The Network Layer: Routing

CPSC 433/533, Spring 2021

Anurag Khandelwal

Administrivia

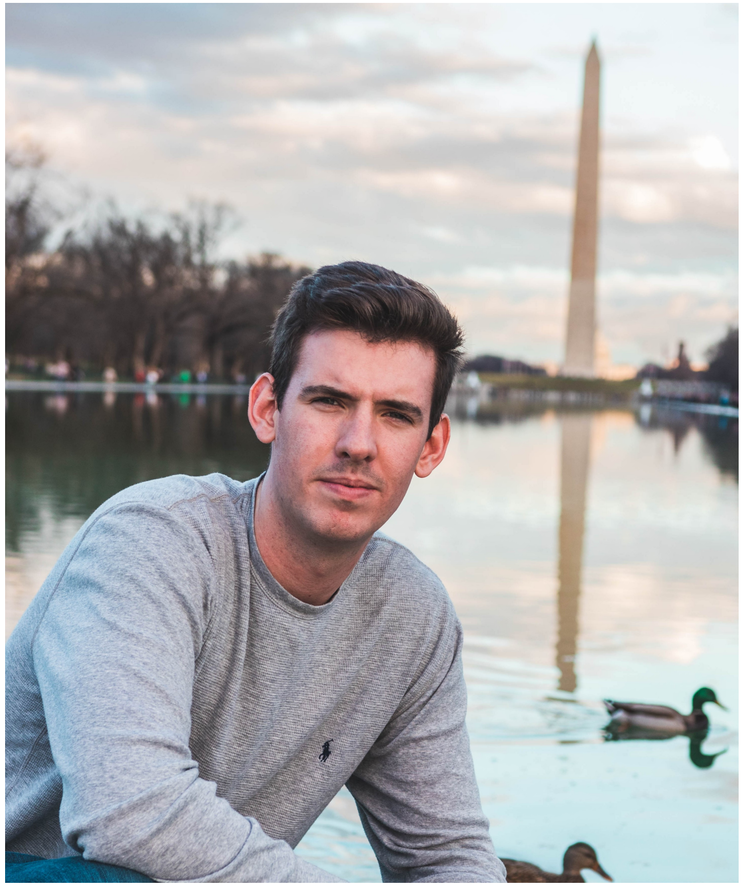
- Have to shift my OH from **4-5pm ET** to **5-6pm ET**
- ULA Introductions

Jonathan Kraft

- **Senior** in Davenport College
- Joint major in **CS** and **Mathematics**
- Office hours: **Wed 11:00am - 12:00pm ET**
  - Zoom (see Canvas for link)
- **jonathan.kraft@yale.edu**

Josh Beasley

- **Senior** in Timothy Dwight College
- Major in **CS**
- Office hours: **Thu 3:00pm - 4:00pm ET**
  - Zoom (see Canvas for link)
- **josh.beasley@yale.edu**



Recap

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- Forwarding "data plane"
  - *Directing one data packet*
  - *Each router using local routing state*

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  - *Jointly computed by routers using a distributed protocol*

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- **Forwarding "data plane"**
  - *Directing one data packet*
  - *Each router using local routing state*
- **Routing "control plane"**
  - *Computing the forwarding tables that guide packets*
  - *Jointly computed by routers using a distributed protocol*
- Routing will be our focus for the next couple of lectures

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- **Goal of routing protocols:** compute valid state
  - But how can you tell if routing state is valid
- Need a **succinct** correctness condition for routing

Necessary and Sufficient Condition

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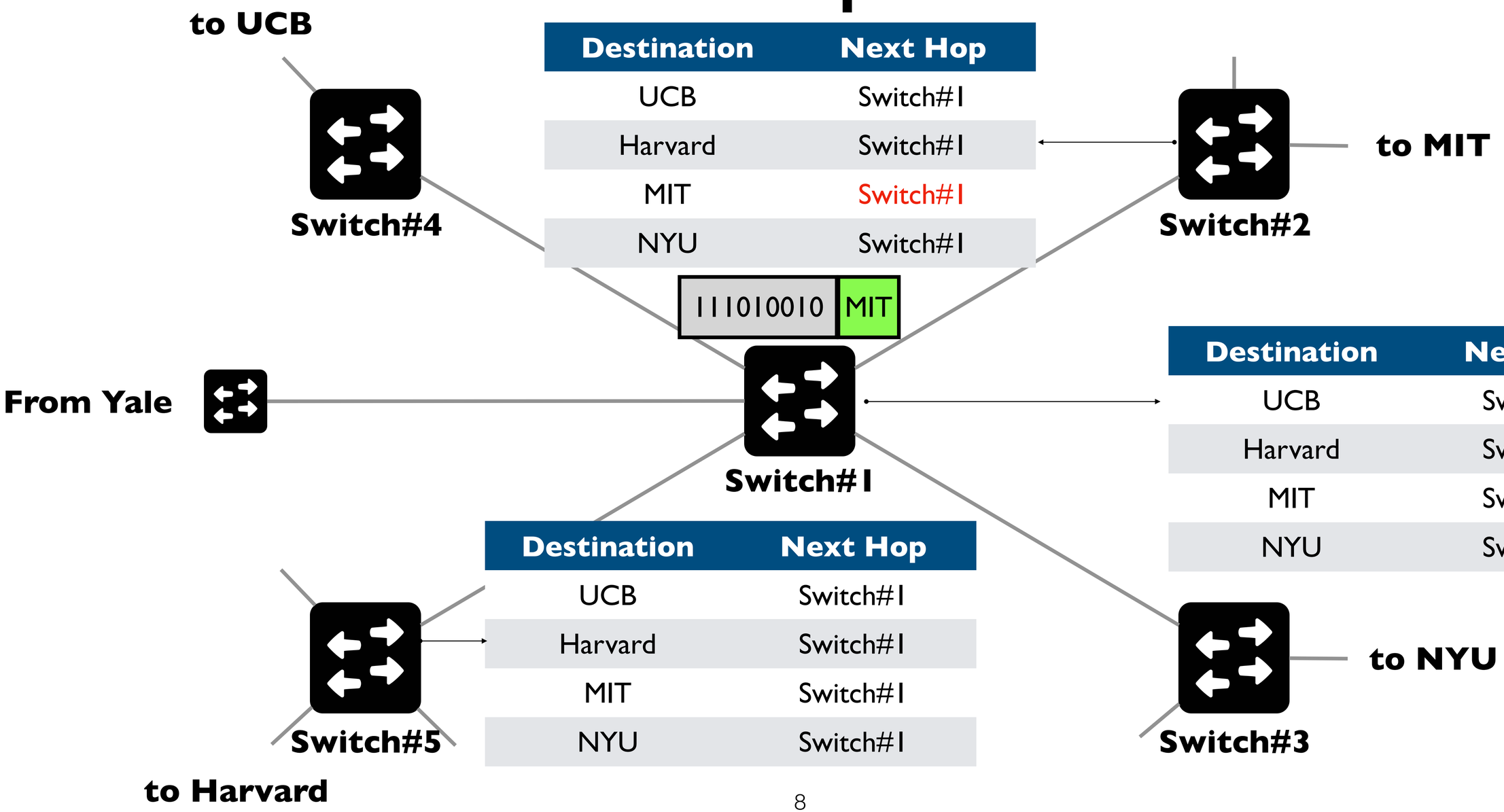
- <u>Loop</u>: when a packet cycles around the same set of nodes forever

Loops



Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
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Destination	Next Hop
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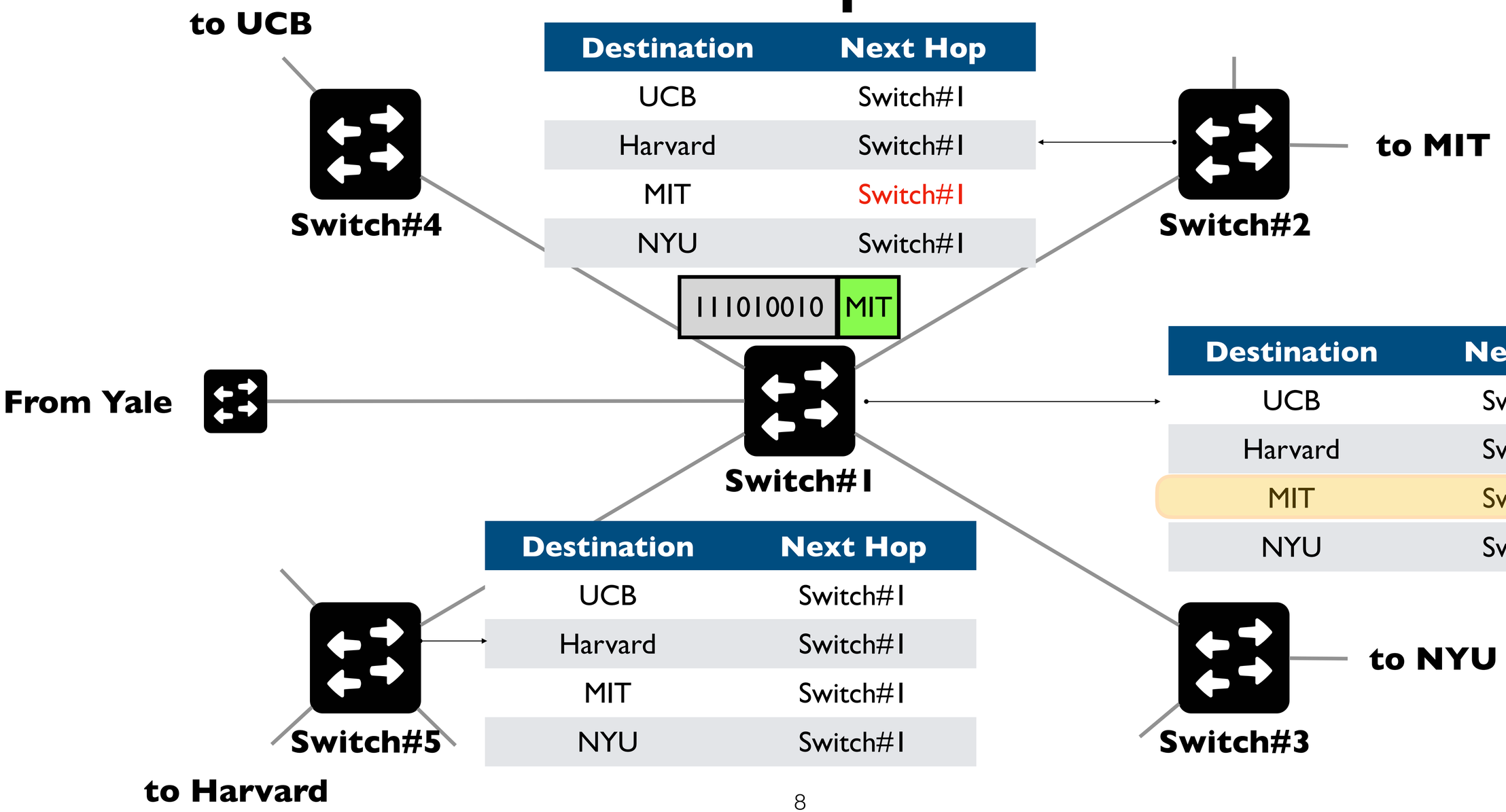

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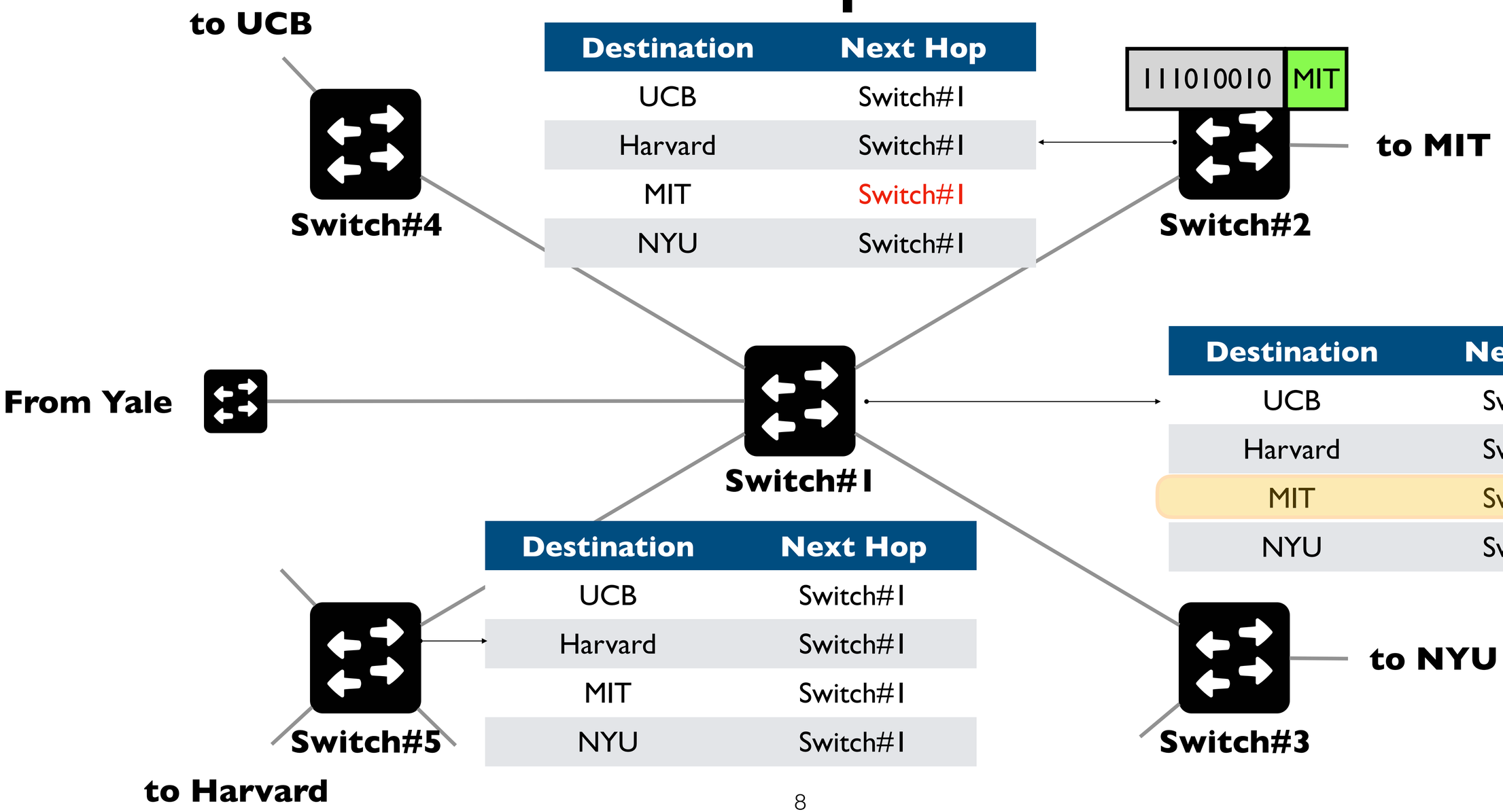

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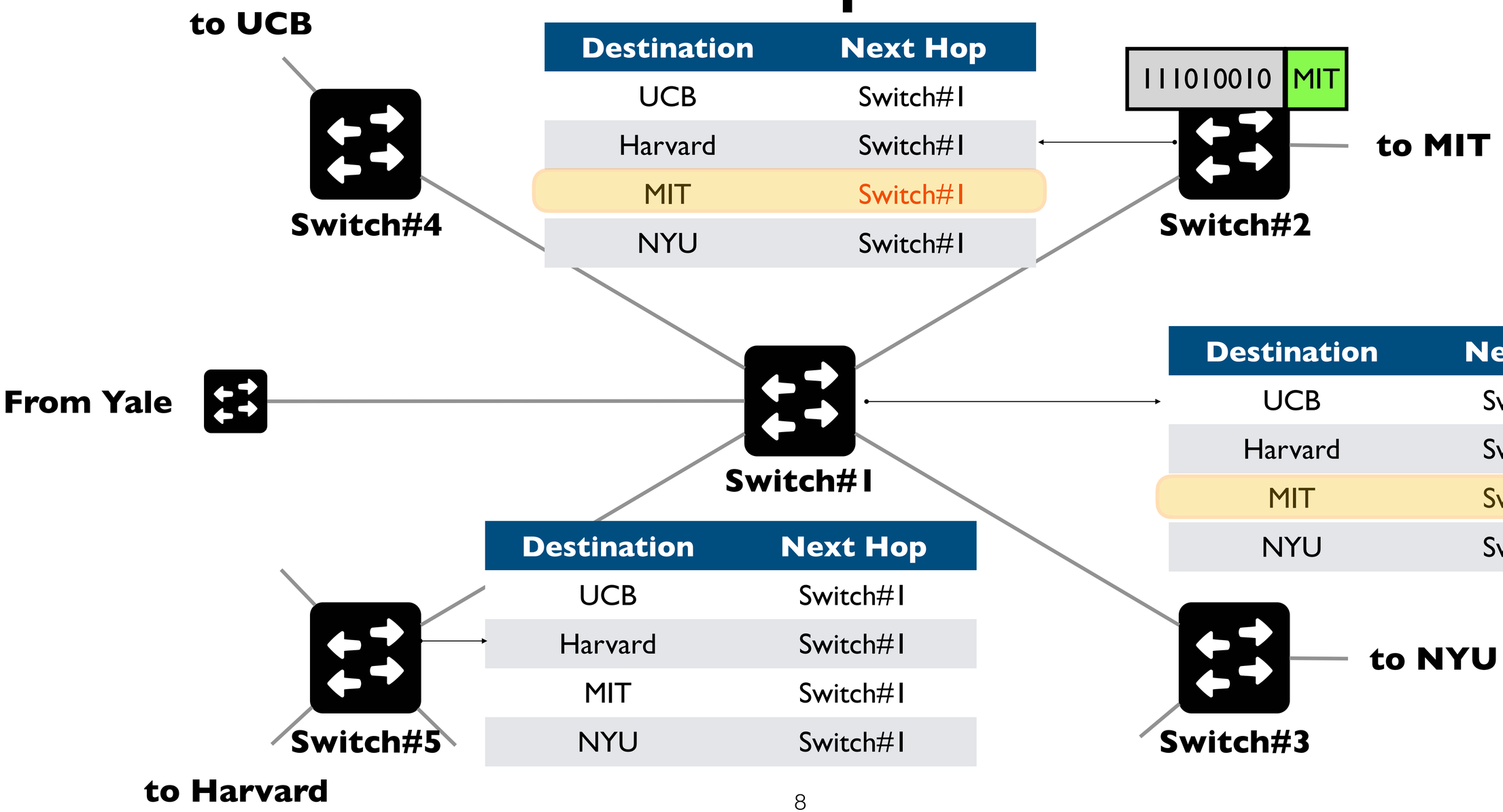

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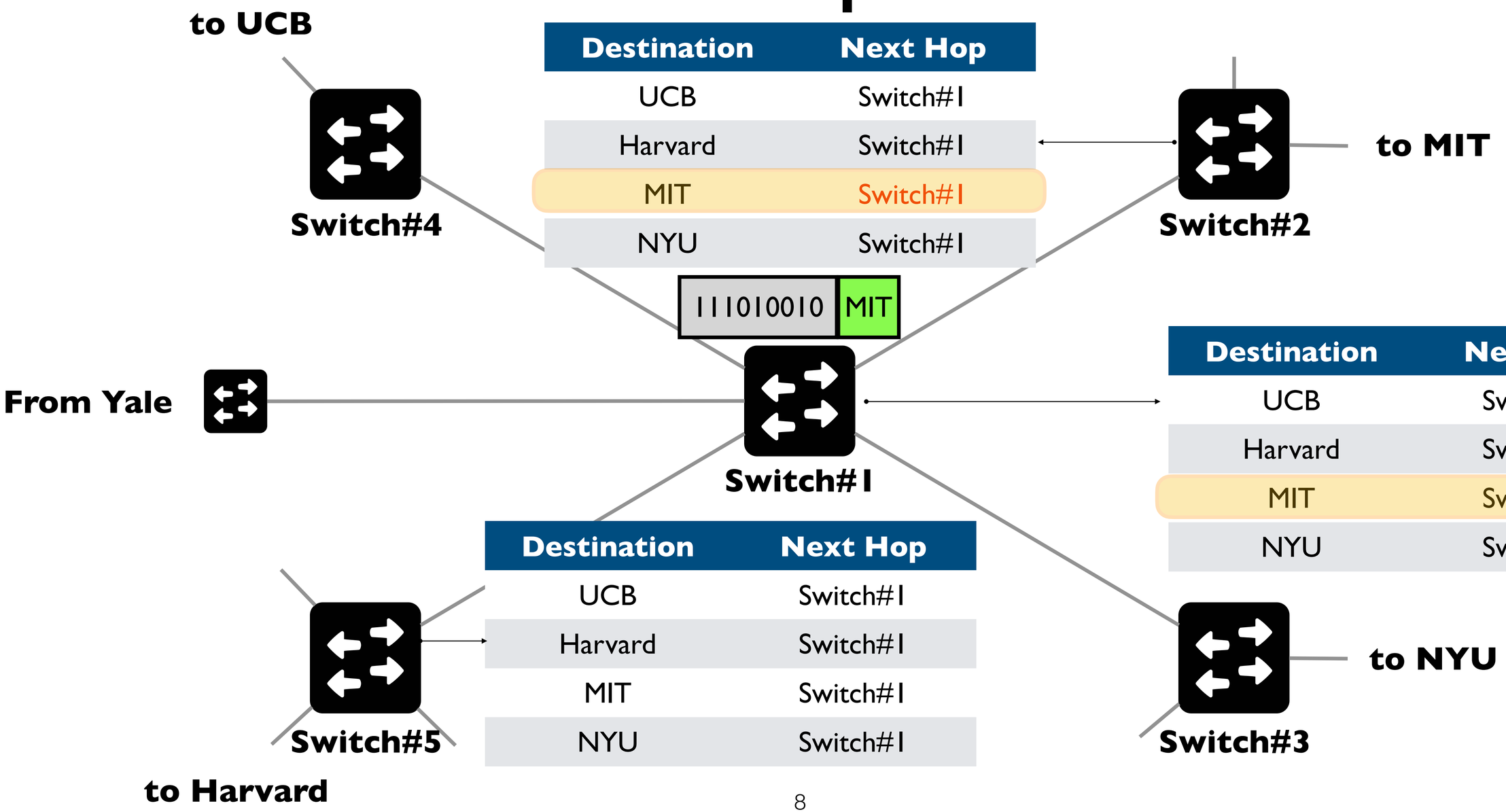

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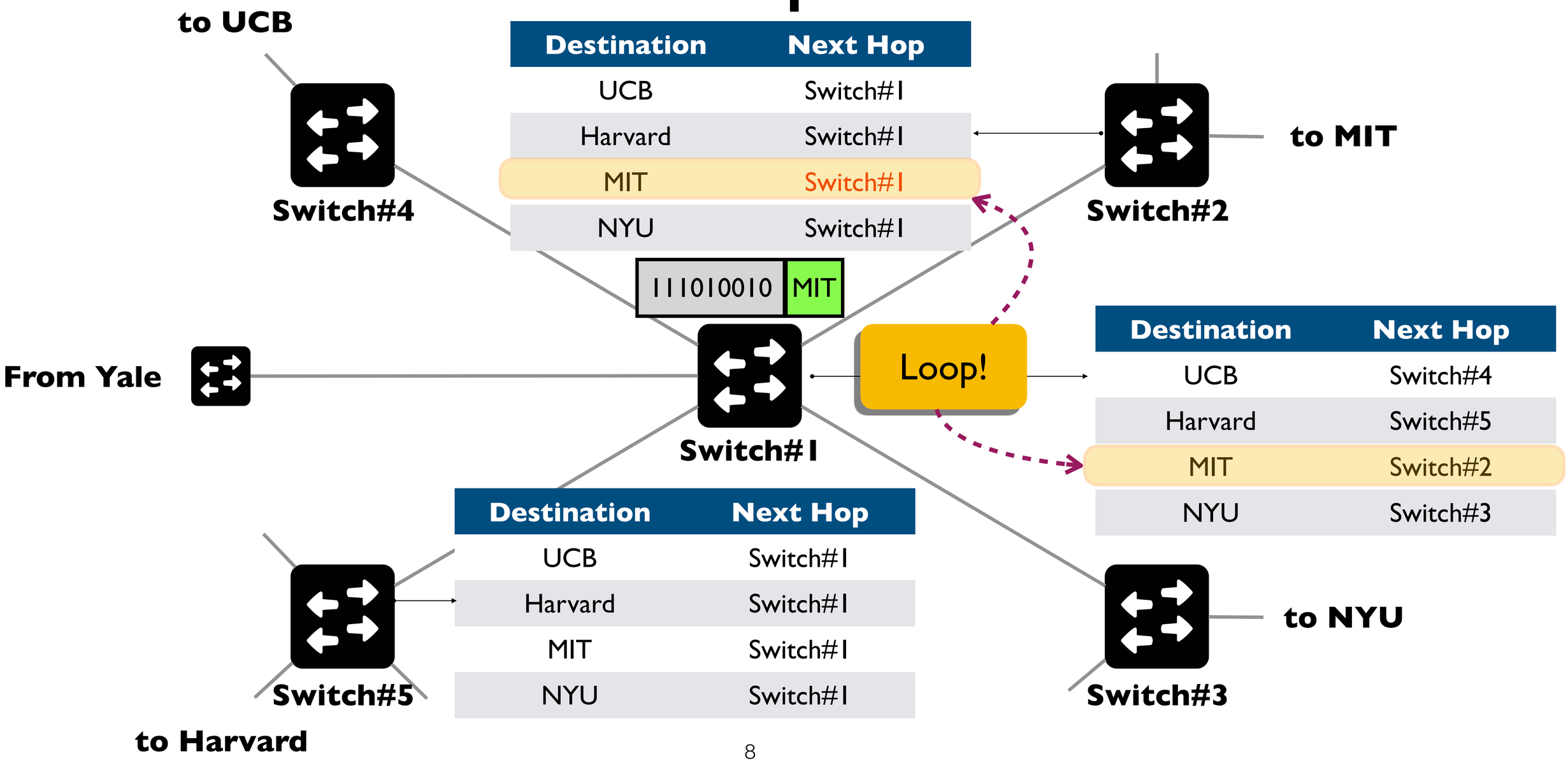

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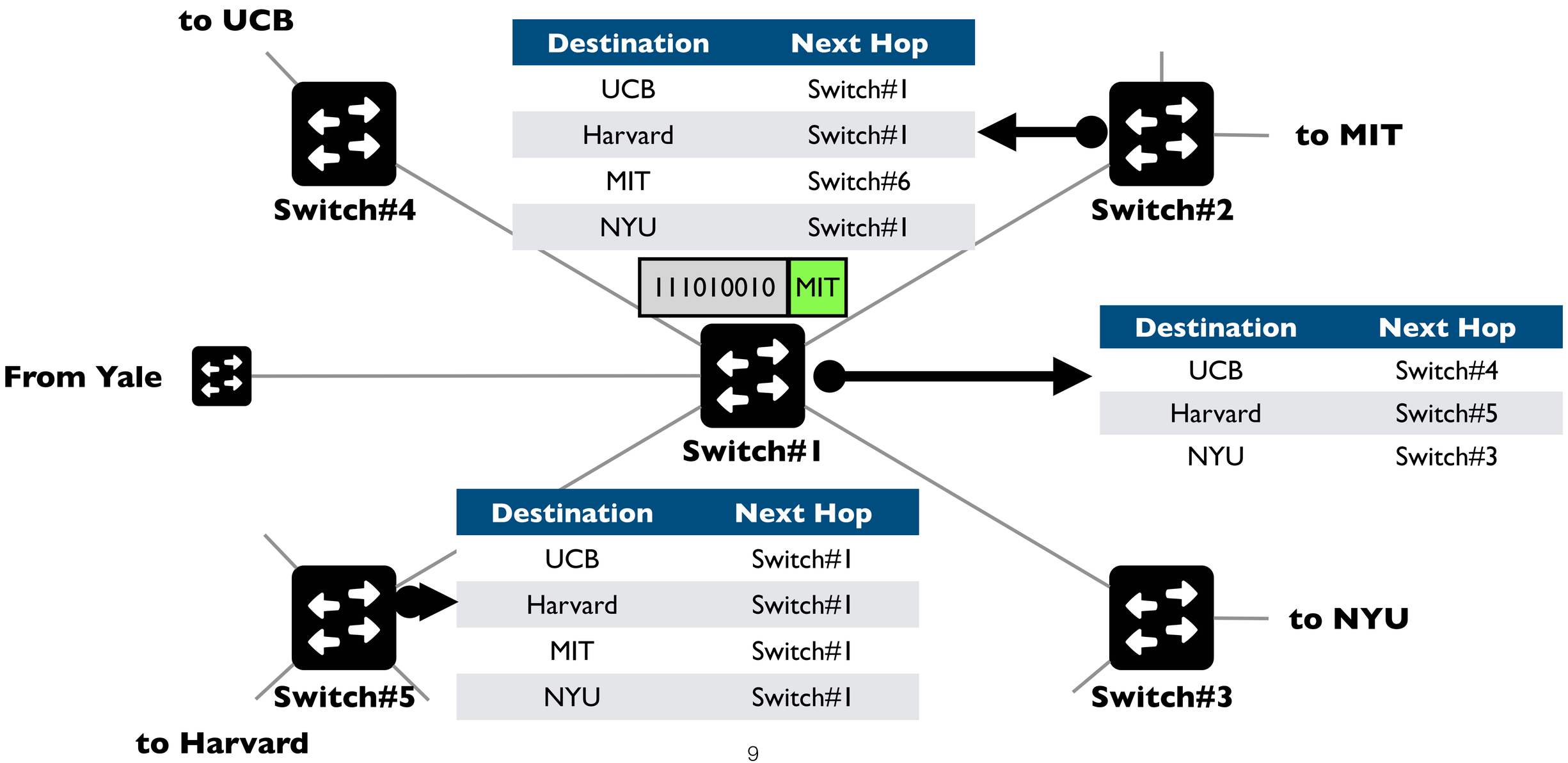

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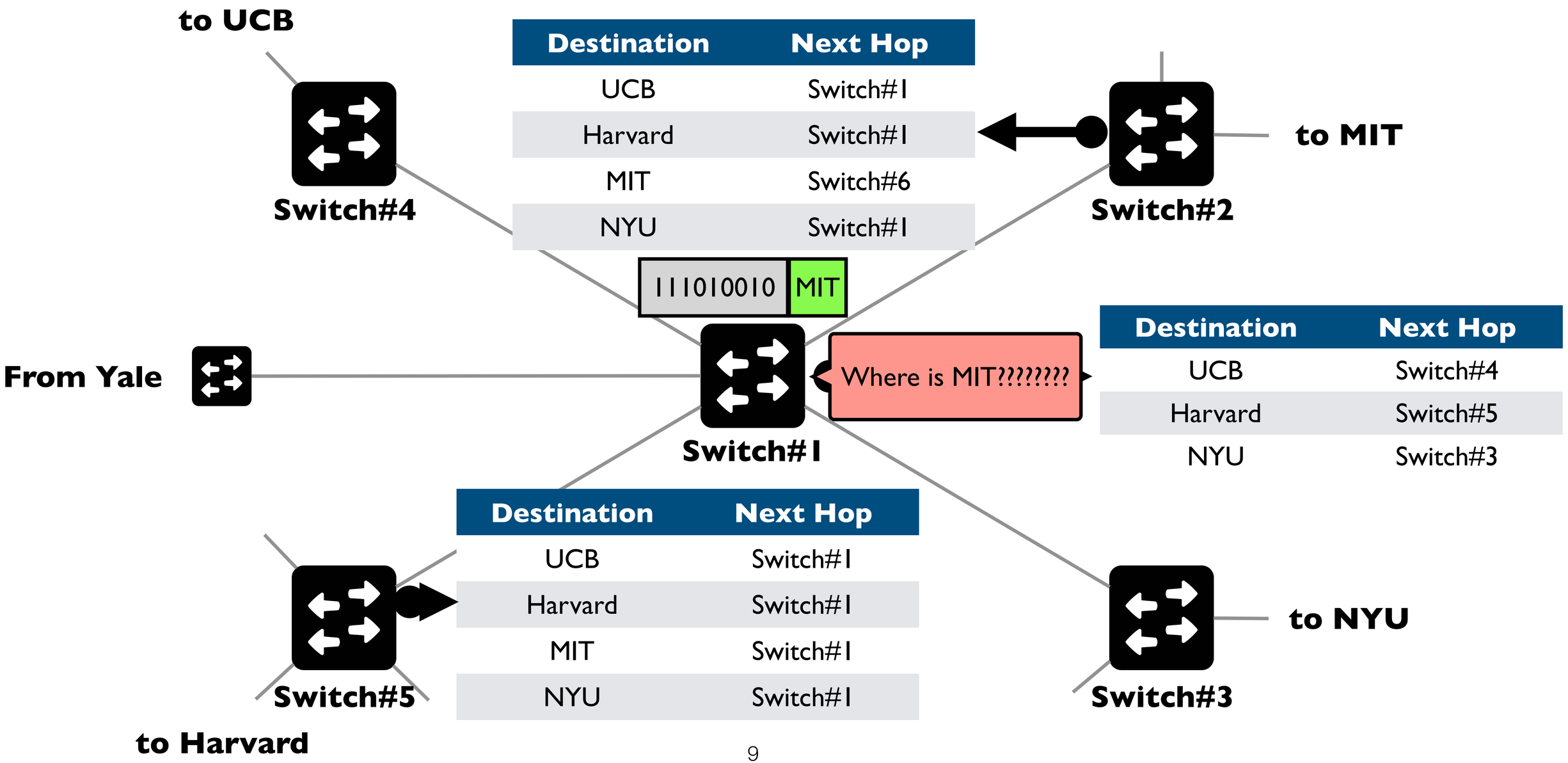

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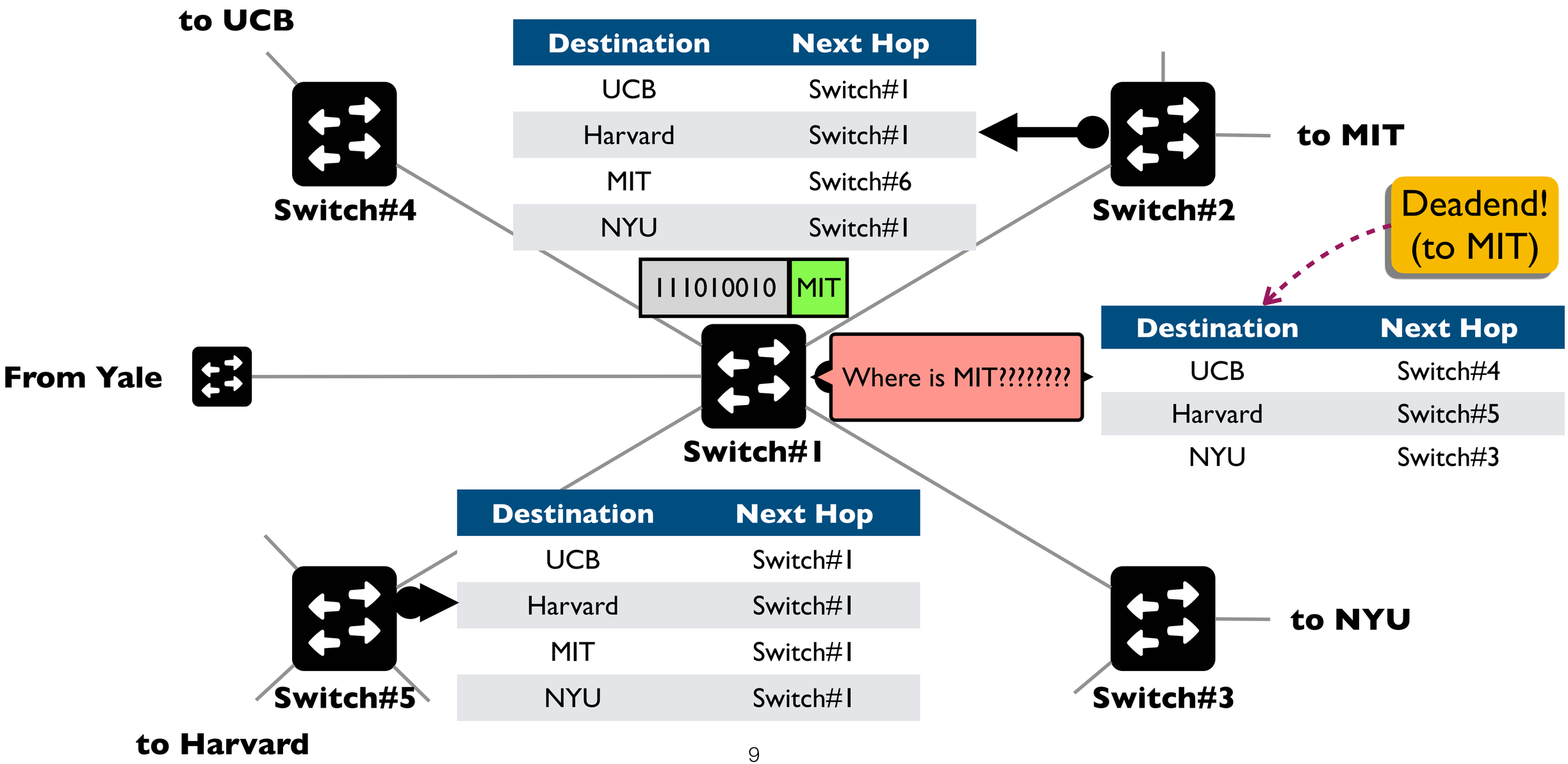

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- If you run into a dead-end before reaching destination, you’ll **never** reach the destination
- If you run into a loop before reaching destination, you’ll **never** reach the destination

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Sufficient (“if”)

- Assume no dead-ends, no loops
- Packets may keep wandering, but without repeating link
  - If ever a packet enters the same switch from the same link, there must be a loop
- Only a finite number of possible links for it to visit
  - It cannot keep wandering forever without looping
  - Must eventually hit destination!

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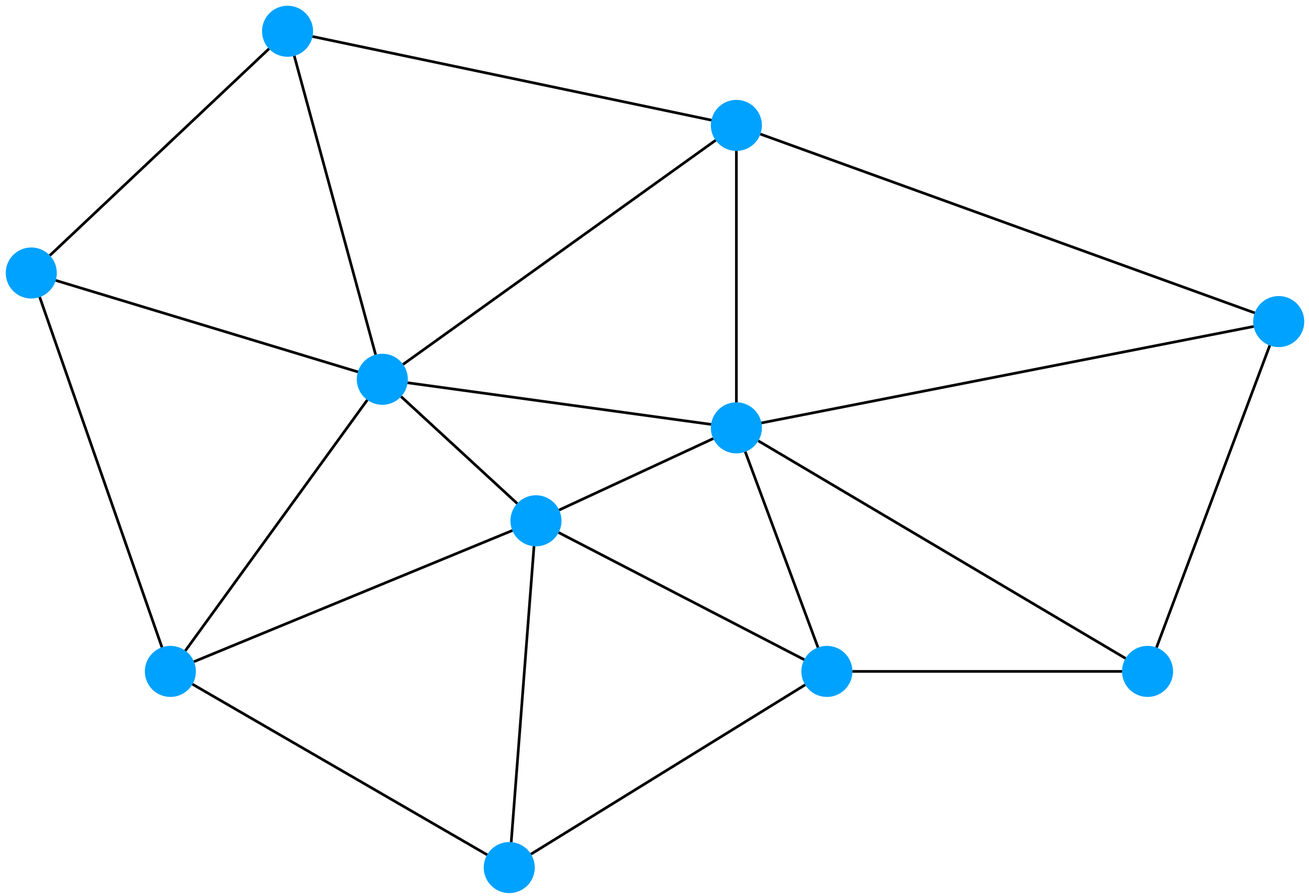
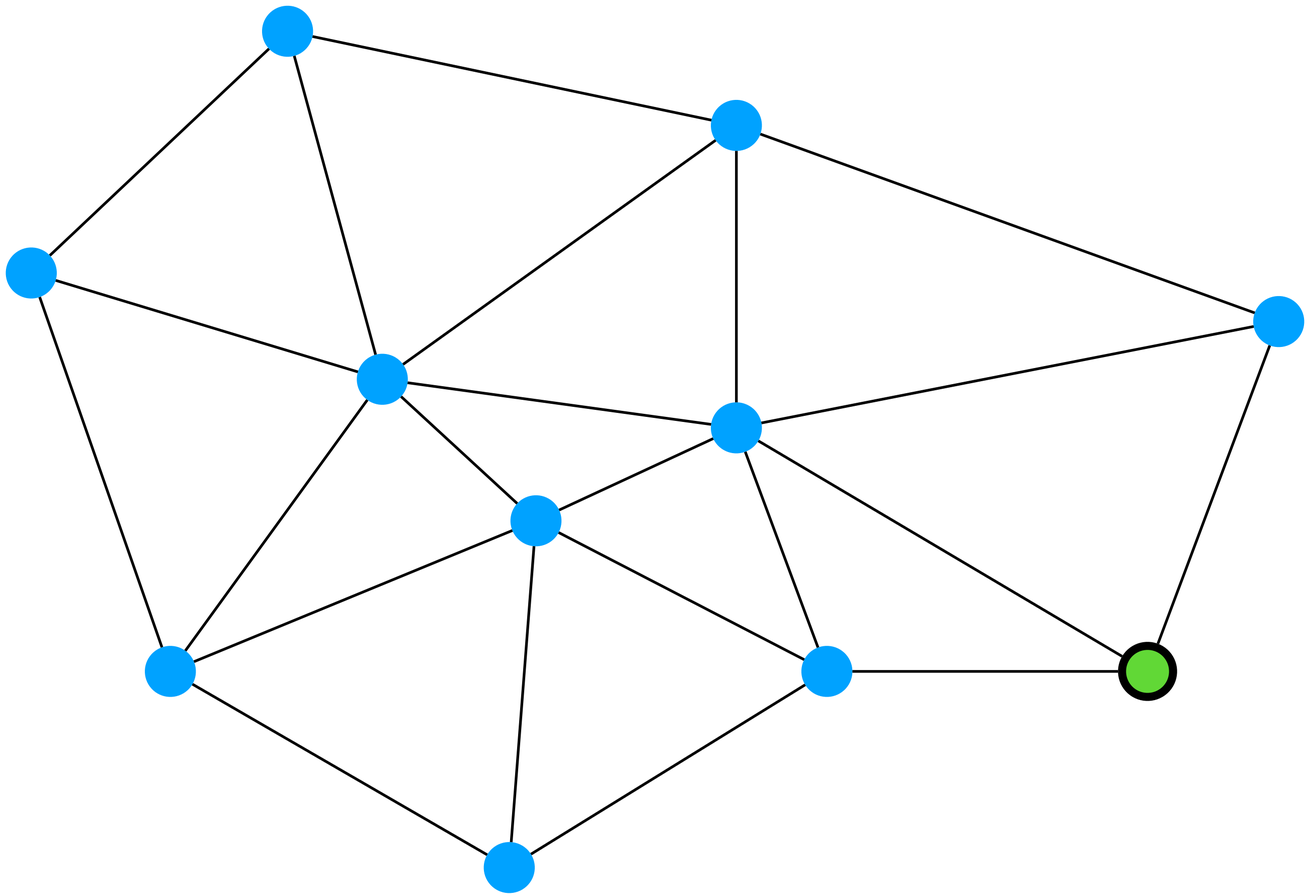
- **Eliminate all links with no arrows**
  - Look at what's left…

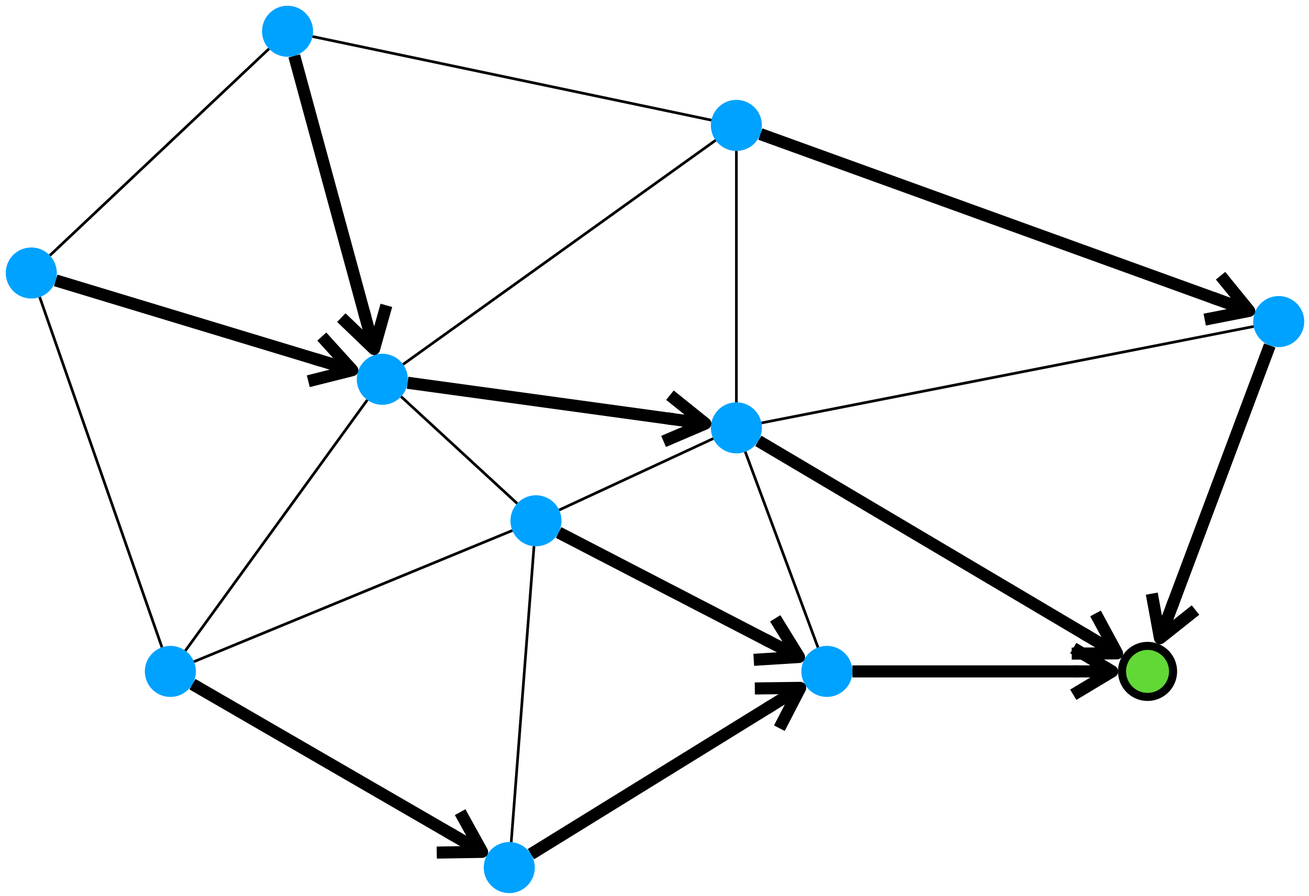
Example 1



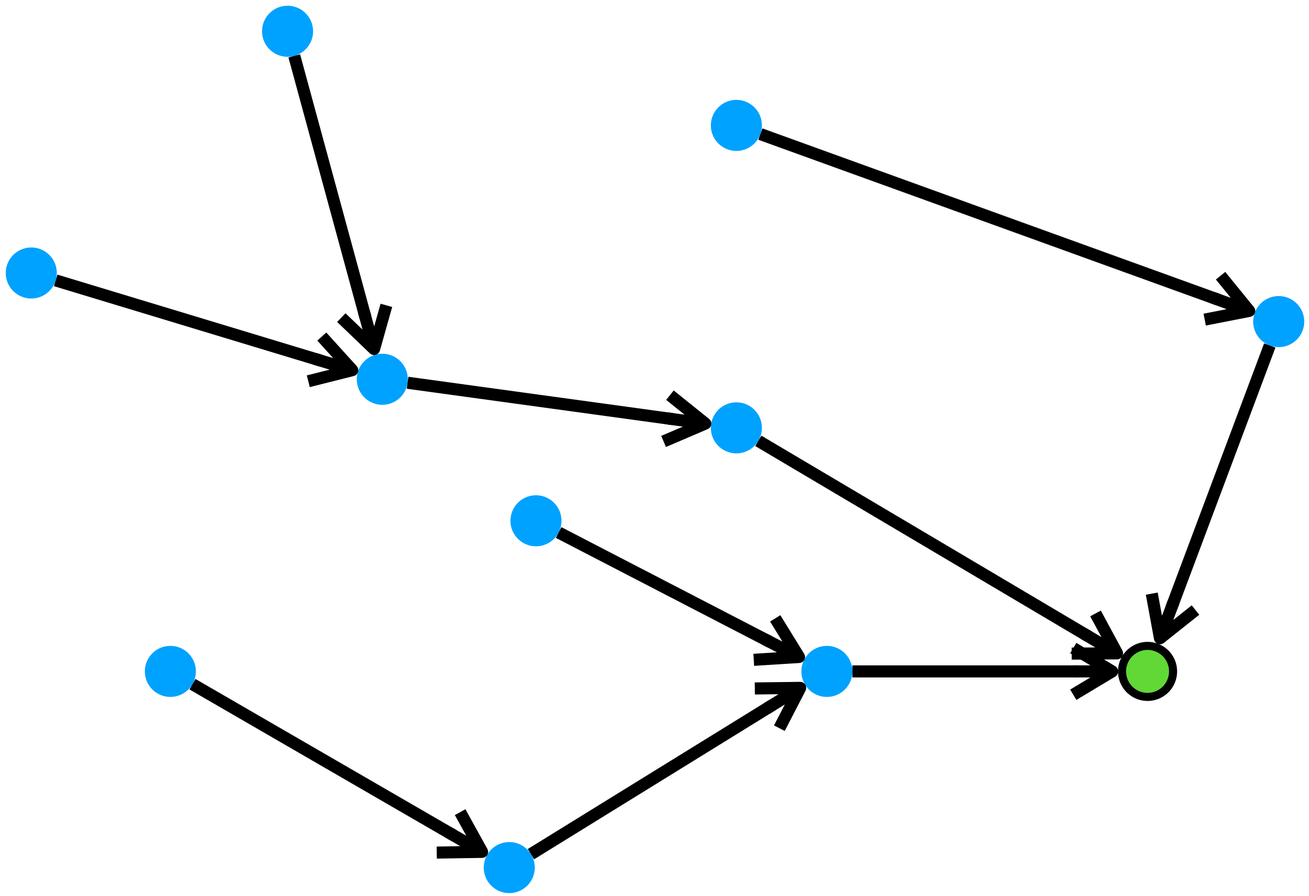
Pick Destination



Put arrows on outgoing links (to green dot)



