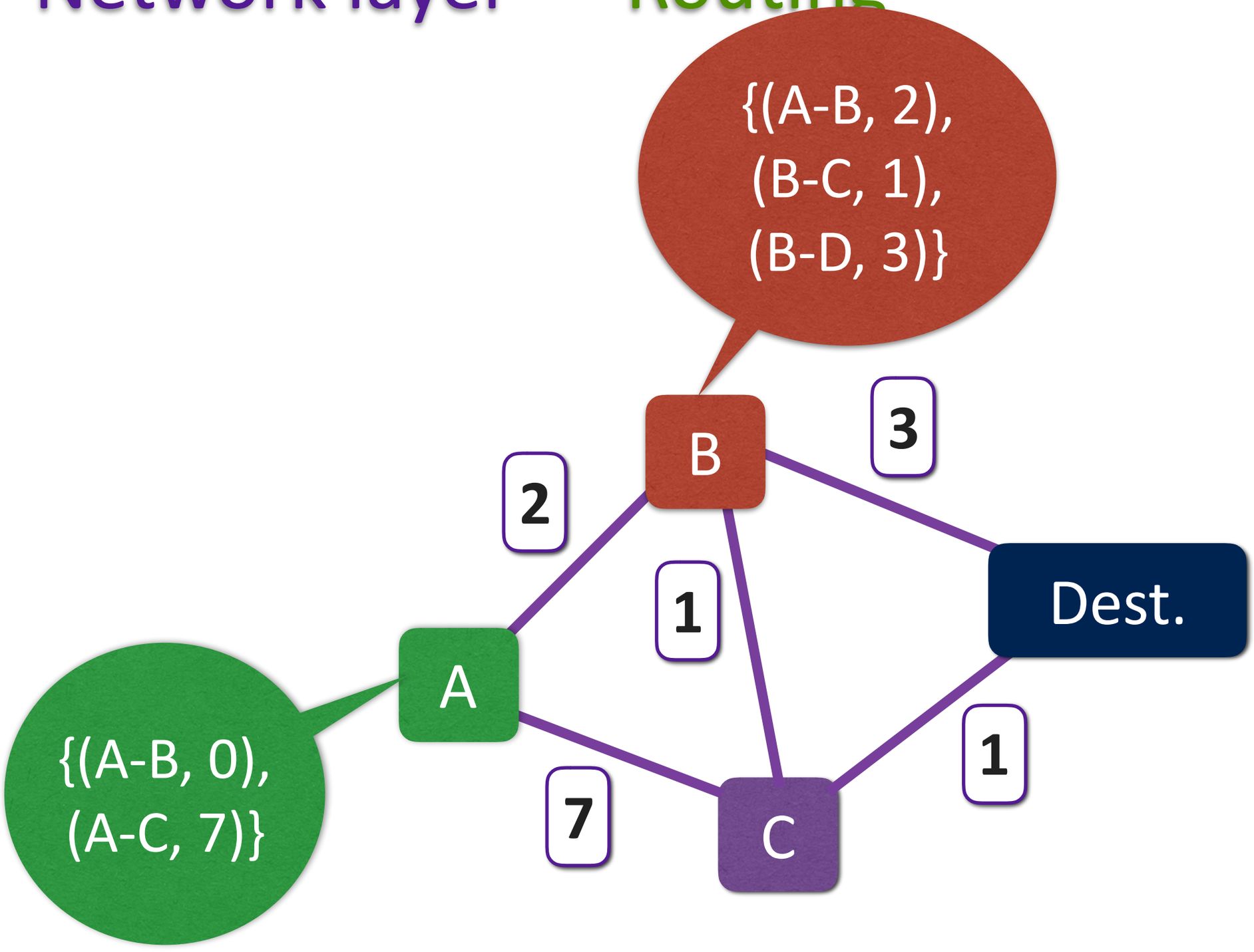

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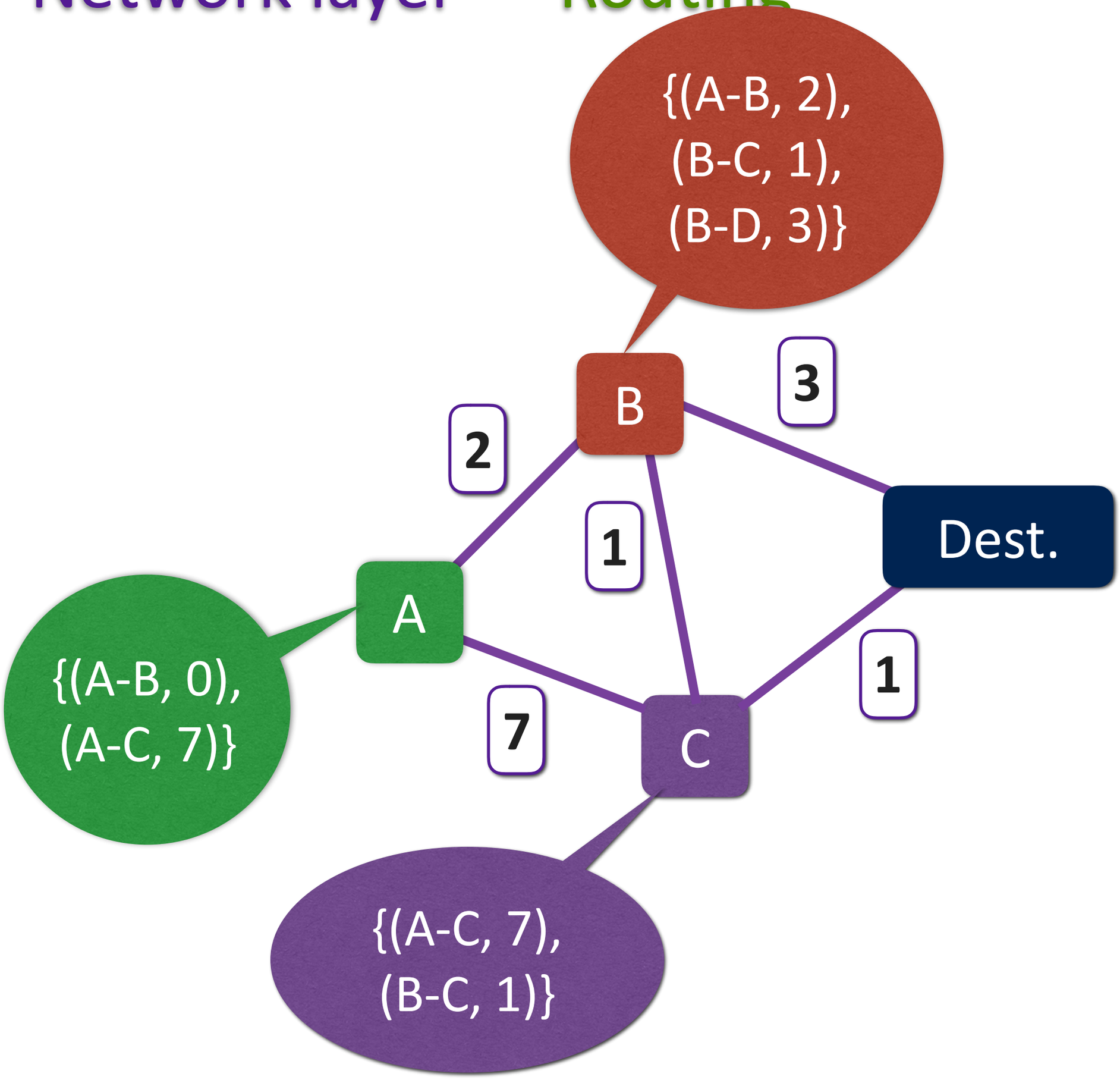