Remove Unused Links



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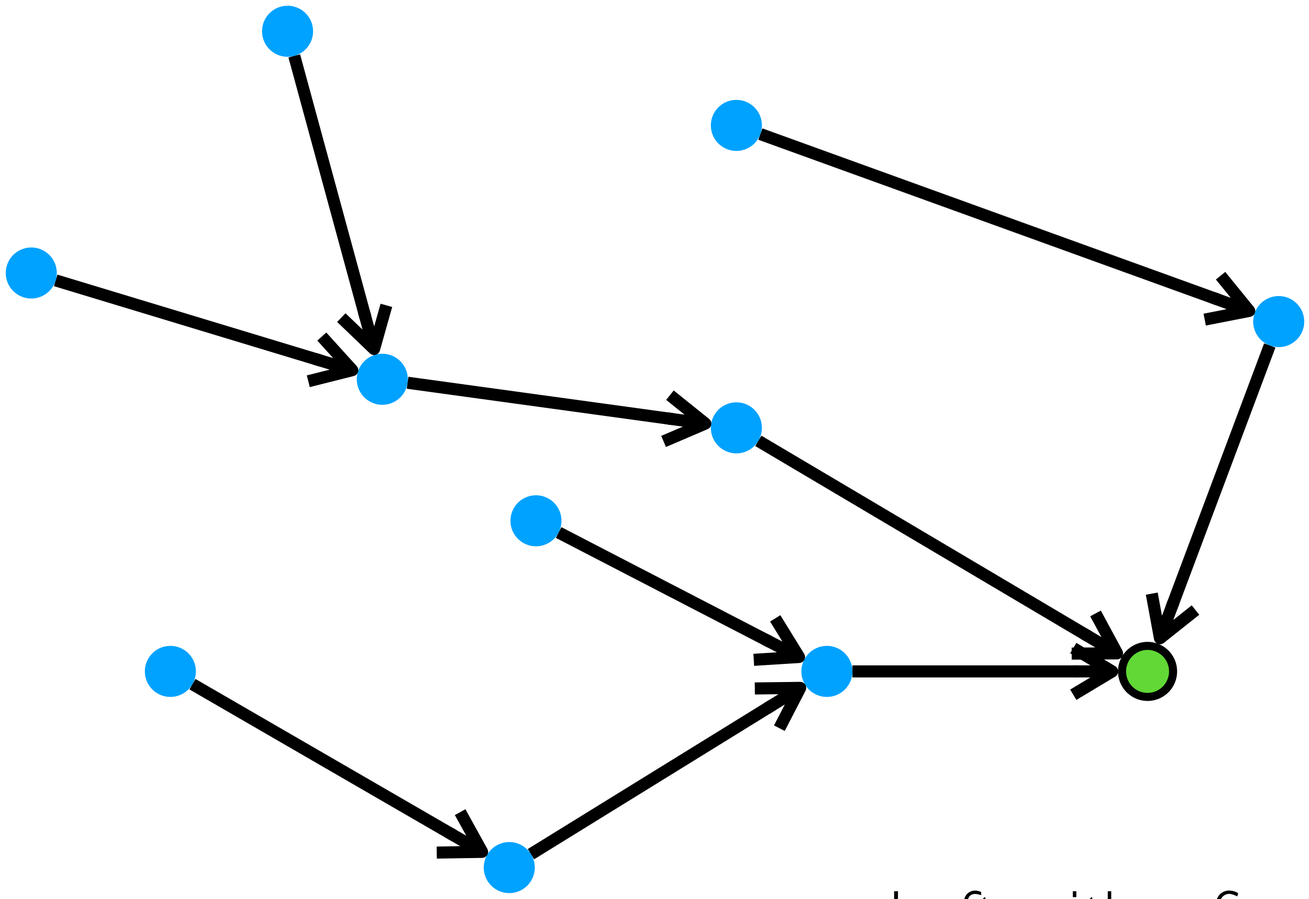
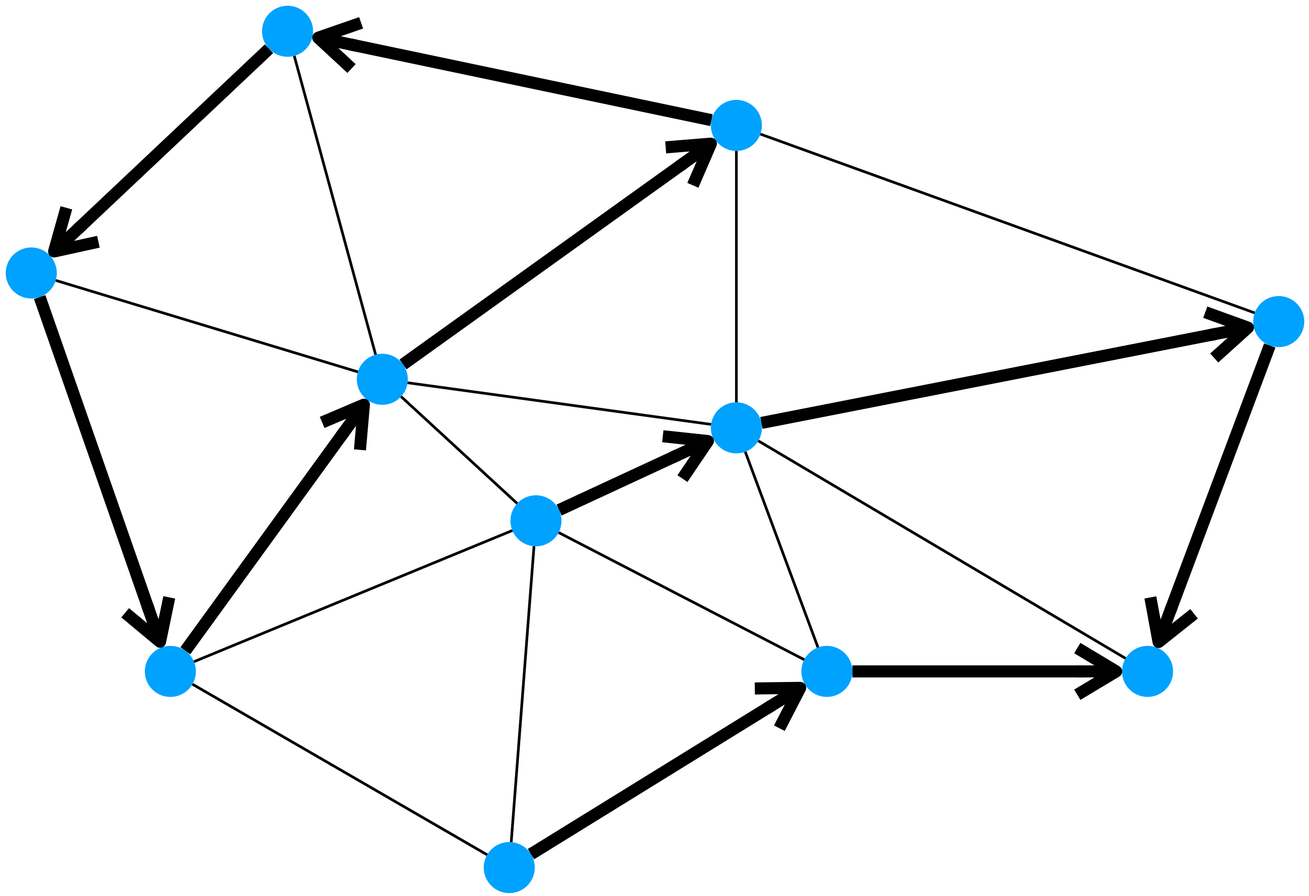


Left with a *Spanning Tree*: **Valid**

Example 2



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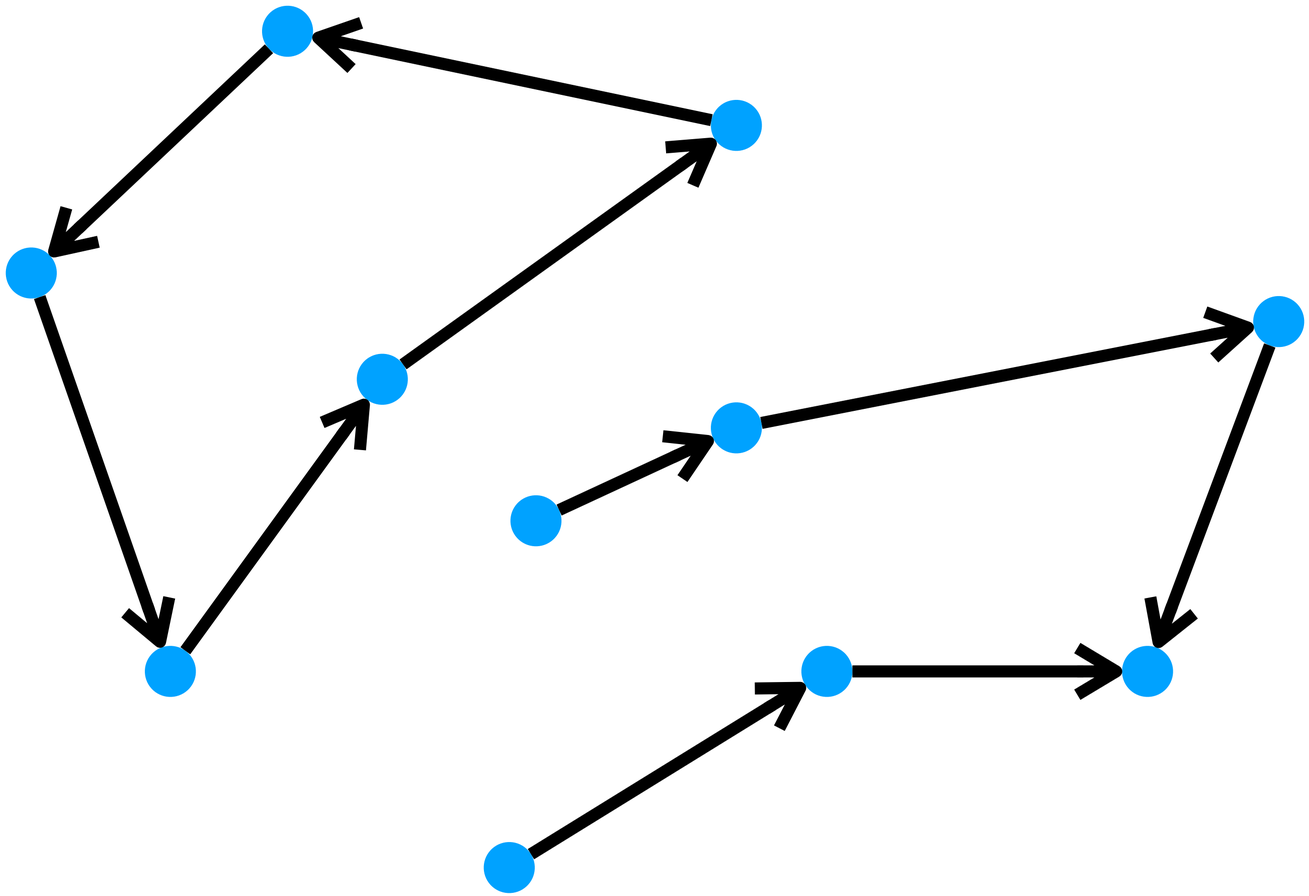

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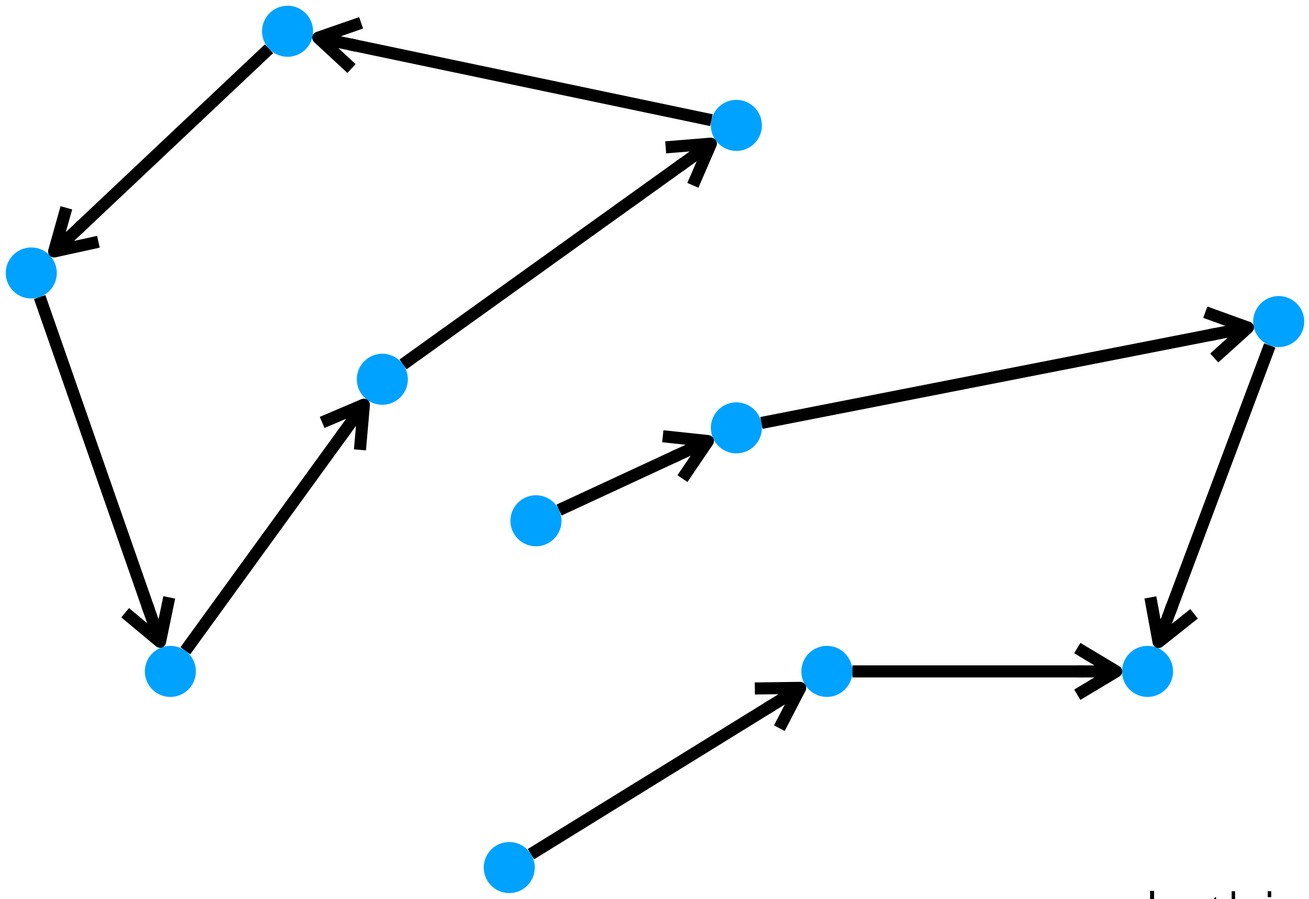

Is this **Valid?**

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  - Node without outgoing arrow
- Loops are obvious
  - Disconnected from the rest of the graph

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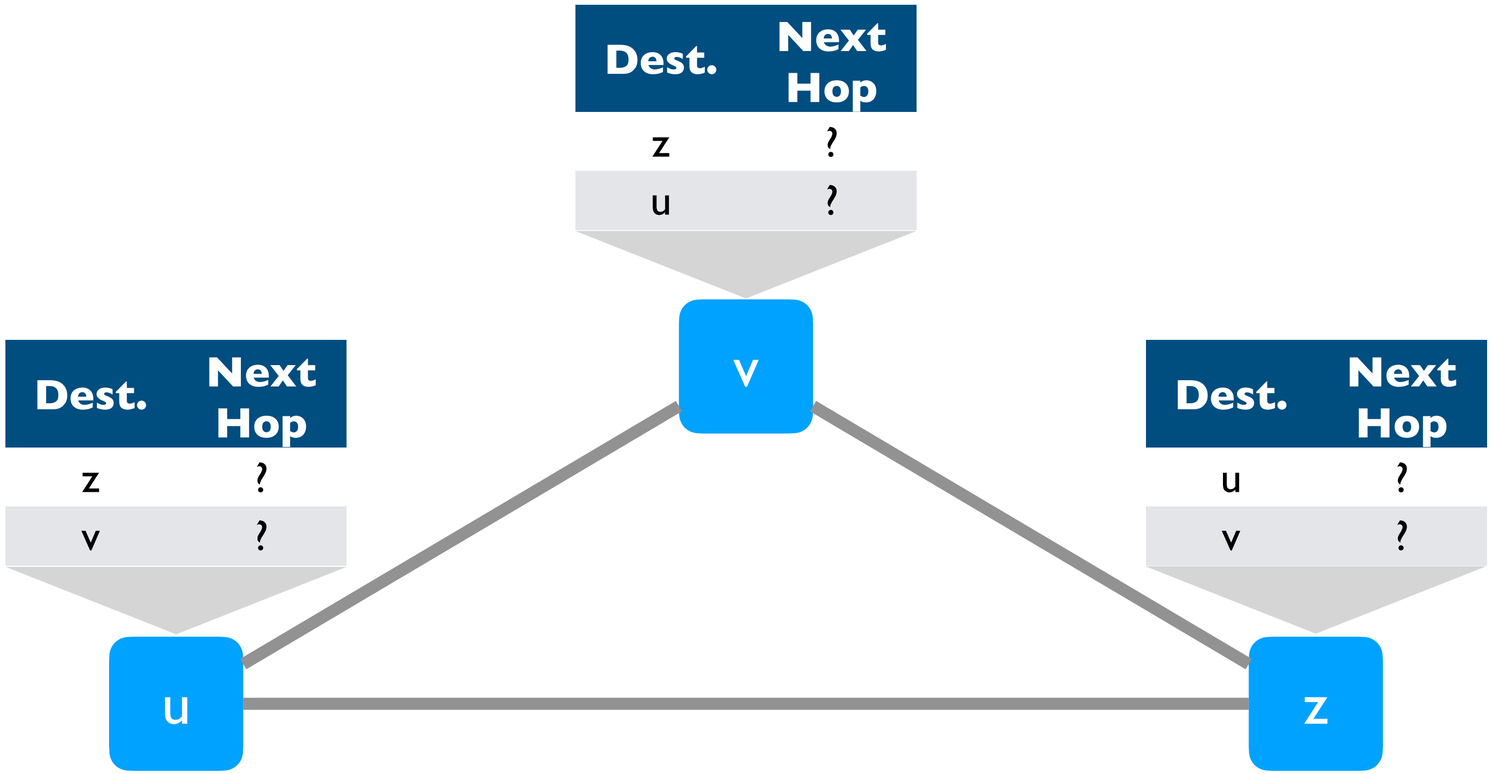
- **V2: Find a *least cost path* to a given destination**


Dest.
Next Hop
z
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u
?
v
Dest.
Next Hop
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?
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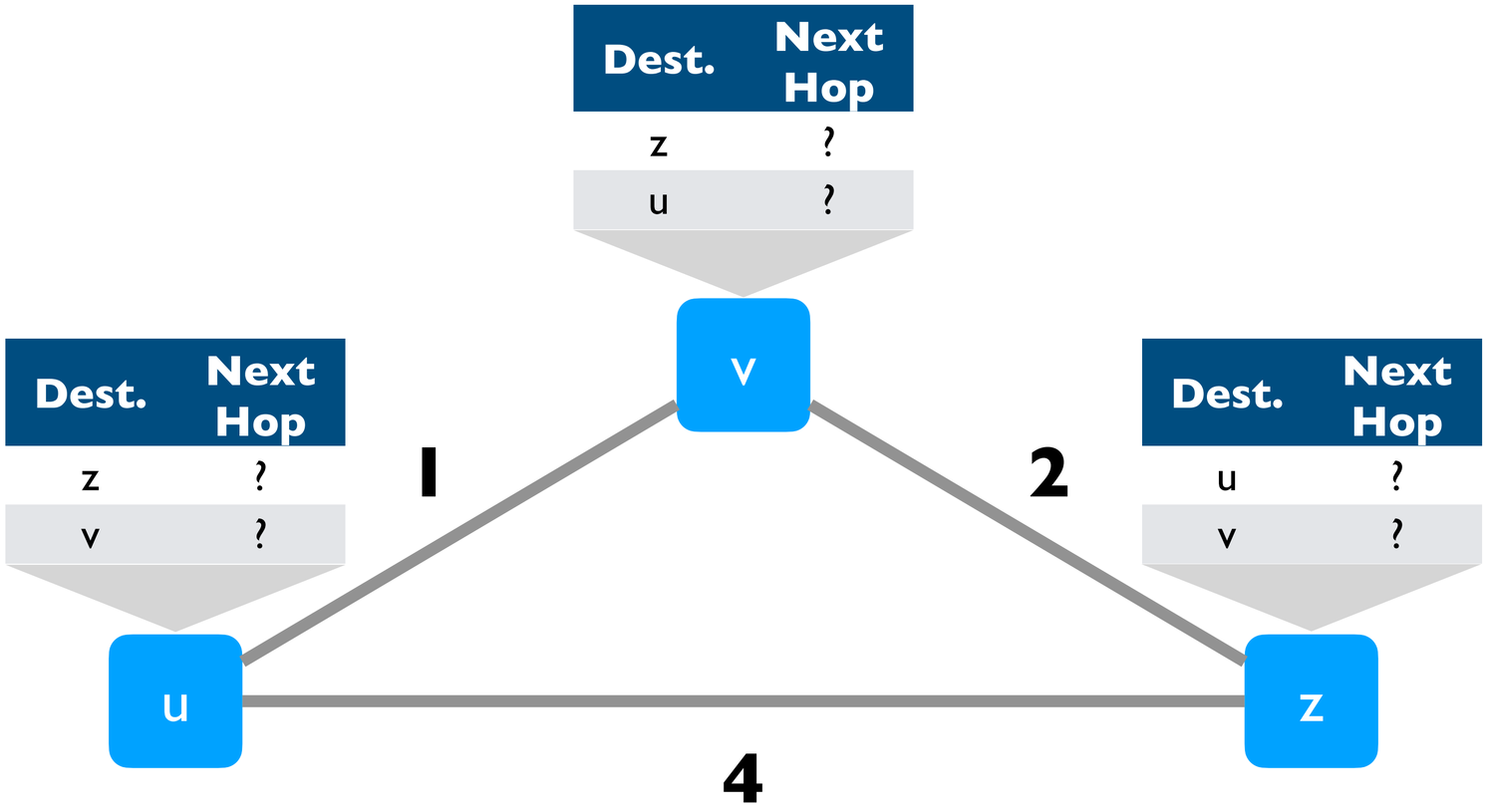
Dest.
Next Hop
u
?
v
?
z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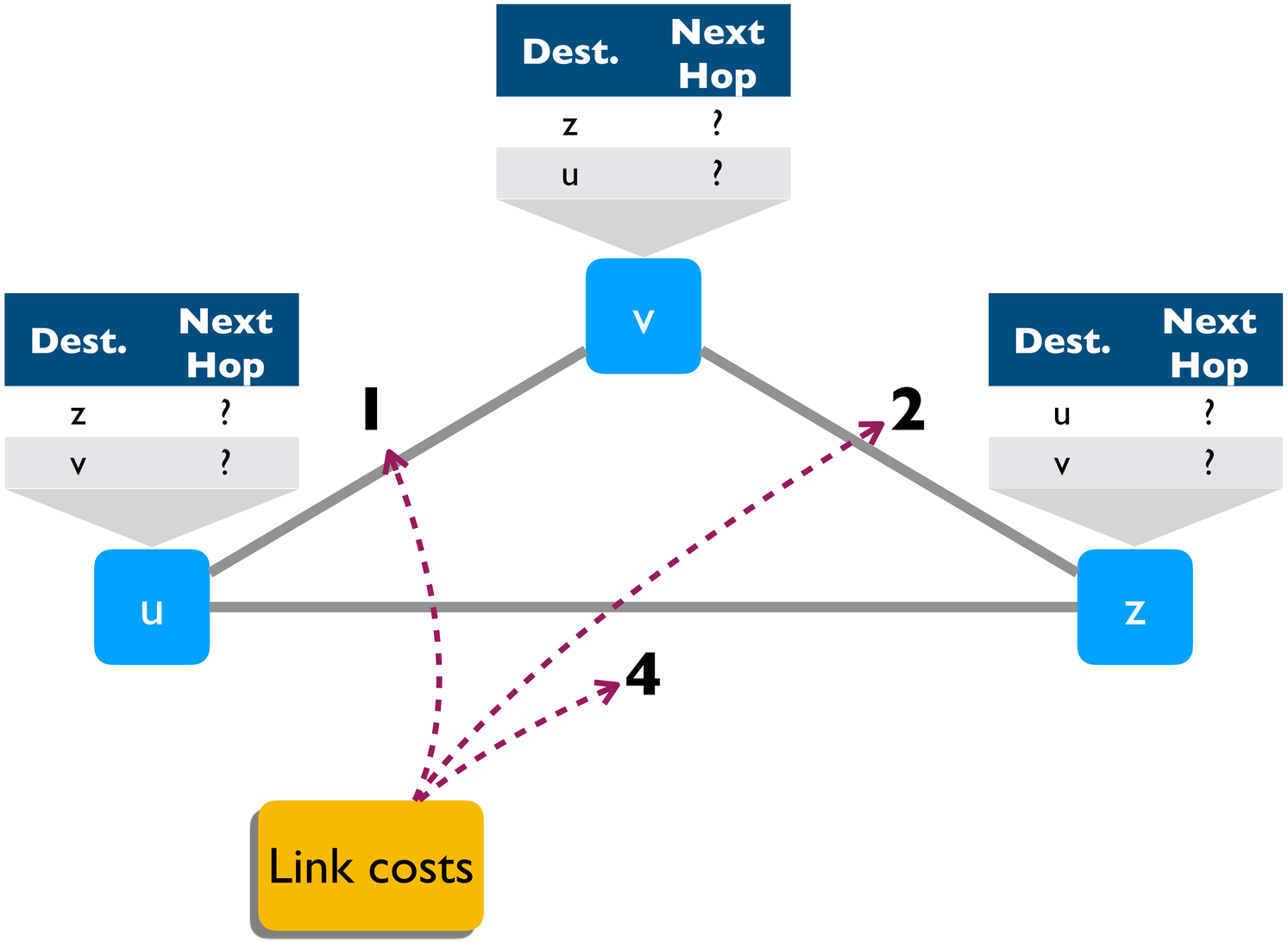
?
u
1
2
Dest.
Next Hop
u
?
v
?
z
4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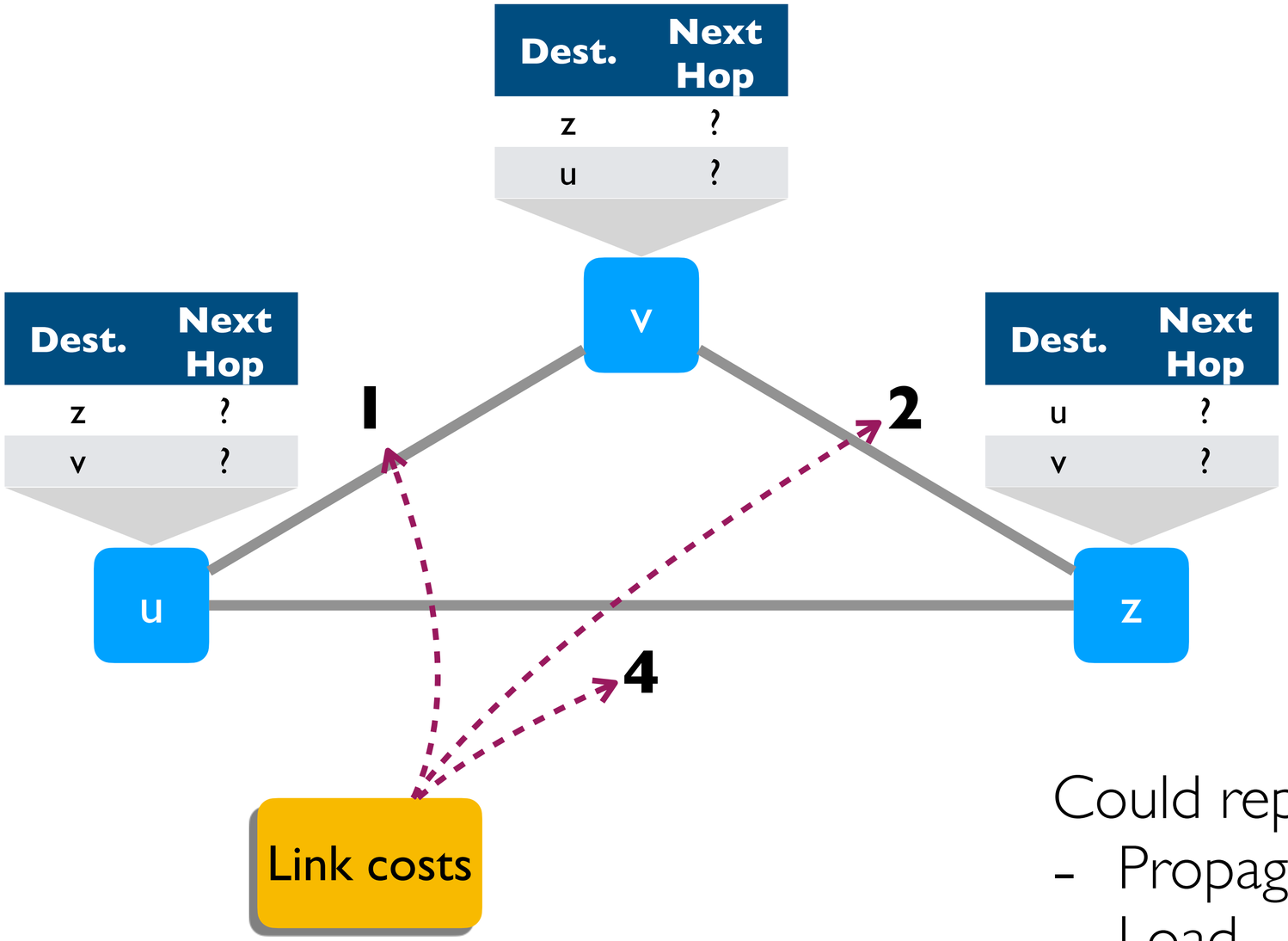
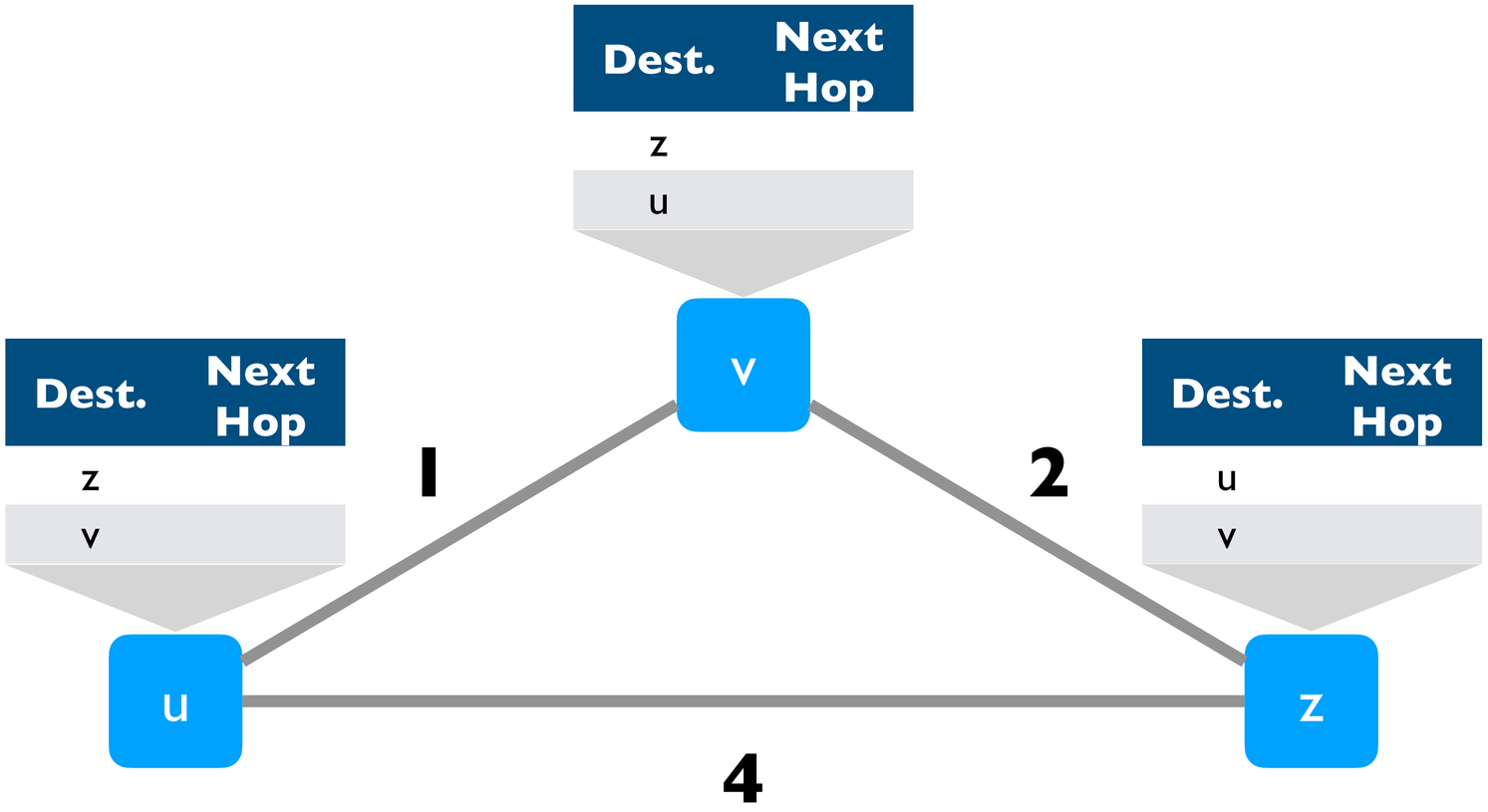
Link costs



Could represent:

- Propagation delay
- Load
- Cost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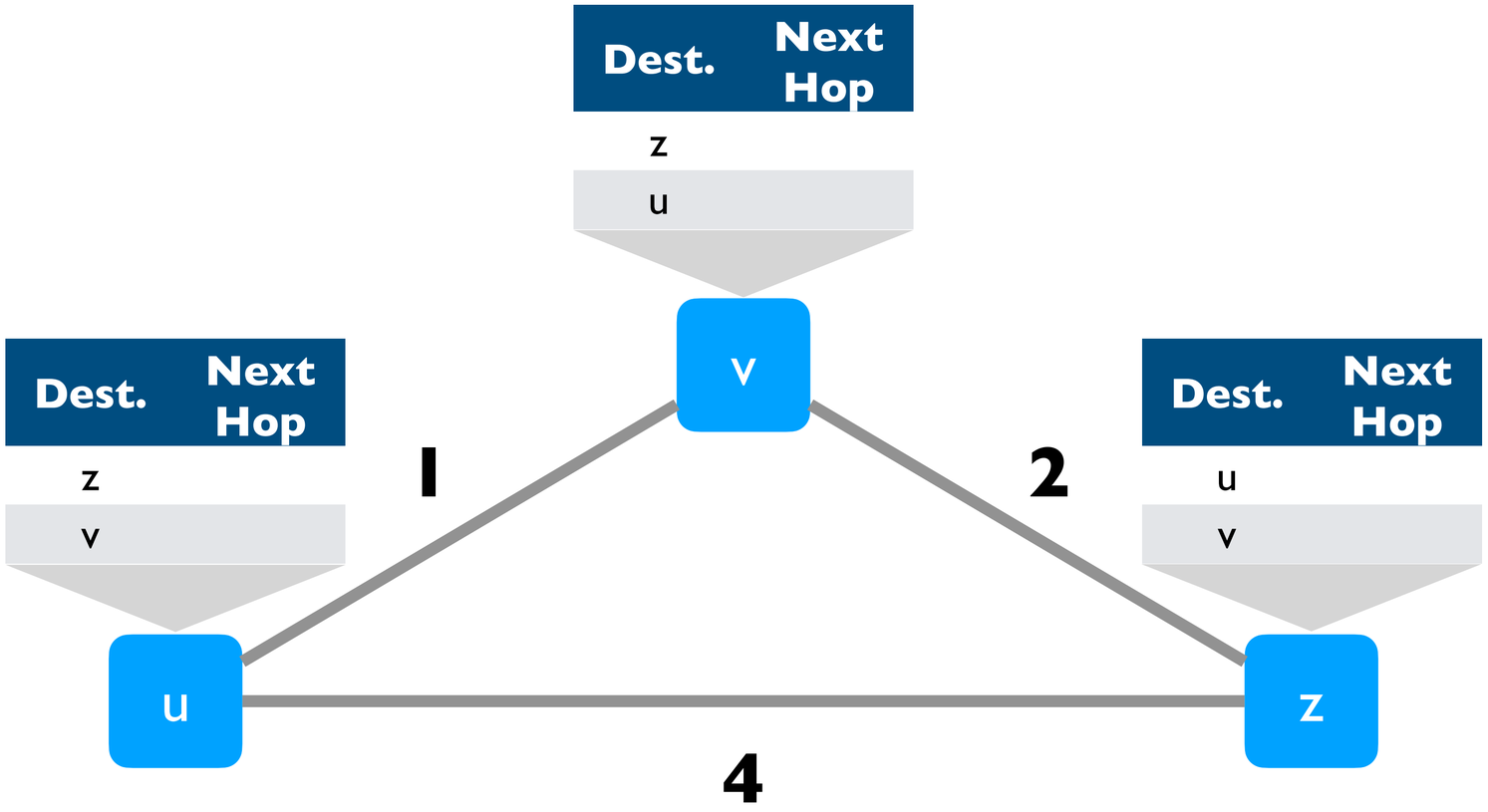
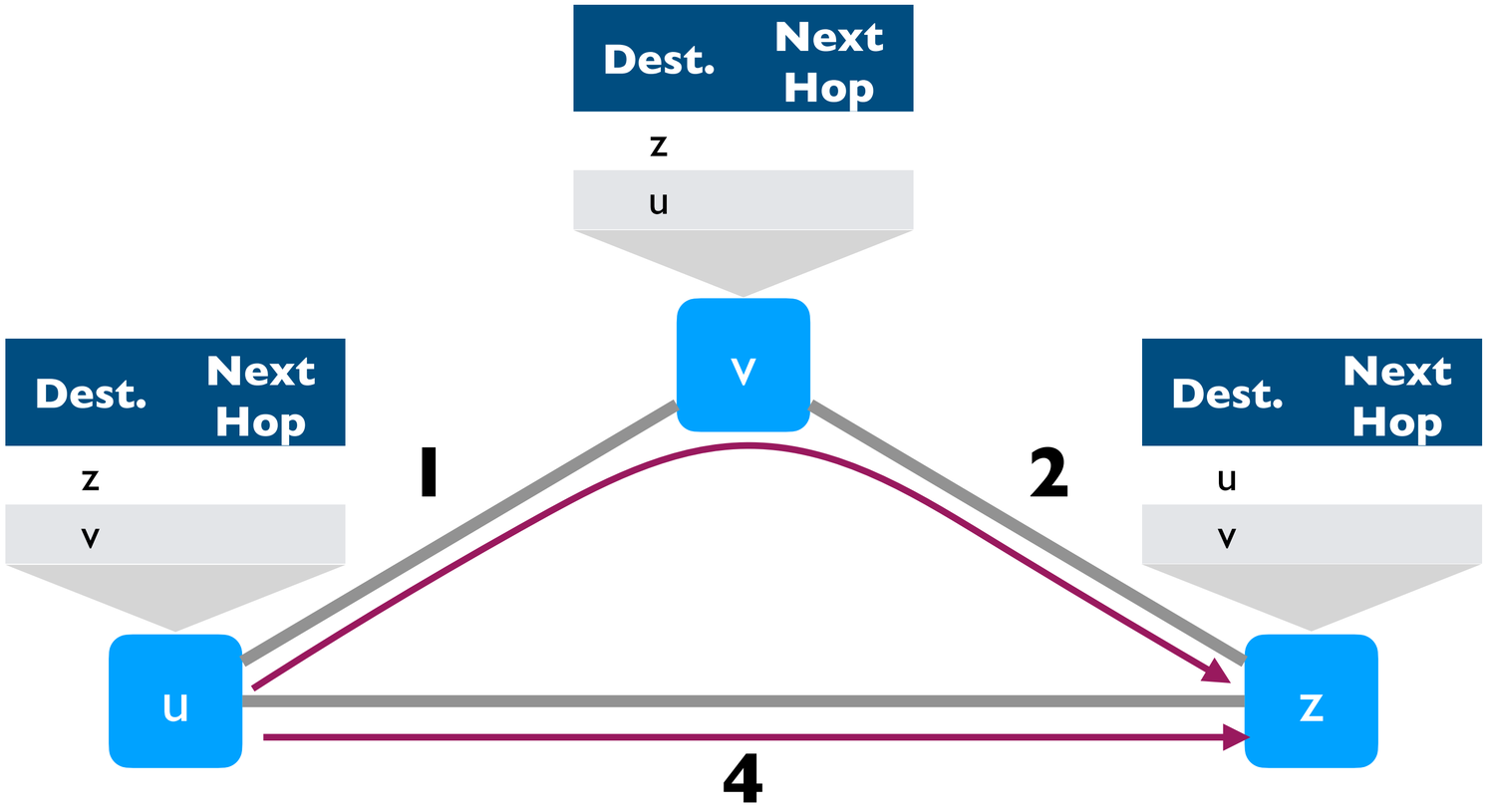


Least-cost path from **u** to **z**:



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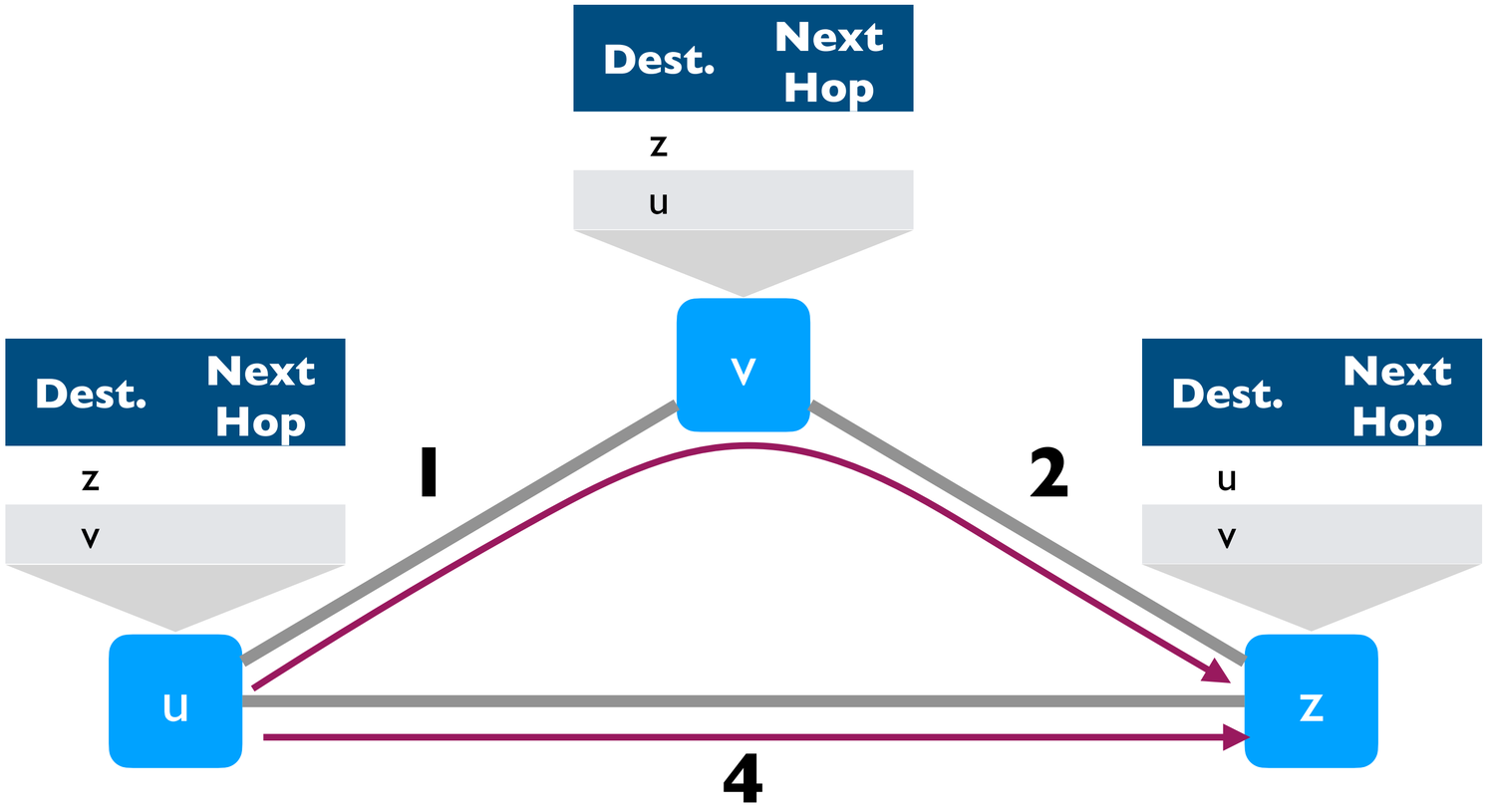
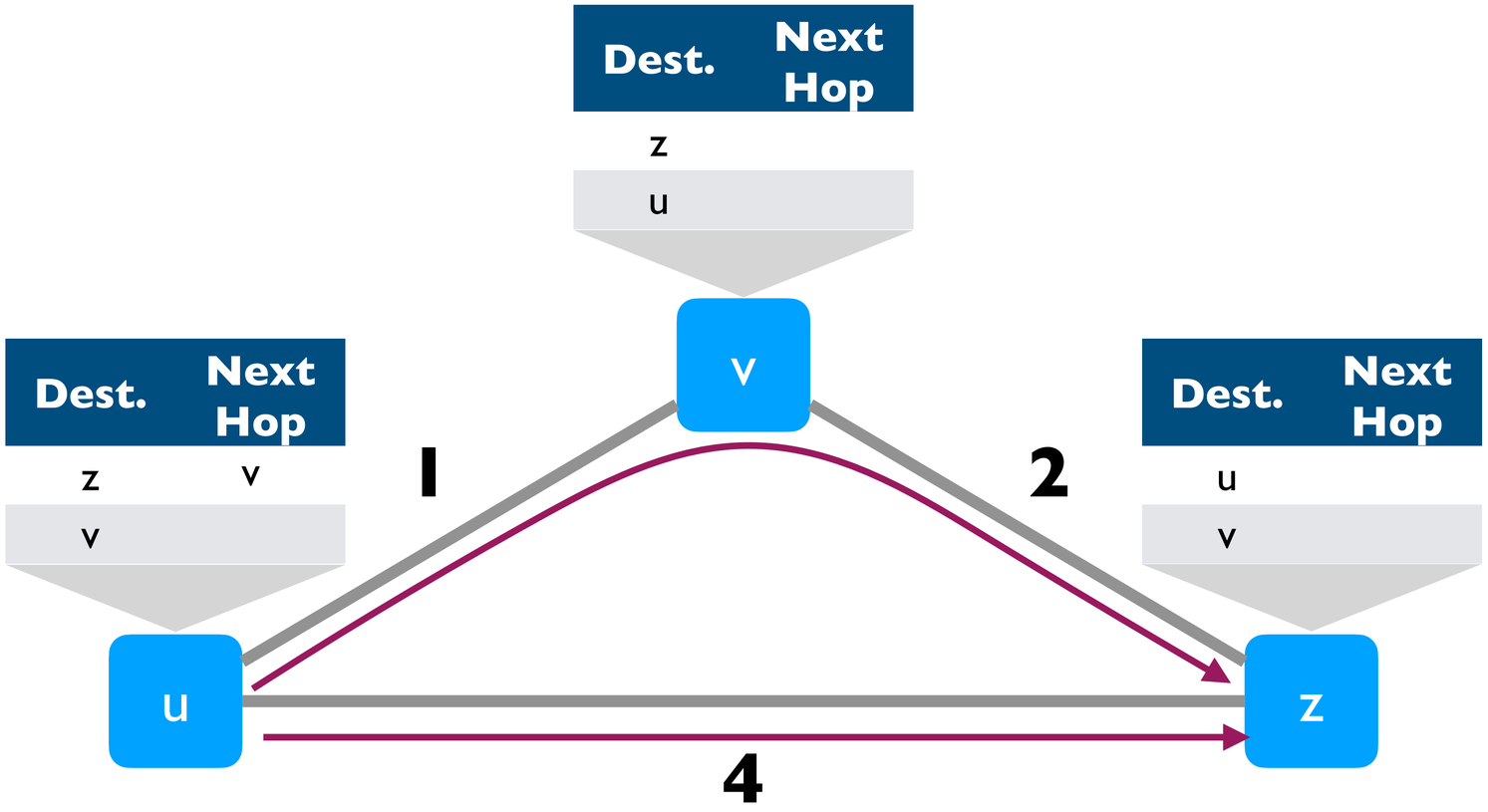


Least-cost path from **u** to **z**: **u v z**



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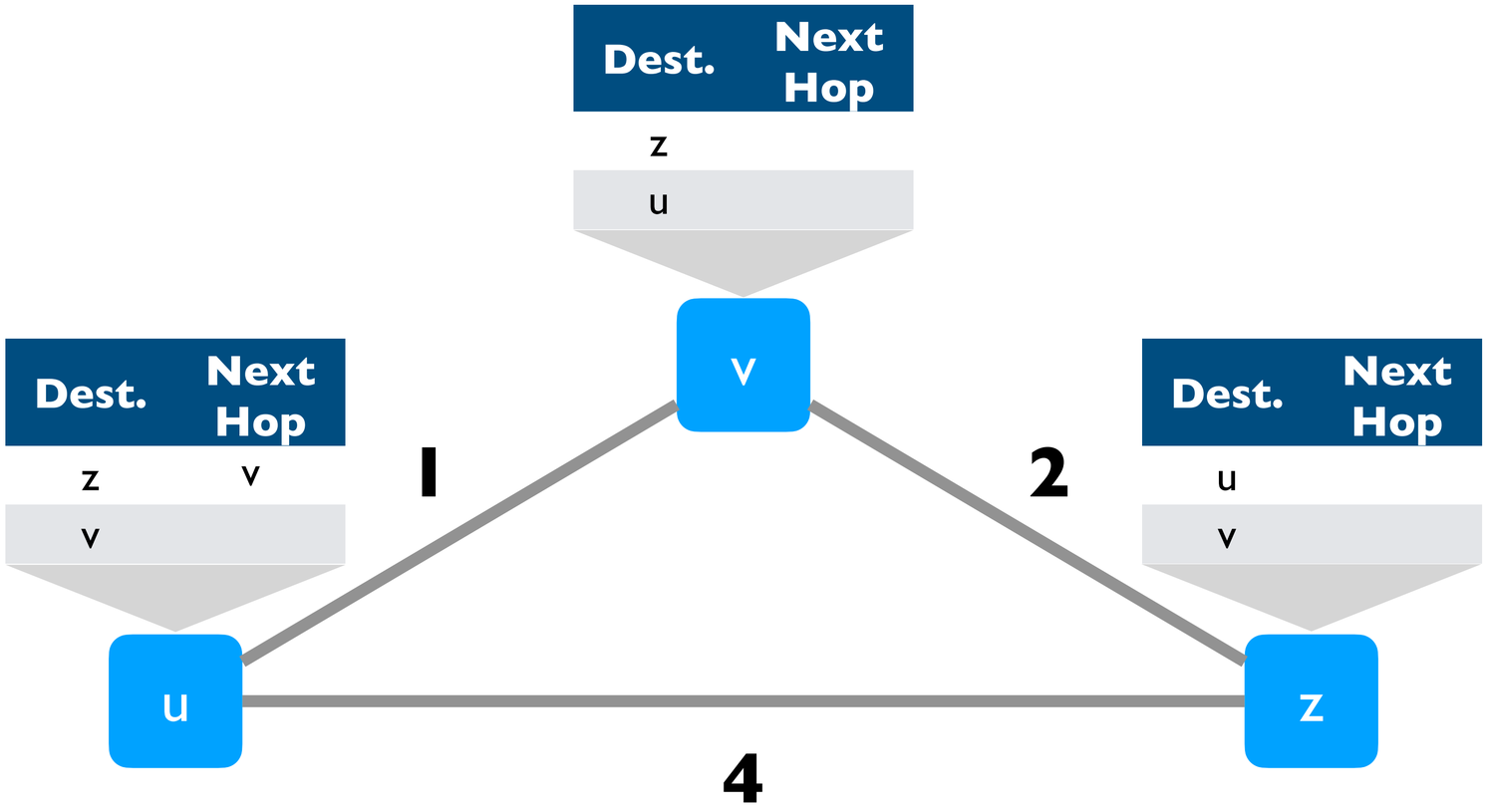

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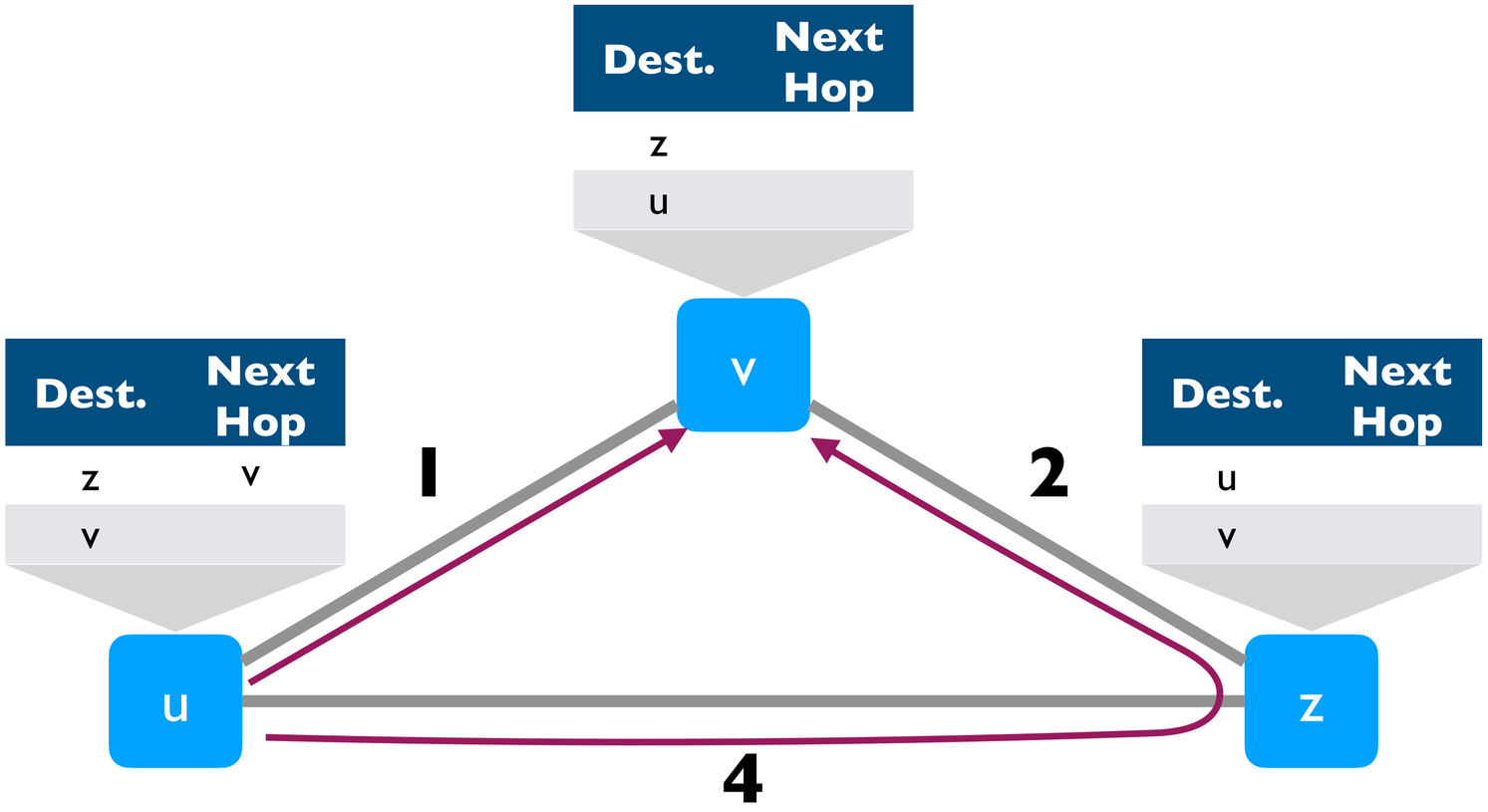
Least-cost path from **u** to **v**:



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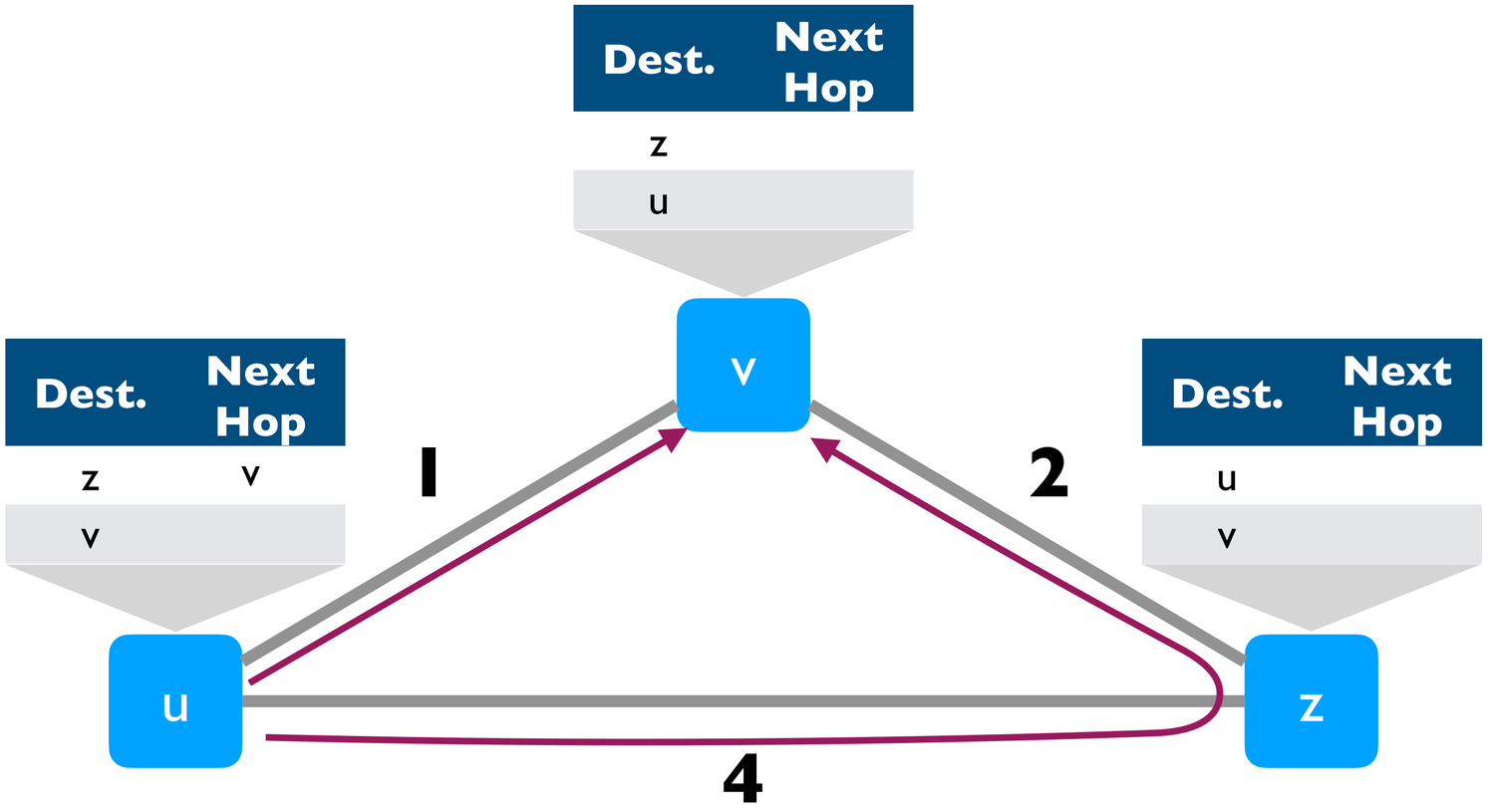

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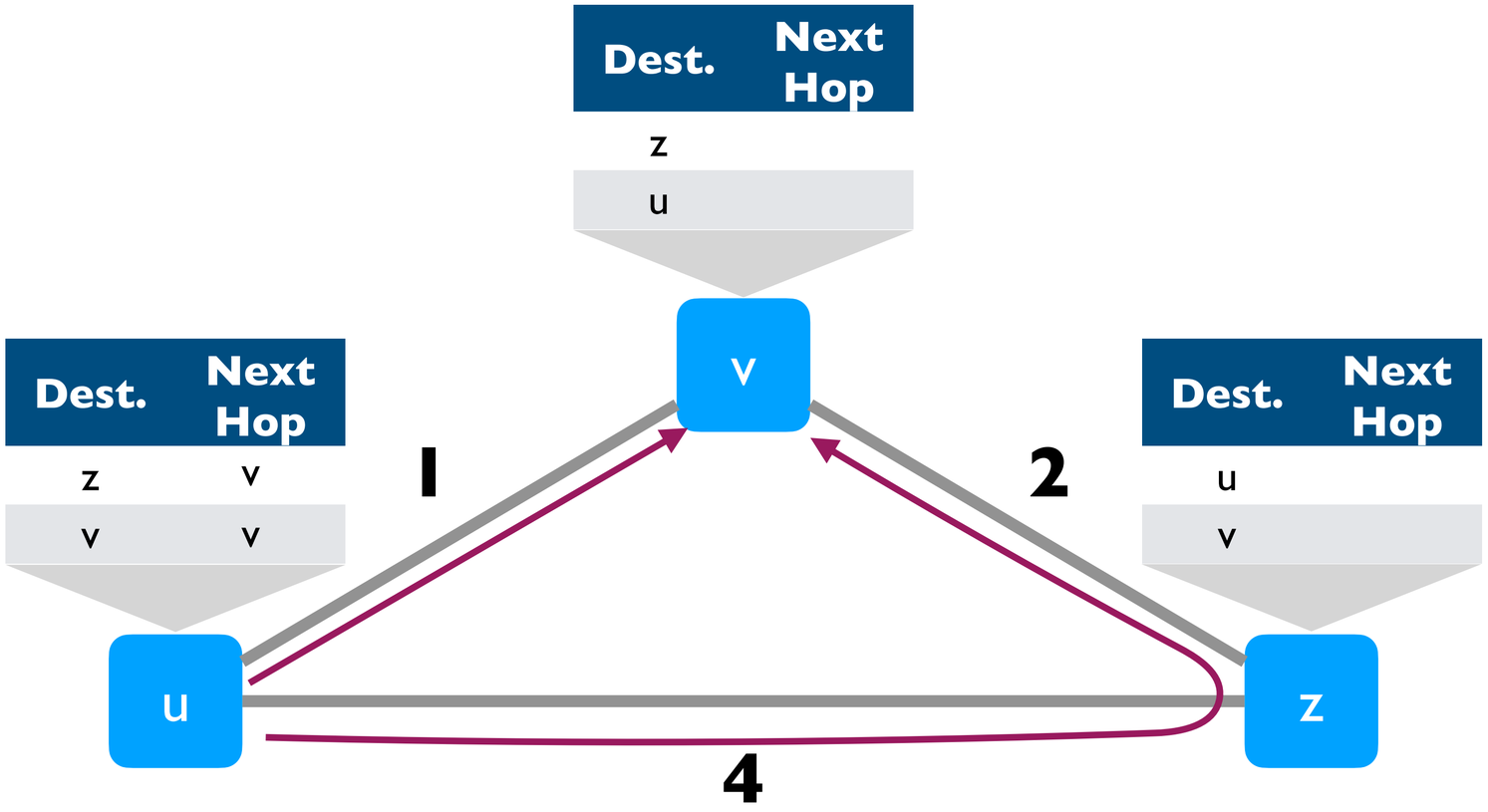

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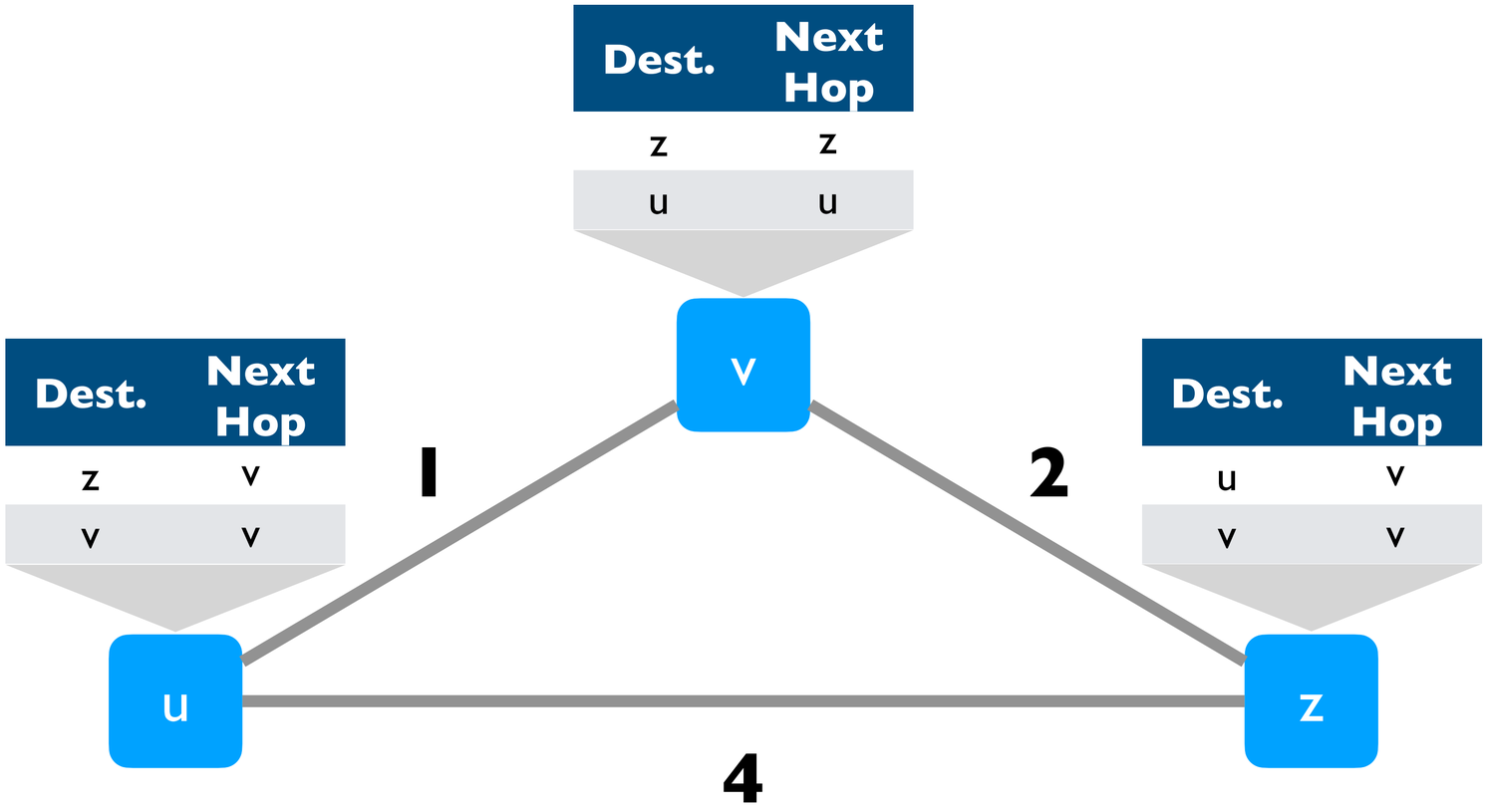

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Least-cost path routing

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- **Given:** Router graph & link costs

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- **Goal:** find least-cost path
  from each source router
  to each destination router

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  - *No **sensible** cost metric is minimized by traversing a loop*
- Least cost routes are also “destination-based”
  - *i.e., they do not depend on the source*
- Least cost paths form a spanning tree

Outline

- Approach 1: link-state routing
- Approach 2: distance-vector routing
- Routing in the internet

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- The network can be abstracted as a graph **G = (N, E)**
  Nodes **N** corresponding to routers
  Edges **E** correspond to links
  Each edge has an associated cost

Dijkstra’s Algorithm

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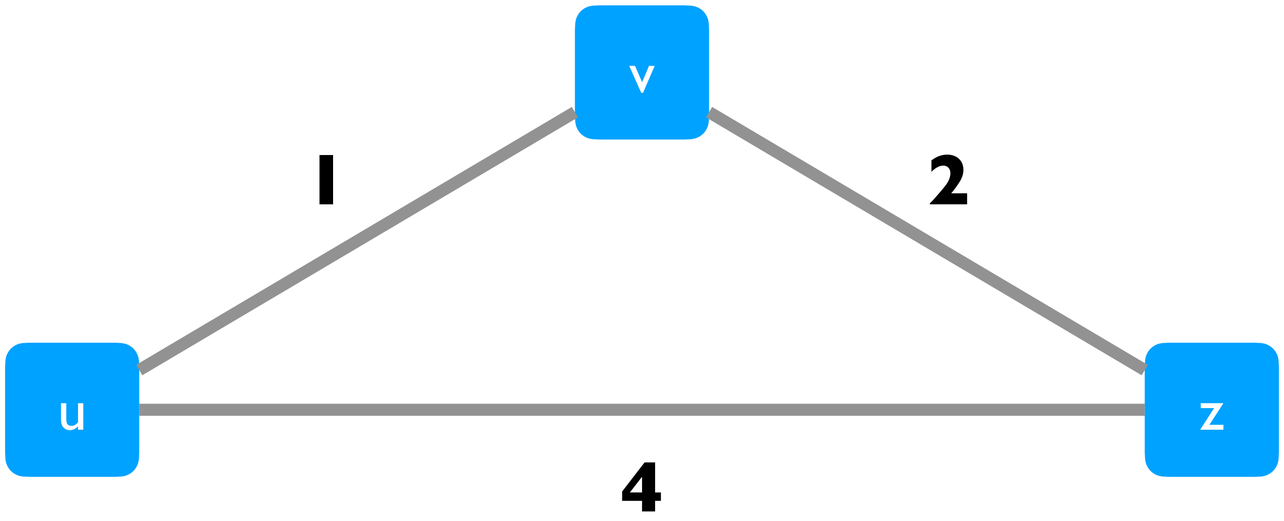
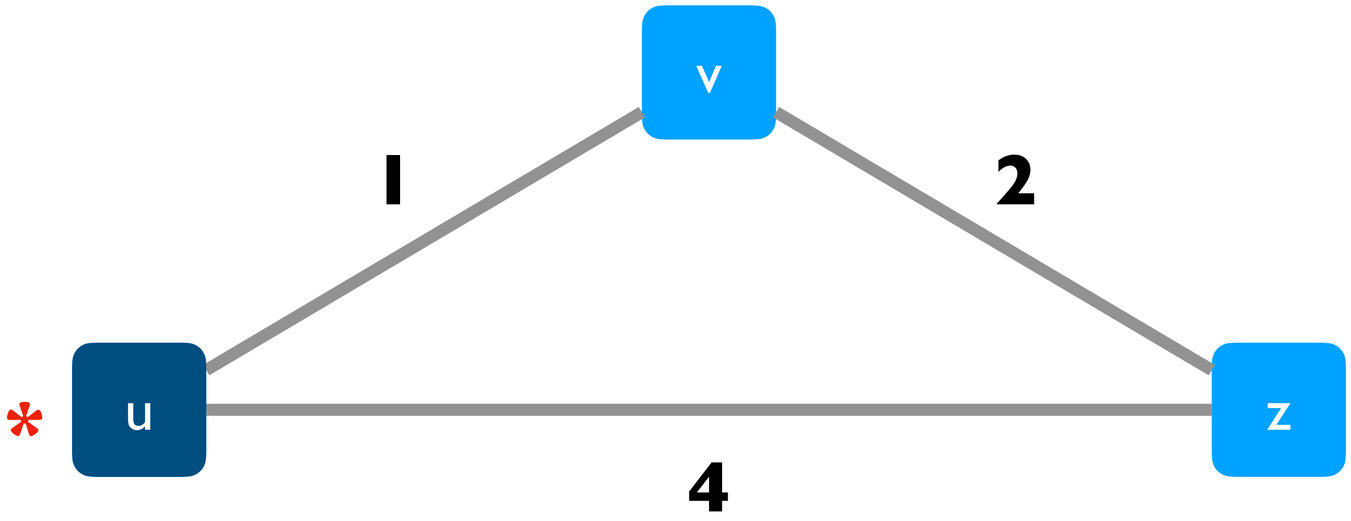
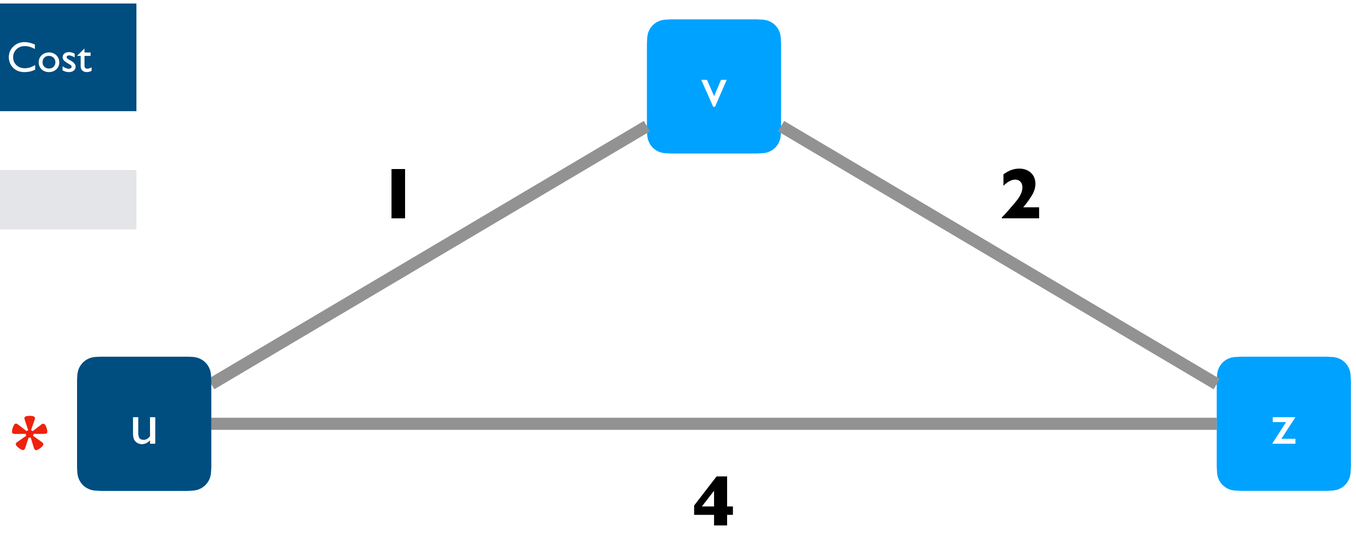
- See text for exact algorithm

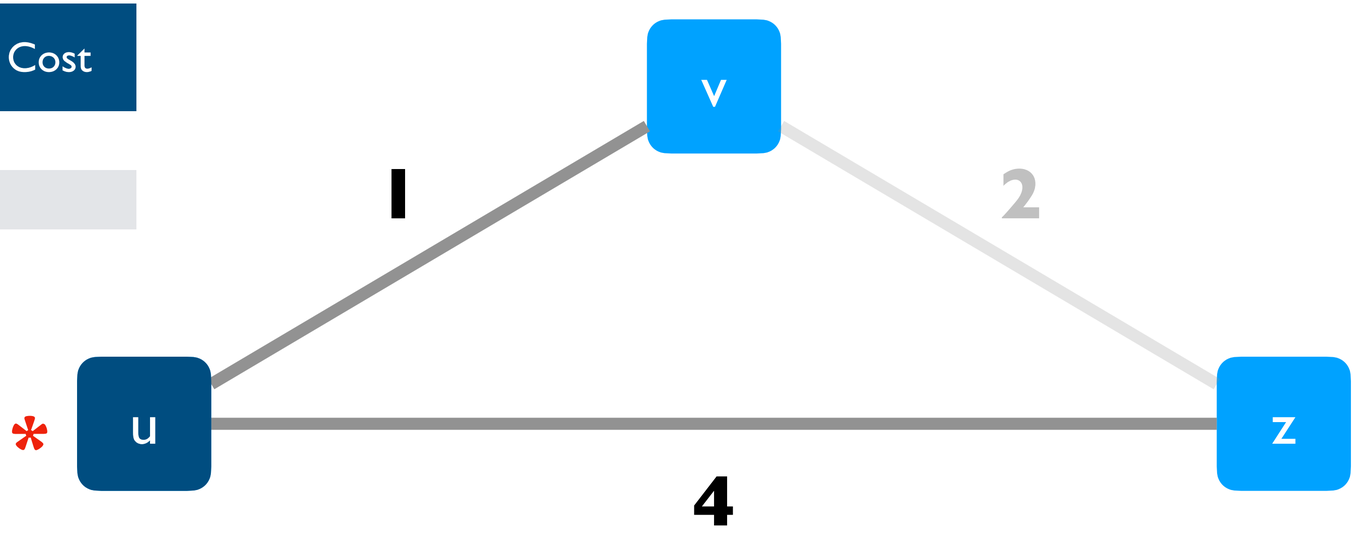

v
1
2
u
z
4


v
1
2
*
u
z
4

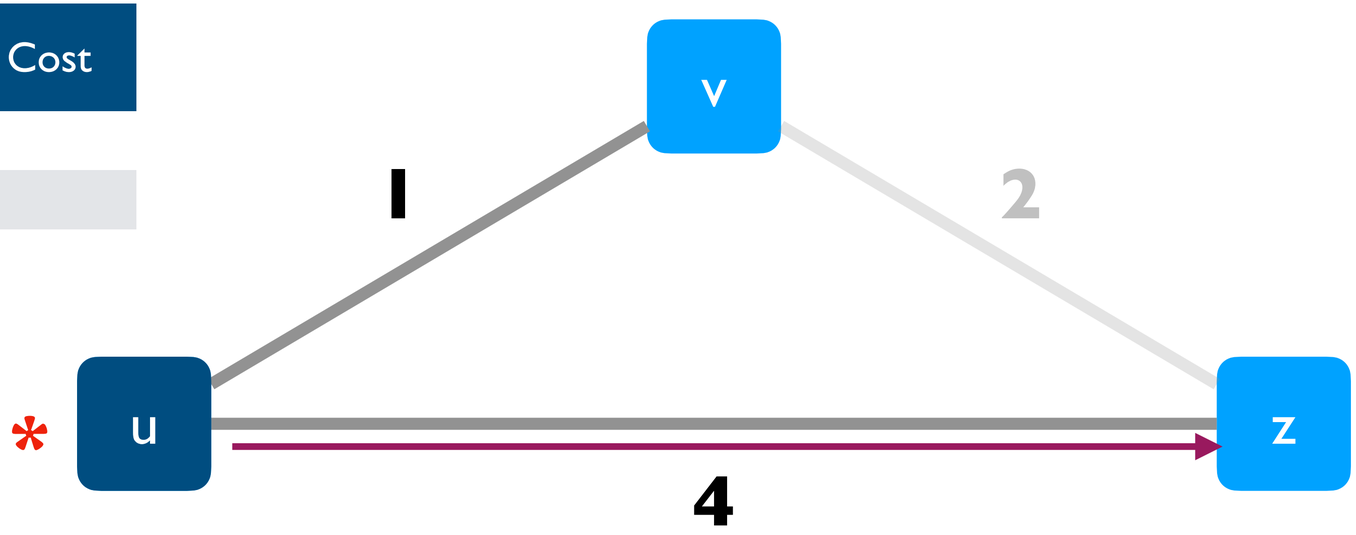
Dest.	Next Hop	Cost
z		
v		



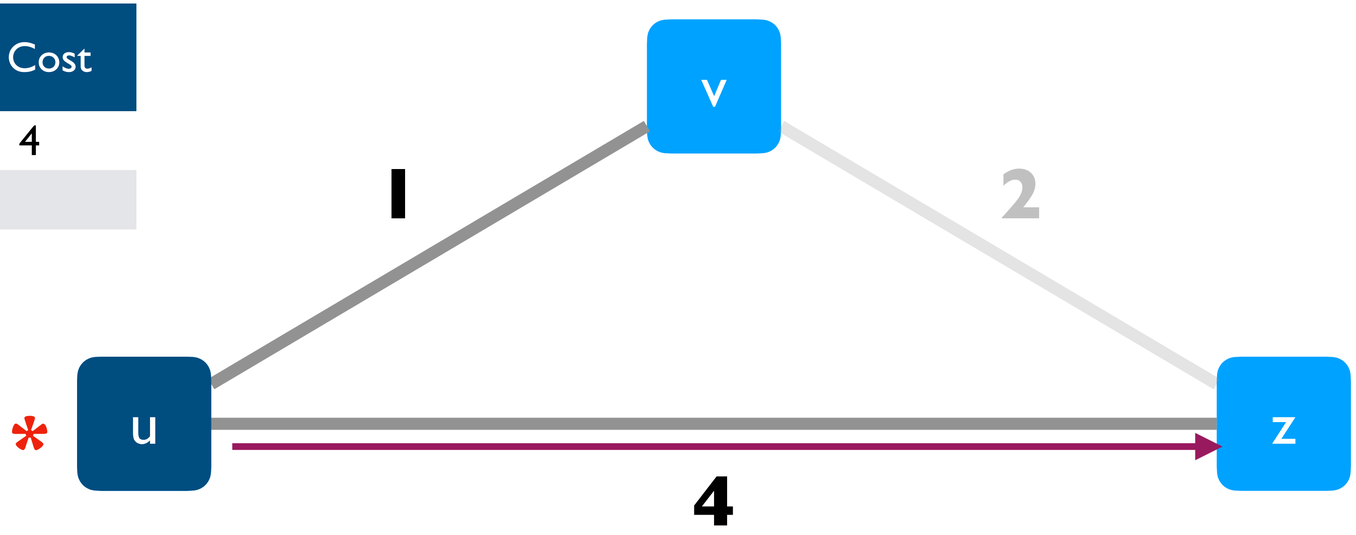
Dest.	Next Hop	Cost
z		
v		



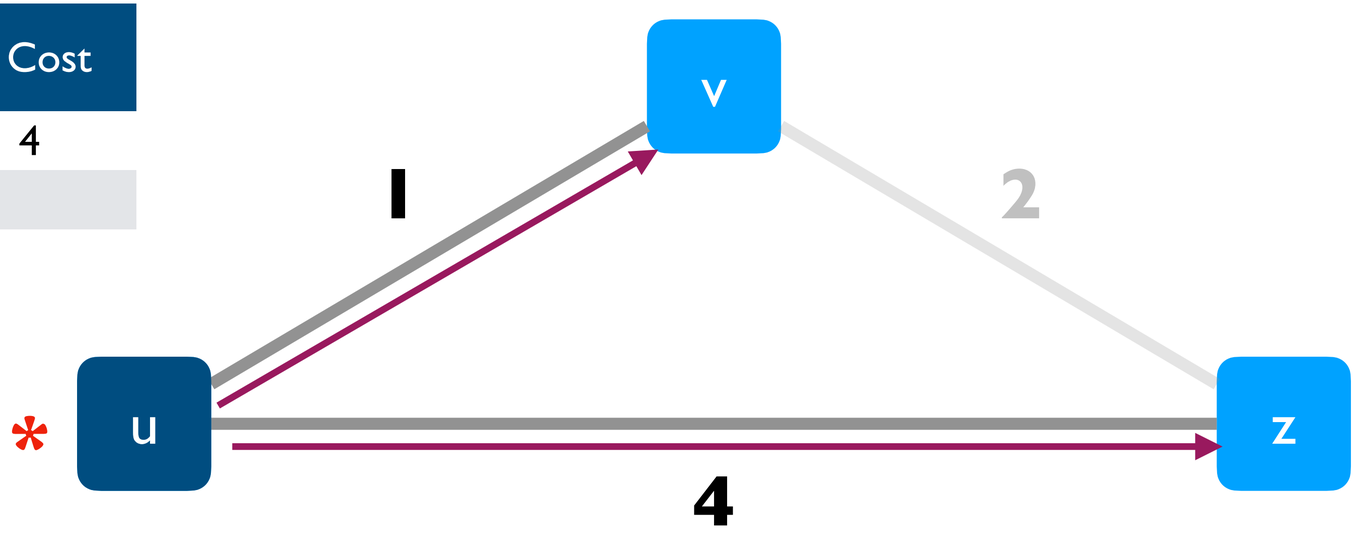
Dest.	Next Hop	Cost
z		
v		



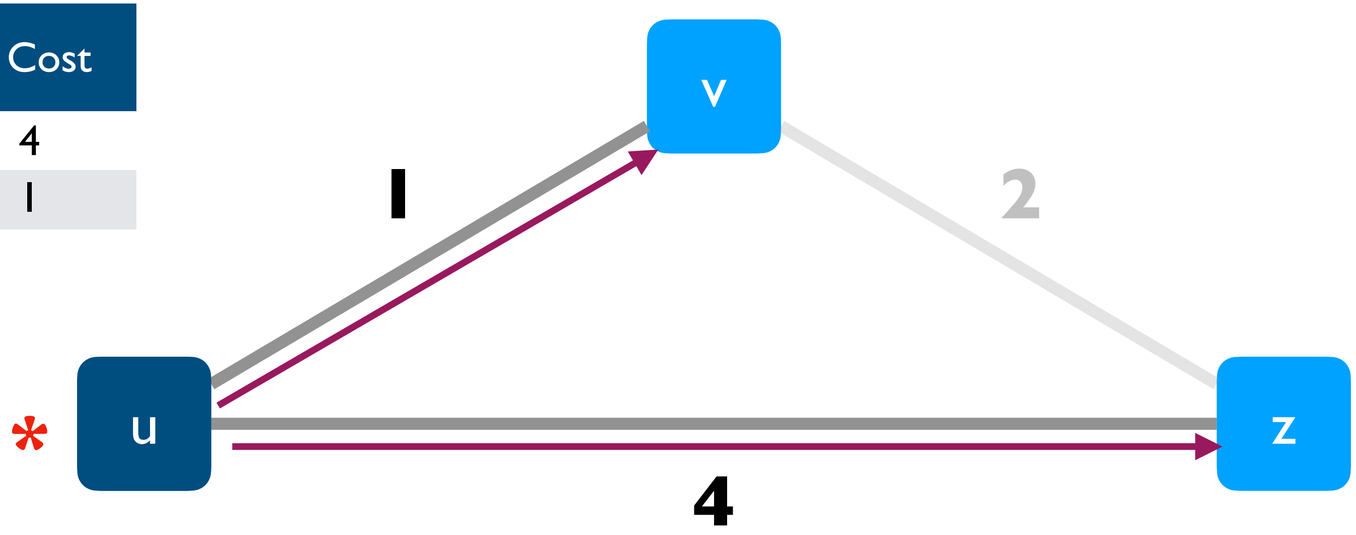
Dest.	Next Hop	Cost
z	z	4
v		



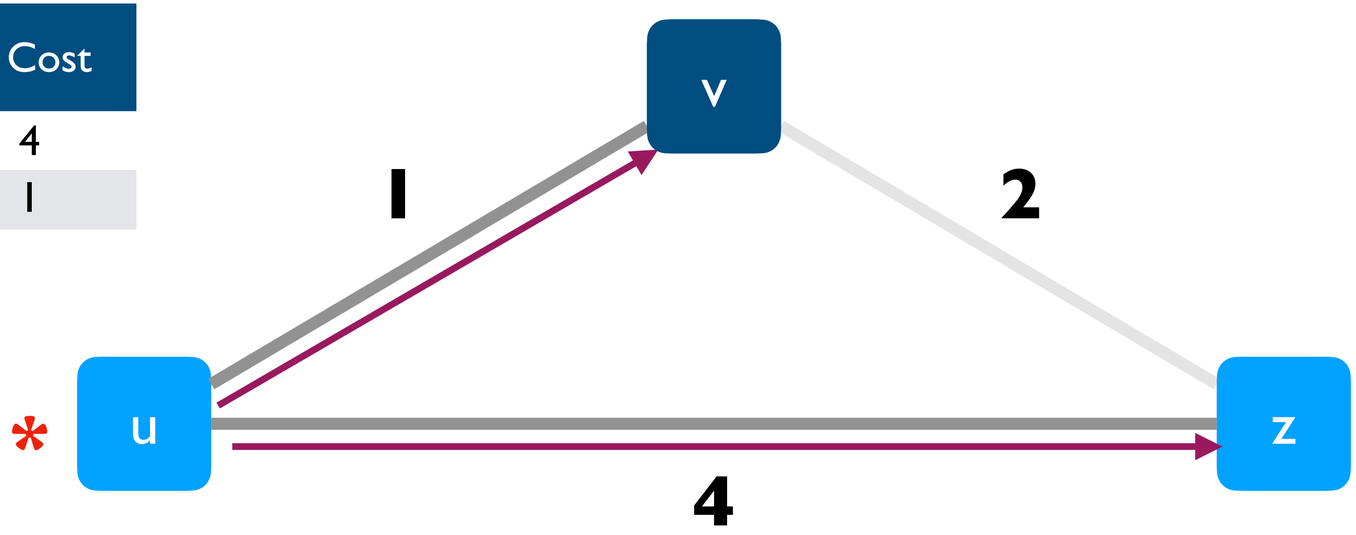
Dest.	Next Hop	Cost
z	z	4
v		



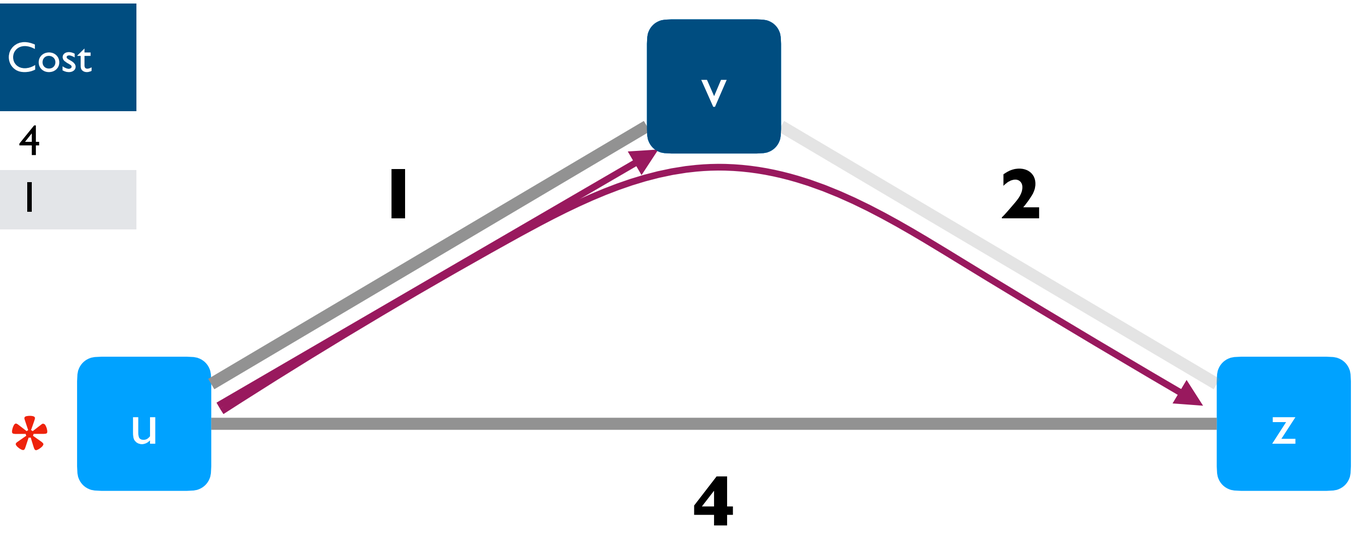
Dest.	Next Hop	Cost
z	z	4
v	v	1



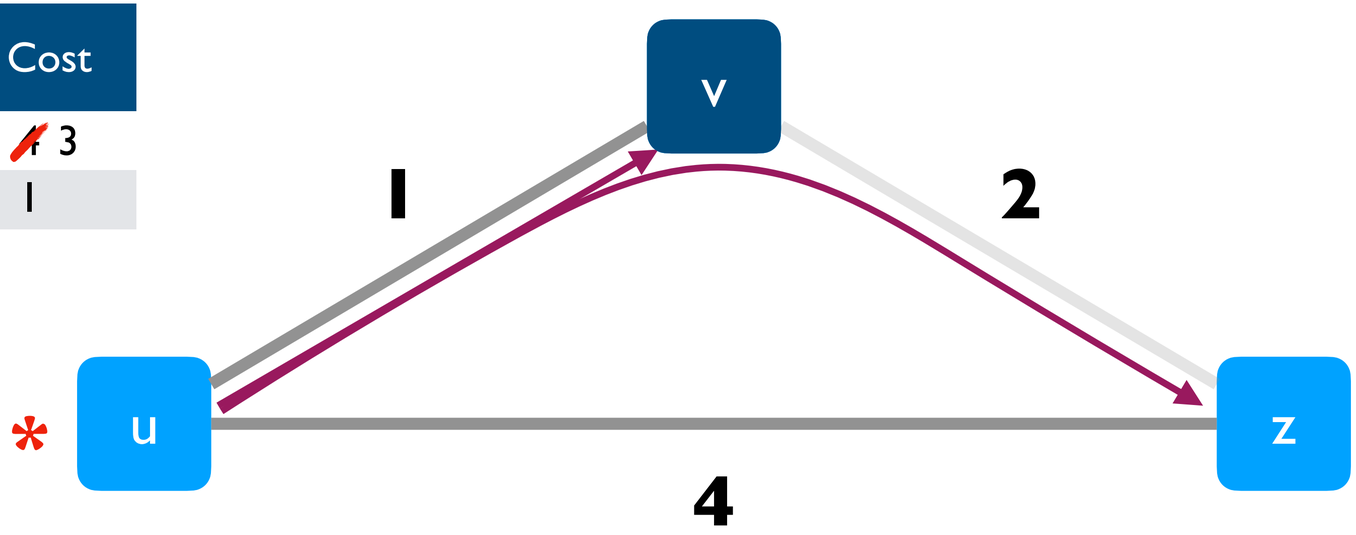
Dest.	Next Hop	Cost
z	z	4
v	v	1



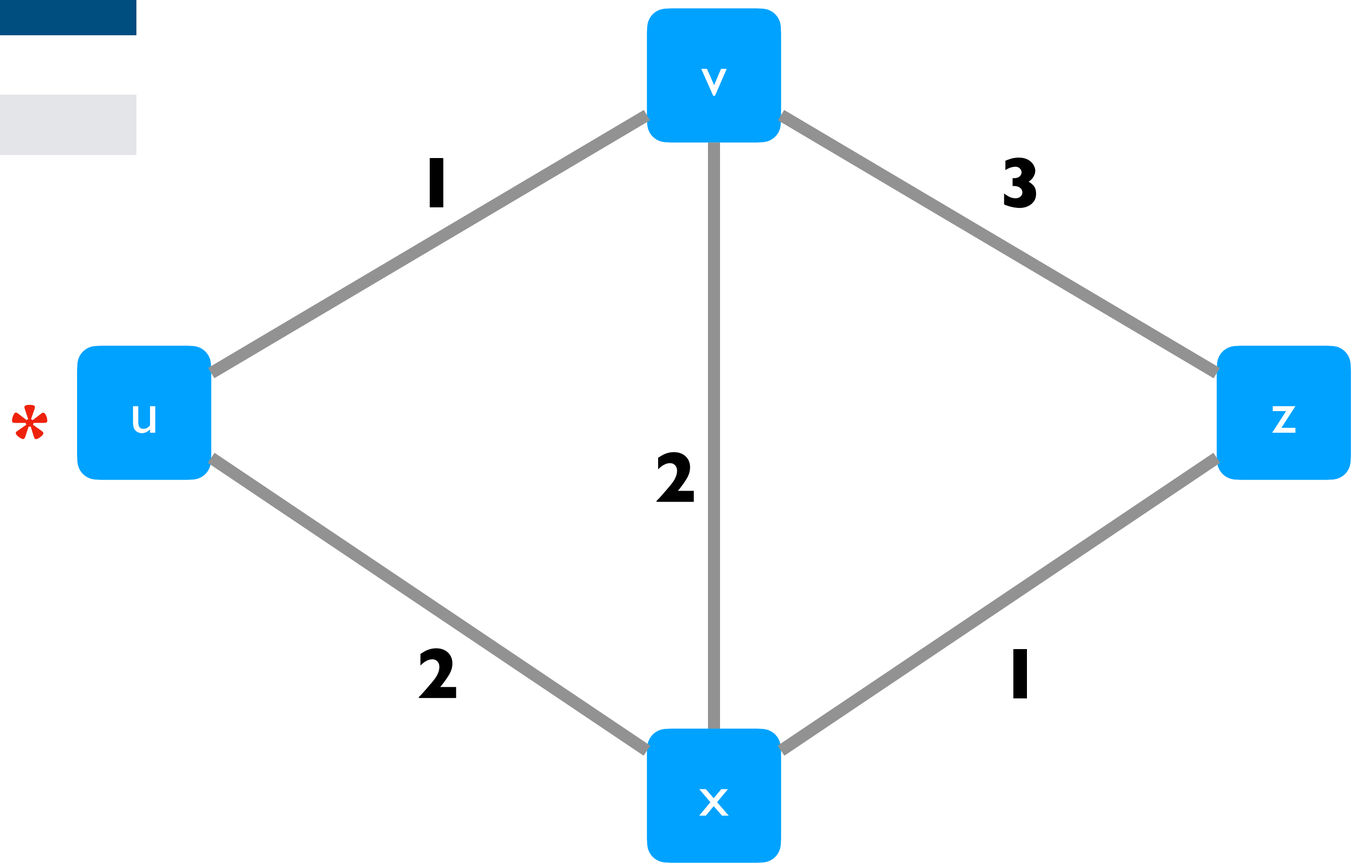
Dest.	Next Hop	Cost
z	z	4
v	v	1



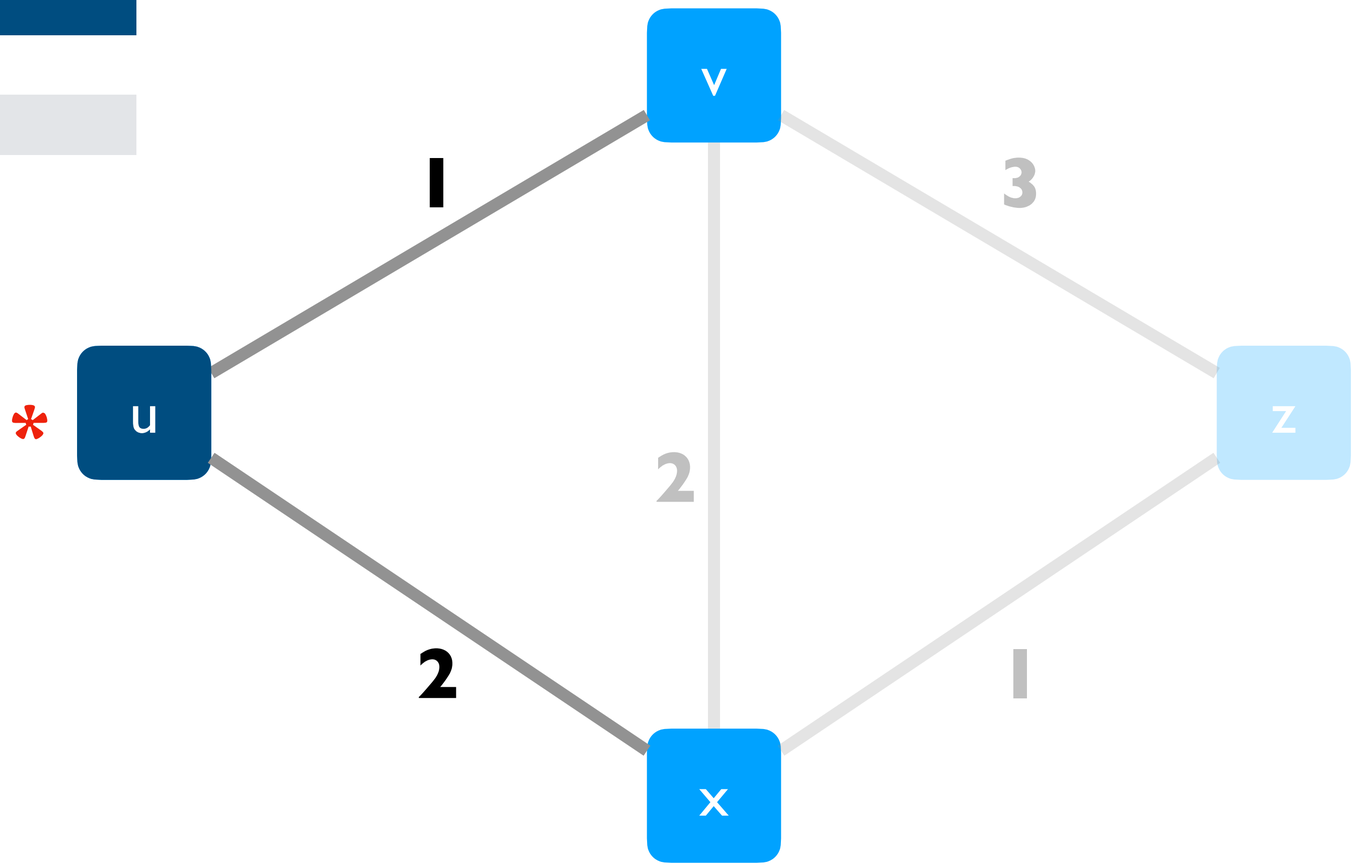
Dest.	Next Hop	Cost
z	~~z~~ v	~~4~~ 3
v	v	1