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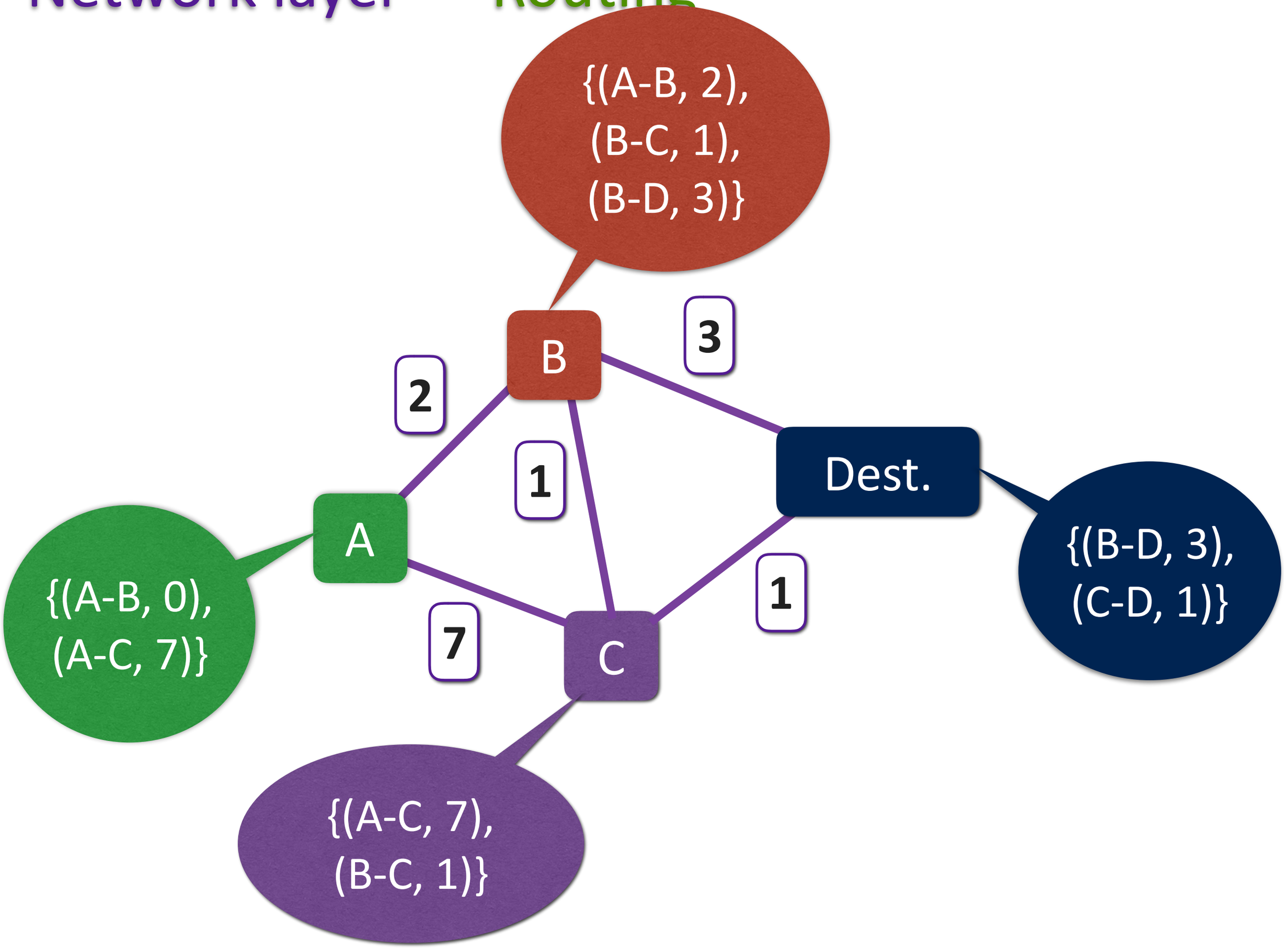