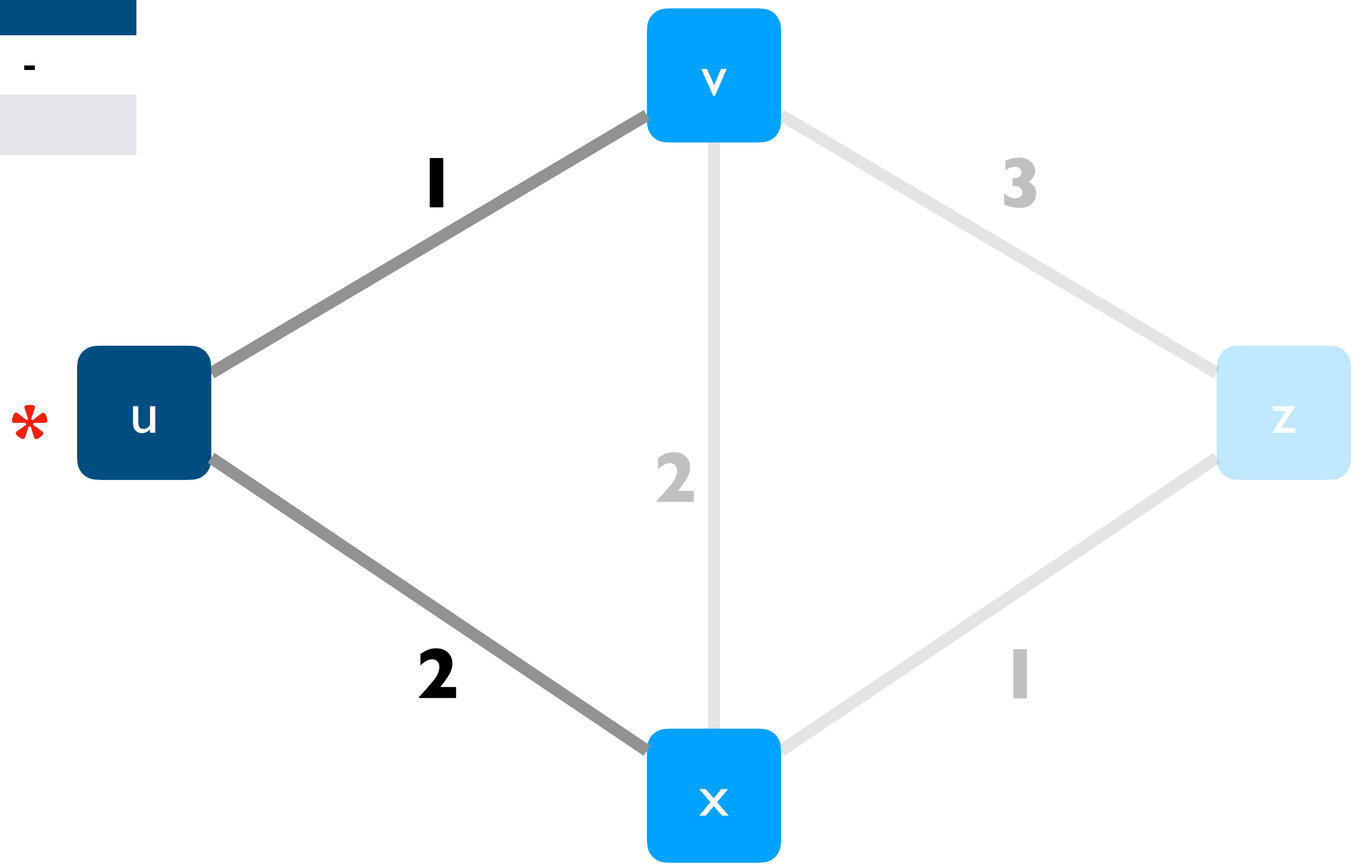
Dest.	Next Hop	Cost
z		
v		
x		



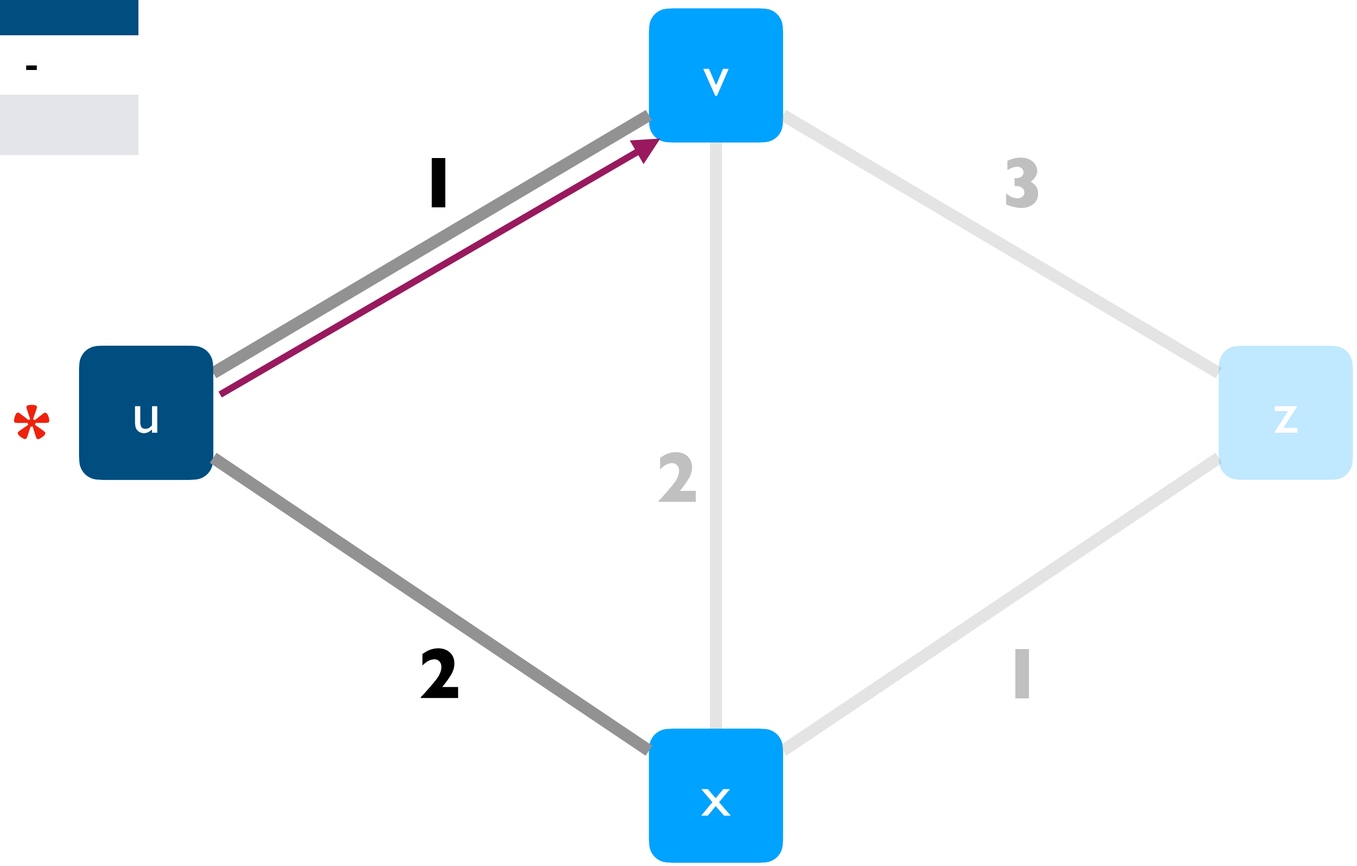
Dest.	Next Hop	Cost
z		
v		
x		



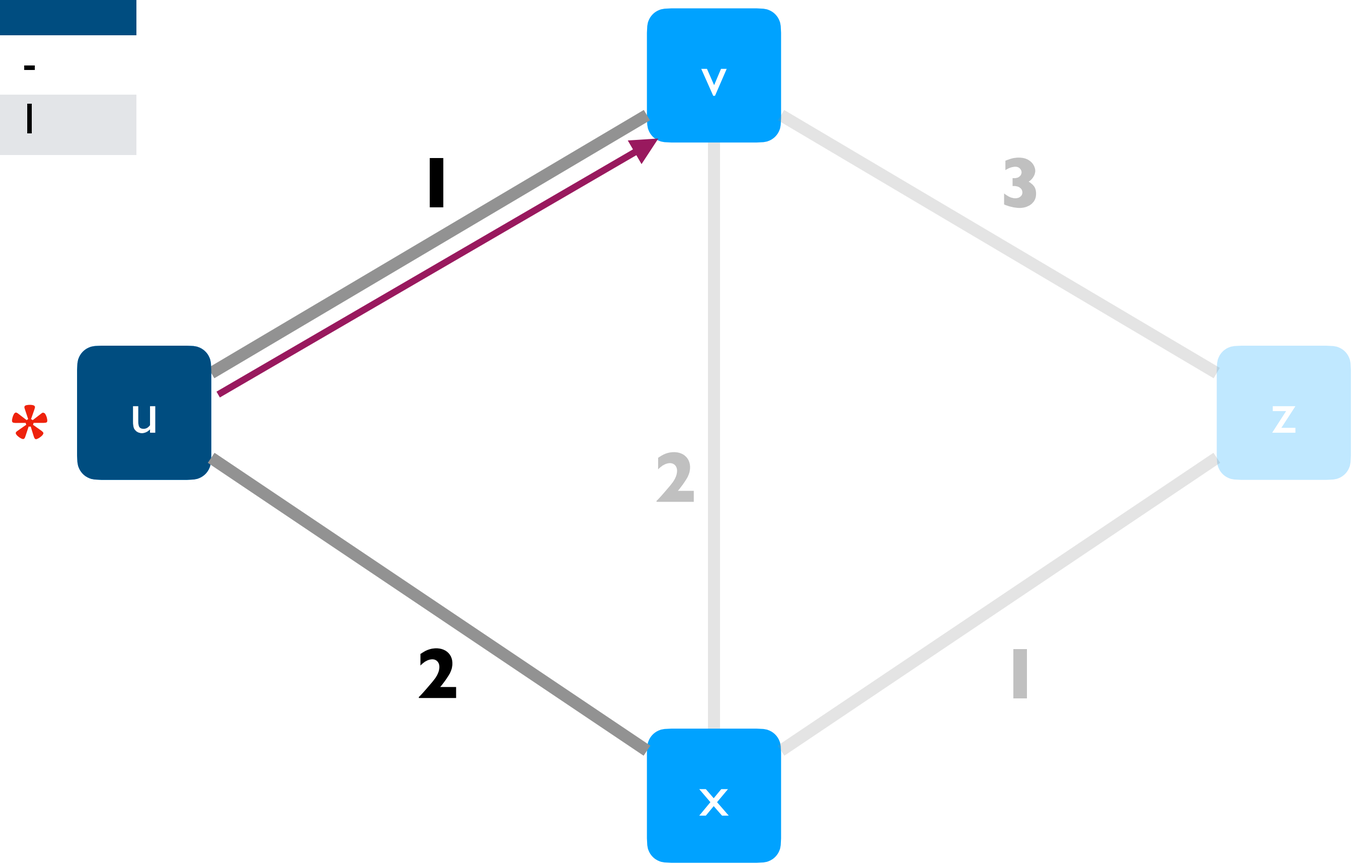
Dest.	Next Hop	Cost
z	-	-
v		
x		



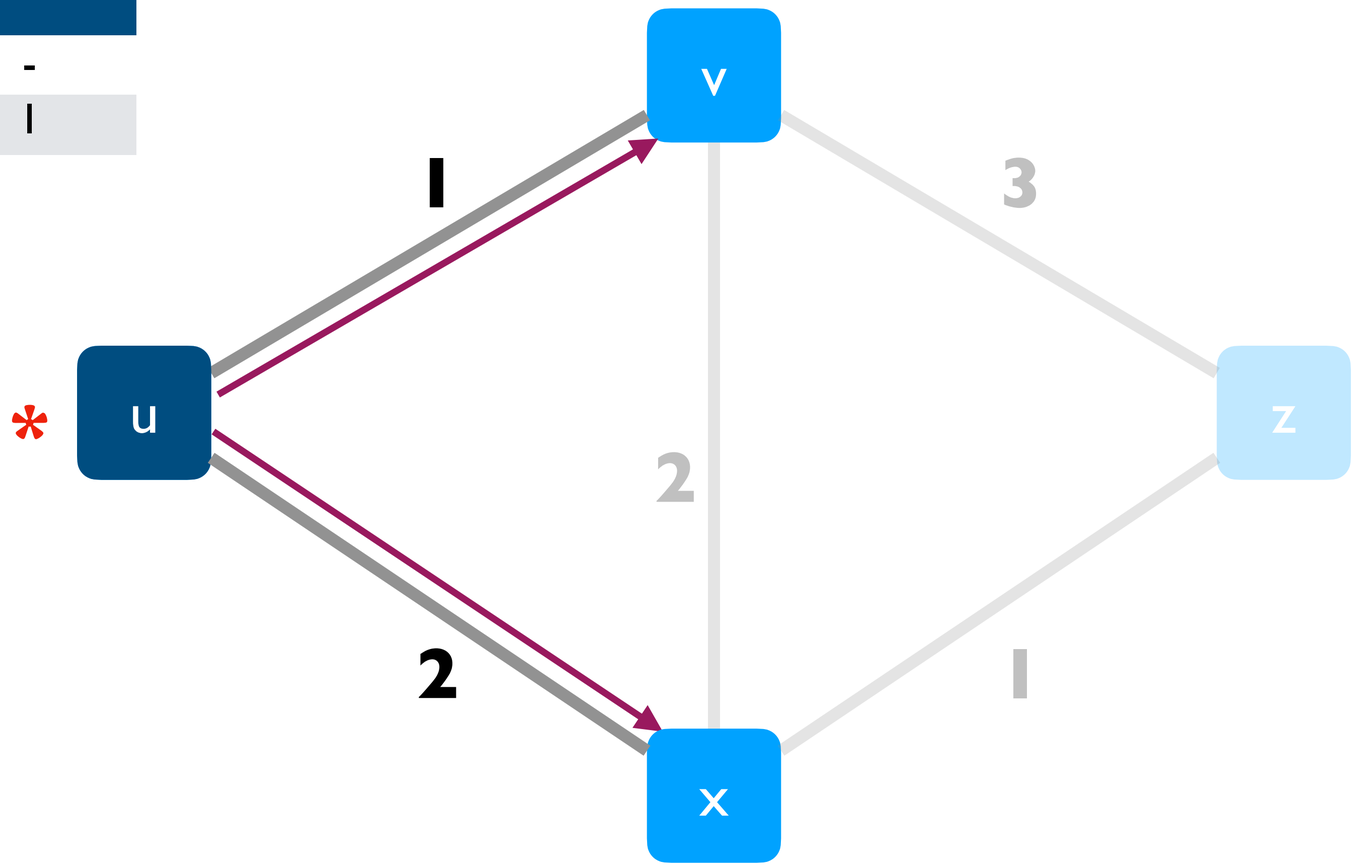
Dest.	Next Hop	Cost
z	-	-
v		
x		



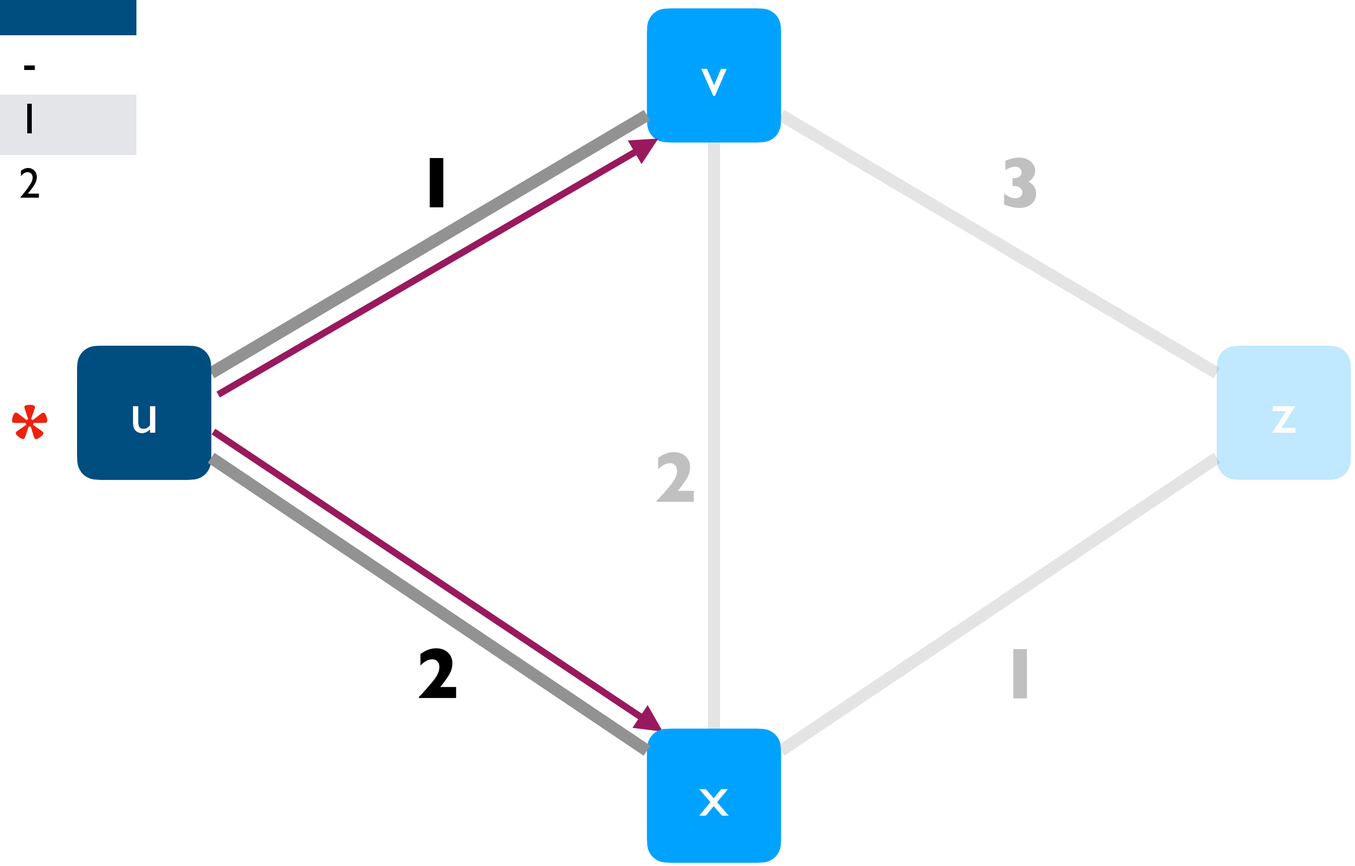
Dest.	Next Hop	Cost
z	-	-
v	v	1
x		



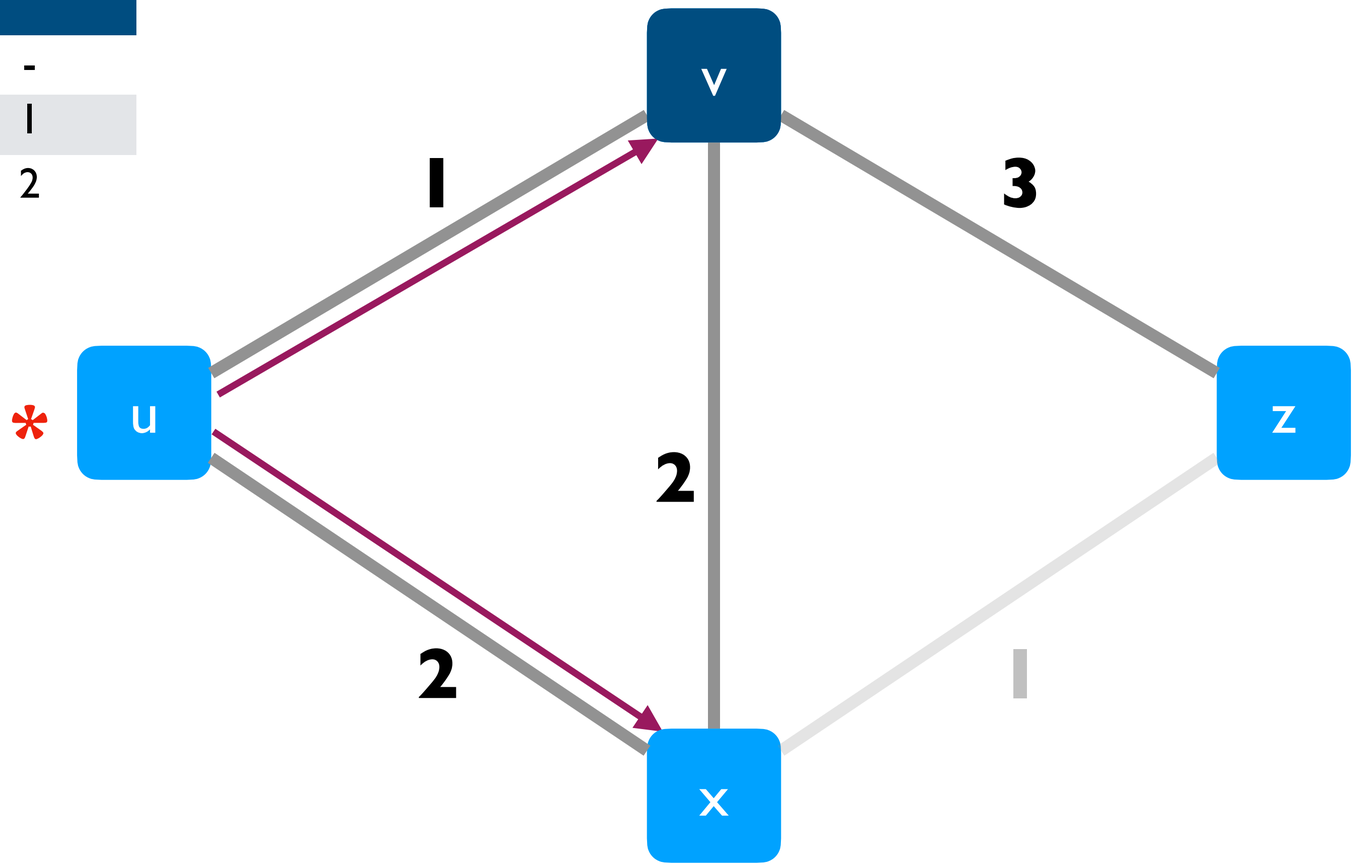
Dest.	Next Hop	Cost
z	-	-
v	v	1
x		



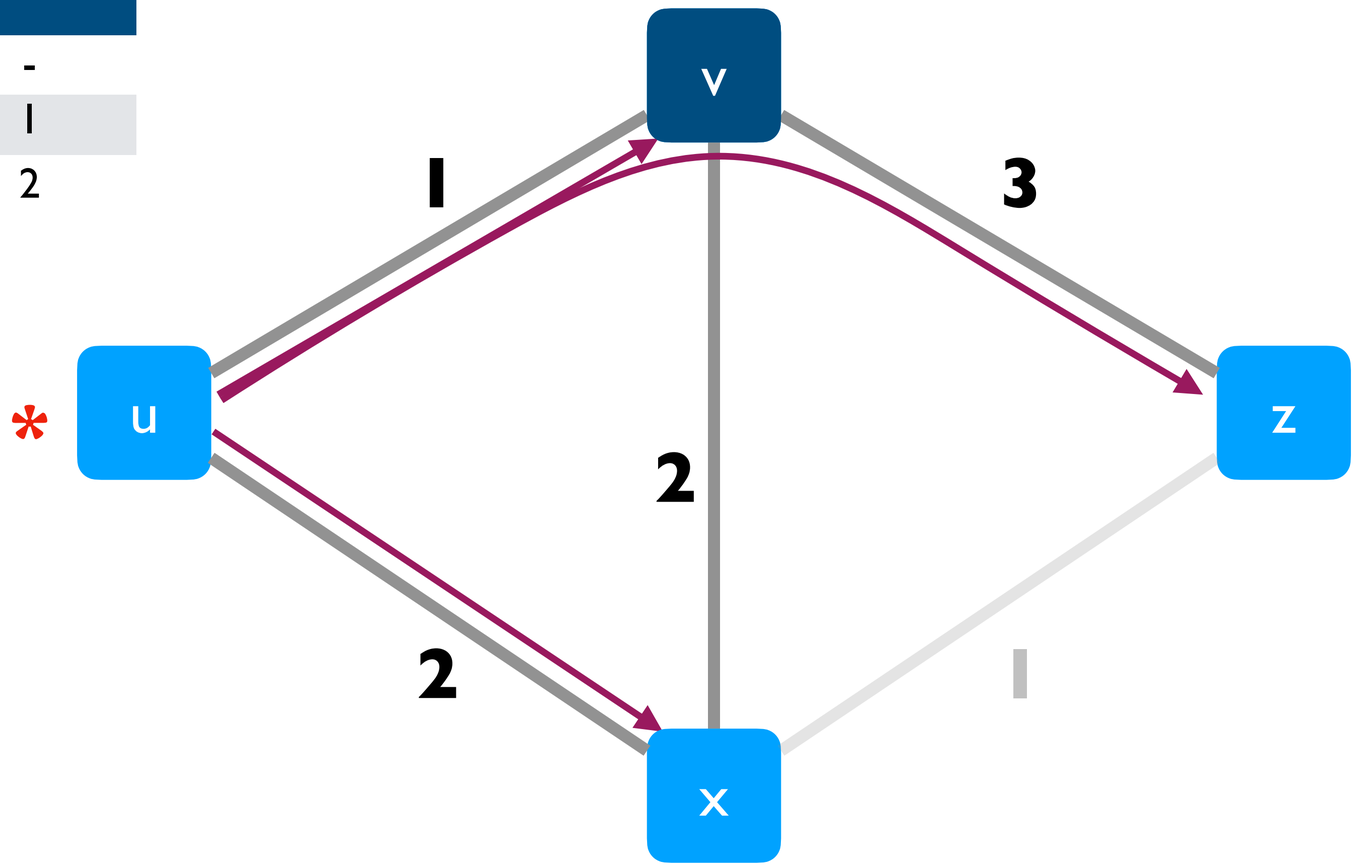
Dest.	Next Hop	Cost
z	-	-
v	v	1
x	x	2



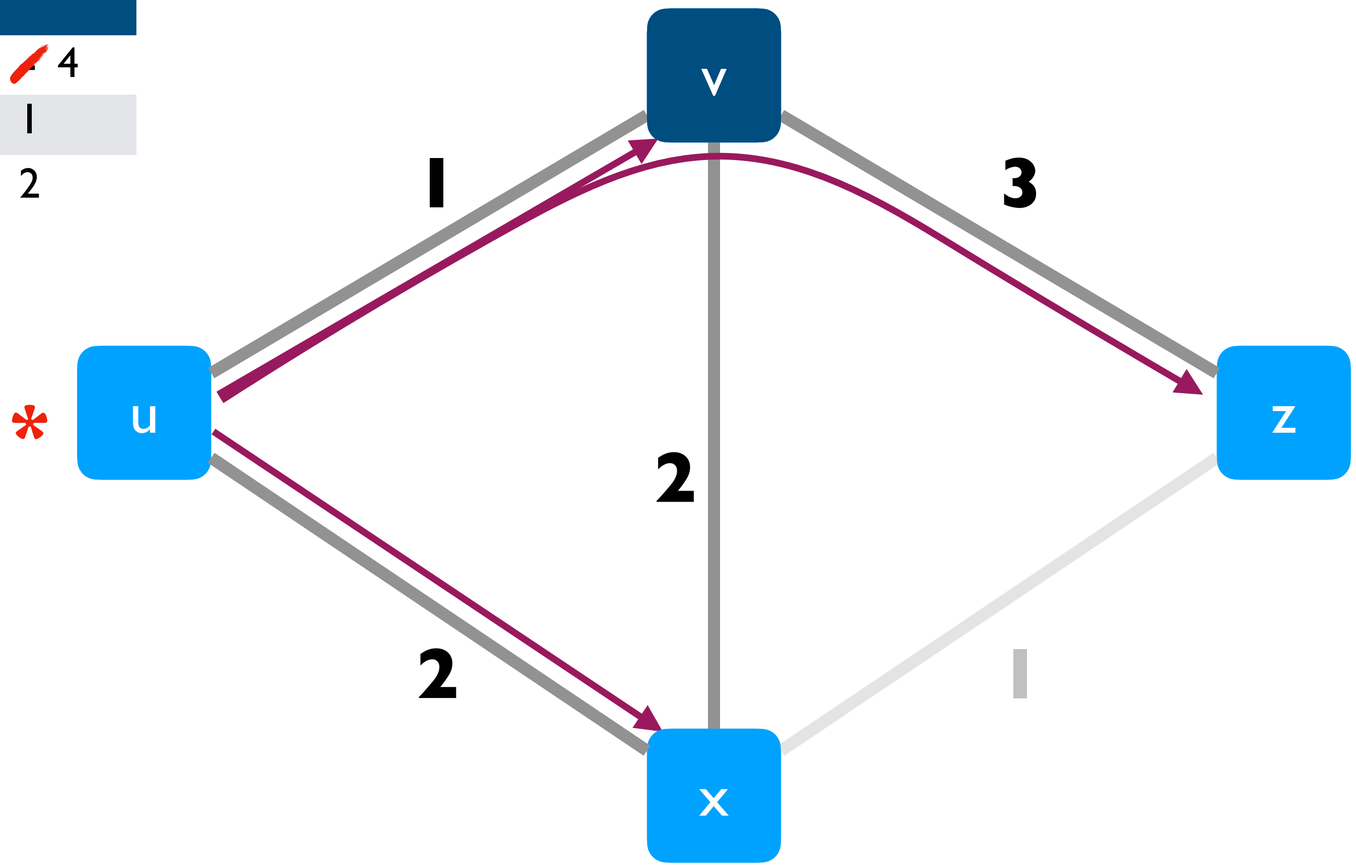
Dest.	Next Hop	Cost
z	-	-
v	v	1
x	x	2



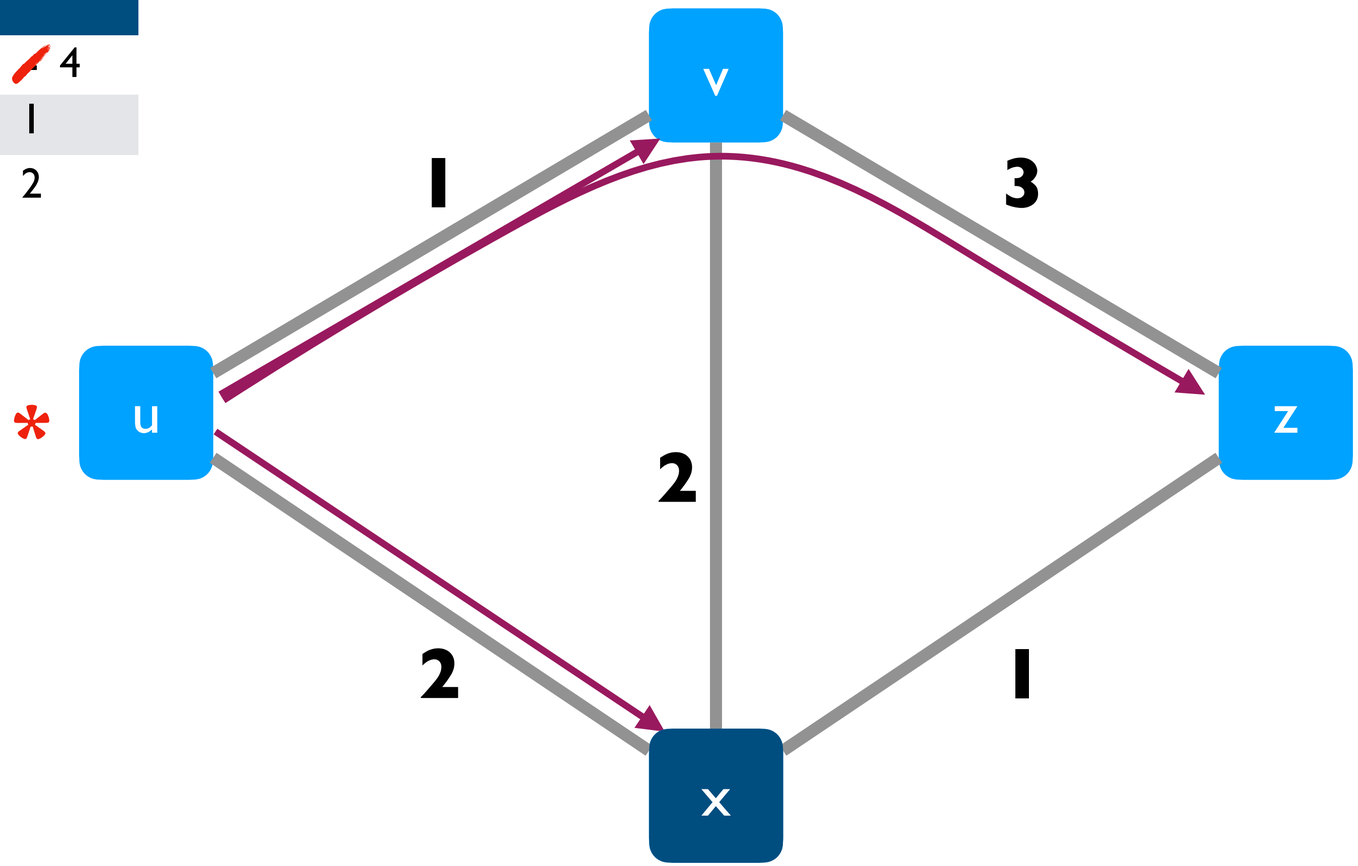
Dest.	Next Hop	Cost
z	-	-
v	v	1
x	x	2



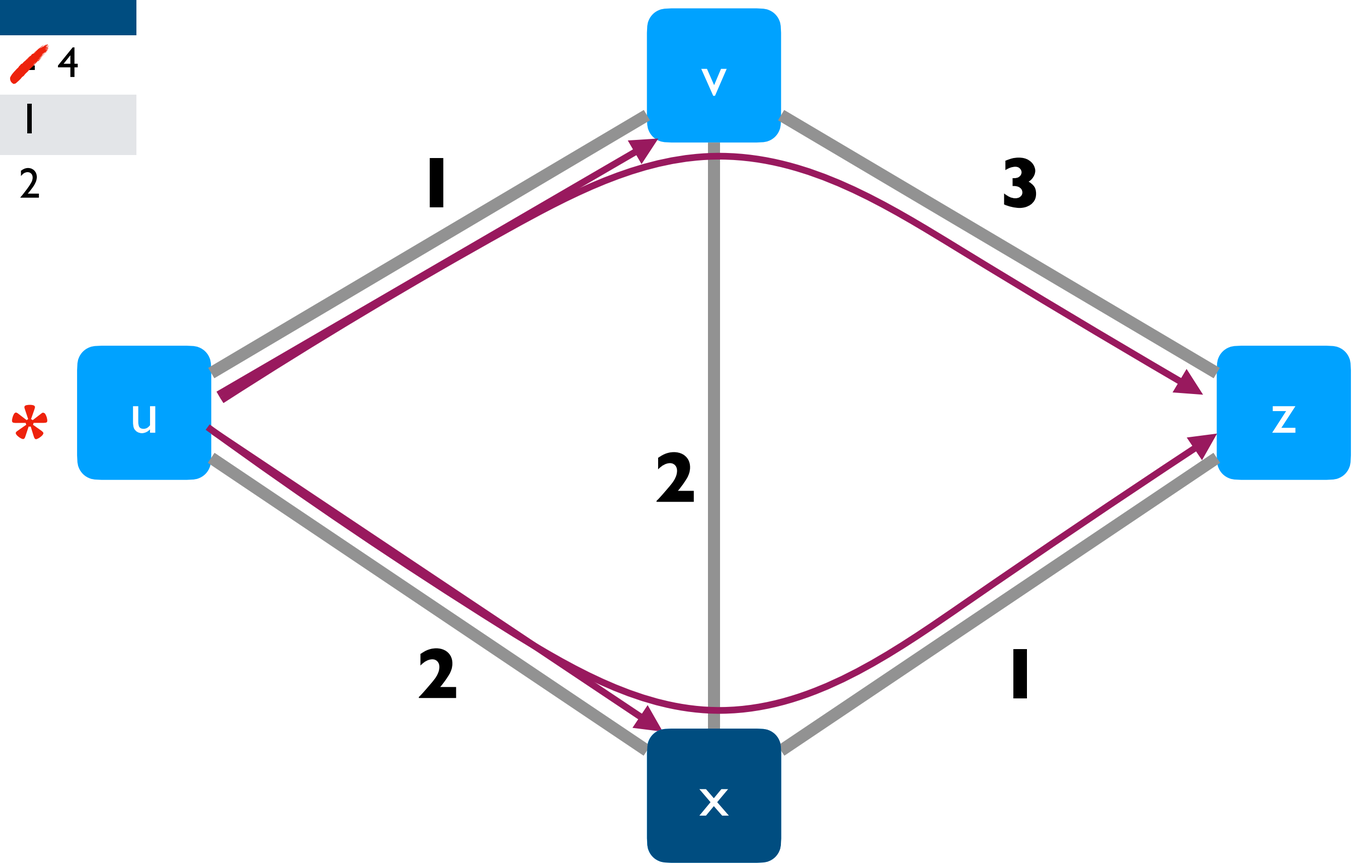
Dest.	Next Hop	Cost
z	~~-~~ v	~~-~~ 4
v	v	1
x	x	2



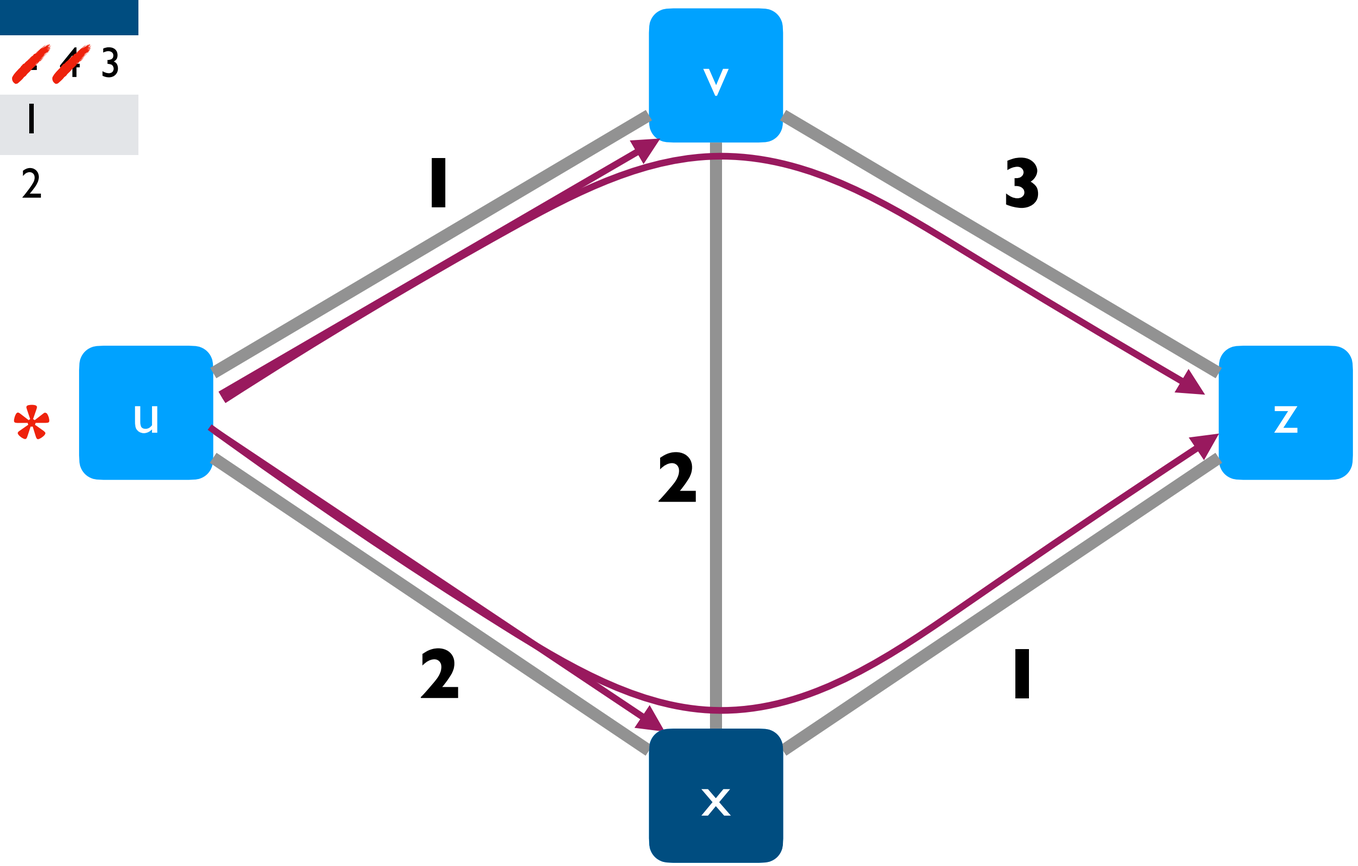
Dest.	Next Hop	Cost
z	~~-~~ v	~~-~~ 4
v	v	1
x	x	2



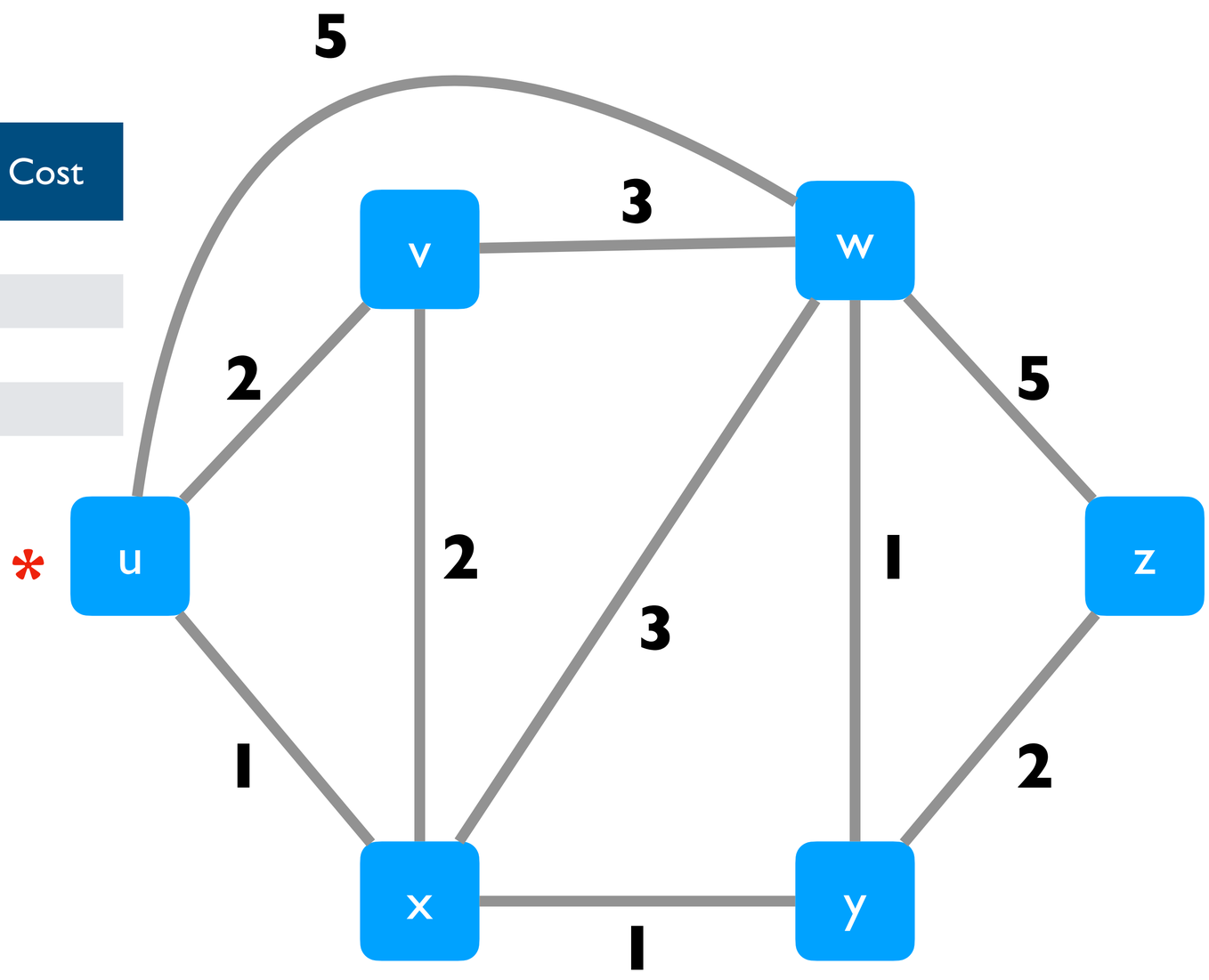
Dest.	Next Hop	Cost
z	~~-~~ v	~~-~~ 4
v	v	1
x	x	2



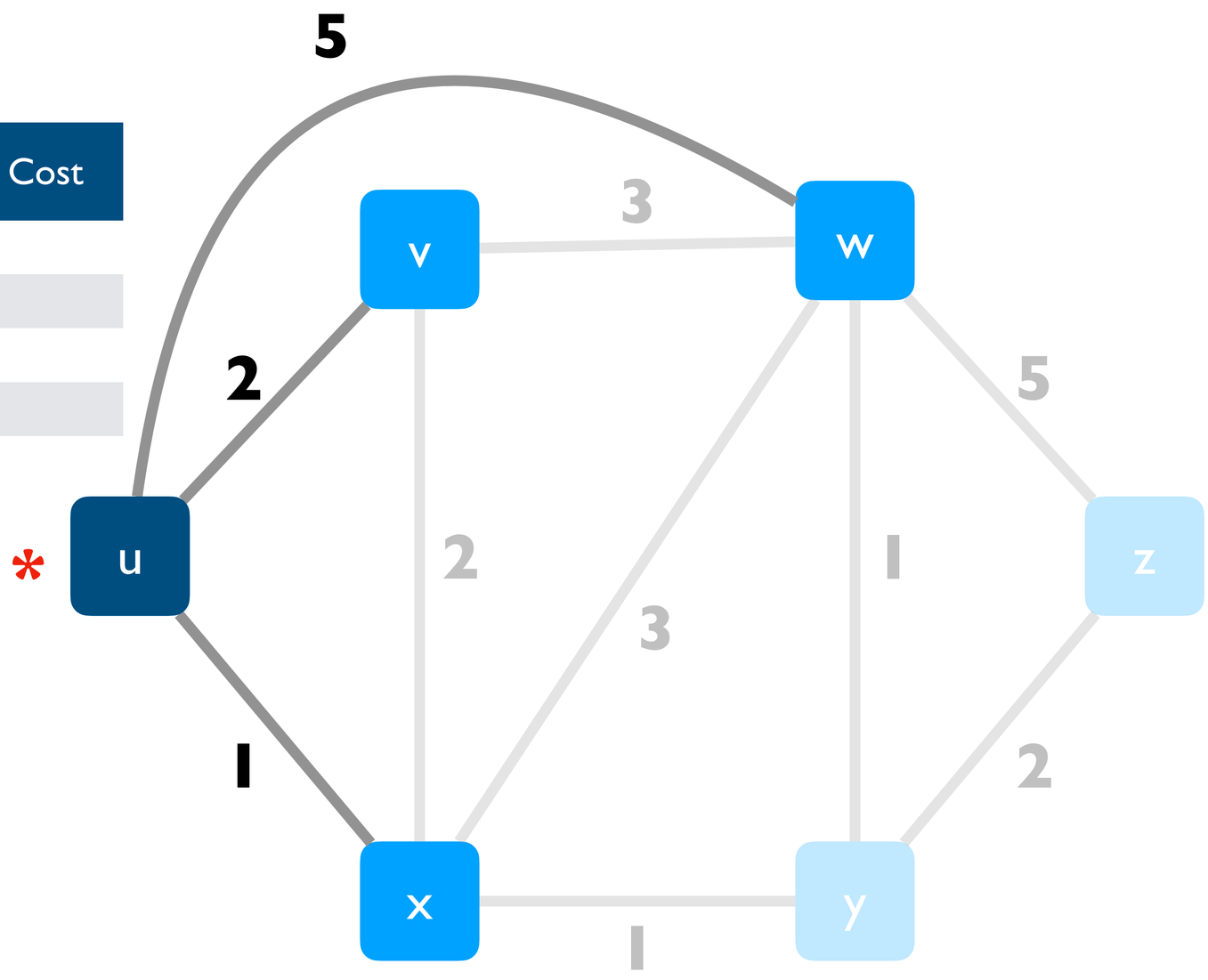
Dest.	Next Hop	Cost
z	~~-~~ ~~v~~ x	~~-~~ ~~4~~ 3
v	v	1
x	x	2



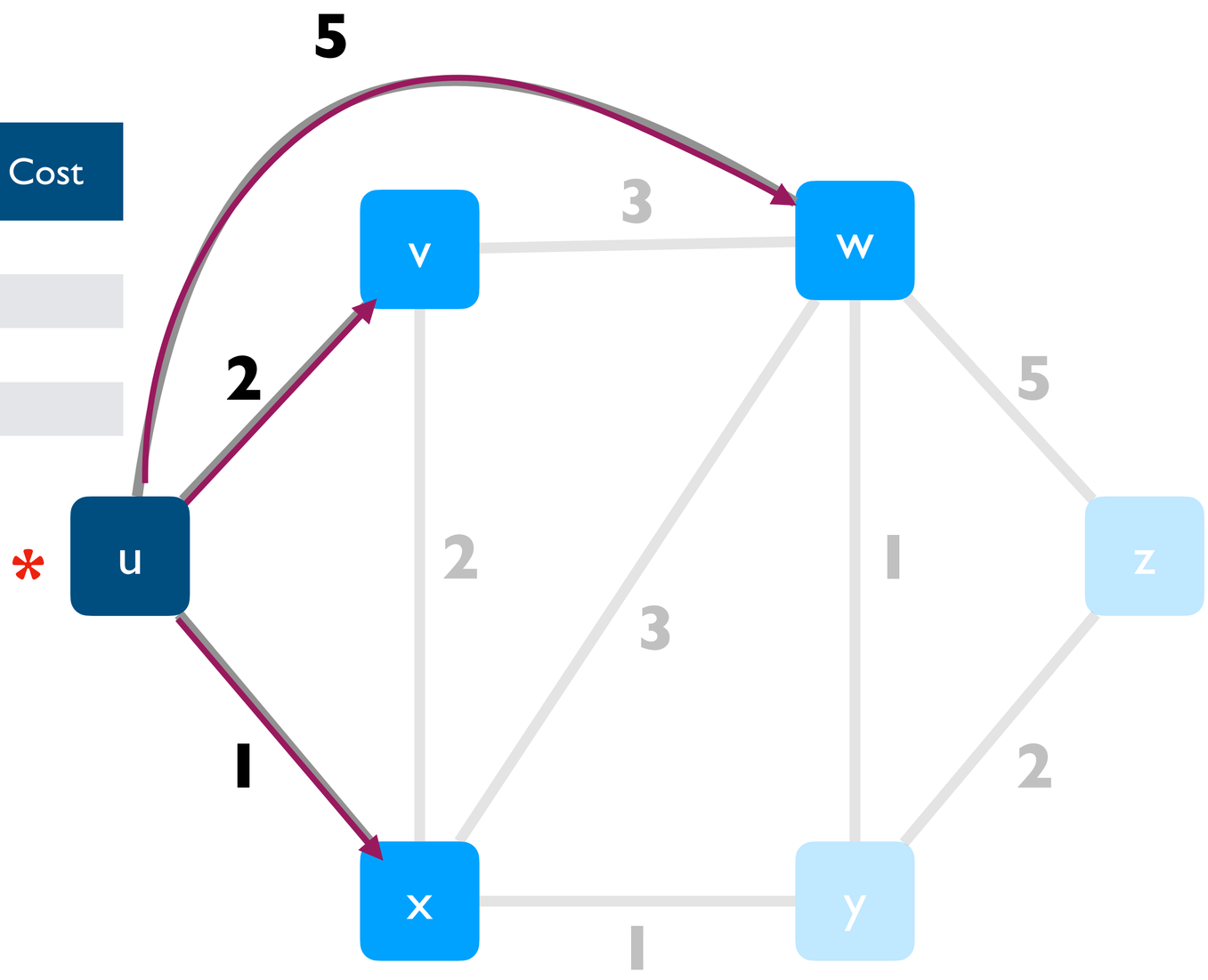
Dest.	Next Hop	Cost
z		
w		
y		
v		
x		



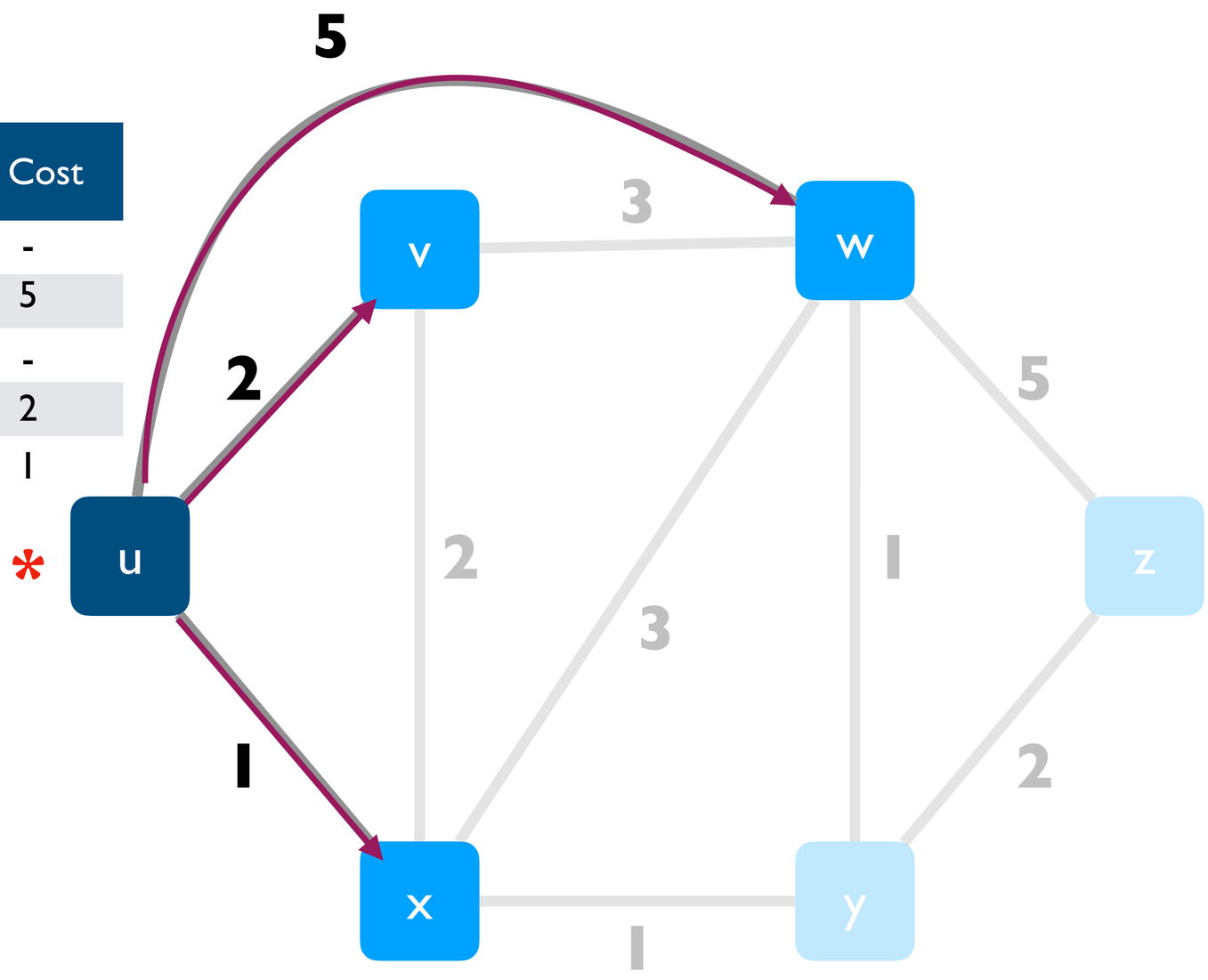
Dest.	Next Hop	Cost
z		
w		
y		
v		
x		



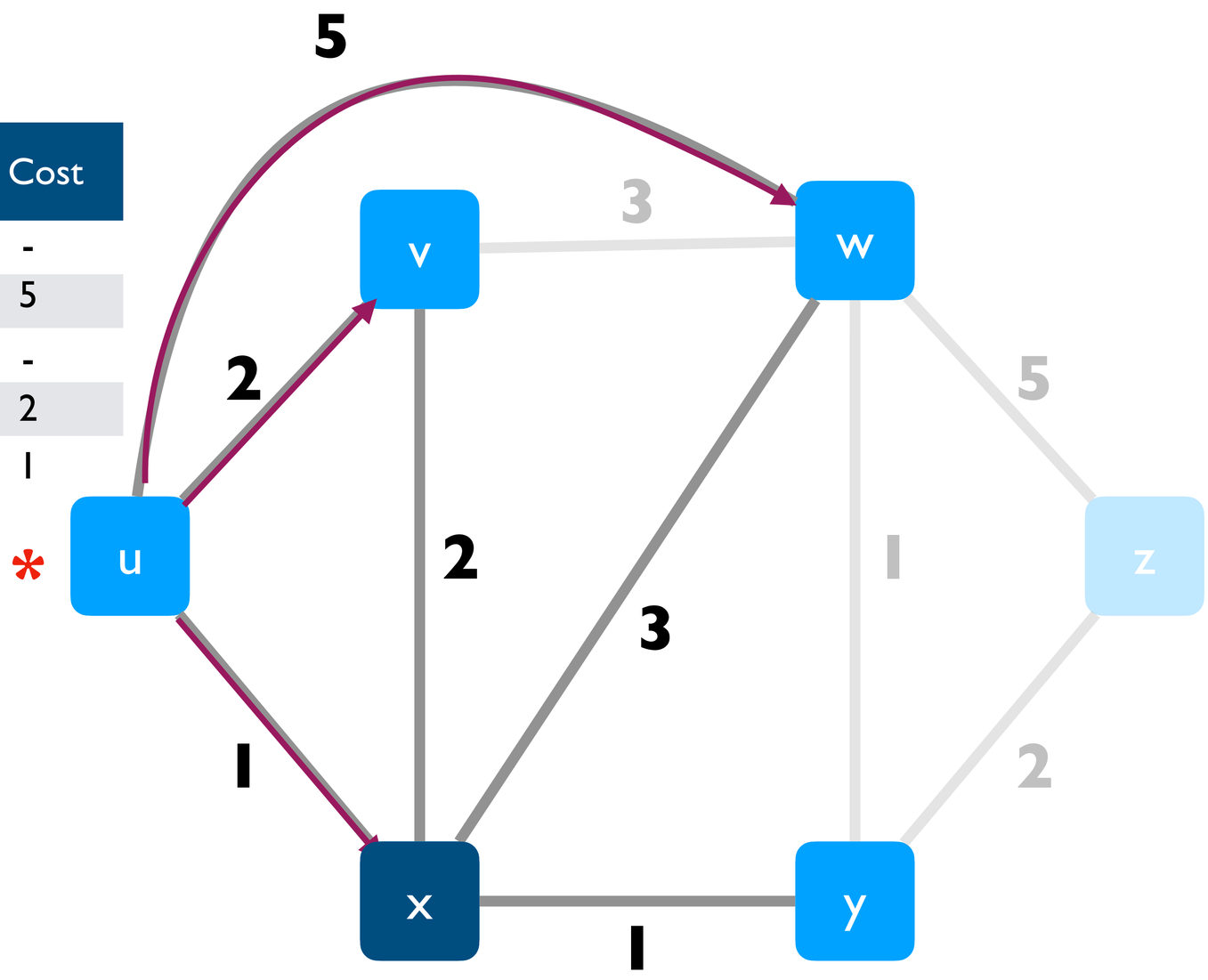
Dest.	Next Hop	Cost
z		
w		
y		
v		
x		



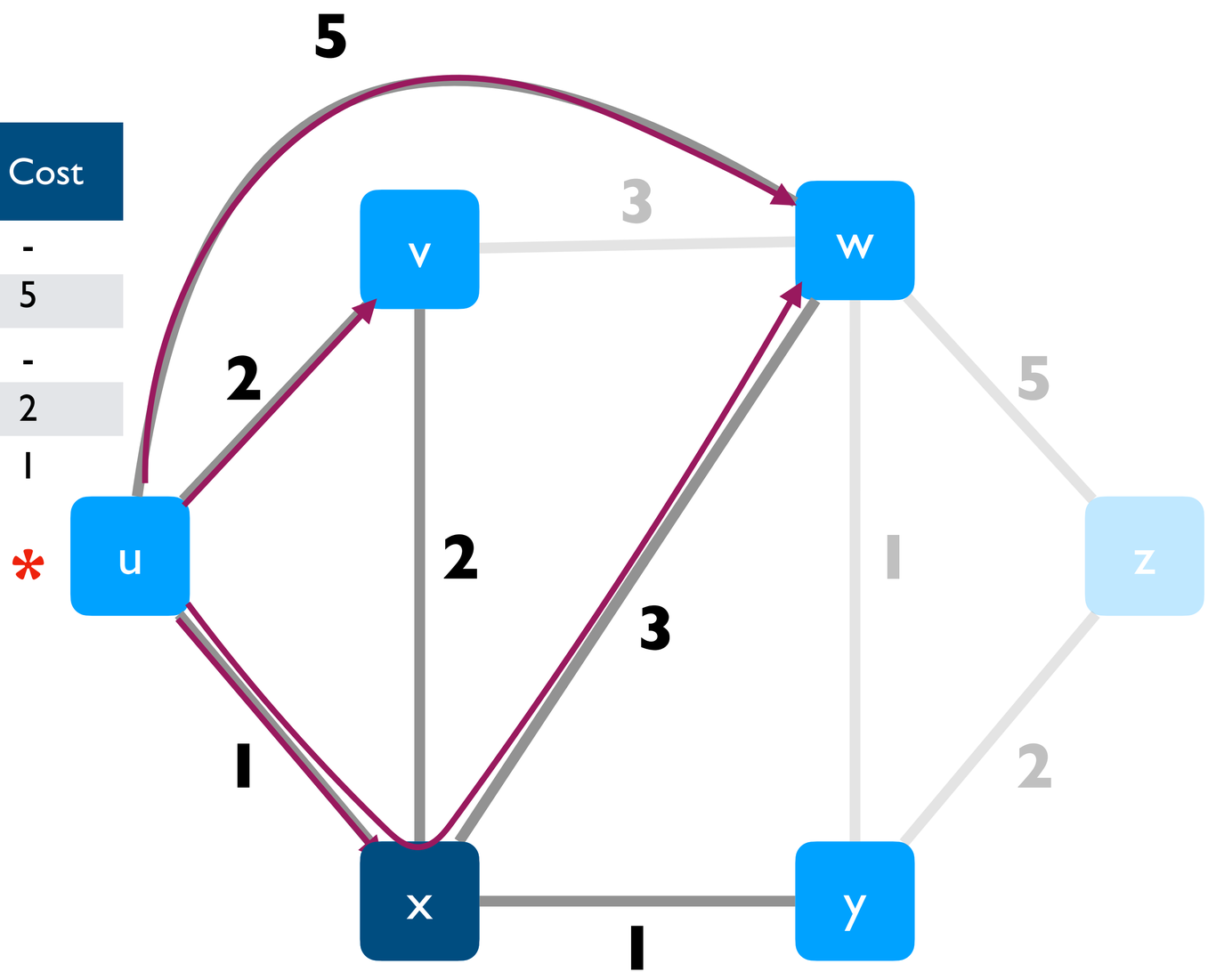
Dest.	Next Hop	Cost
z	-	-
w	w	5
y	-	-
v	v	2
x	x	1



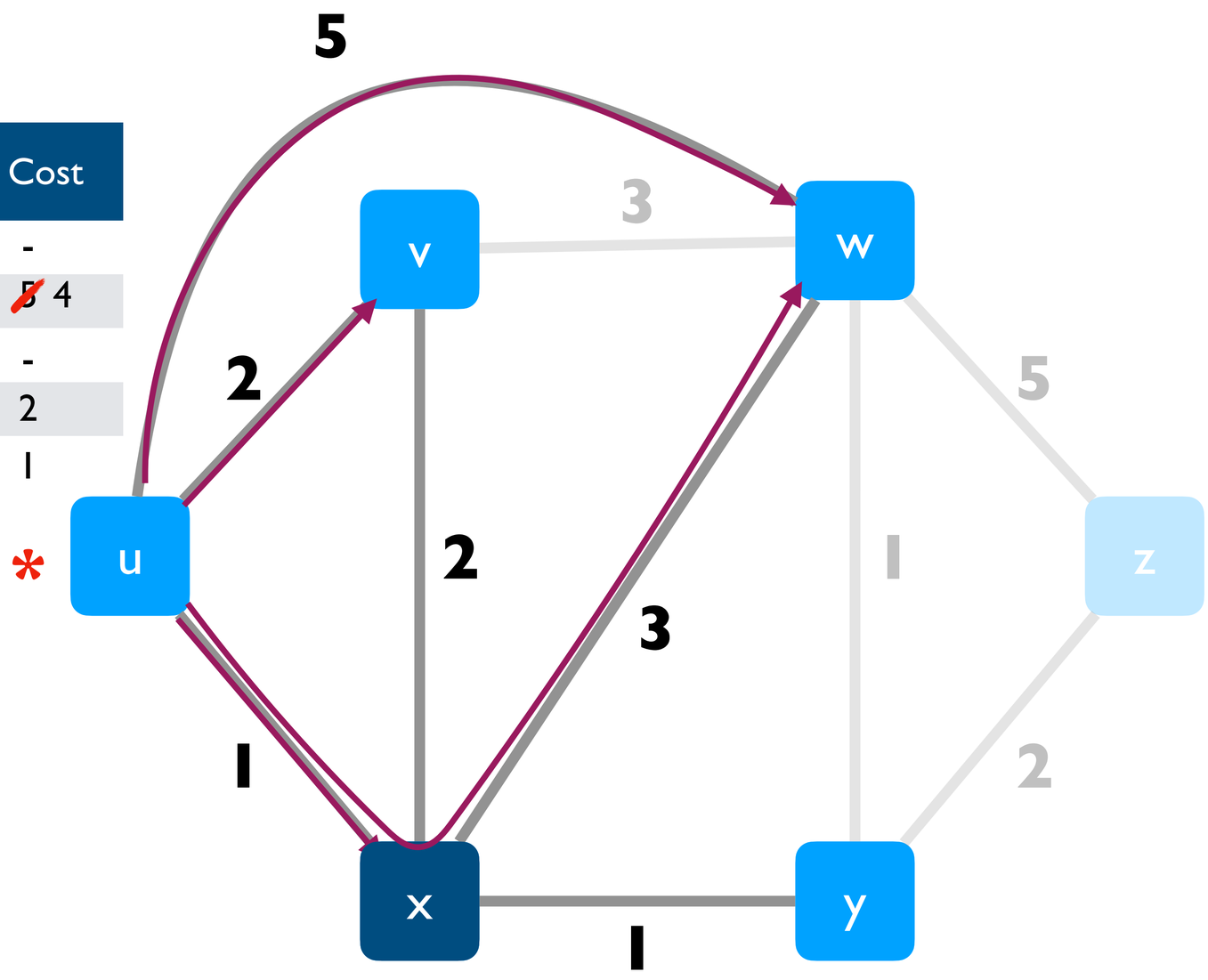
Dest.	Next Hop	Cost
z	-	-
w	w	5
y	-	-
v	v	2
x	x	1



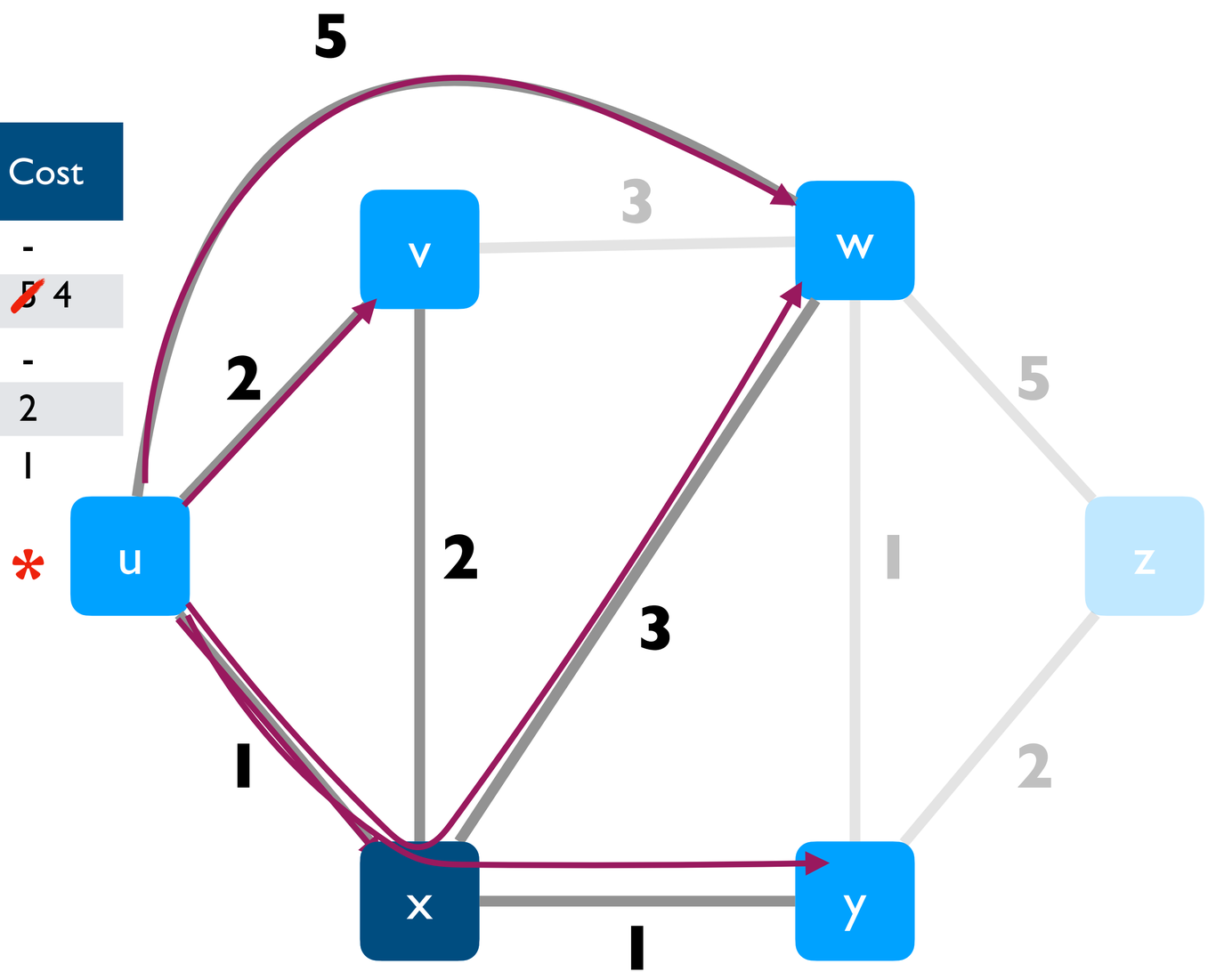
Dest.	Next Hop	Cost
z	-	-
w	w	5
y	-	-
v	v	2
x	x	1



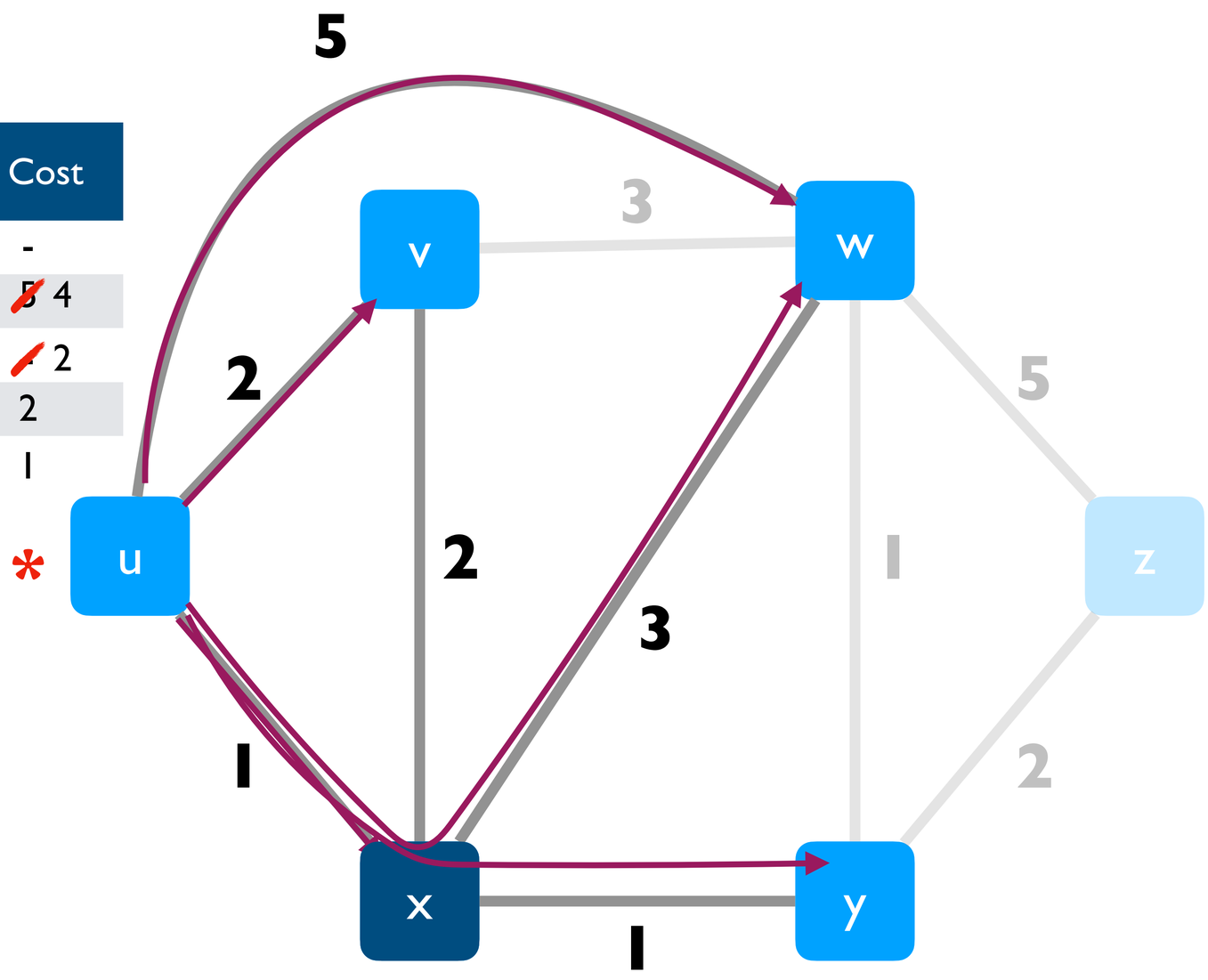
Dest.	Next Hop	Cost
z	-	-
w	~~w~~ x	~~5~~ 4
y	-	-
v	v	2
x	x	1



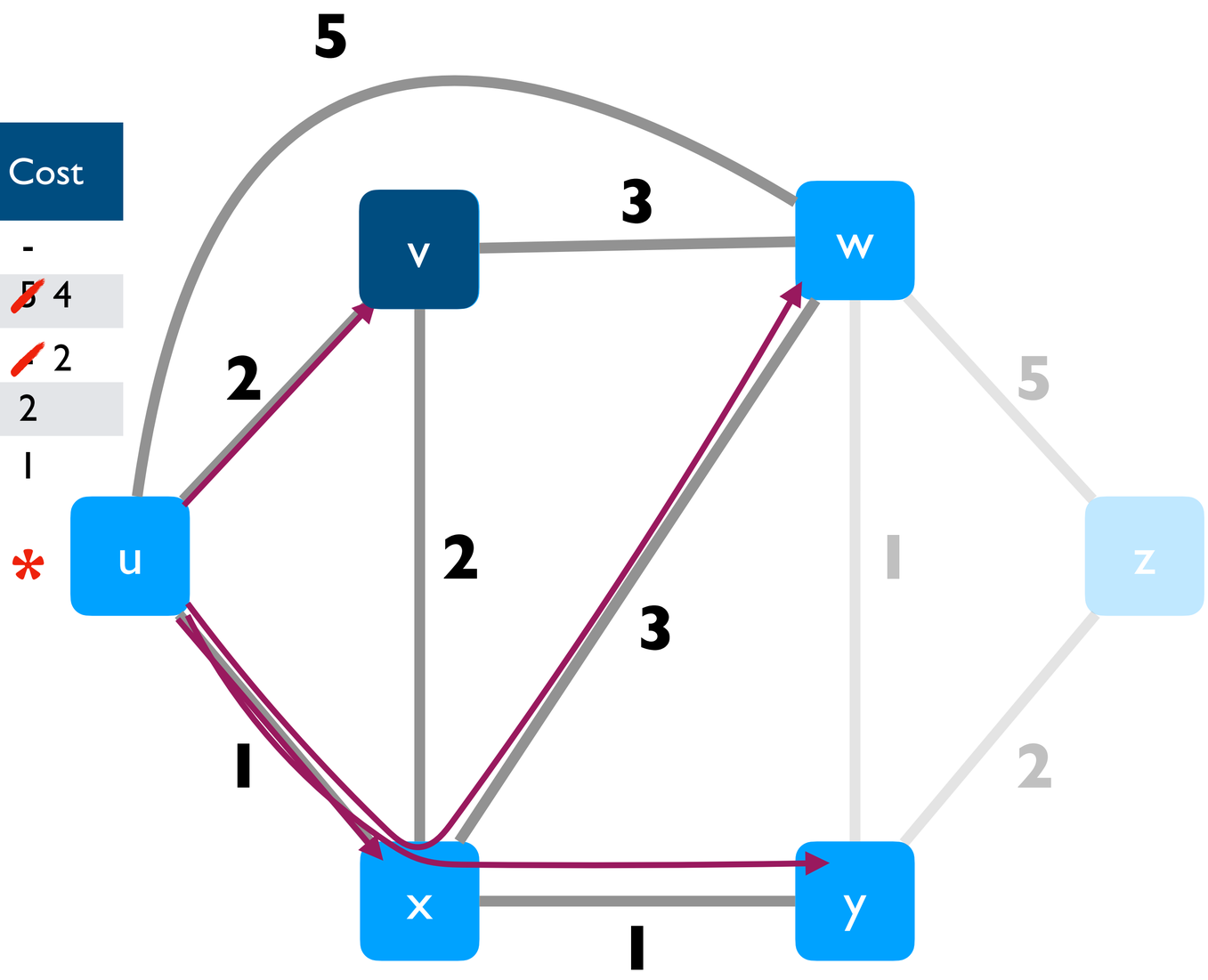
Dest.	Next Hop	Cost
z	-	-
w	~~w~~ x	~~5~~ 4
y	-	-
v	v	2
x	x	1



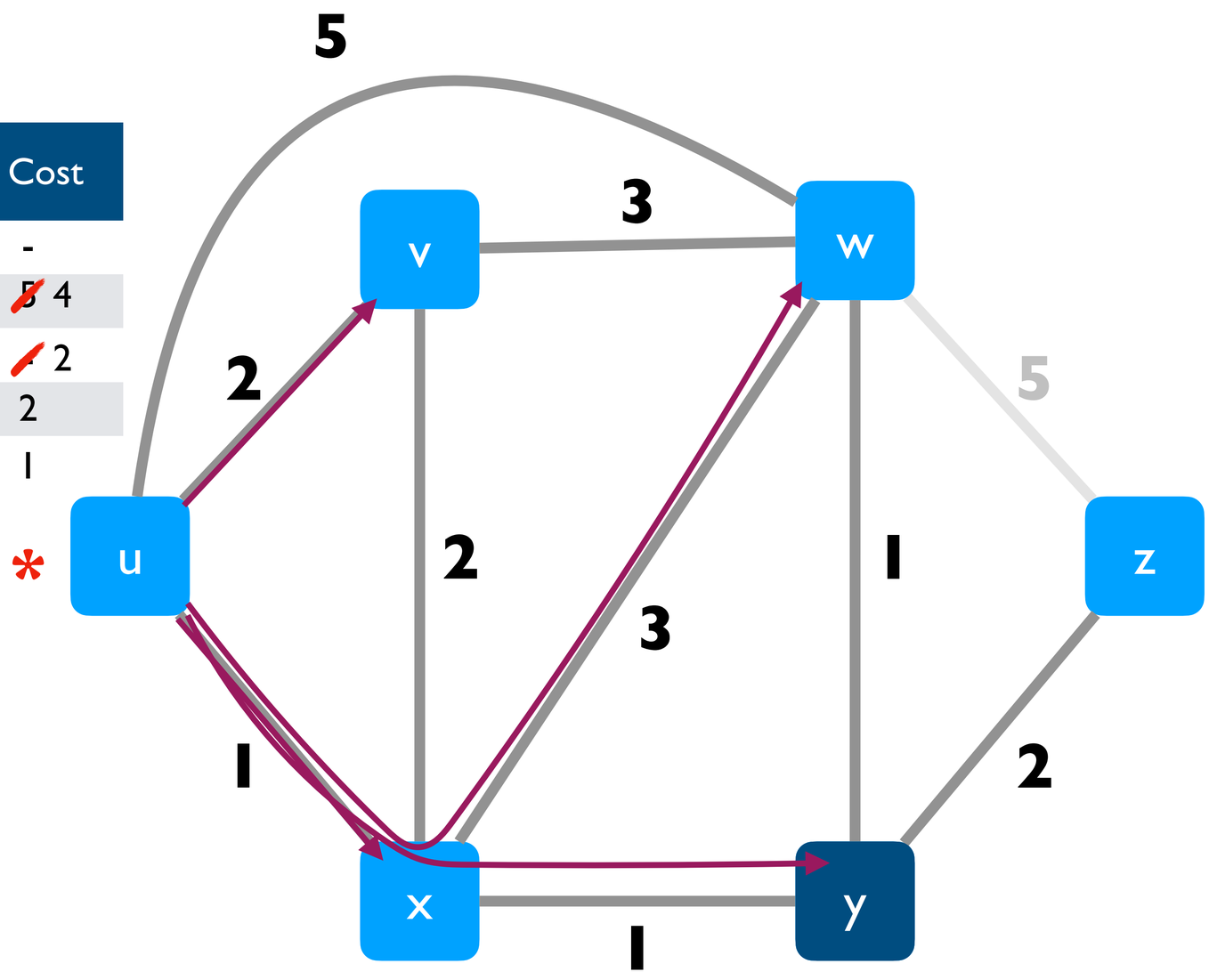
Dest.	Next Hop	Cost
z	-	-
w	~~w~~ x	~~5~~ 4
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



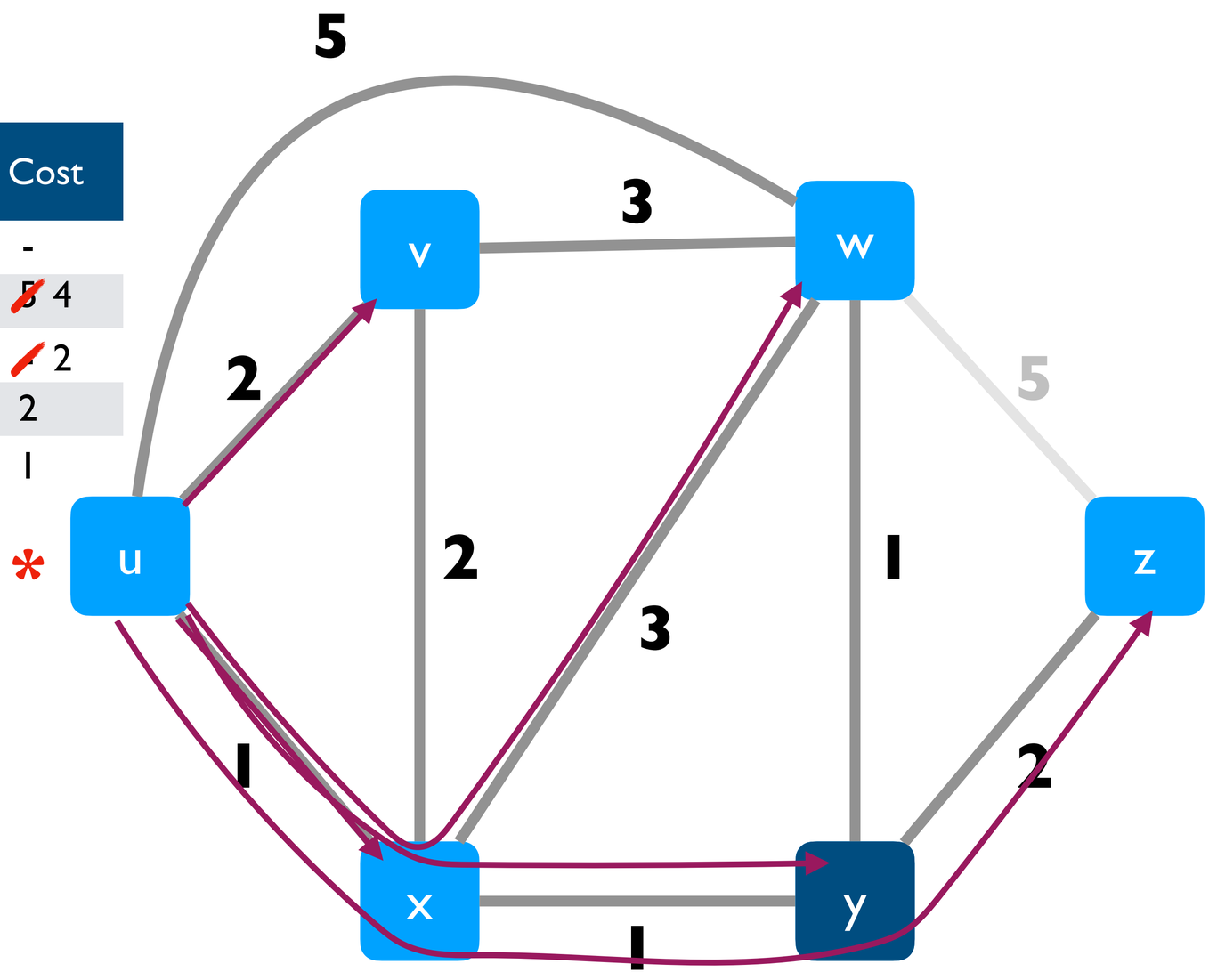
Dest.	Next Hop	Cost
z	-	-
w	~~w~~ x	~~5~~ 4
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



Dest.	Next Hop	Cost
z	-	-
w	~~w~~ x	~~5~~ 4
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



Dest.	Next Hop	Cost
z	-	-
w	~~w~~ x	~~5~~ 4
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



Dest.	Next Hop	Cost
z	~~-~~ x	~~-~~ 4
w	~~w~~ x	~~5~~ 4
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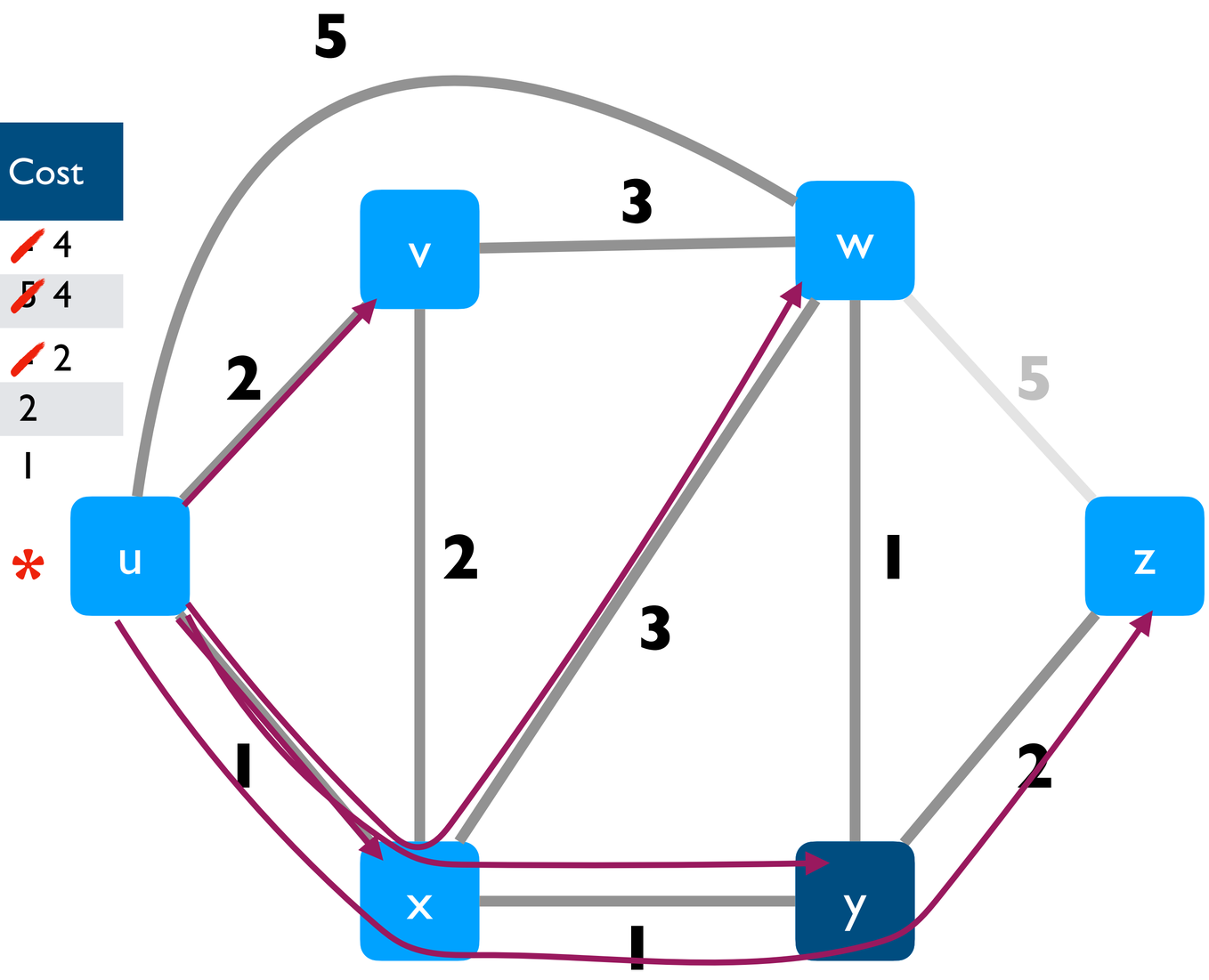
x	x	1



Dest.	Next Hop	Cost
z	~~-~~ x	~~-~~ 4
w	~~w~~ x	~~5~~ 4
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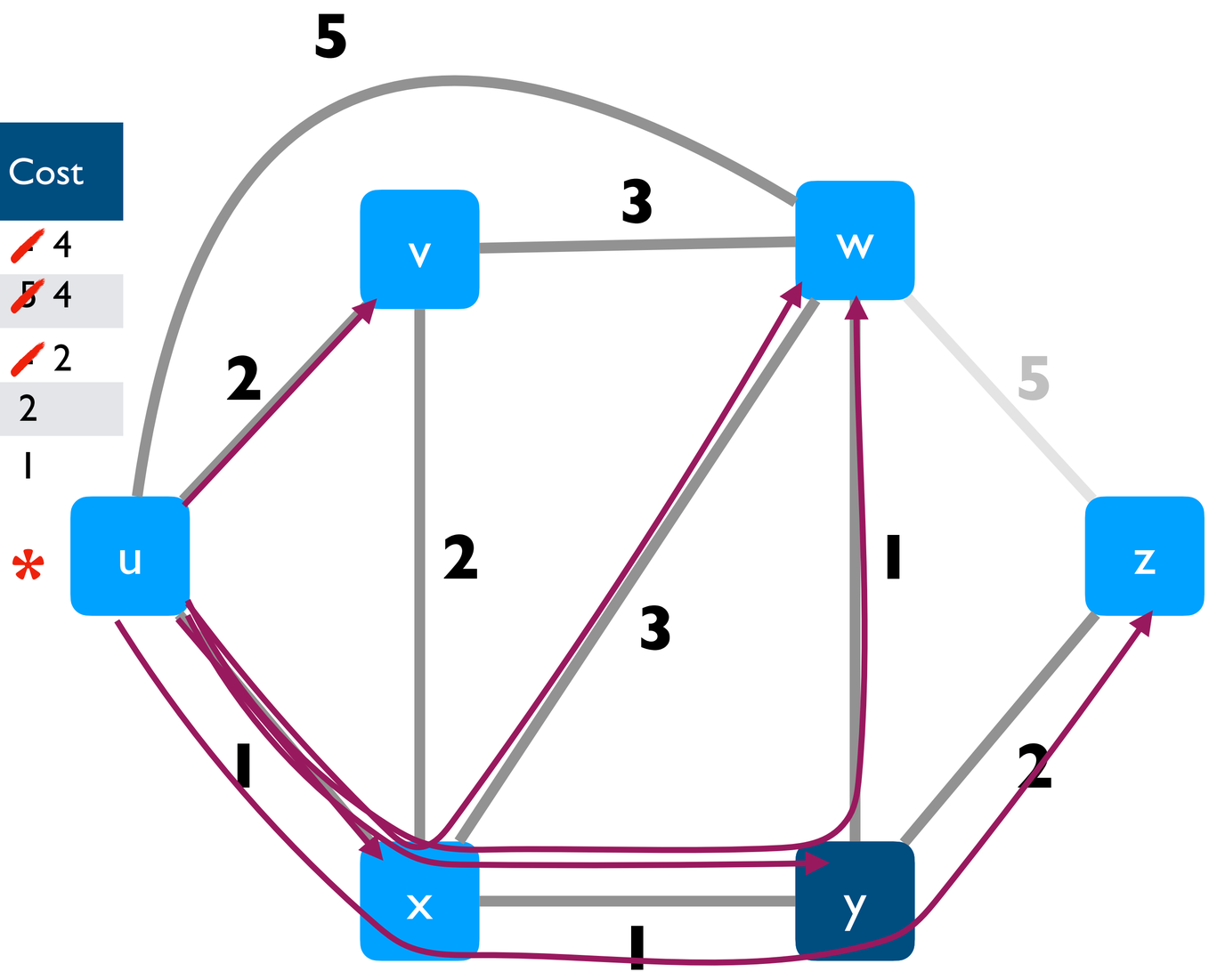
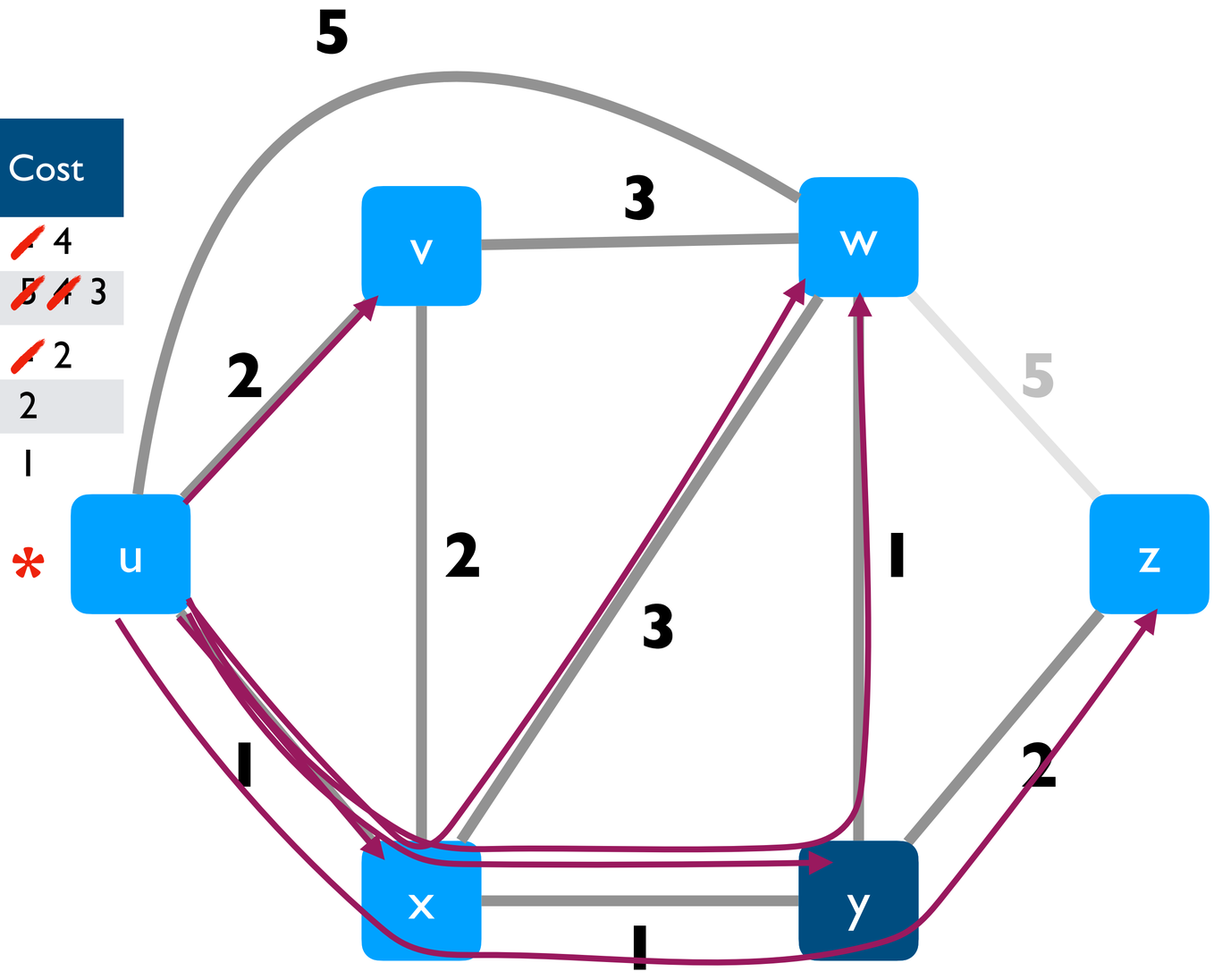
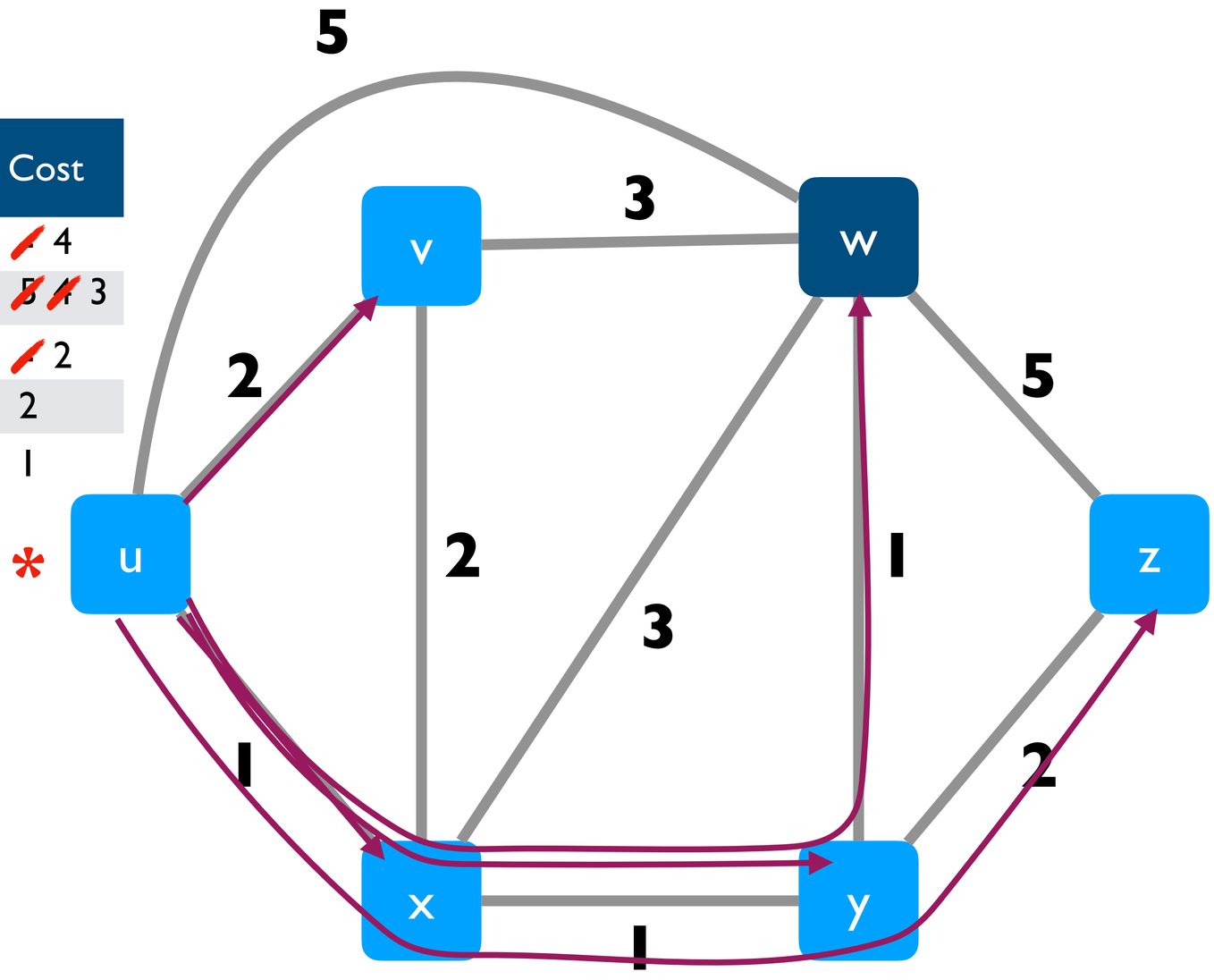


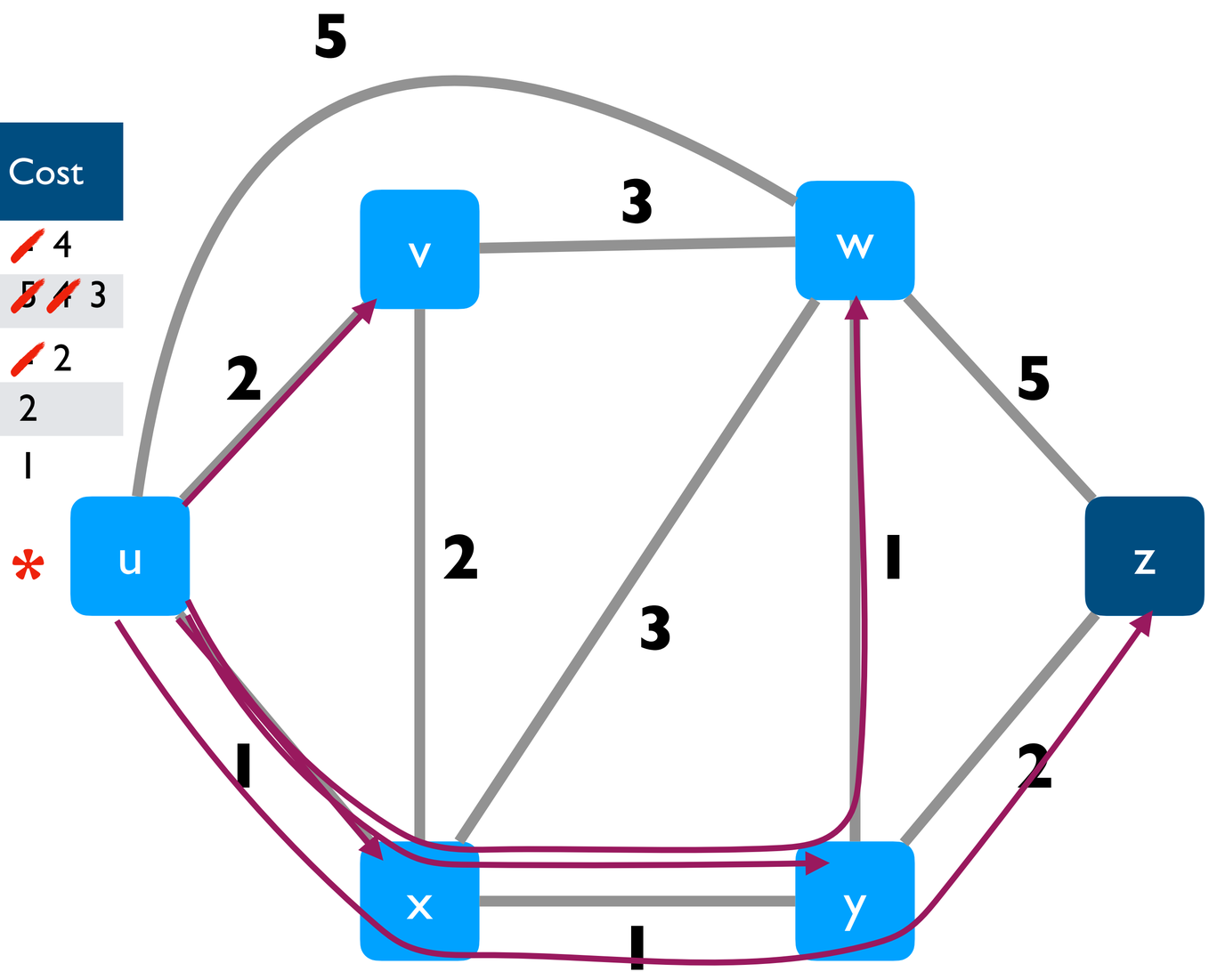
Dest.	Next Hop	Cost
z	~~-~~ x	~~-~~ 4
w	~~w~~ x	~~5~~ ~~4~~ 3
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



Dest.	Next Hop	Cost
z	~~-~~ x	~~-~~ 4
w	~~w~~ x	~~5~~ ~~4~~ 3
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



Dest.	Next Hop	Cost
z	~~-~~ x	~~-~~ 4
w	~~w~~ x	~~5~~ ~~4~~ 3
y	~~-~~ x	~~-~~ 2
v	v	2
x	x	1



From Routing Algorithm to Protocol

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- We will talk about Option#1 when we talk about Software Defined Networks (SDNs)

Link State Routing

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- Hence, every router learns the entire network graph
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- OSPF is a link-state protocol (IETF RFC 2328 or 5340)

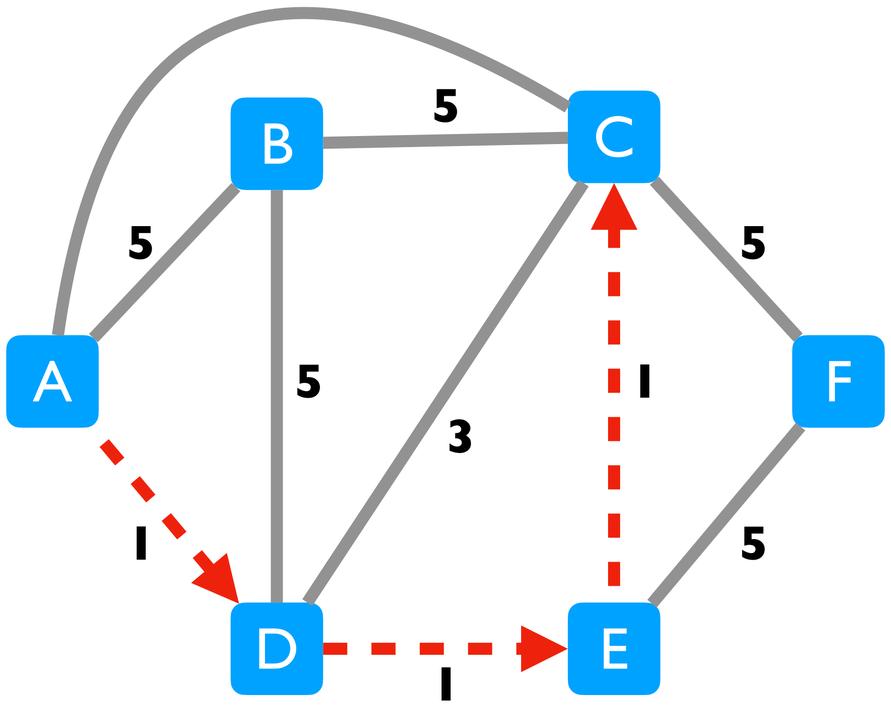
Link State Routing

Link State Routing

Are loops possible?