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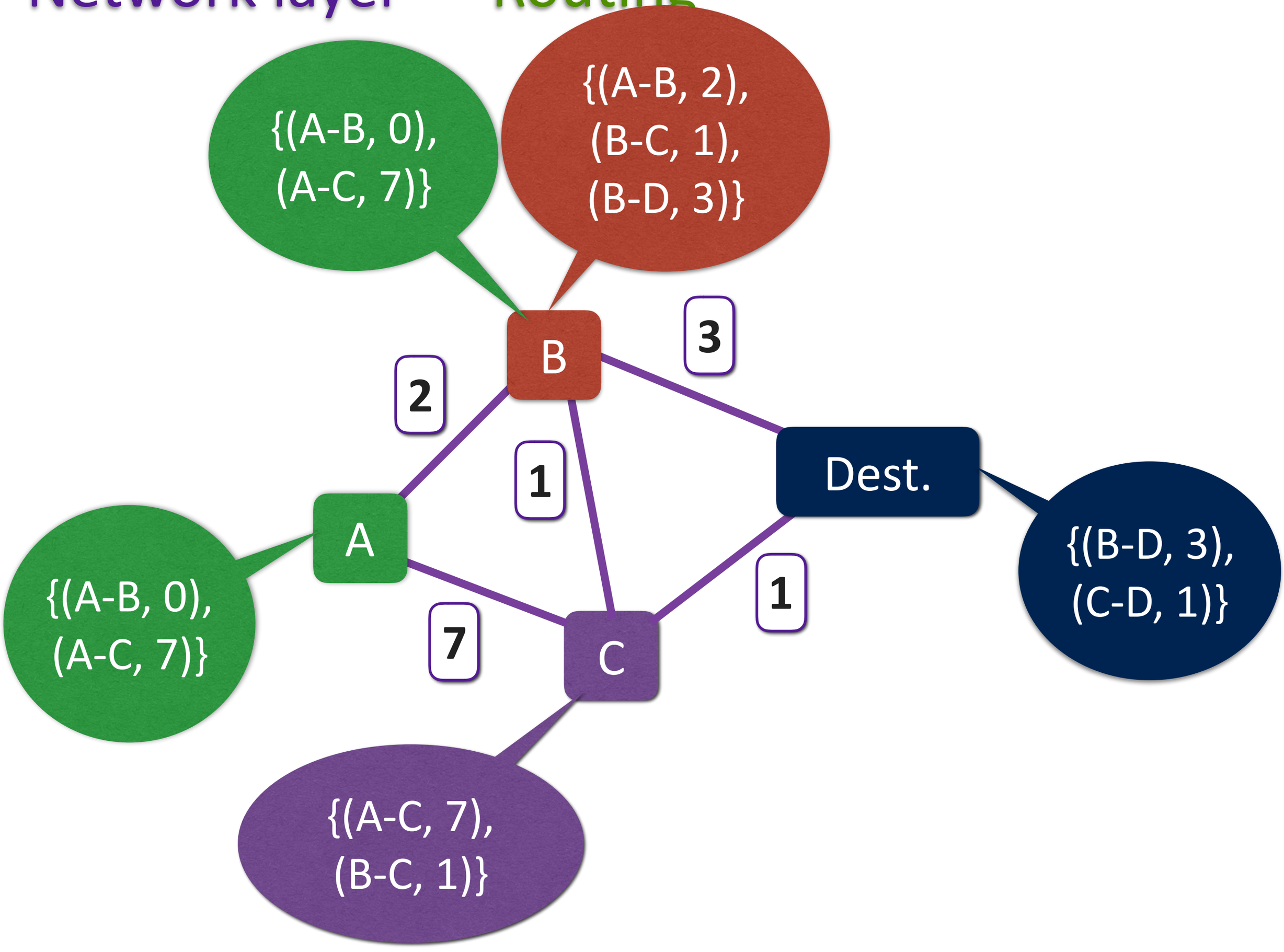