Link State Routing

Are loops possible?



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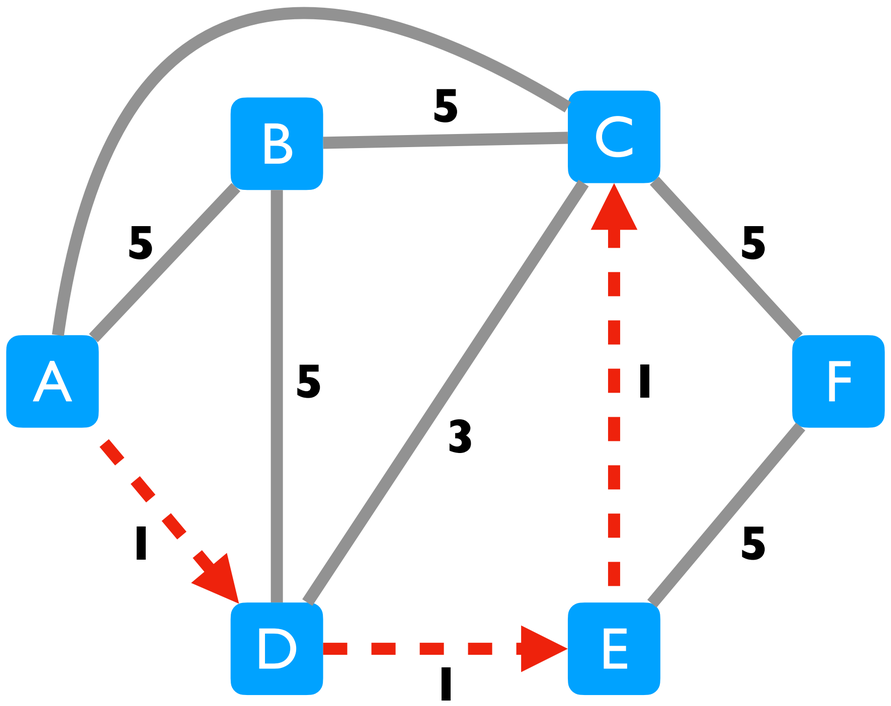

A and D think this is the path to C

Link State Routing

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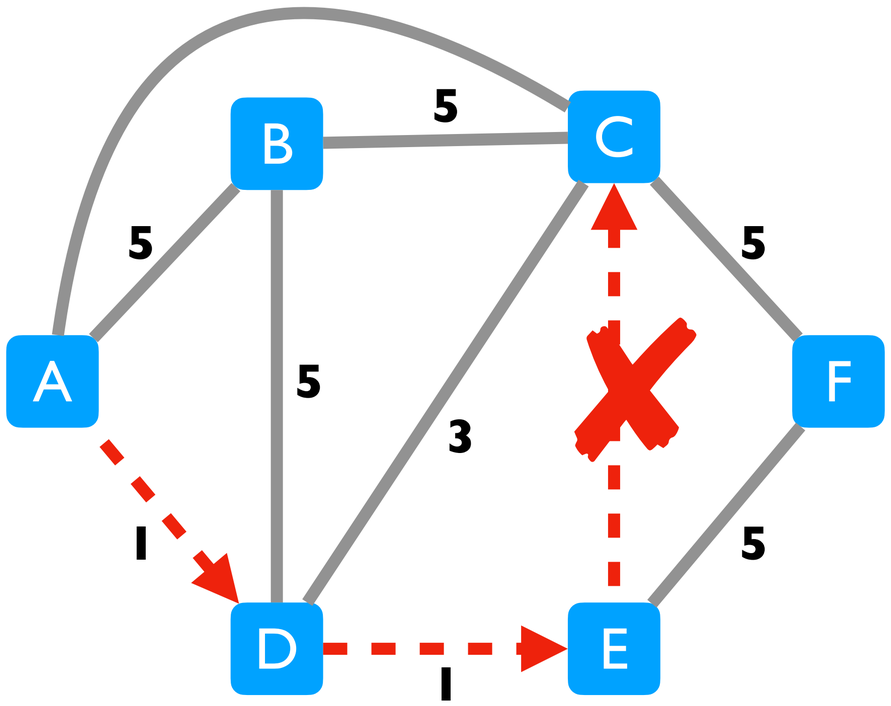

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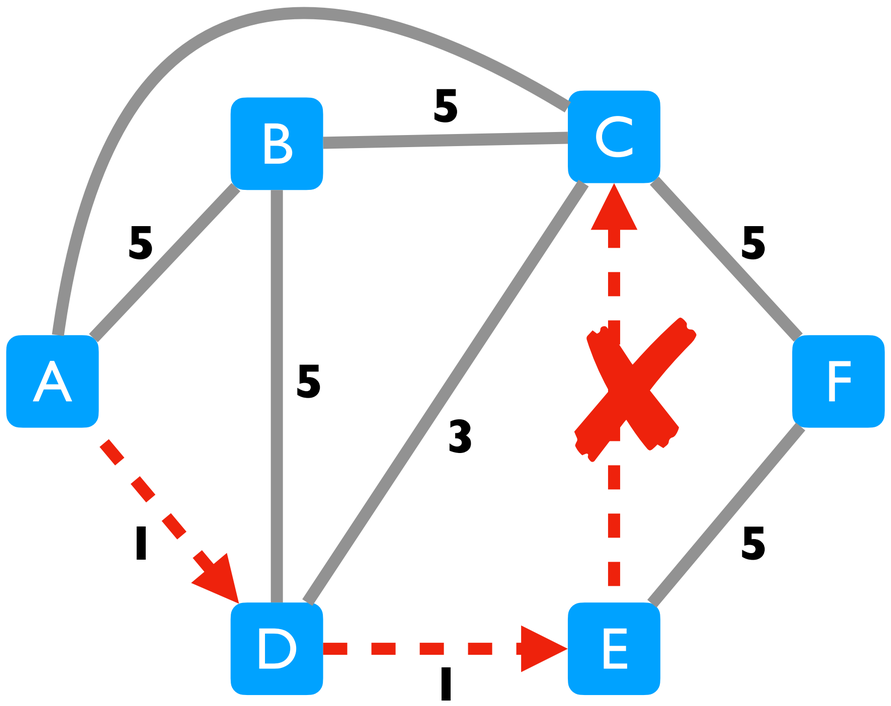
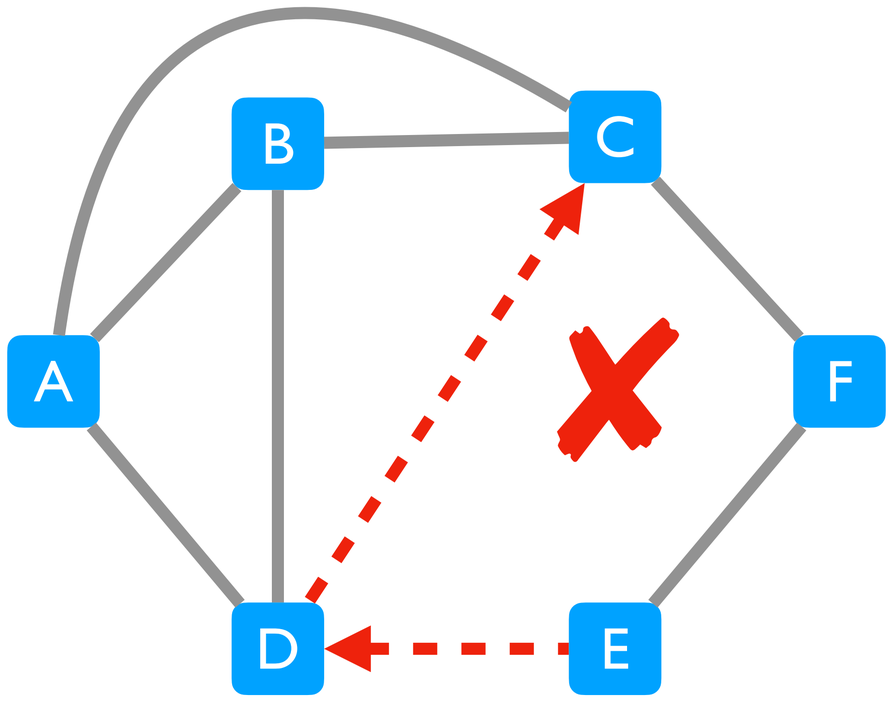
Link State Routing

Are loops possible?

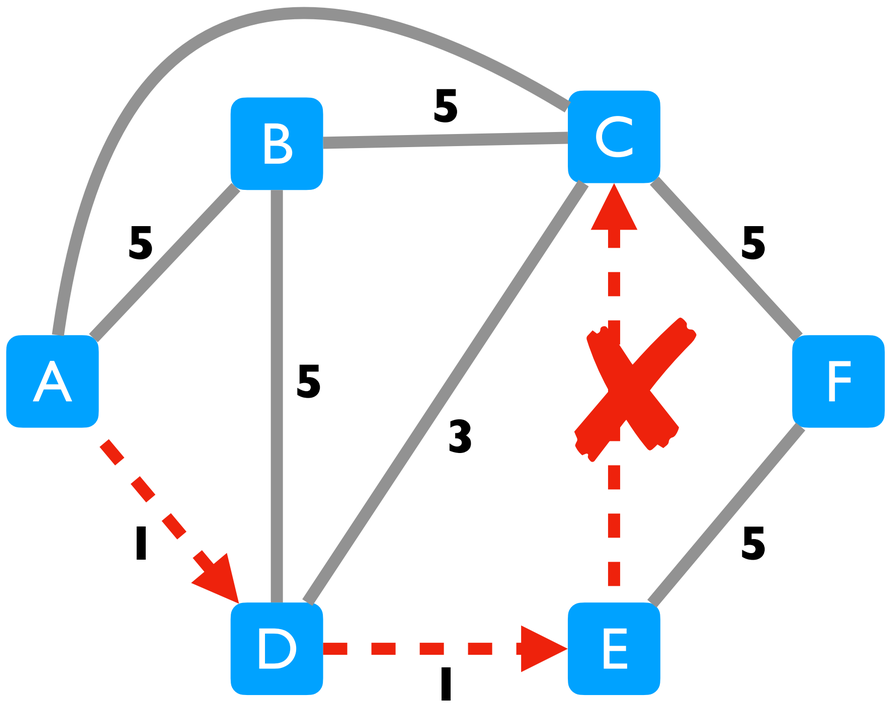




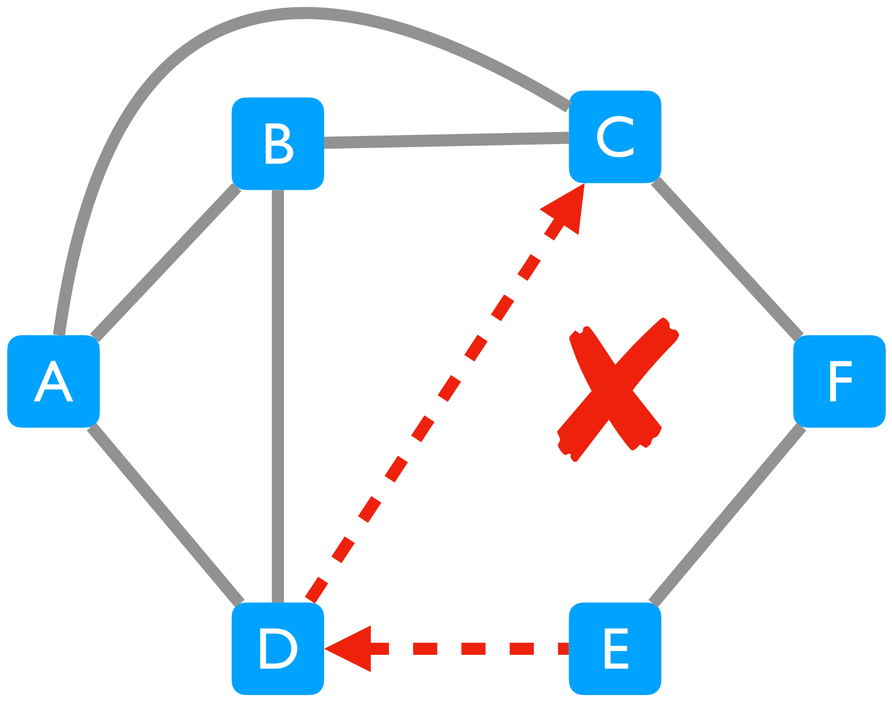
A and D think this is the path to C

Link State Routing

Are loops possible?



A and D think this is the path to C



E thinks that this is the path to C

Convergence

Convergence

- All routers have consistent routing information
  - *E.g., all nodes having the same link-state database*

Convergence

- All routers have consistent routing information
  - *E.g., all nodes having the same link-state database*
- Forwarding is consistent after convergence
  - *All nodes have the same link-state database*
  - *All nodes forward packets on the same paths*

Convergence Delay

Convergence Delay

- Time to achieve convergence

Convergence Delay

- Time to achieve convergence
- Sources of convergence delay?

Convergence Delay

- Time to achieve convergence
- Sources of convergence delay?
  - *Time to detect failure*

Convergence Delay

- Time to achieve convergence
- Sources of convergence delay?
  - *Time to detect failure*
  - *Time to flood link-state information*

Convergence Delay

- Time to achieve convergence
- Sources of convergence delay?
  - *Time to detect failure*
  - *Time to flood link-state information*
  - *Time to recompute forwarding tables*

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- Performance during convergence period?

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- Sources of convergence delay?
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  - *Time to flood link-state information*
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  - *Lost packets due to "black-holes"*

Convergence Delay

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- Sources of convergence delay?
  - *Time to detect failure*
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  - *Lost packets due to "black-holes"*
  - *Looping packets*

Convergence Delay

- Time to achieve convergence
- Sources of convergence delay?
  - *Time to detect failure*
  - *Time to flood link-state information*
  - *Time to recompute forwarding tables*
- Performance during convergence period?
  - *Lost packets due to "black-holes"*
  - *Looping packets*
  - *Out-of-order packets reaching the destination*

Link State Routing

Link State Routing

- Are loops possible?
  - *Yes, until convergence*

Link State Routing

- Are loops possible?
  - *Yes, until convergence*
- Scalability?
  - *O(NE) messages*
  - *O(N^2) computation time*
  - *O(network diameter) convergence time*
  - *O(N) entries in forwarding table*

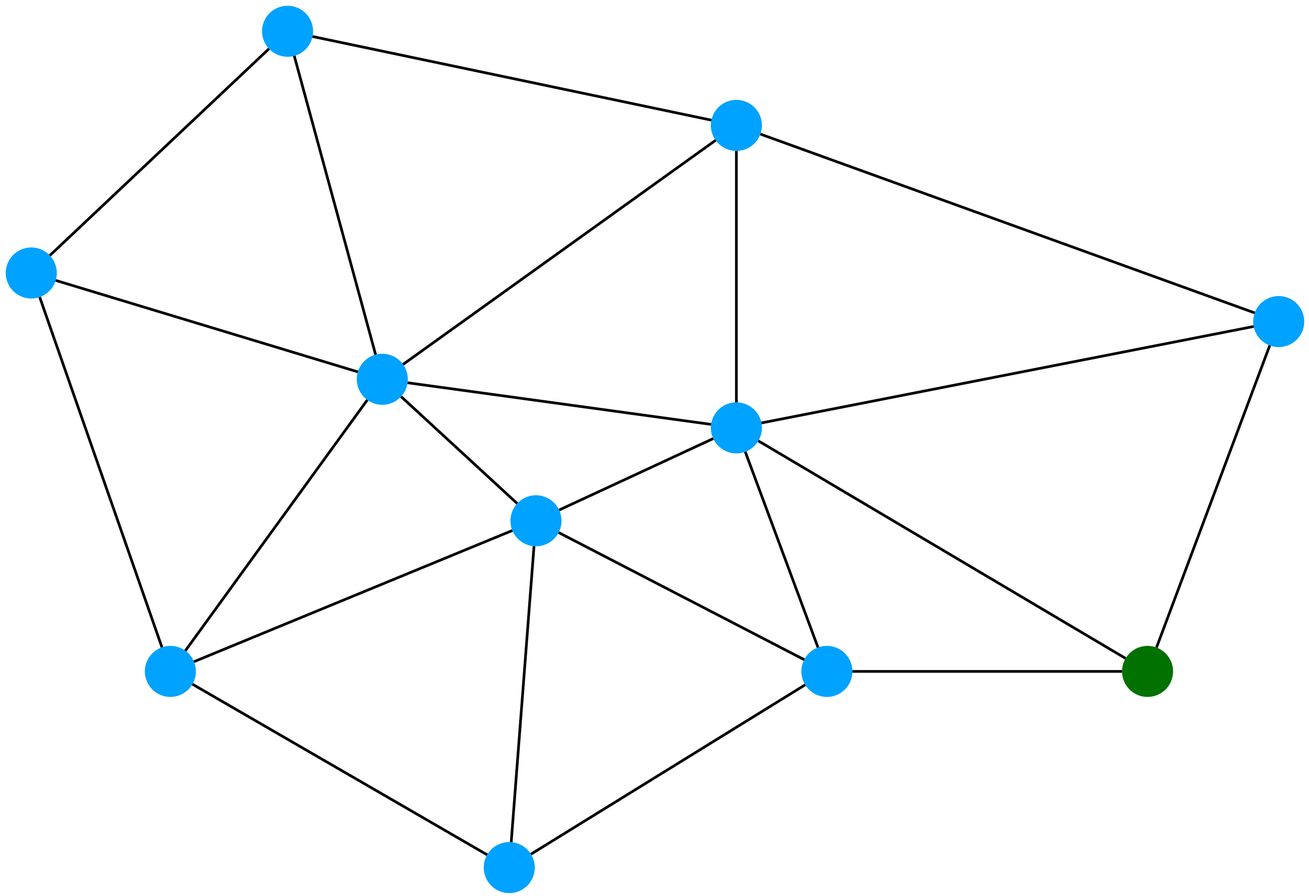
Link State Routing

- Are loops possible?
  - *Yes, until convergence*
- Scalability?
  - *O(NE) messages*
  - *O(N^2) computation time*
  - *O(network diameter) convergence time*
  - *O(N) entries in forwarding table*
- Do we have to use Dijkstra's?

Outline

- Approach 1: link-state routing
- Approach 2: distance-vector routing
- Routing in the internet

Distance Vector Routing: An example of ***Distributed*** Computation



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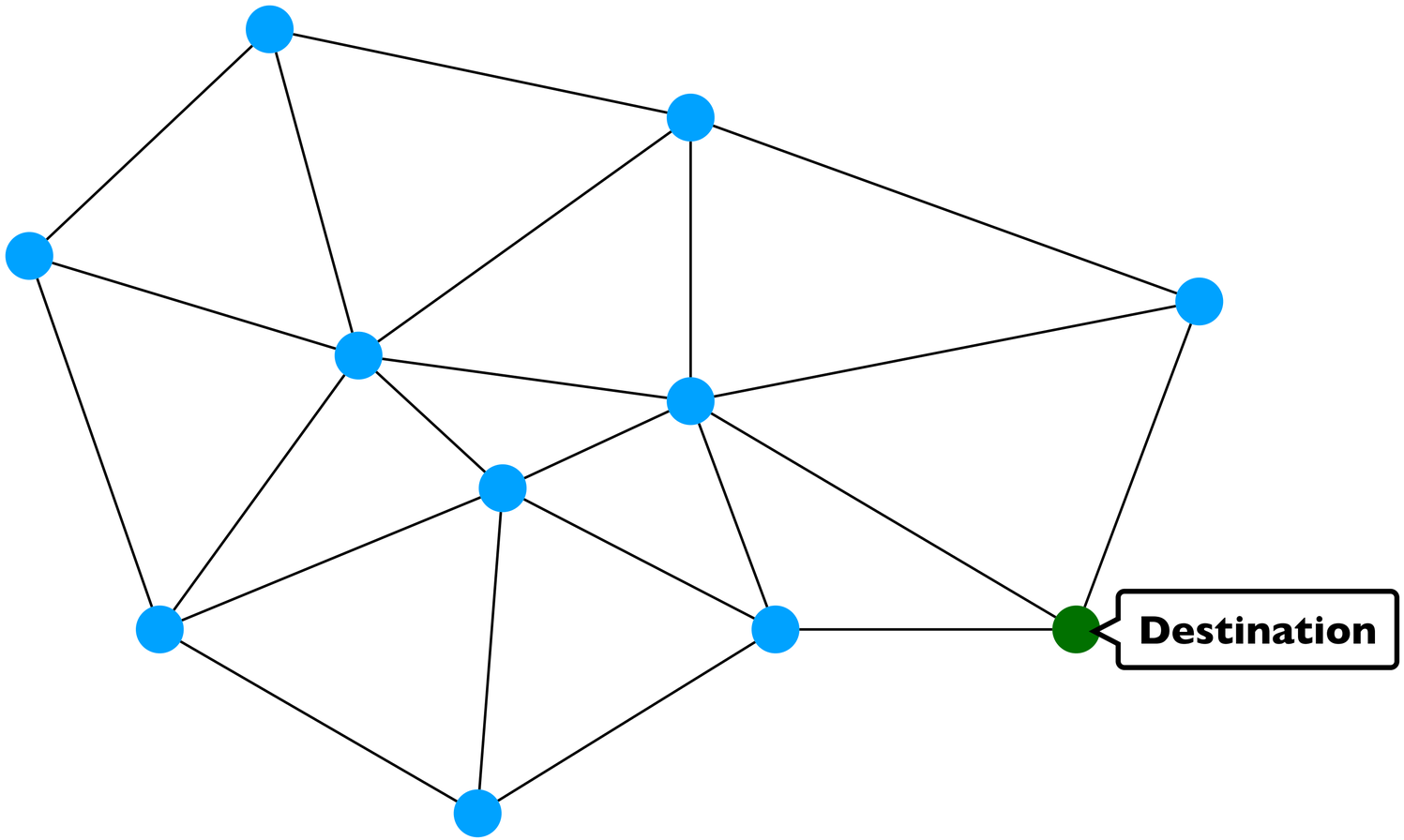

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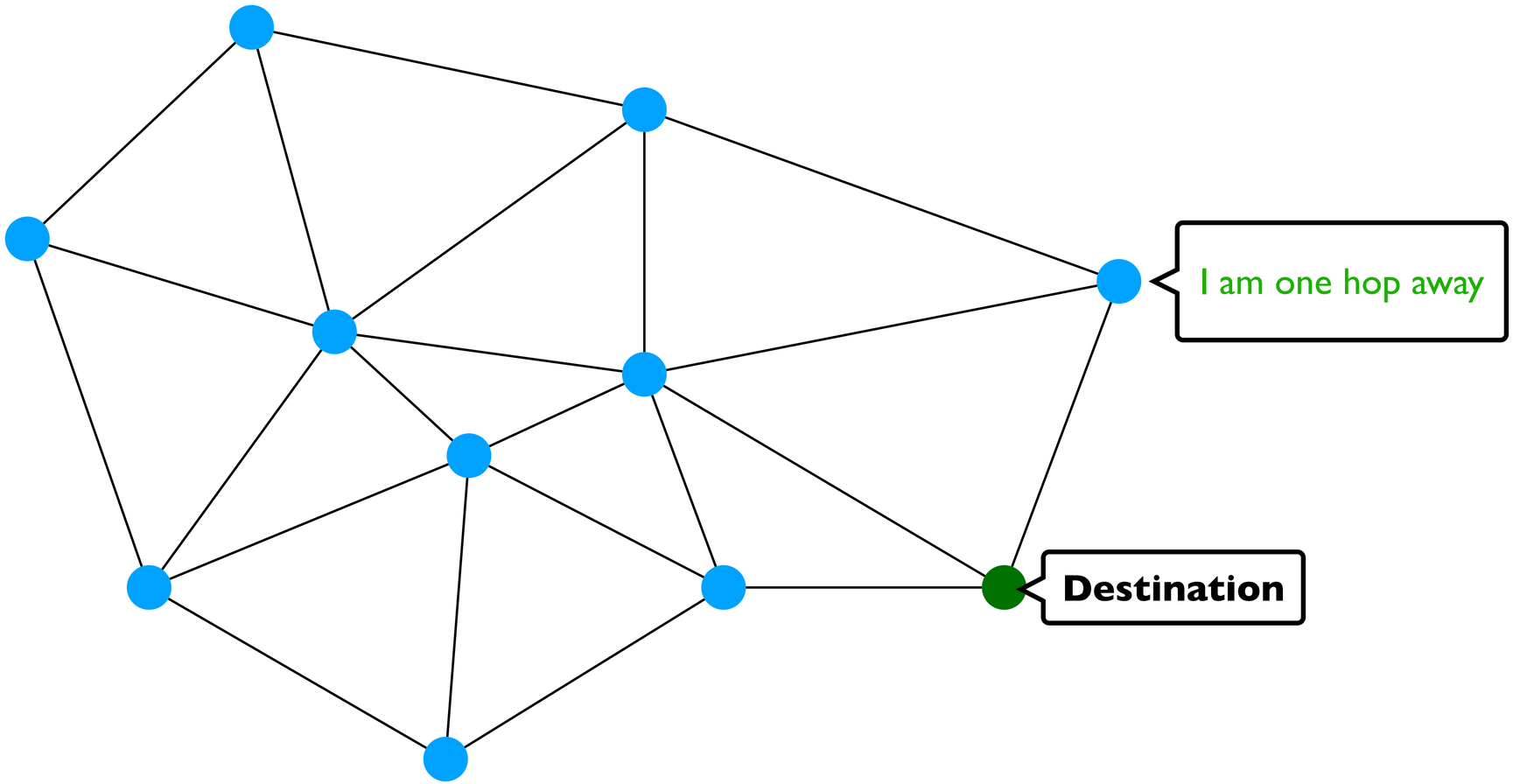

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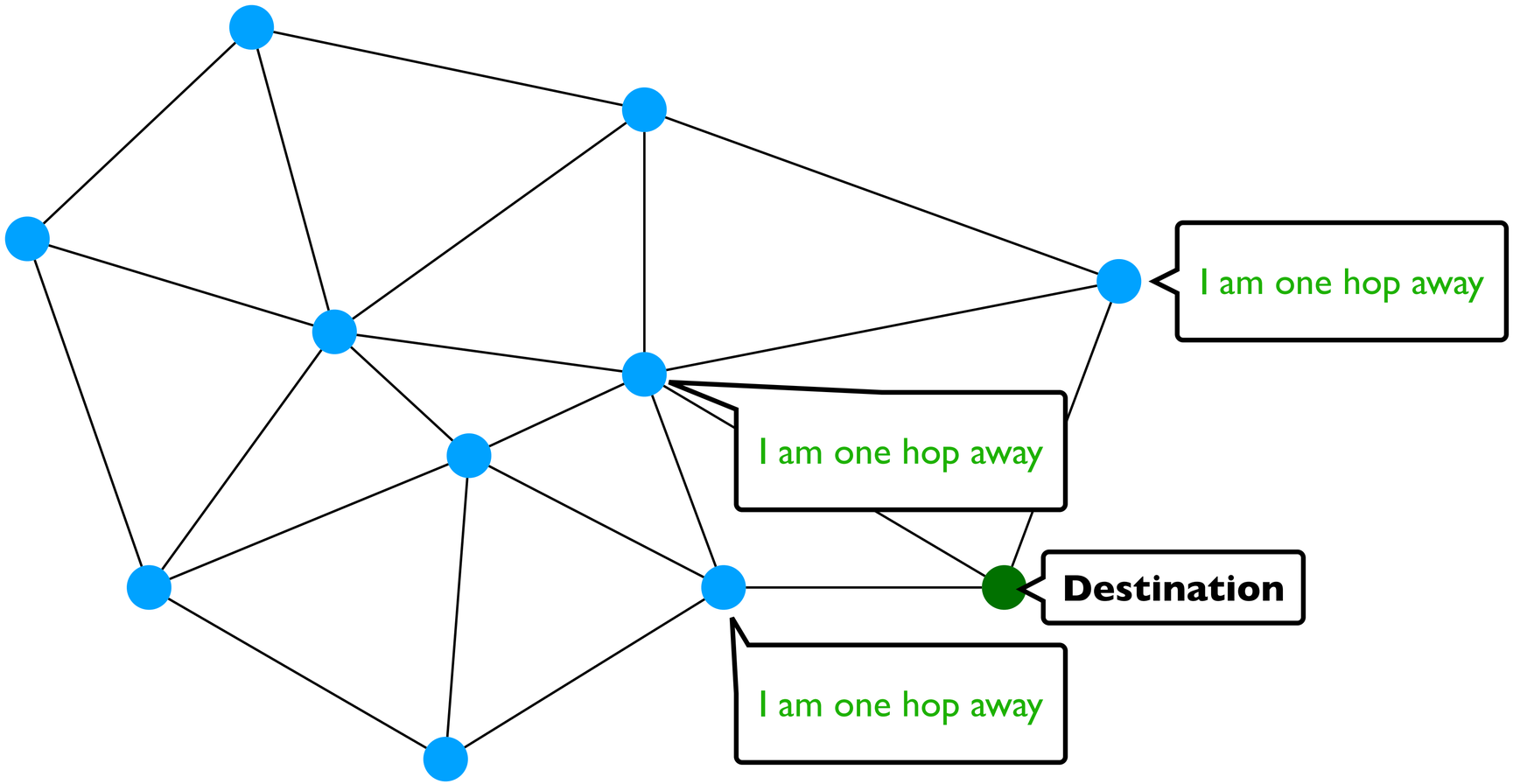

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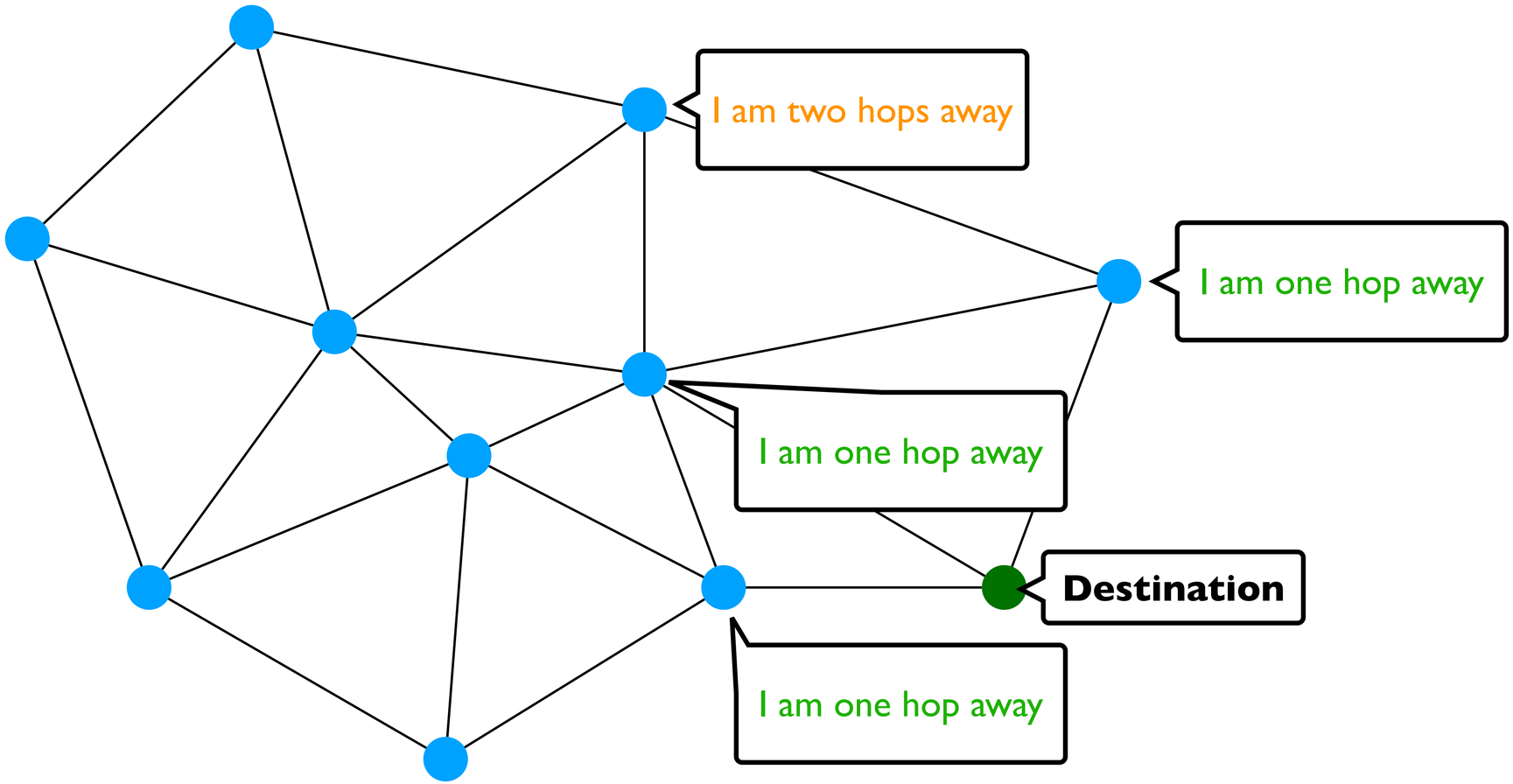

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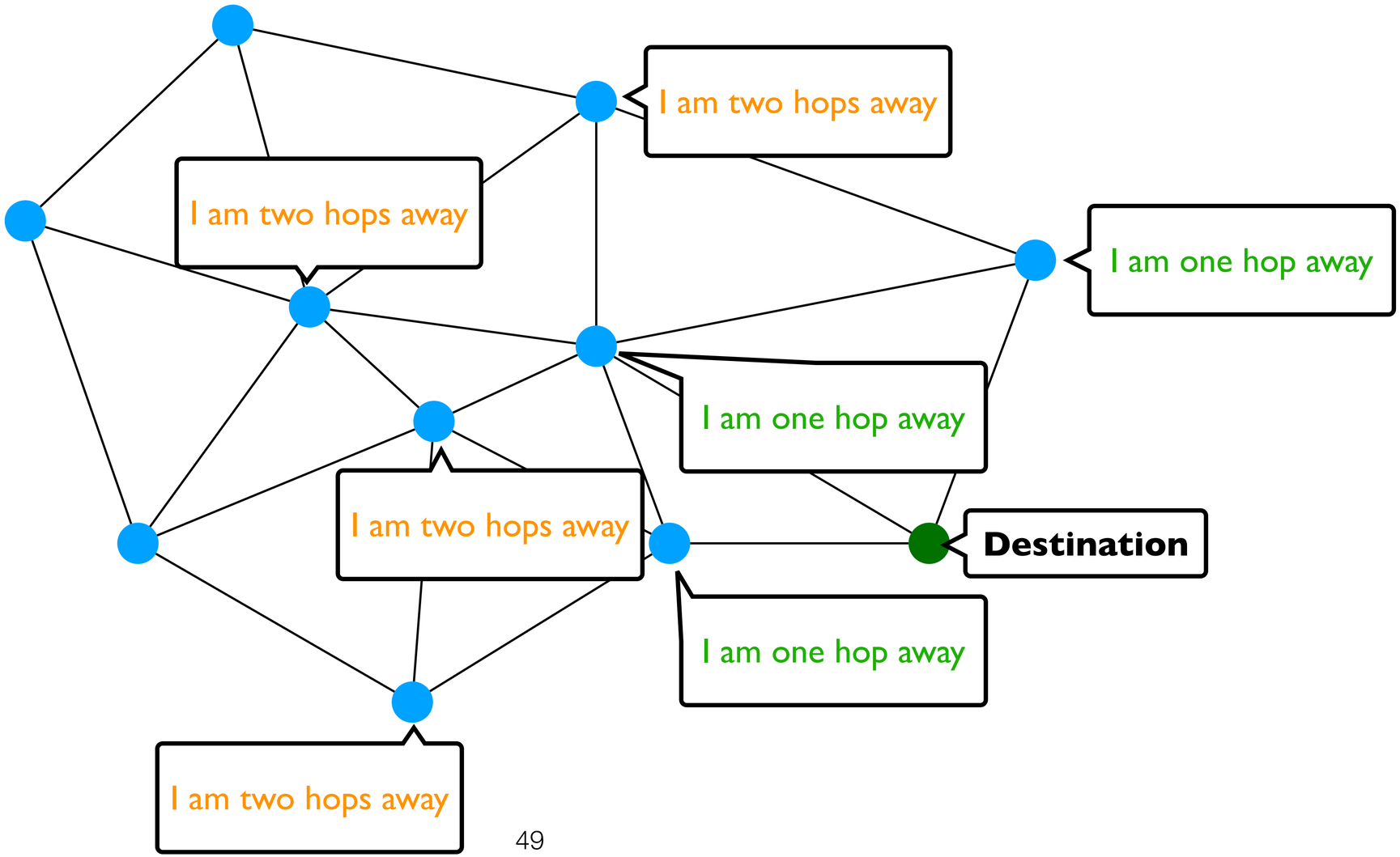

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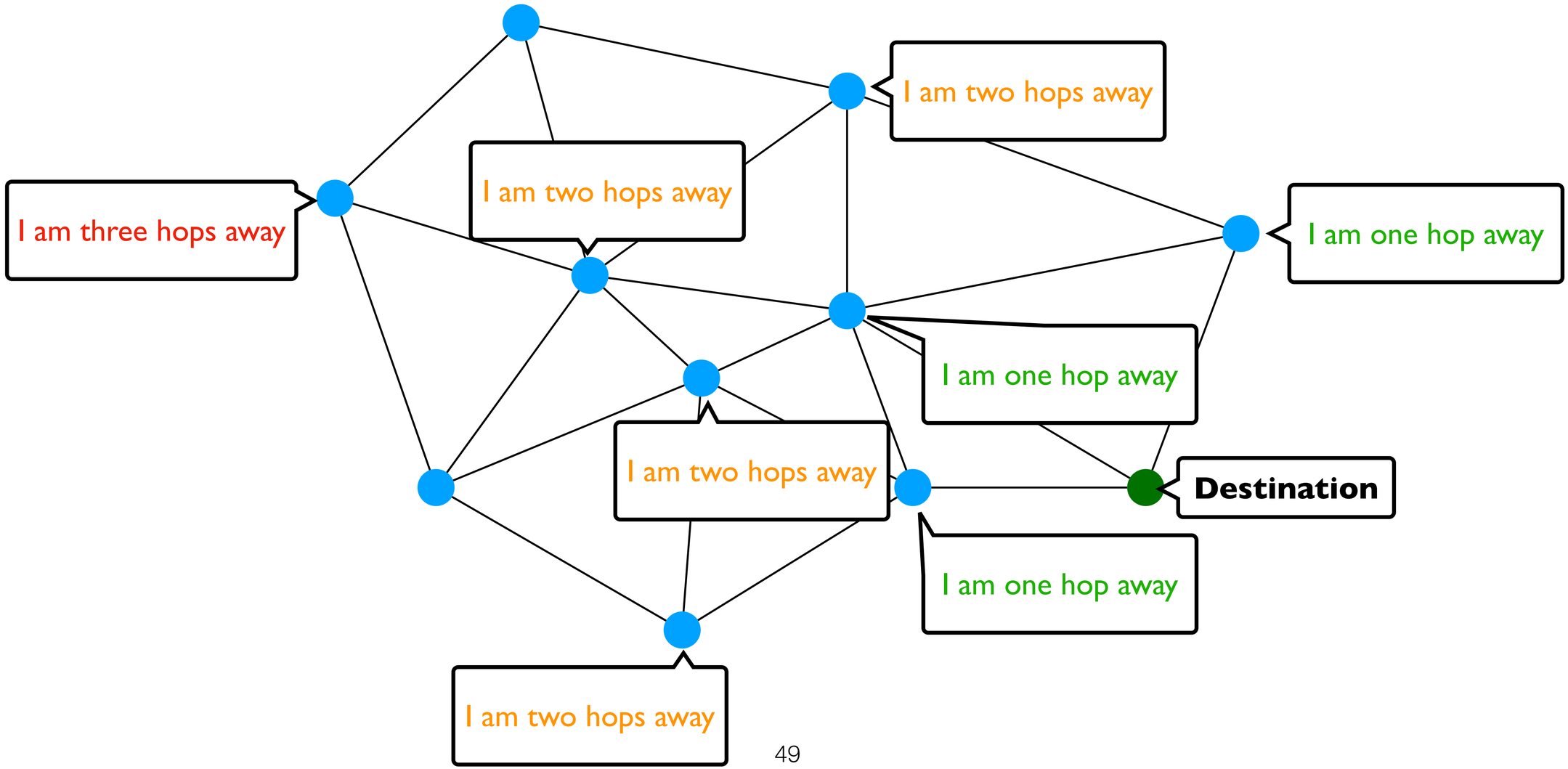

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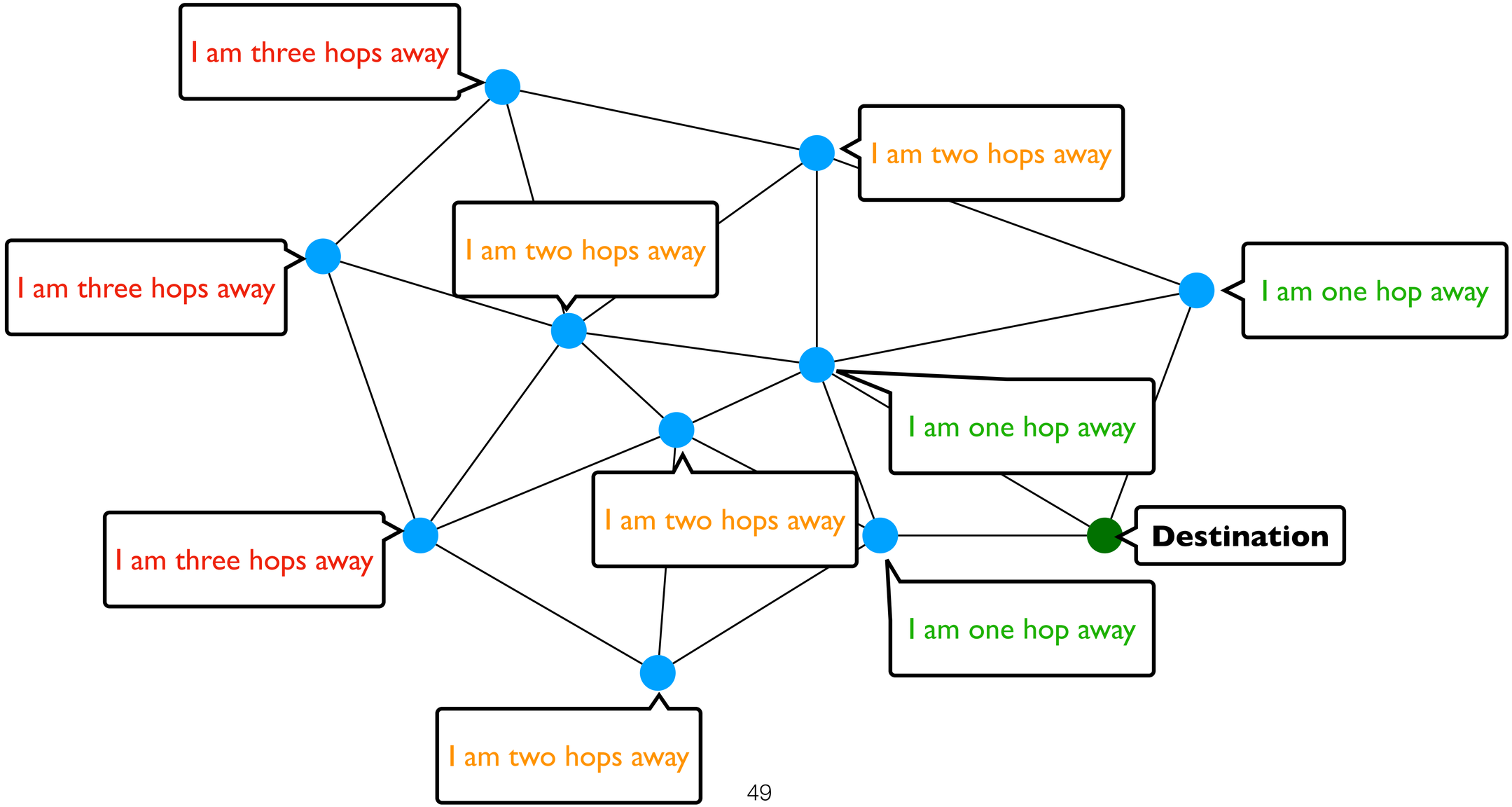
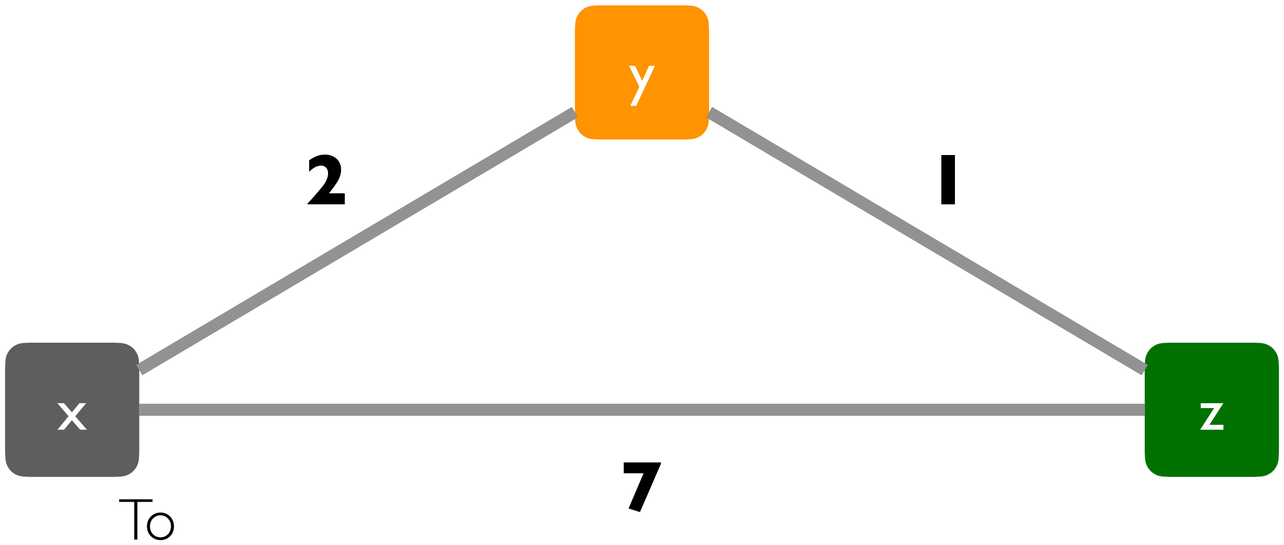


	x	y	z
x	-	-	-
y	2	0	1
z	-	-	-



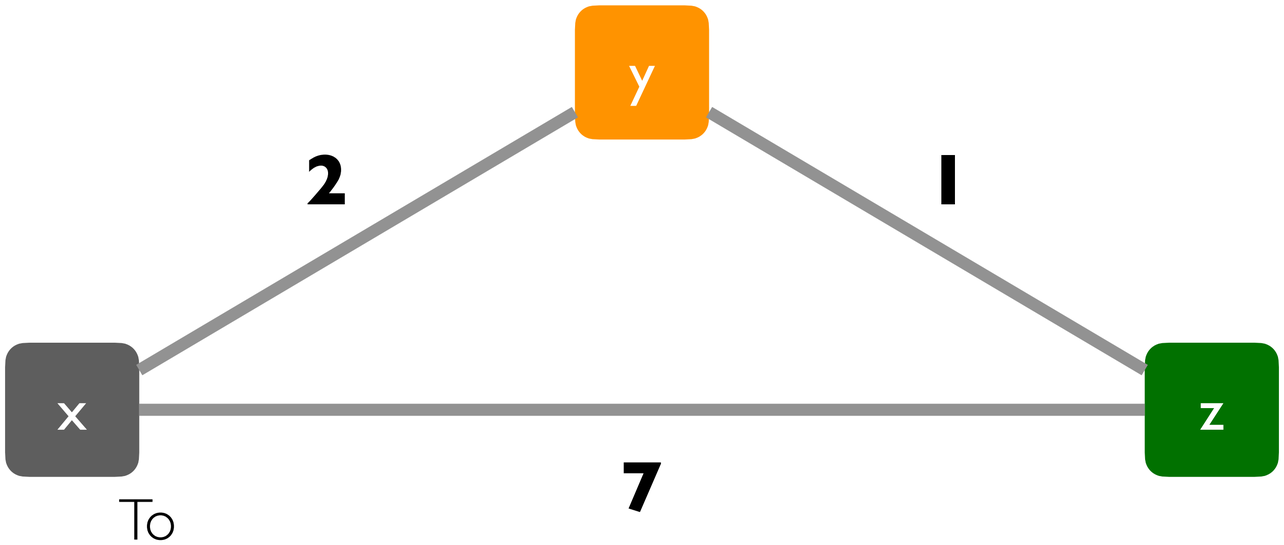
To

From

	x	y	z
x	0	2	7
y	-	-	-
z	-	-	-

	x	y	z
x	-	-	-
y	-	-	-
z	7	1	0

	x	y	z
x	-	-	-
y	2	0	1
z	-	-	-



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From

	x	y	z
x	0	2	7
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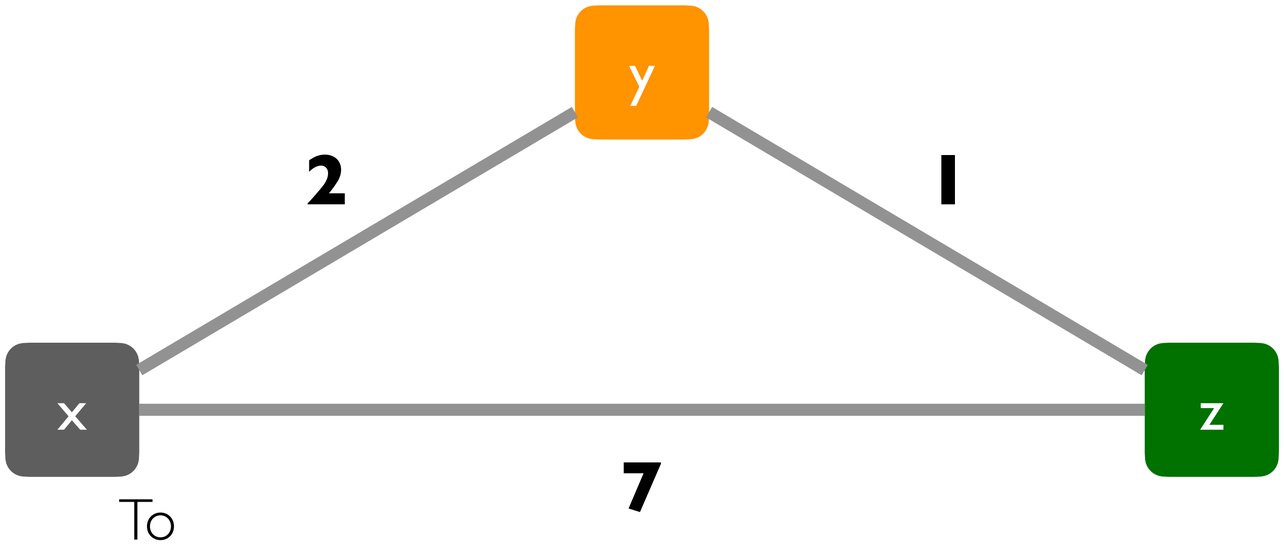
z	-	-	-

	x	y	z
x	-	-	-
y	-	-	-
z	7	1	0

This is y's "distance vector"

	x	y	z
x	-	-	-
y	2	0	1
z	-	-	-



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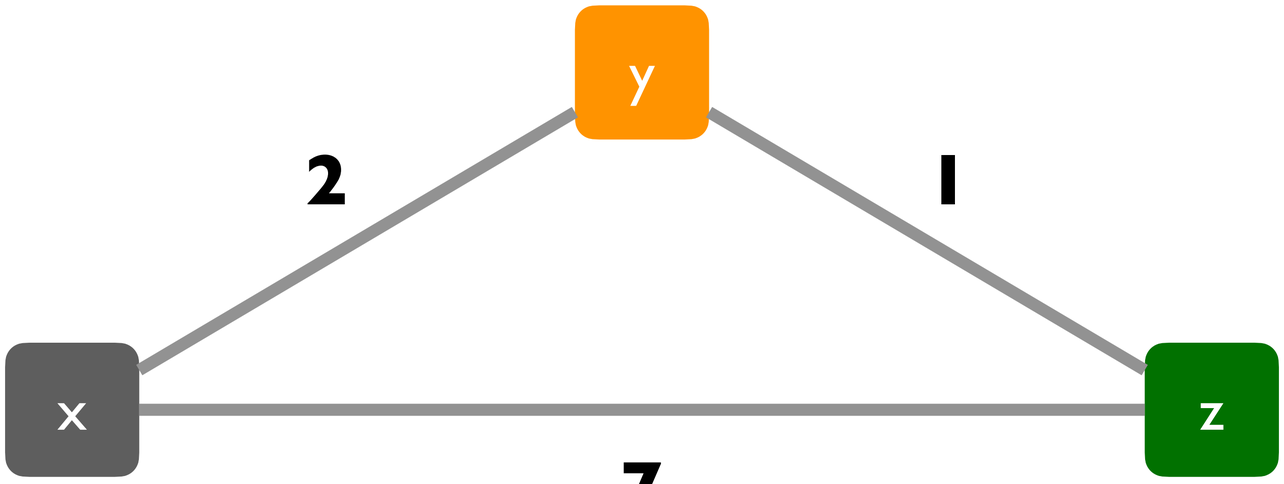

To

From

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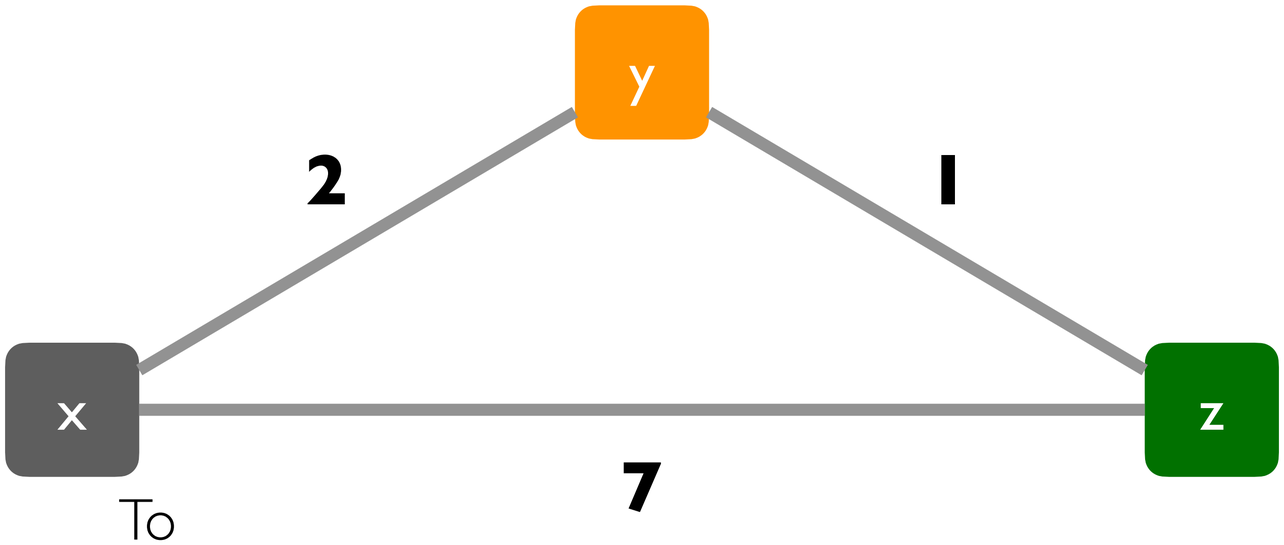
x	0	2	7
y	-	-	-
z	-	-	-

	x	y	z
x	-	-	-
y	-	-	-
z	7	1	0

	x	y	z
x			
y	2	0	1
z			



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y			
z			

	x	y	z
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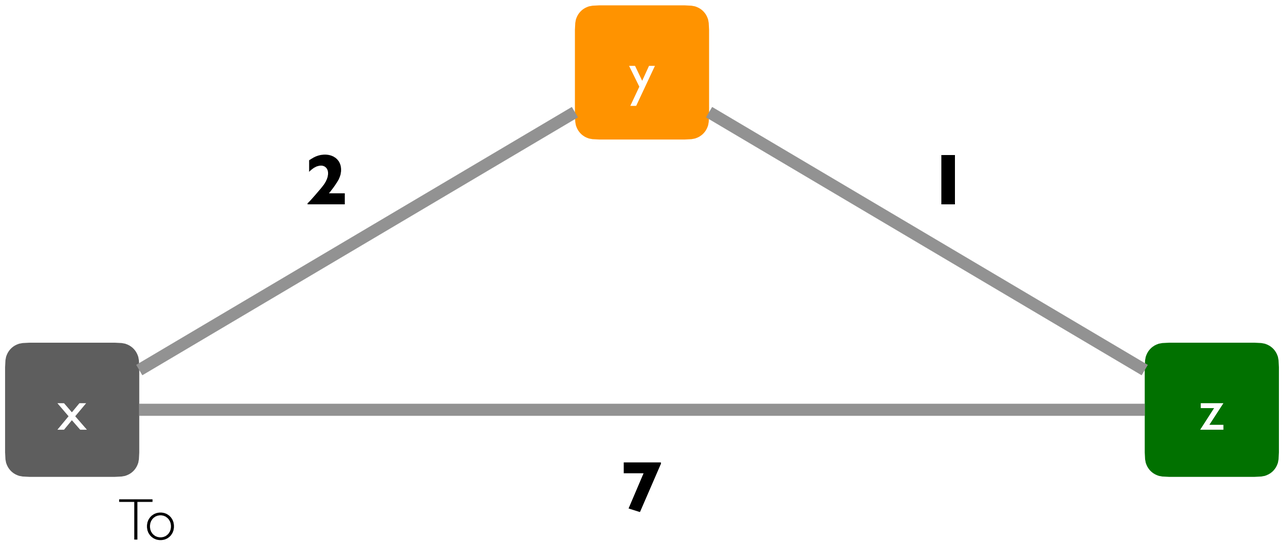
z			



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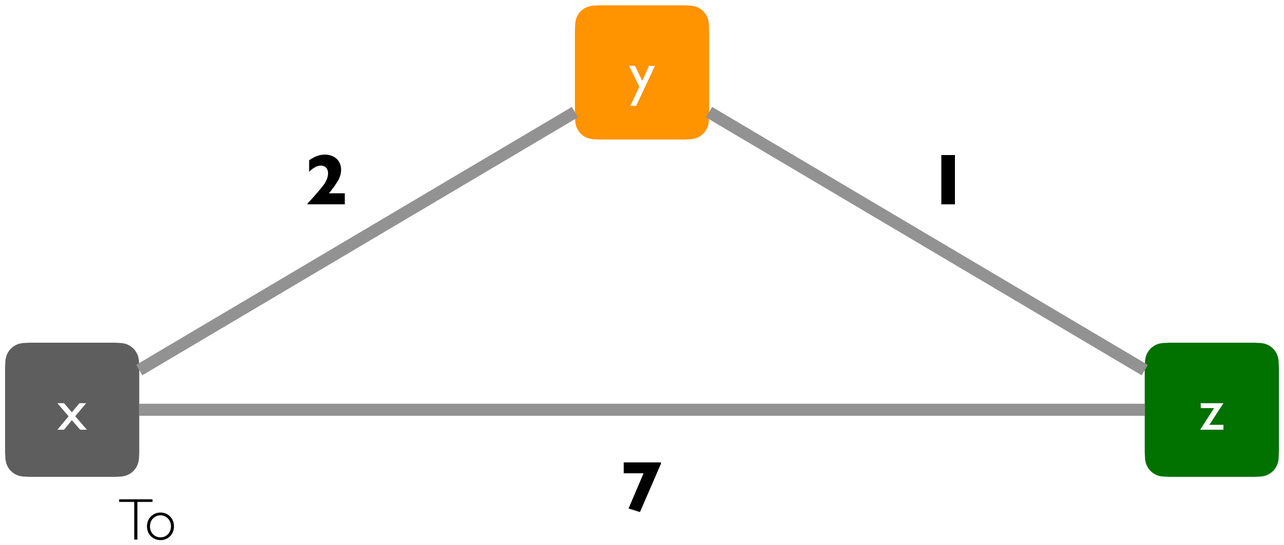

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x	0	2	7
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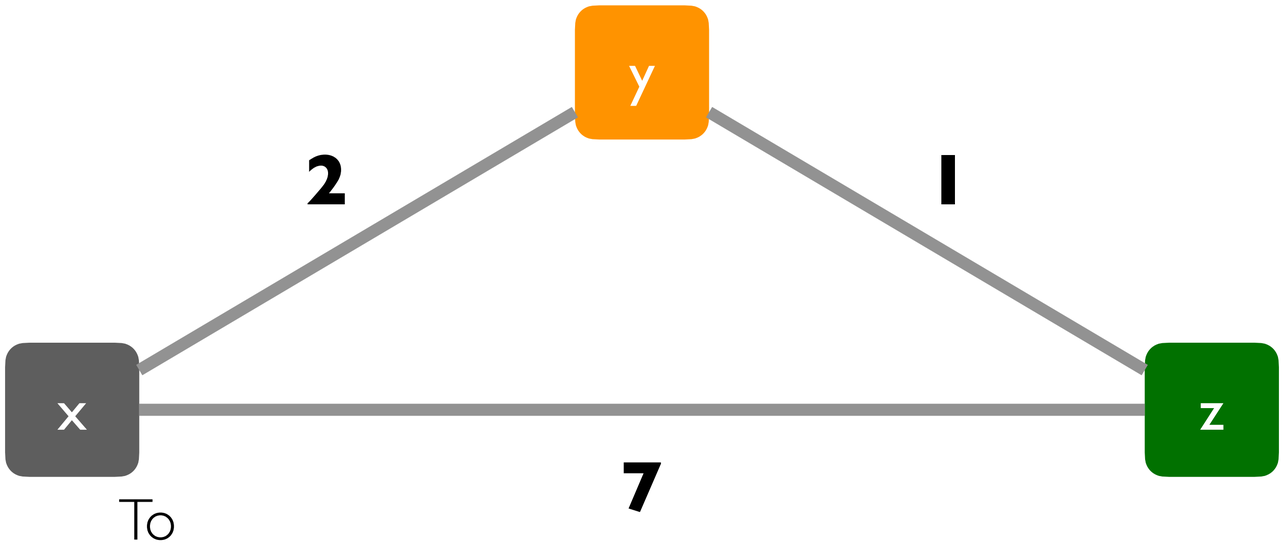

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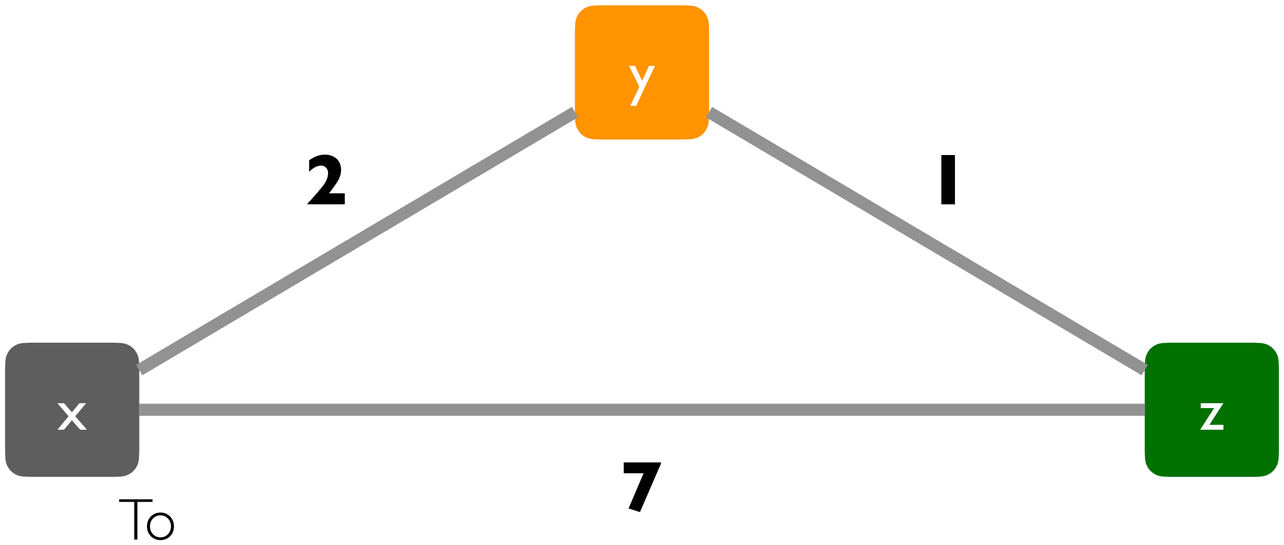

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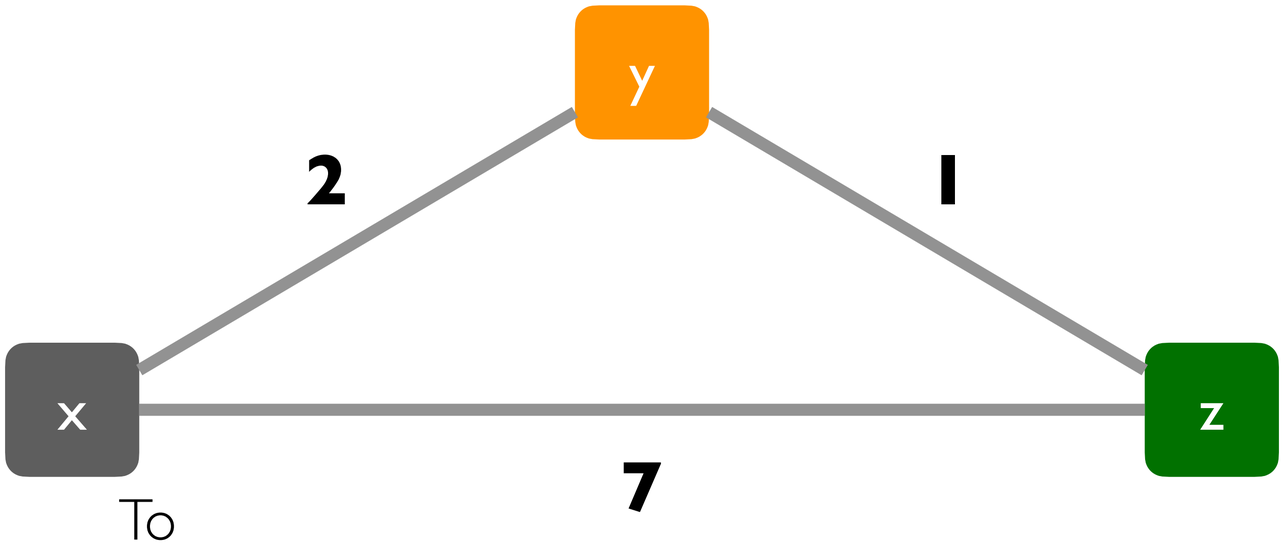


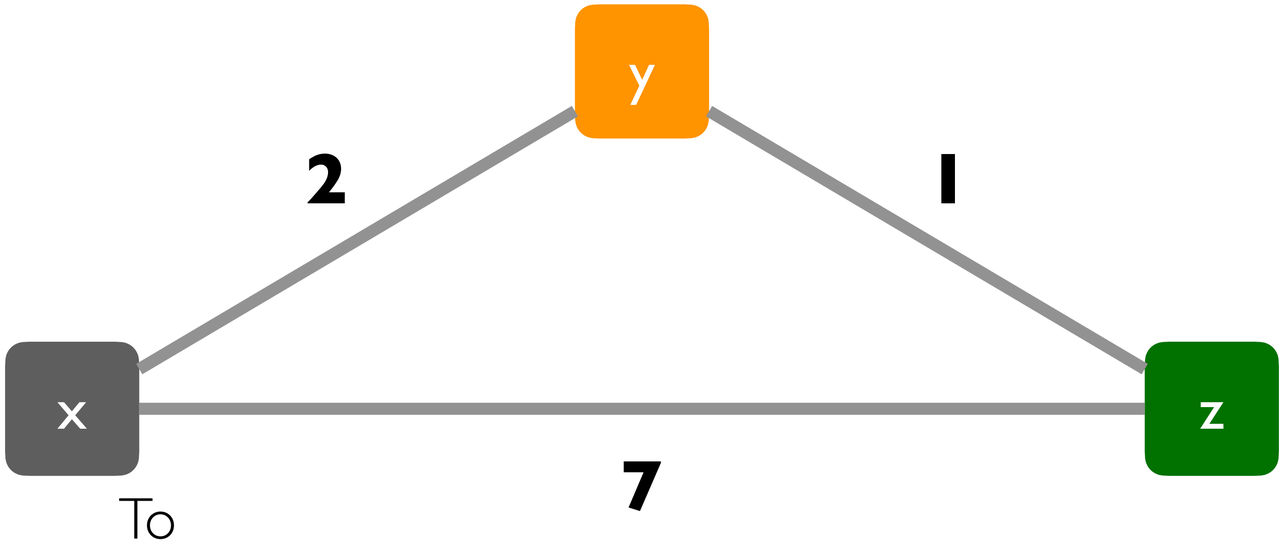
To

From

	x	y	z
x	0	2	~~7~~
y	2	0	1
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0



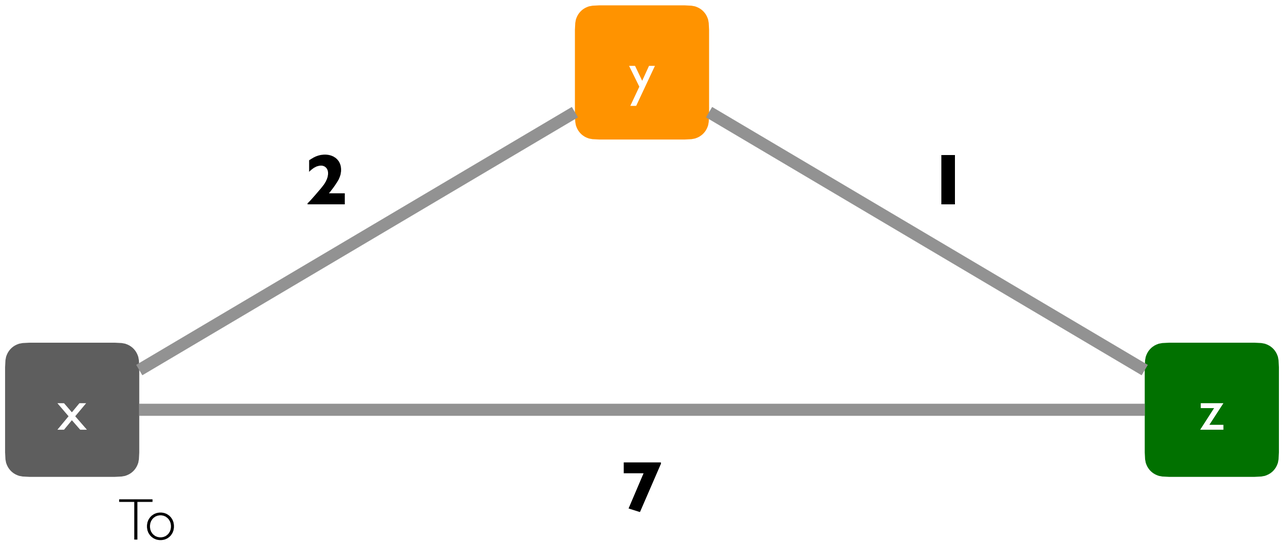
To

From

	x	y	z
x	0	~~2~~	~~7~~
y	2	0	~~1~~
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0



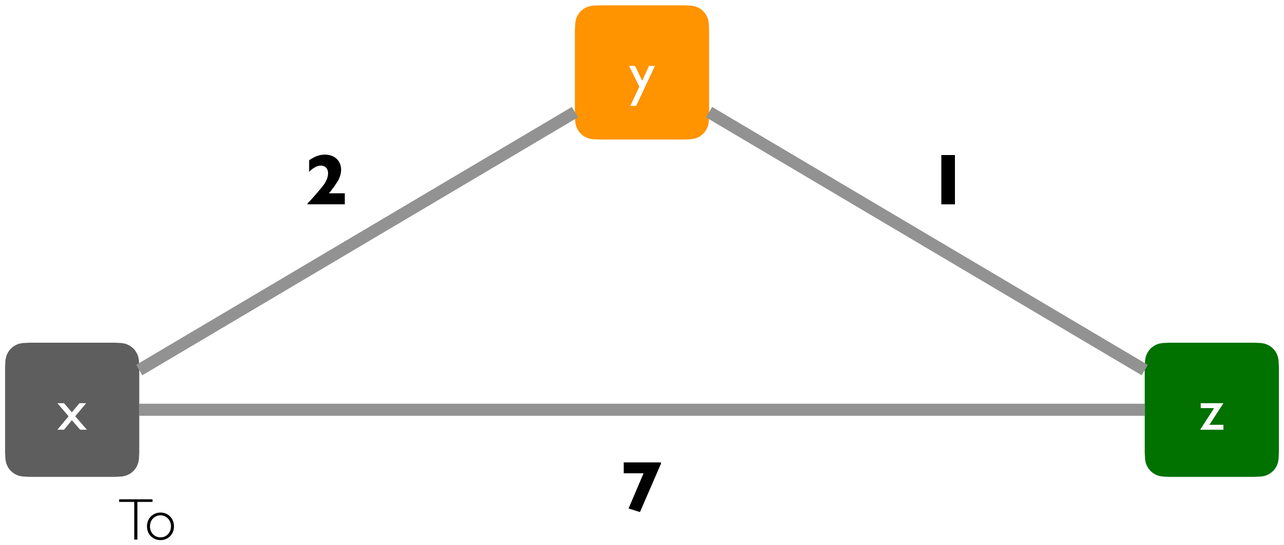
To

From

	x	y	z
x	0	~~2~~	3
y	2	0	~~1~~
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0



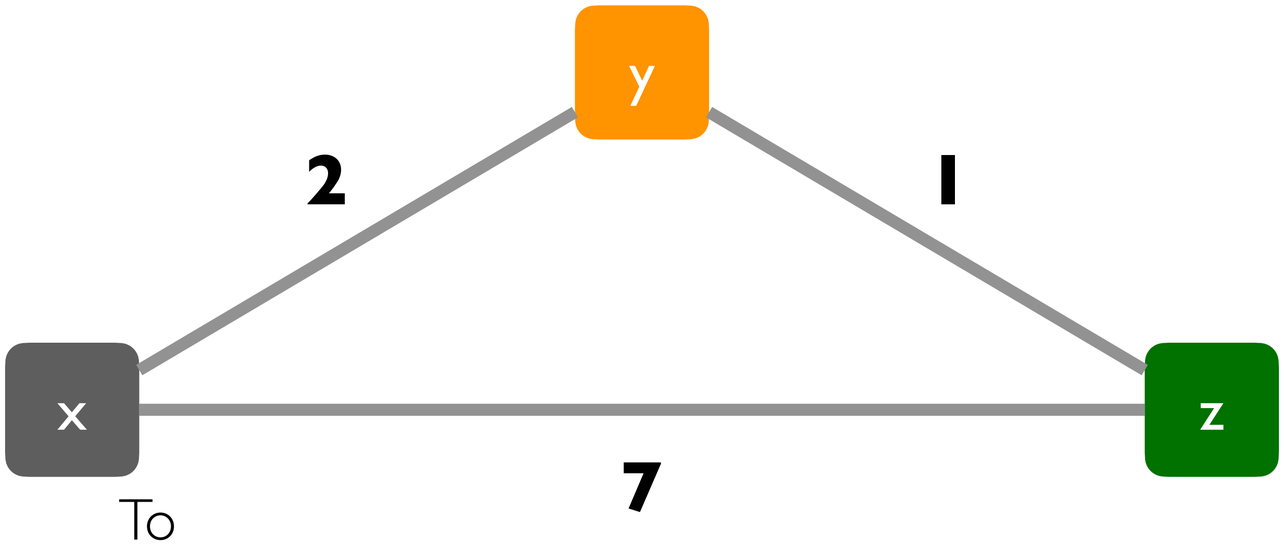
To

From

	x	y	z
x	0	~~2~~	3
y	2	0	~~1~~
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	~~7~~	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0



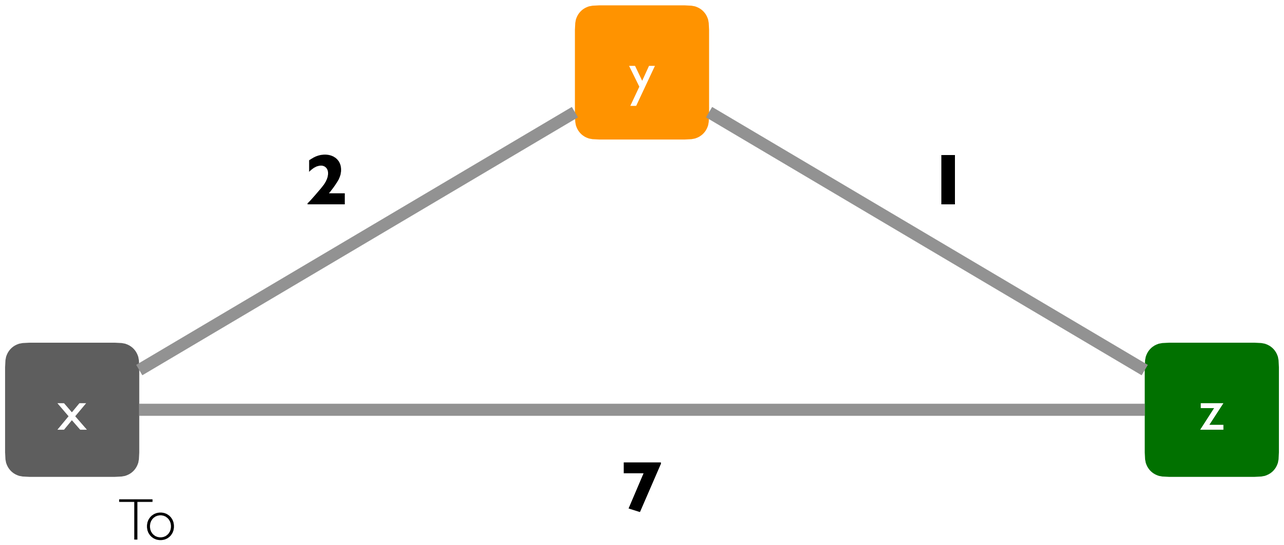
To

From

	x	y	z
x	0	~~2~~	3
y	2	0	~~1~~
z	7	1	0

	x	y	z
x	0	2	7
y	~~2~~	0	1
z	~~7~~	~~1~~	0

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0



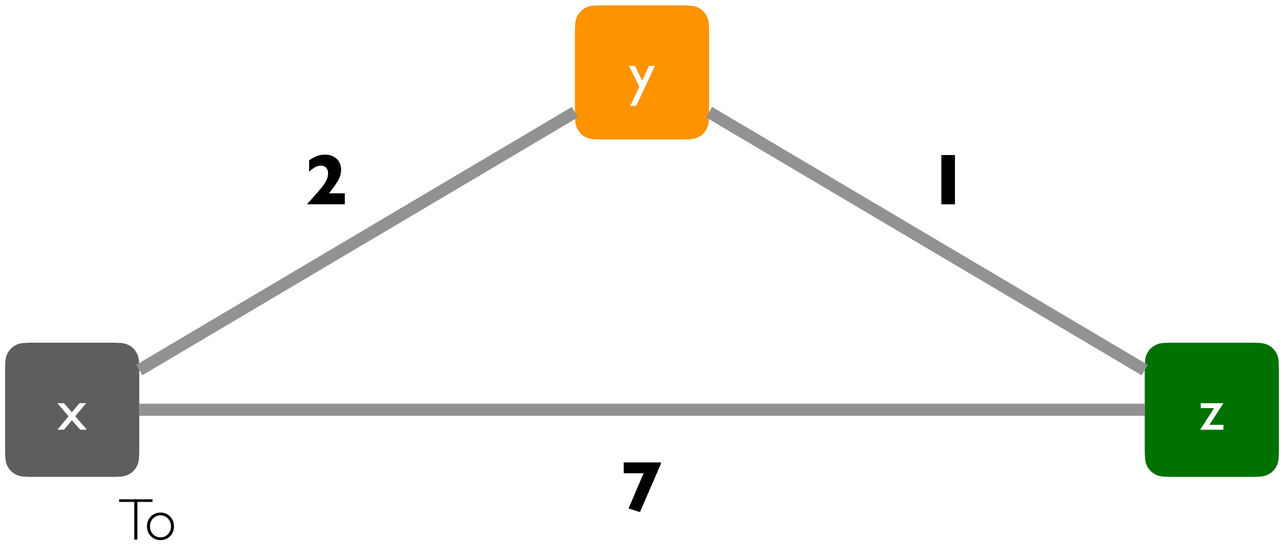
To

From

	x	y	z
x	0	~~2~~	3
y	2	0	~~1~~
z	7	1	0

	x	y	z
x	0	2	7
y	~~2~~	0	1
z	3	~~1~~	0

	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0



To

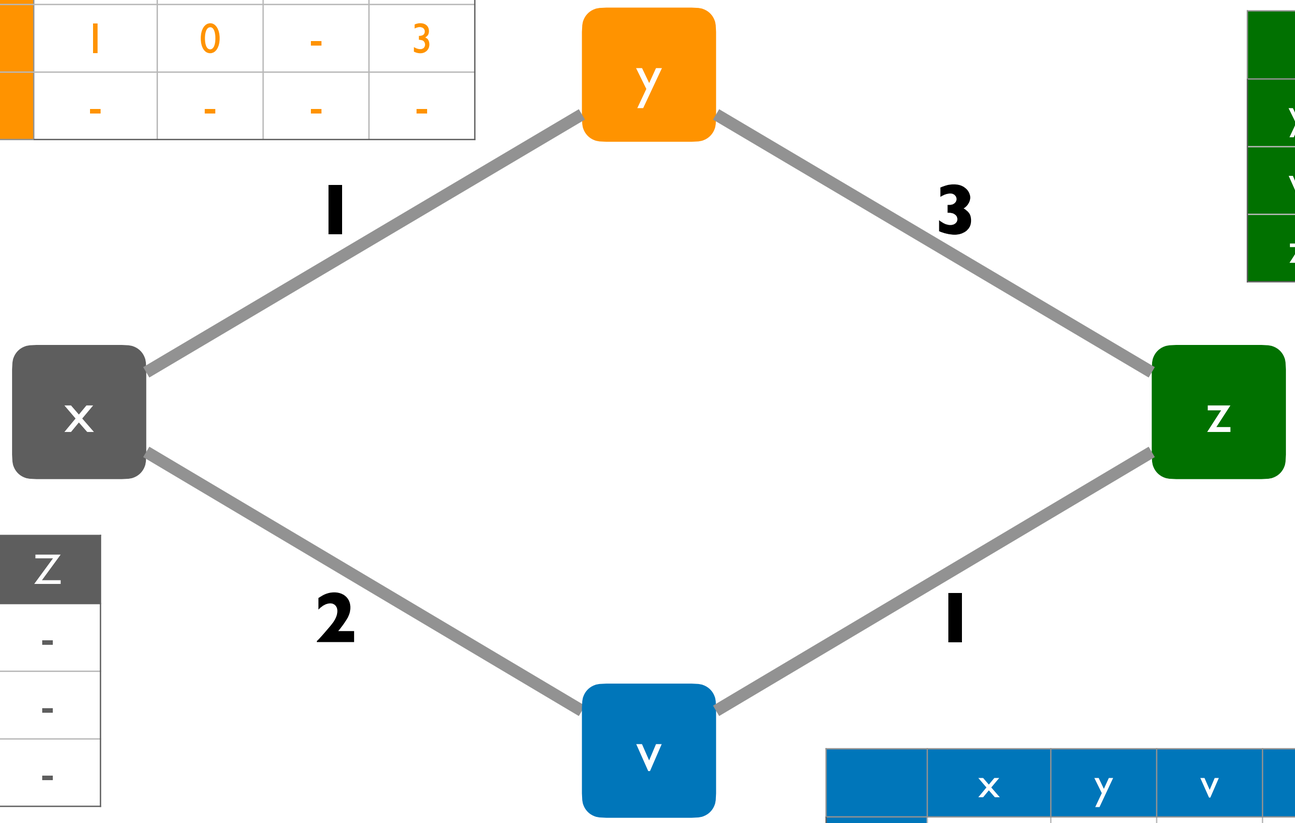
From

	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

	x	y	v	z
x	-	-	-	-
y	1	0	-	3
z	-	-	-	-

	x	y	v	z
y	-	-	-	-
v	-	-	-	-
z	-	3	1	0



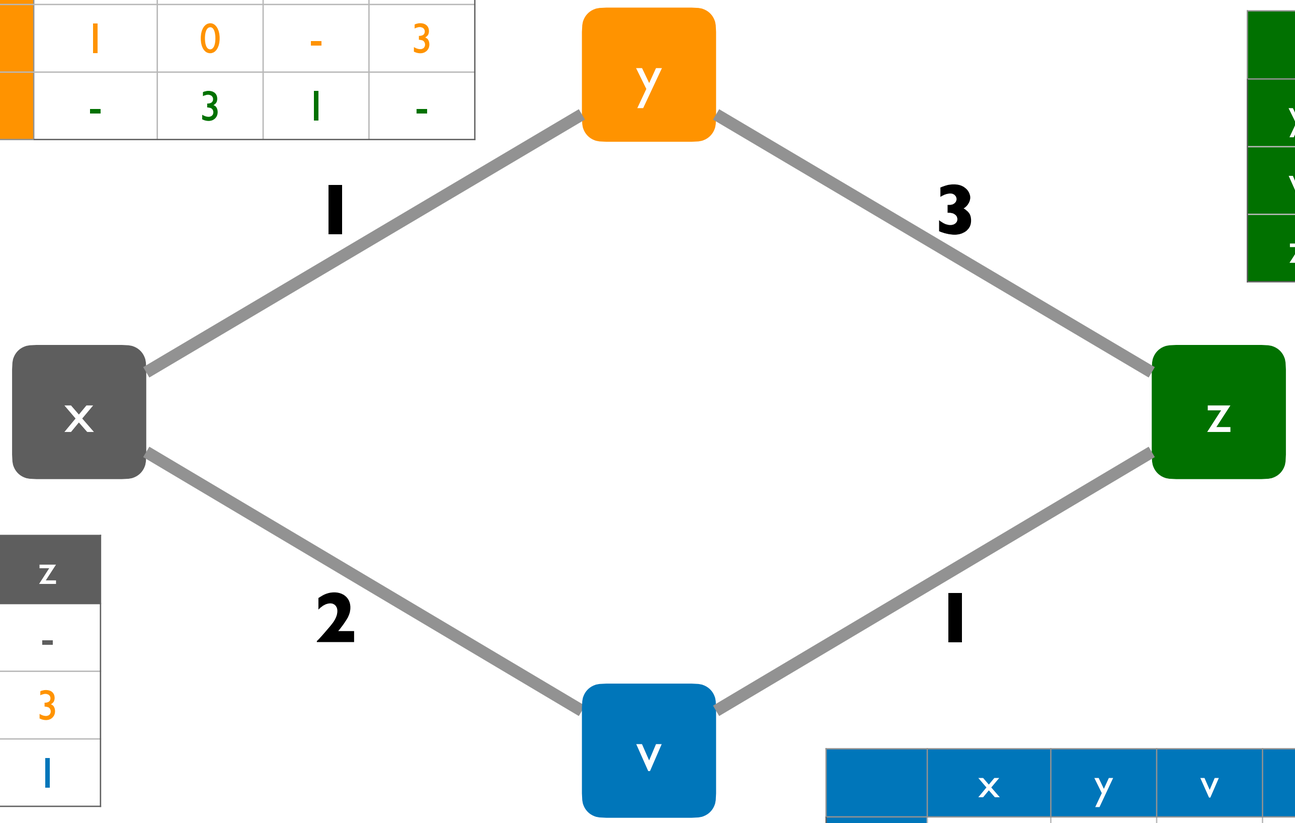
To

From

	x	y	v	Z
x	0	1	2	-
y	-	-	-	-
v	-	-	-	-

	x	y	v	z
x	-	-	-	-
v	2	-	0	1
z	-	-	-	-

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
z	-	3	1	-



	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	-	3	1	0

To

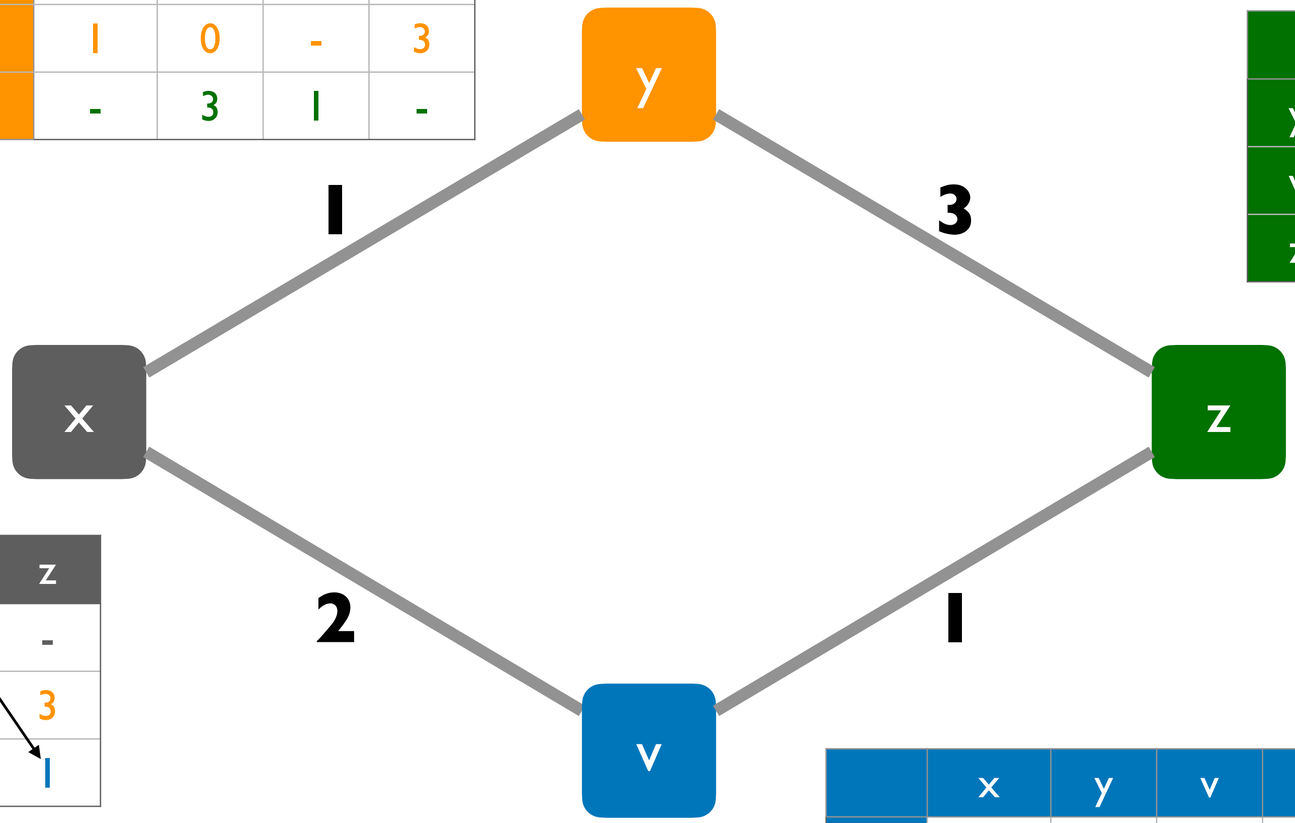
From

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	-	3	1	0



To

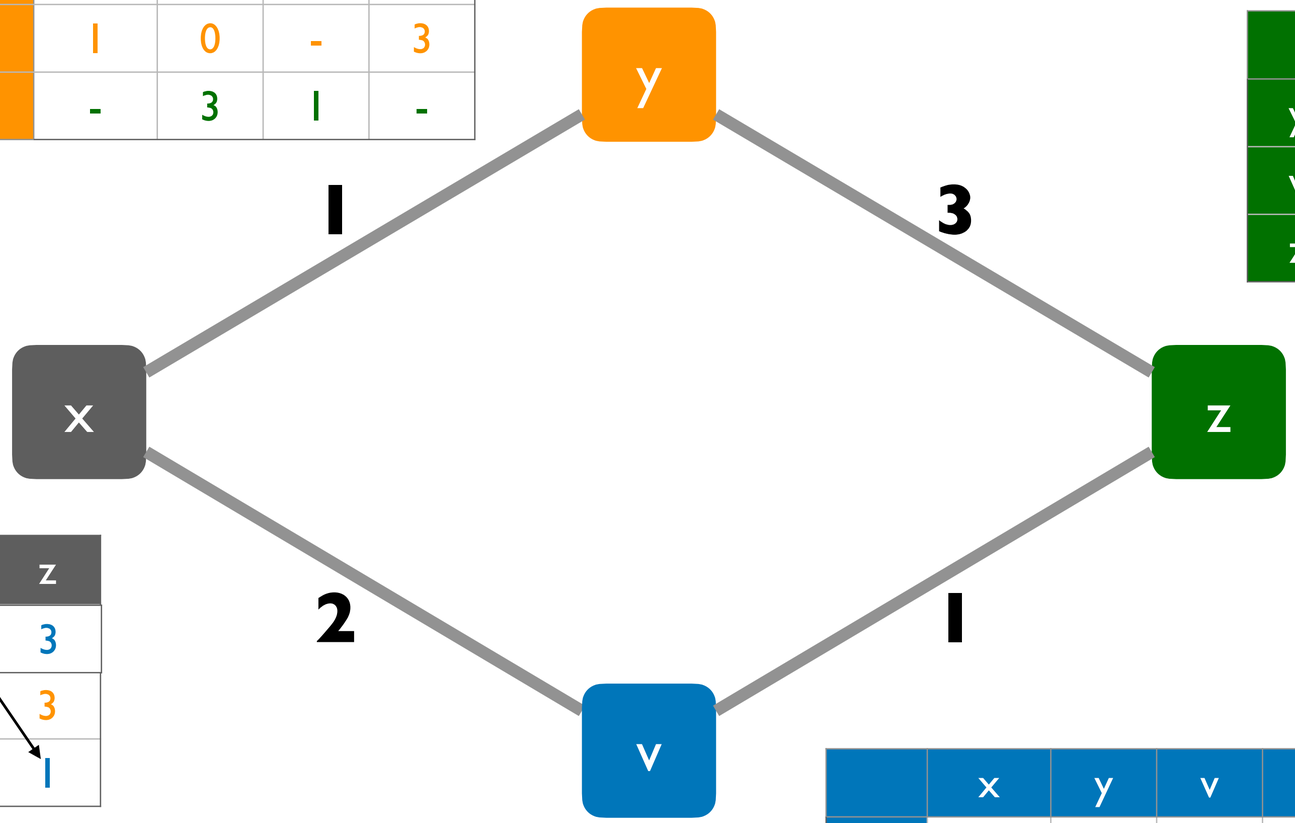
From

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	-	3	1	0



To

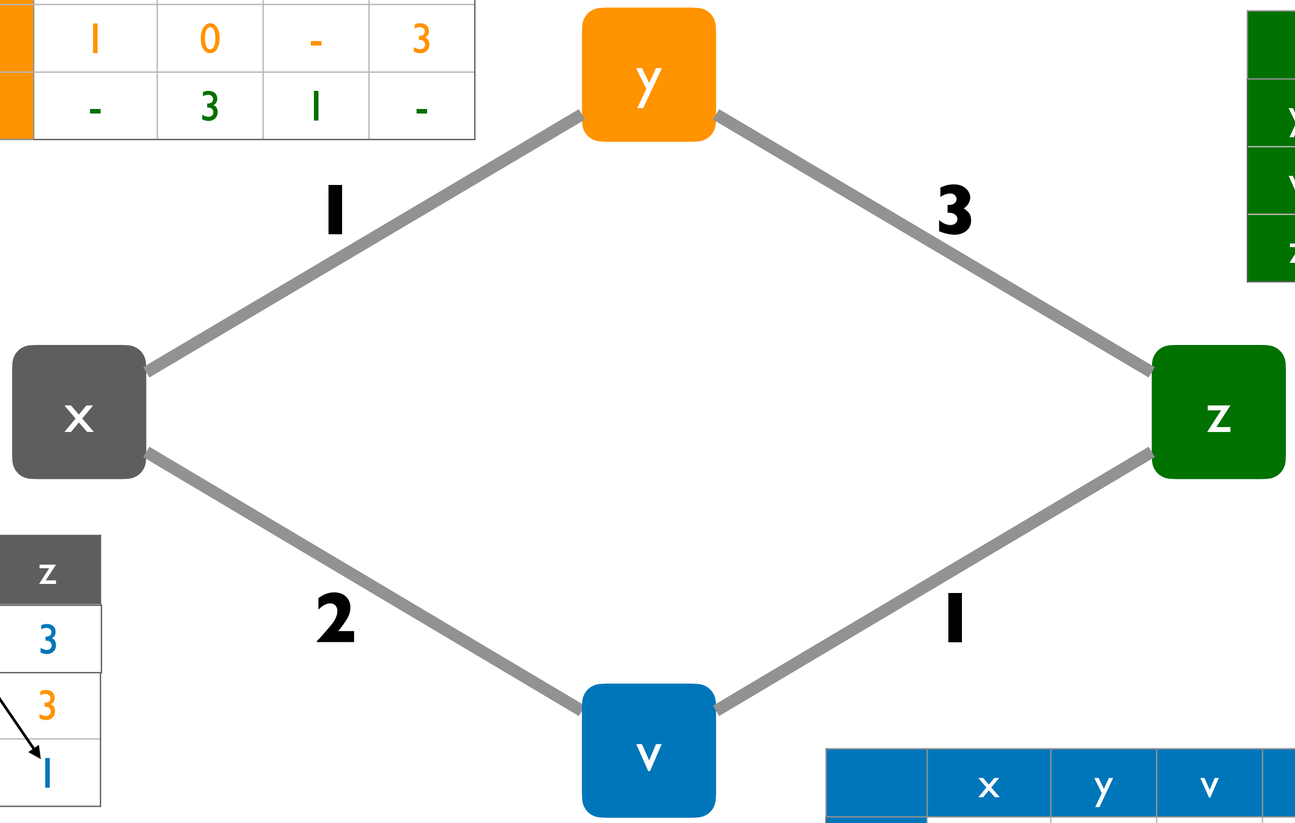
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	-	3	1	0



To

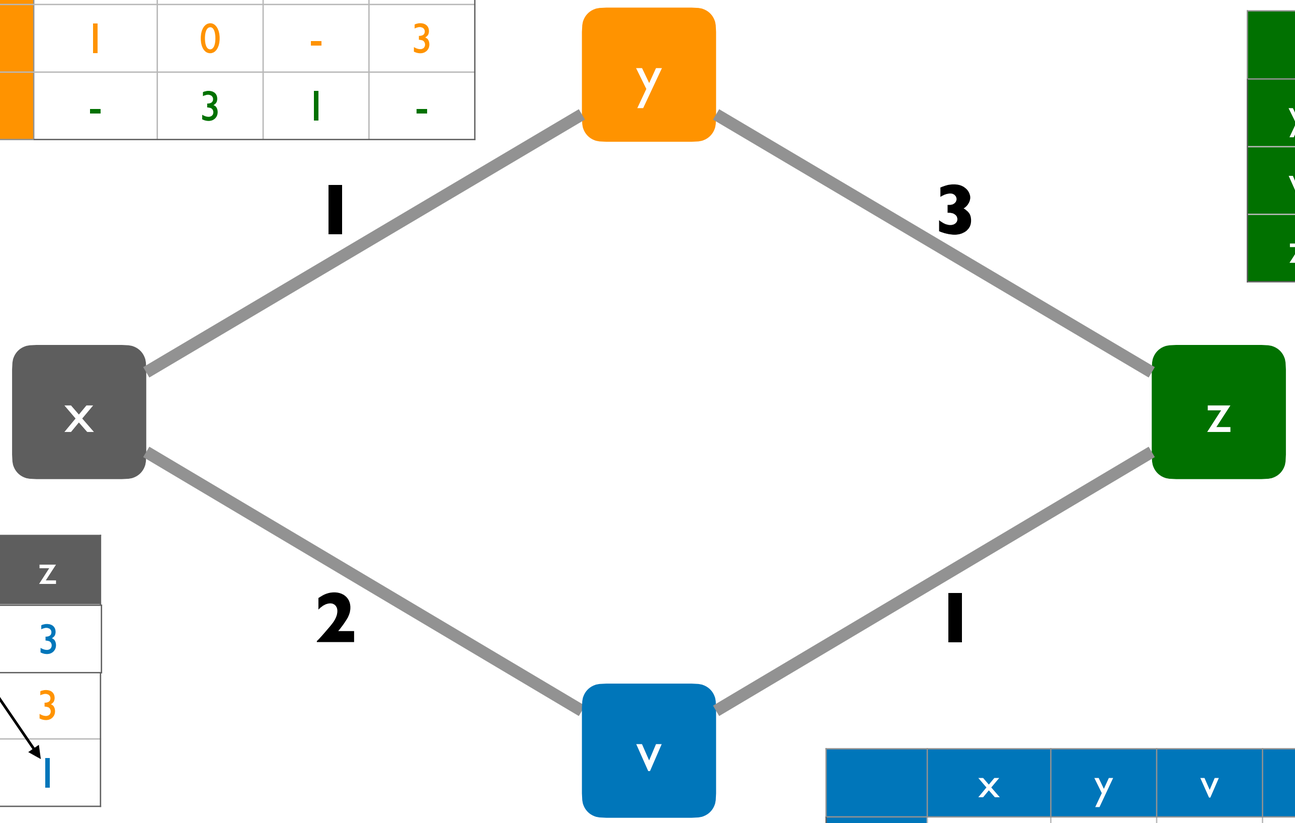
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	3	3	1	0