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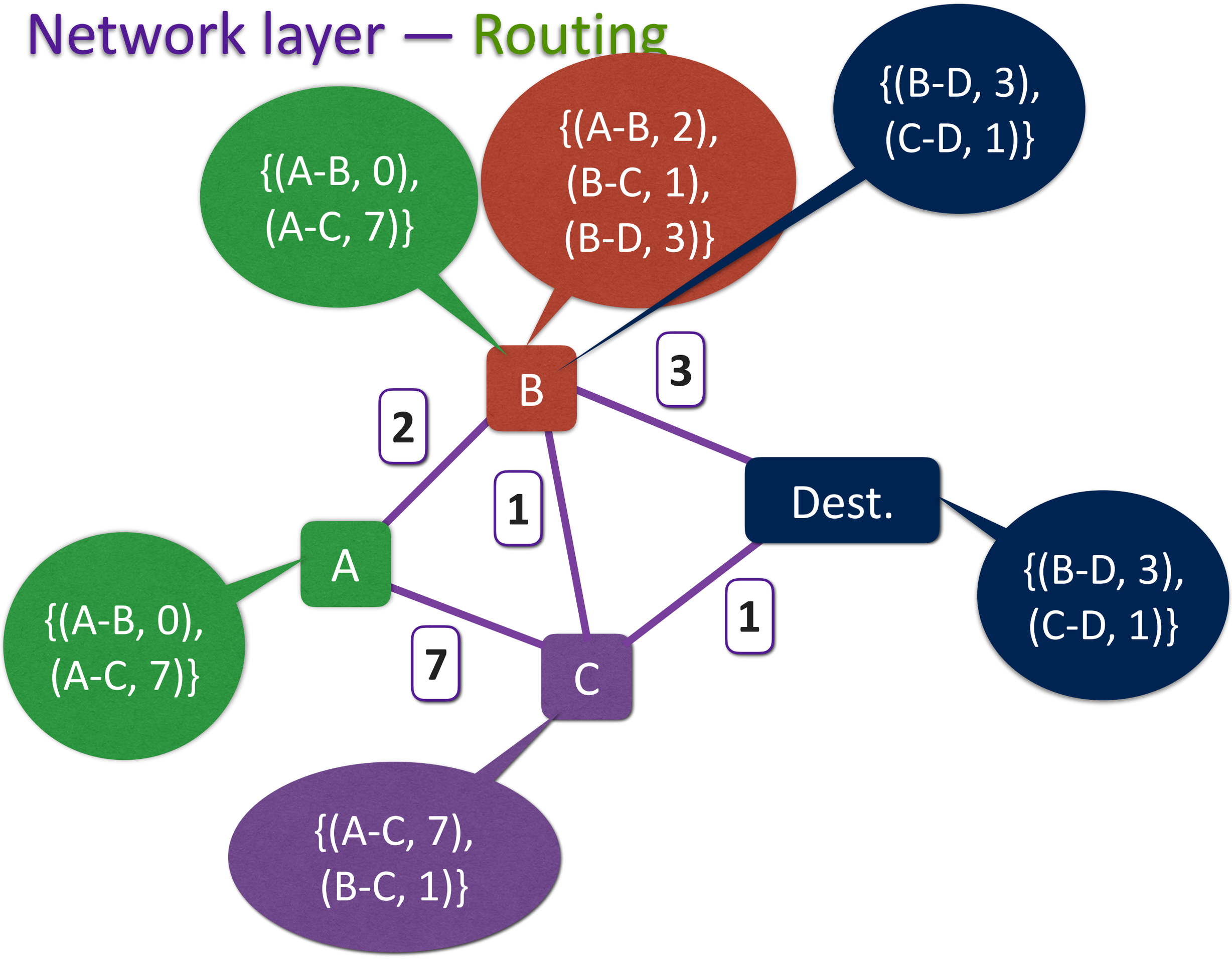

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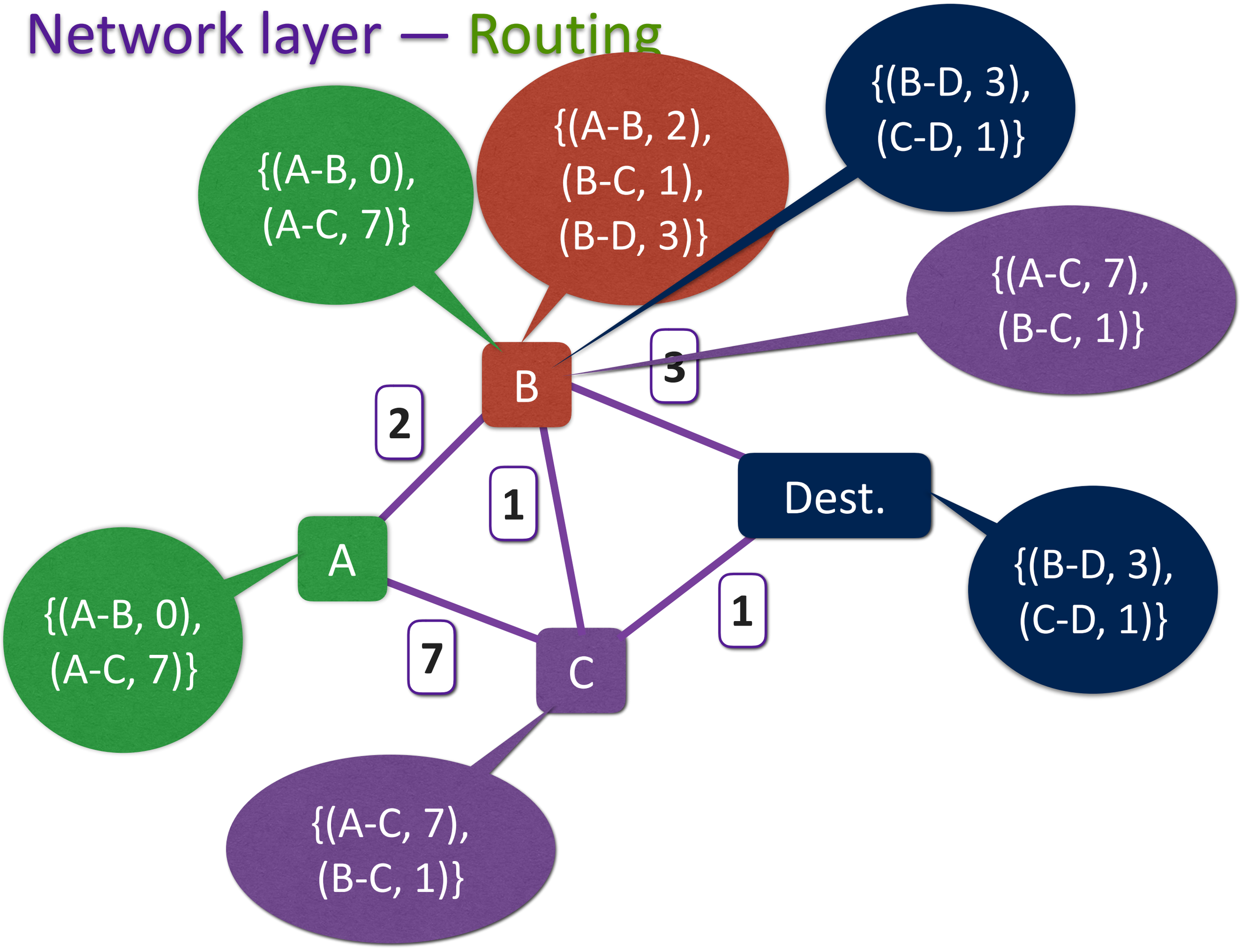

Network layer — Routing

Network layer — Routing

Attempt 2: Link State Routing

Network layer — Routing

Attempt 2: Link State Routing

- **Each router maintains its local “link state” (LS)**

Network layer — Routing

Attempt 2: Link State Routing

- **Each router maintains its local “link state” (LS)**
- **Each router periodically “floods” its LS**

Network layer — Routing

Attempt 2: Link State Routing

- **Each router maintains its local "link state" (LS)**
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    - And forwards all the LS received from other routers

Network layer — Routing

Attempt 2: Link State Routing

- **Each router maintains its local "link state" (LS)**
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- **At one point**

Network layer — Routing

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- **At one point**
    - Every router knows the entire topology

Network layer — Routing

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Network layer — Routing

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Network layer — Routing

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    - More importantly, find next-hop to the destination

Network layer — Routing

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    - Find path to the destination
    - More importantly, find next-hop to the destination
- **Challenge?**

Network layer — Routing

Network layer — Routing

Attempt 3: Distance Vector Routing

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**
    - **maintains its “current distance to destination”**

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**
    - **maintains its “current distance to destination”**
    - **Periodically announces it to all its neighbors**

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**
  - **maintains its "current distance to destination"**
  - **Periodically announces it to all its neighbors**
  - **Update its local table**

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**
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    - **Periodically announces it to all its neighbors**
    - **Update its local table**
        - d(A, dest) = min{d(A, neighbor) + d(neighbor, dest)}

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**
  - **maintains its "current distance to destination"**
  - **Periodically announces it to all its neighbors**
  - **Update its local table**
    - d(A, dest) = min{d(A, neighbor) + d(neighbor, dest)}
    - {dest — distance, neighbor-that-minimizes-distance}

Network layer — Routing

Attempt 3: Distance Vector Routing

- **Each router**
    - **maintains its "current distance to destination"**
    - **Periodically announces it to all its neighbors**
    - **Update its local table**
        - d(A, dest) = min{d(A, neighbor) + d(neighbor, dest)}
        - {dest — distance, neighbor-that-minimizes-distance}
- **Broadcast to all its neighbors**