To

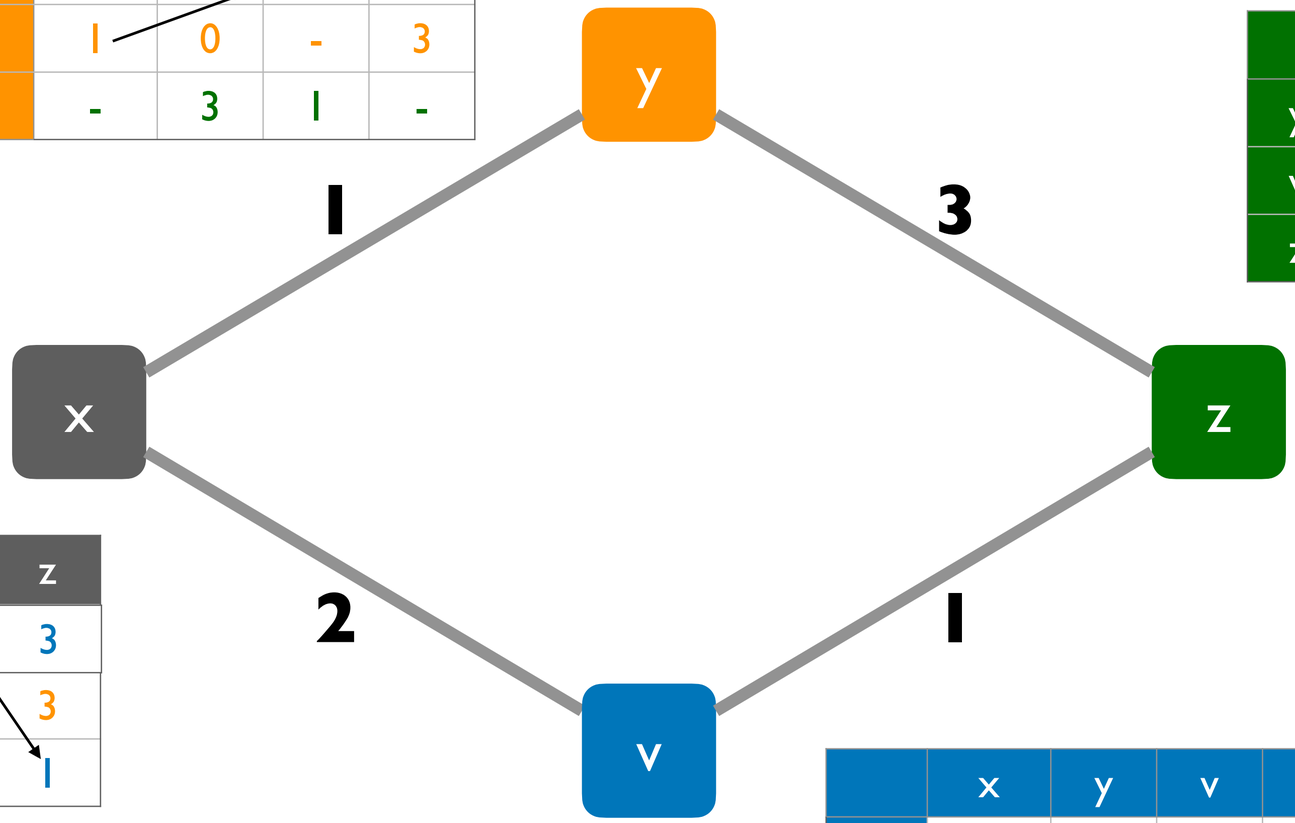
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	-	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	3	3	1	0



To

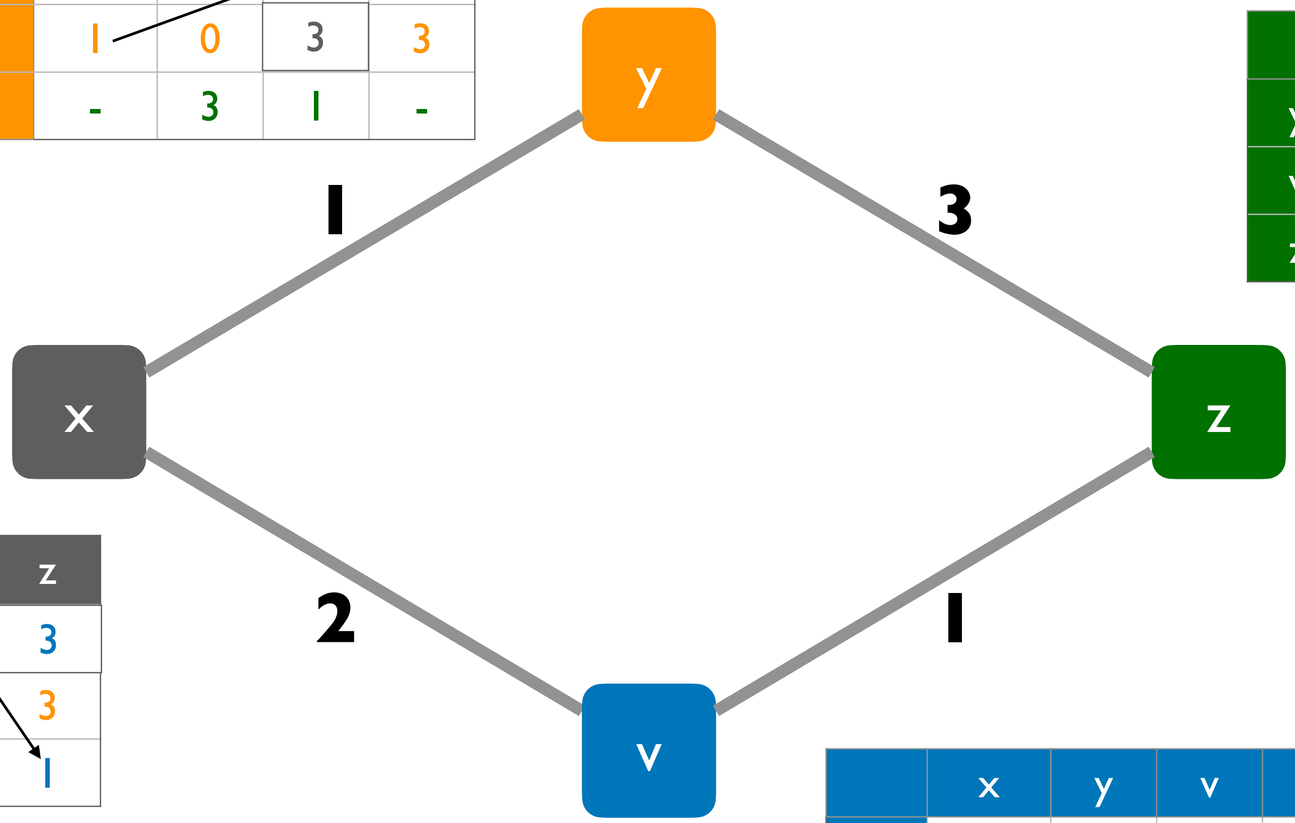
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	3	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	3	3	1	0



To

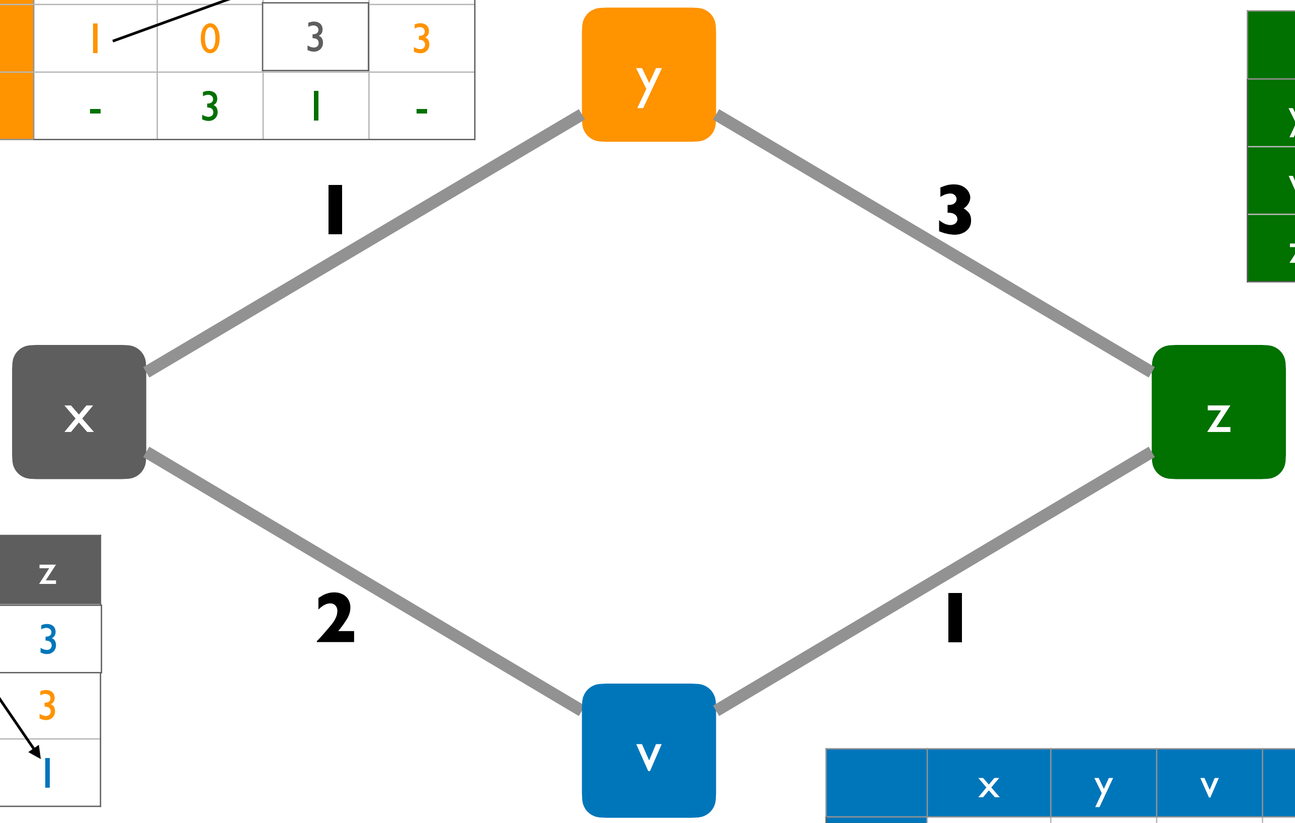
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	3	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	3	3	1	0



To

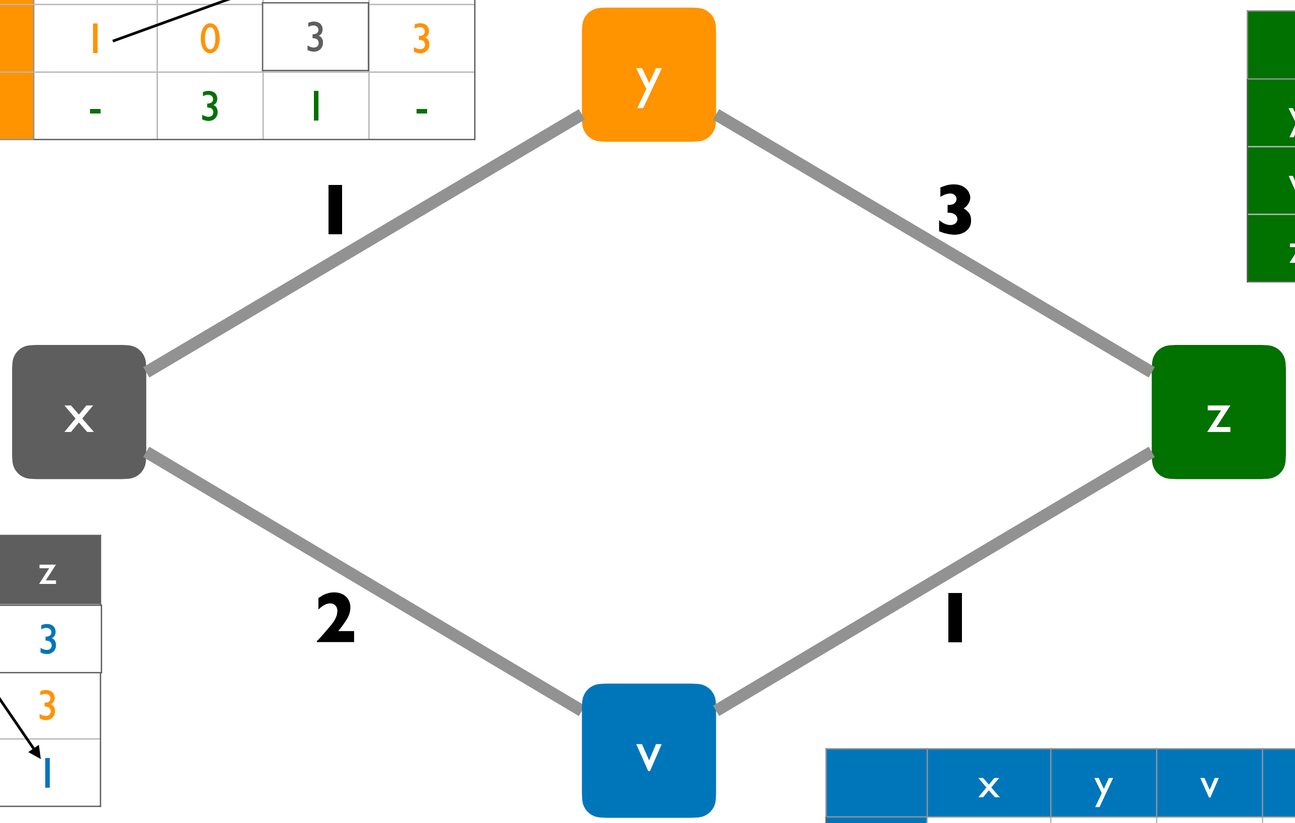
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	-	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	-
y	1	0	3	3
z	-	3	1	-

	x	y	v	z
y	1	0	-	3
v	2	-	0	1
z	3	3	1	0



To

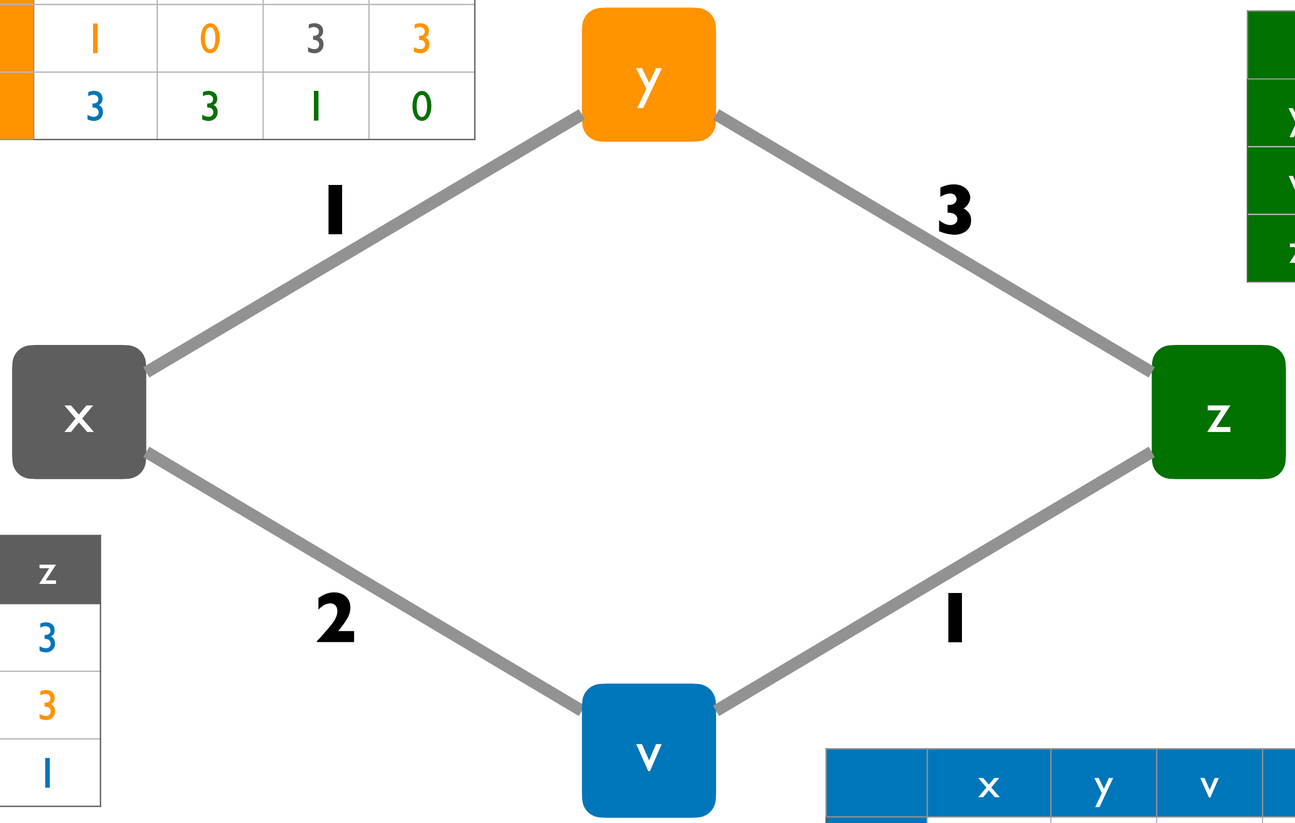
From

	x	y	v	z
x	0	1	2	3
y	1	0	-	3
v	2	-	0	1

	x	y	v	z
x	0	1	2	-
v	2	3	0	1
z	-	3	1	0

	x	y	v	z
x	0	1	2	3
y	1	0	3	3
z	3	3	1	0

	x	y	v	z
y	1	0	3	3
v	2	3	0	1
z	3	3	1	0



To

From

	x	y	v	z
x	0	1	2	3
y	1	0	3	3
v	2	3	0	1

	x	y	v	z
x	0	1	2	3
v	2	3	0	1
z	3	3	1	0

Distance-vector Routing

Distance-vector Routing

- Input to each router:
  - *Local link costs & neighbor messages*

Distance-vector Routing

- Input to each router:
  - *Local link costs & neighbor messages*
- Output of each router:
  - *Least-cost path to every other router*

Distance-vector Routing

Distance-vector Routing

- Distributed algorithm

Distance-vector Routing

- Distributed algorithm
- All routers run it “together"
  - *Each router runs its own instance*
  - *Neighbors exchange and react to each other’s messages*

Bellman-Ford Algorithm

Bellman-Ford Algorithm

- All neighbors exchange information
  - *Each router checks whether it can improve current paths by leveraging the new information*

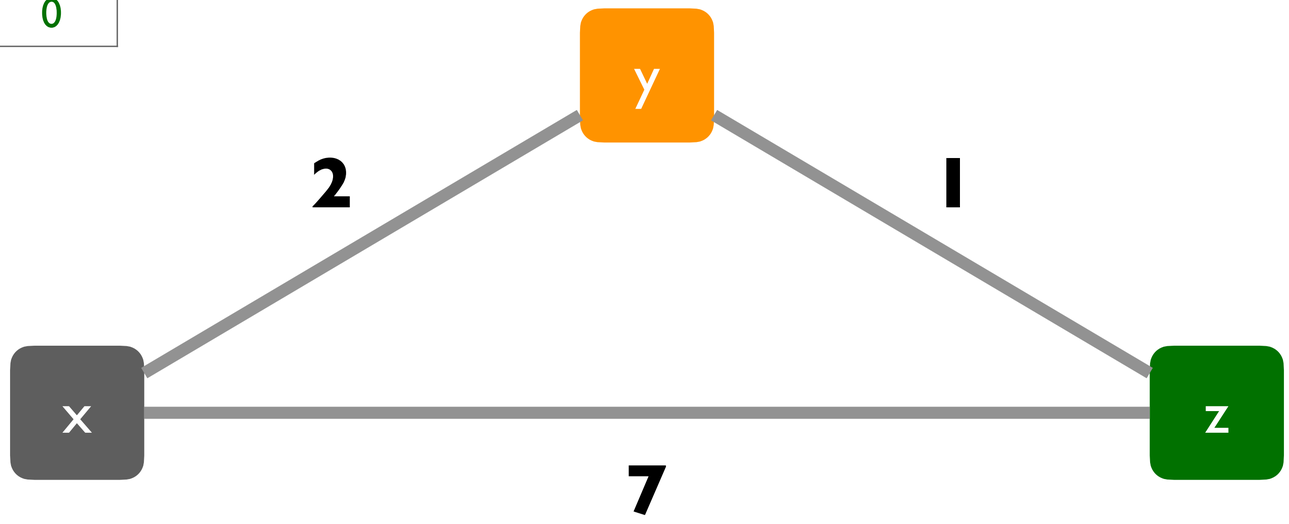
Bellman-Ford Algorithm

- All neighbors exchange information
  - *Each router checks whether it can improve current paths by leveraging the new information*
- Ends when no improvements are possible

To

From

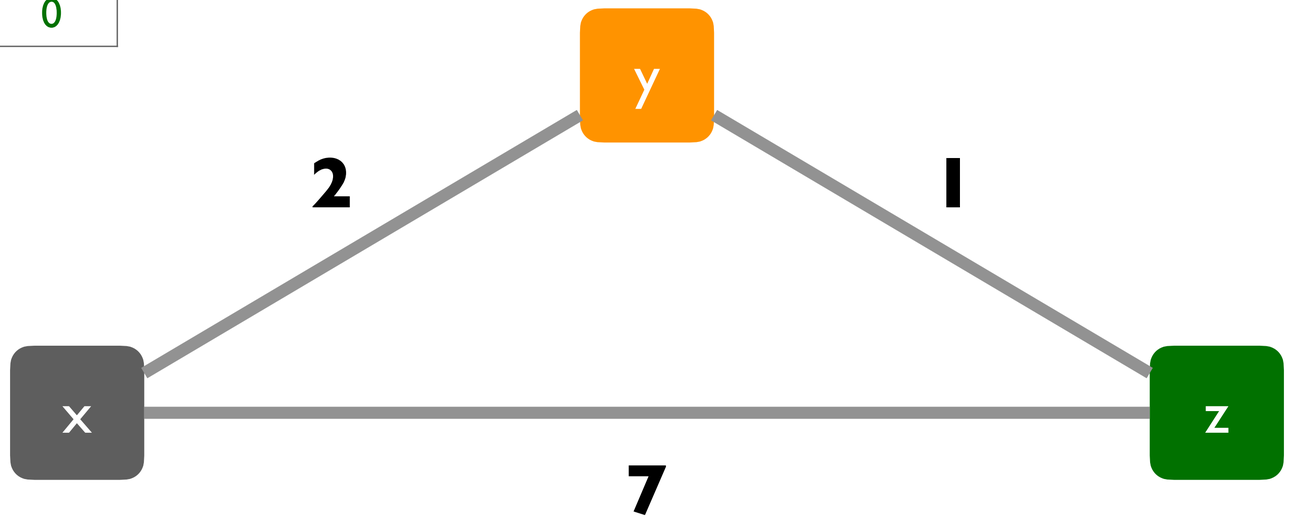
	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0



To

From

	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

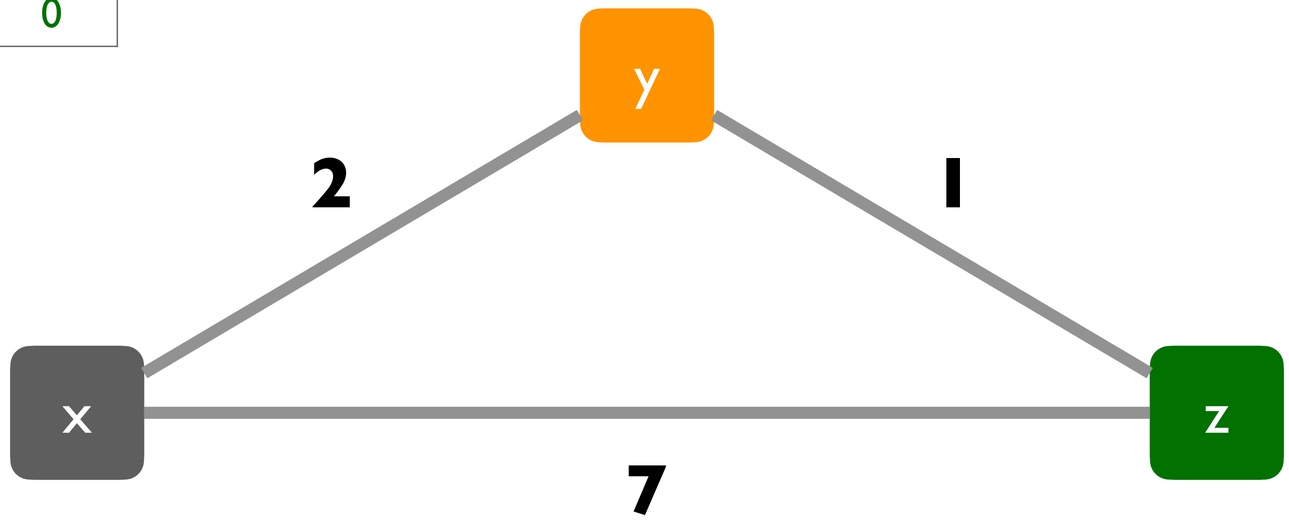


$$d_x(z) =$$

To

From

	x	y	z
x	0	2	~~7~~
y	2	0	1
z	7	1	0

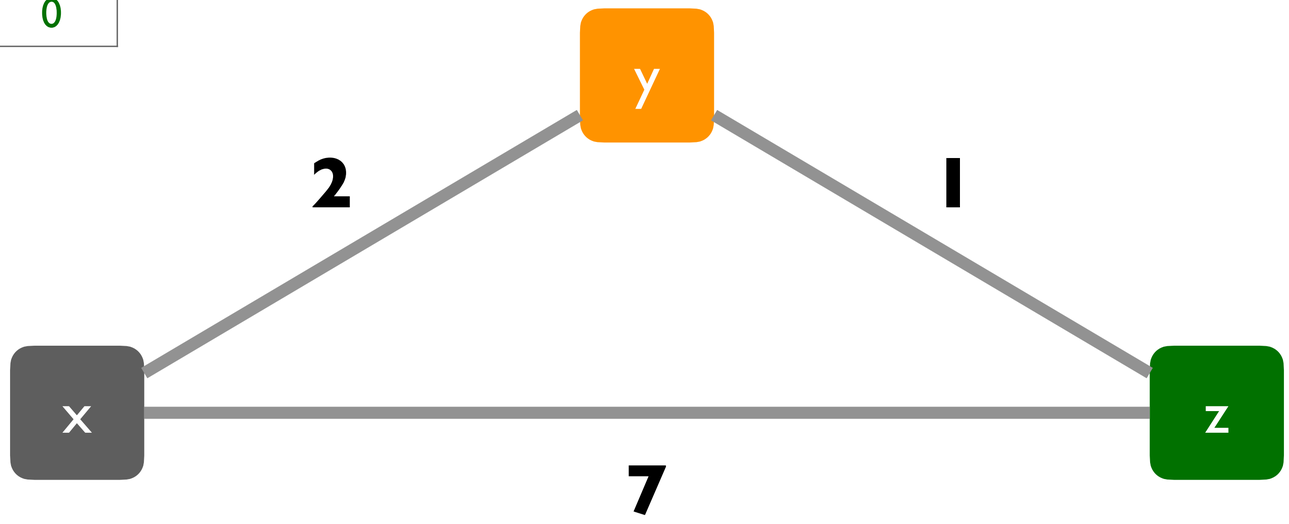


$$d_x(z) = \qquad cost(x, z),$$

To

From

	x	y	z
x	0	~~2~~	~~7~~
y	2	0	~~1~~
z	7	1	0

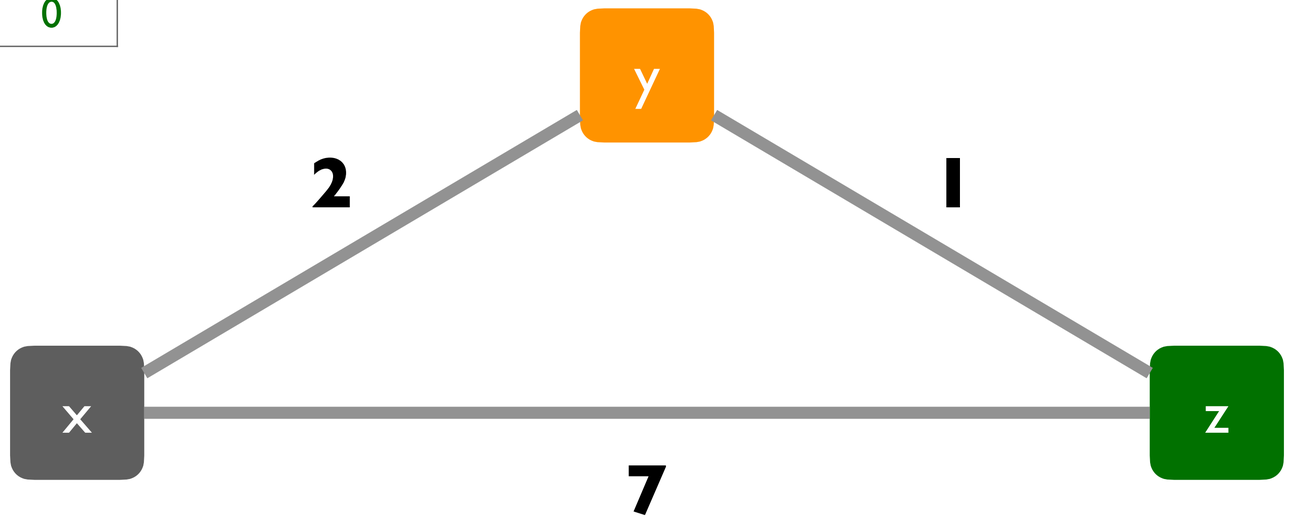


$$d_x(z) = \begin{array}{l} cost(x, z), \\ cost(x, y) + d_y(z) \end{array}$$

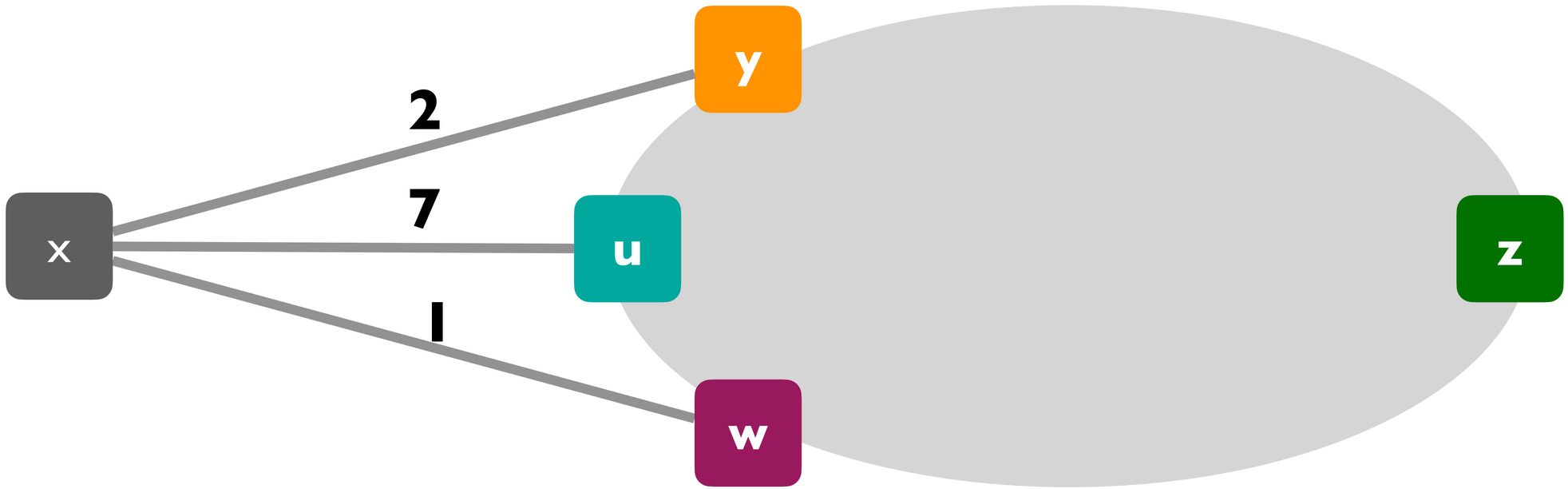
To

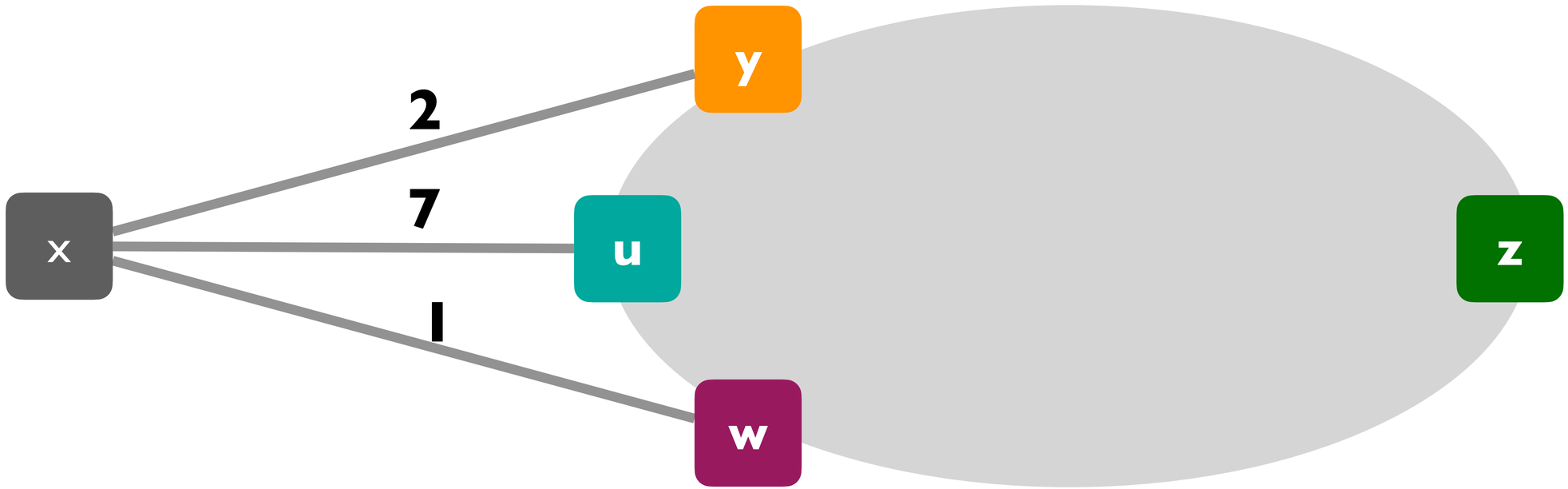
From

	x	y	z
x	0	~~2~~	~~7~~
y	2	0	~~1~~
z	7	1	0

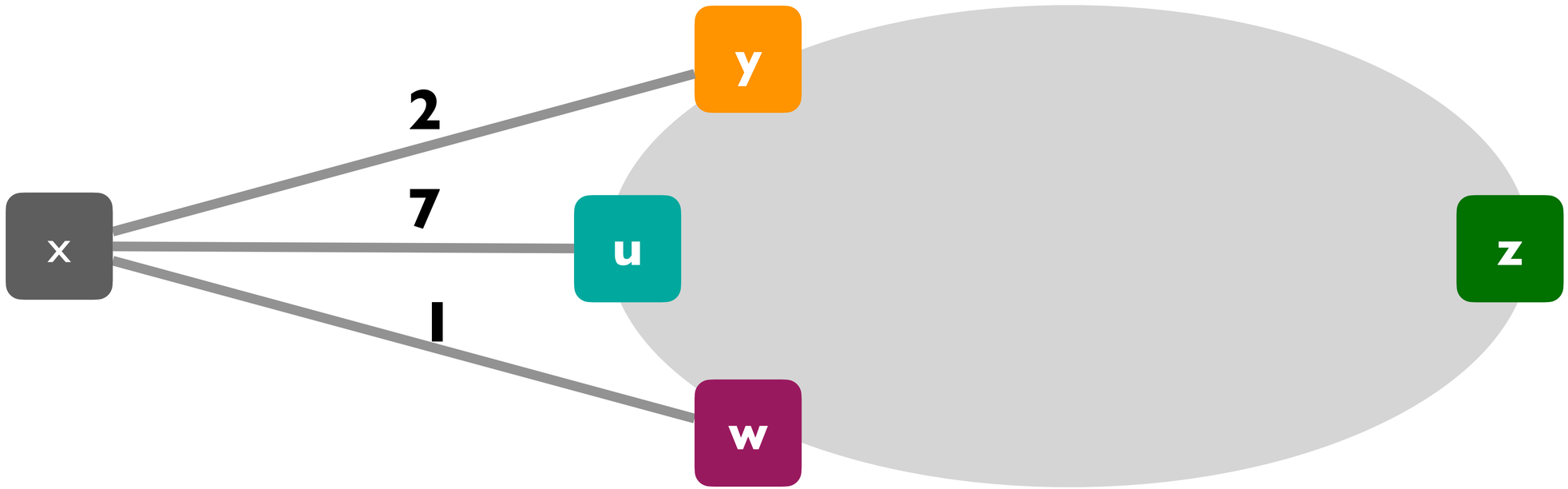


$$d_x(z) = \min\{\ cost(x,z),$$
$$cost(x,y) + d_y(z)\ \}$$

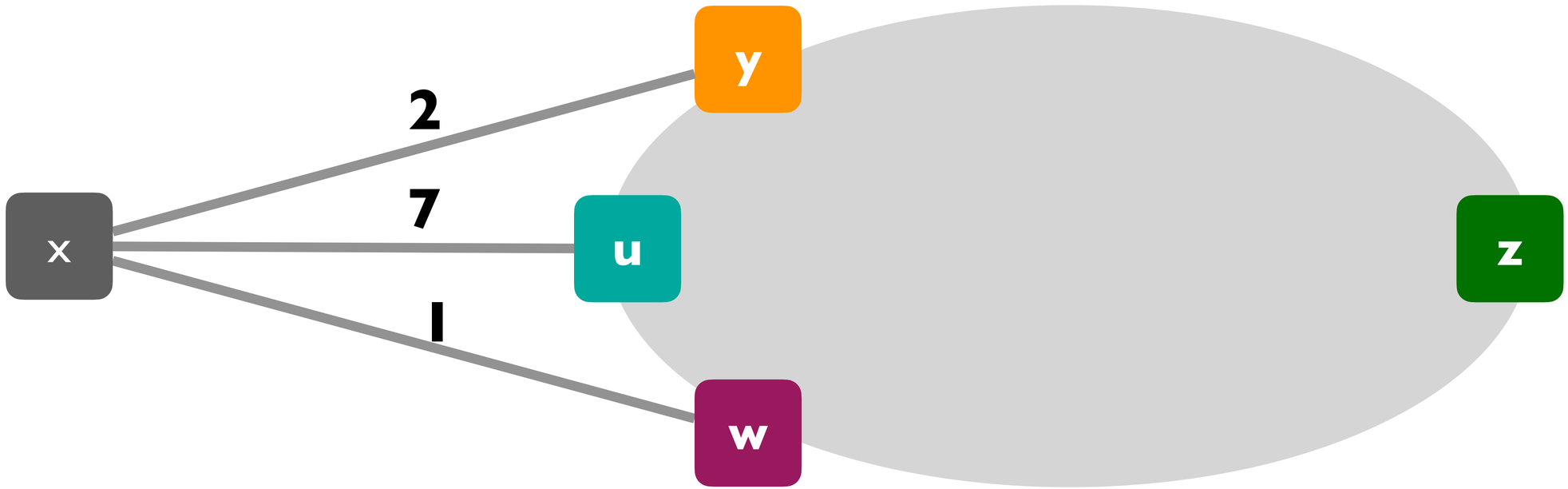

y
2
7
x
u
z
1
w



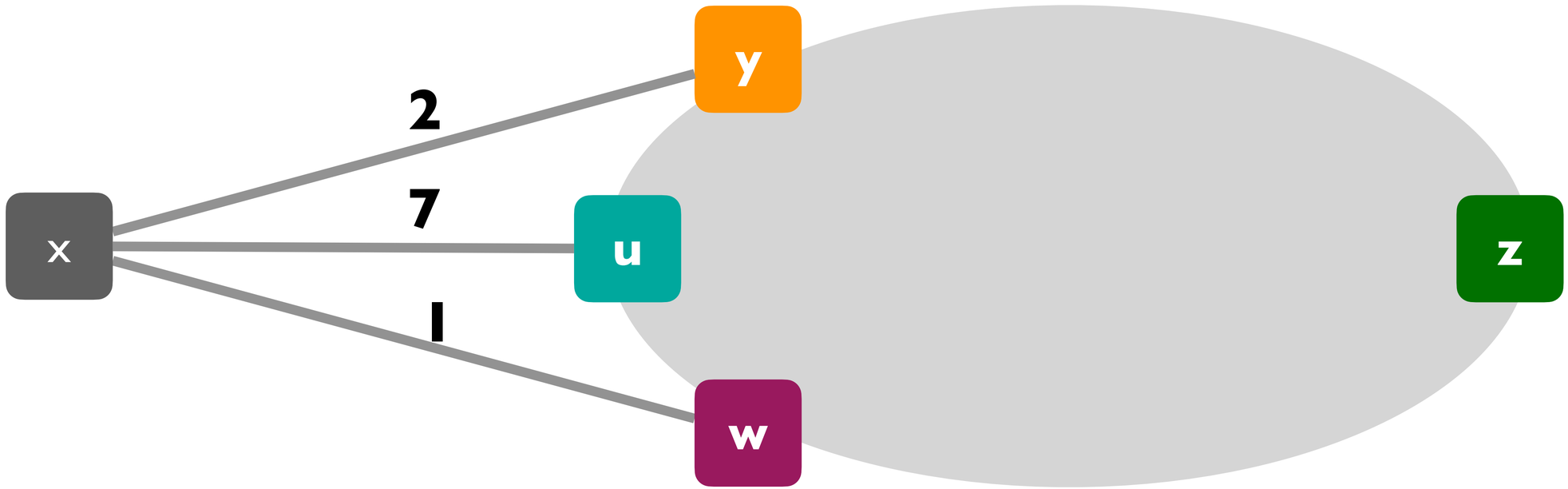
$$d_x(z) =$$



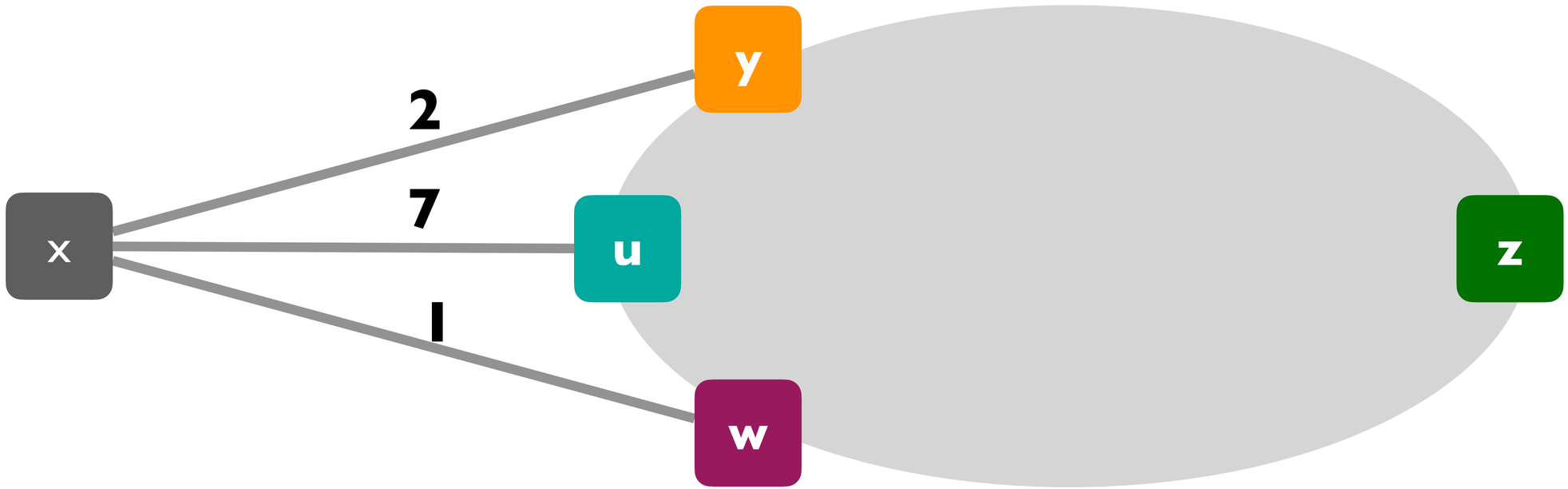
$$d_x(z) = \qquad cost(x, y) + d_y(z),$$



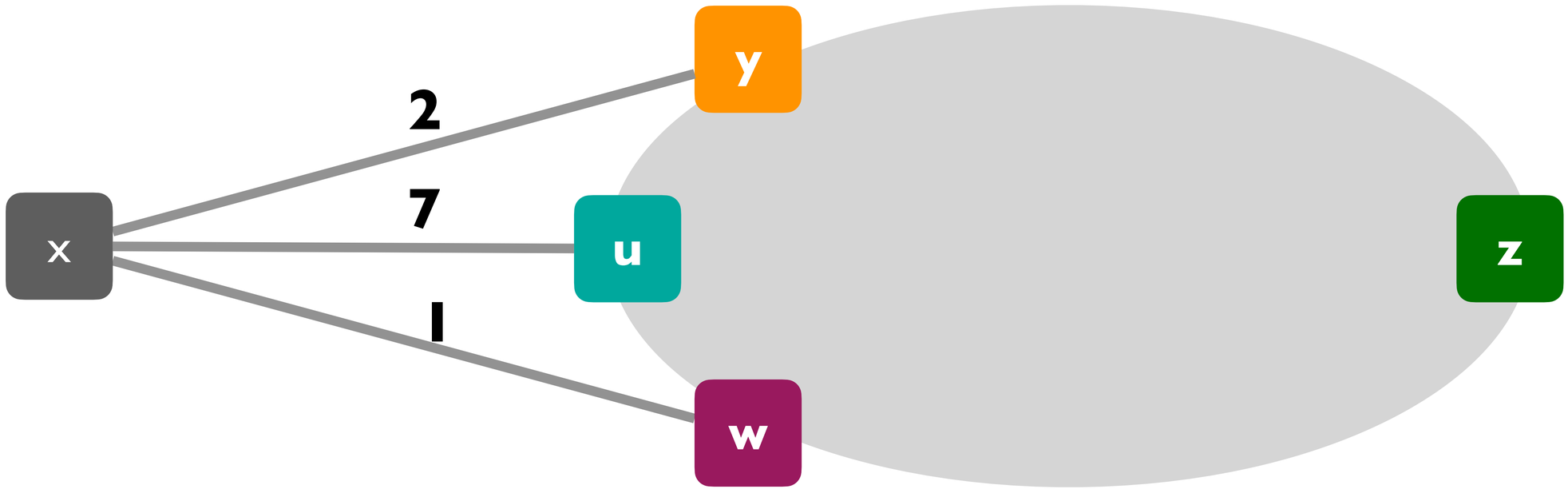
$$d_x(z) = \begin{array}{l} cost(x, y) + d_y(z), \\ cost(x, u) + d_u(z), \end{array}$$



$$d_x(z) = \begin{array}{l} cost(x, y) + d_y(z), \\ cost(x, u) + d_u(z), \\ cost(x, w) + d_w(z) \end{array}$$

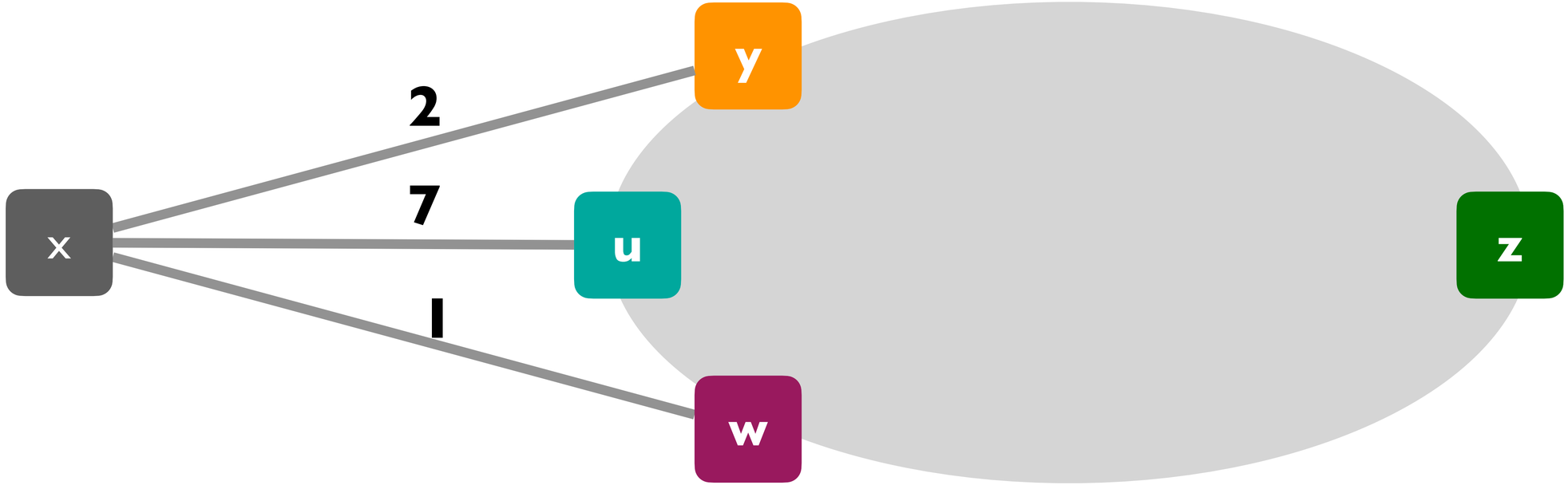


$$
\begin{aligned}
d_x(z) = \ \min\{ \ & cost(x, y) + d_y(z), \\
& cost(x, u) + d_u(z), \\
& cost(x, w) + d_w(z) \ \}
\end{aligned}
$$



$$d_x(z) = \min_n \{ \; cost(x, n) + d_n(z) \; \}$$

For all neighbors n



$$d_x(z) = \min_n \{ \; cost(x, n) + d_n(z) \; \}$$

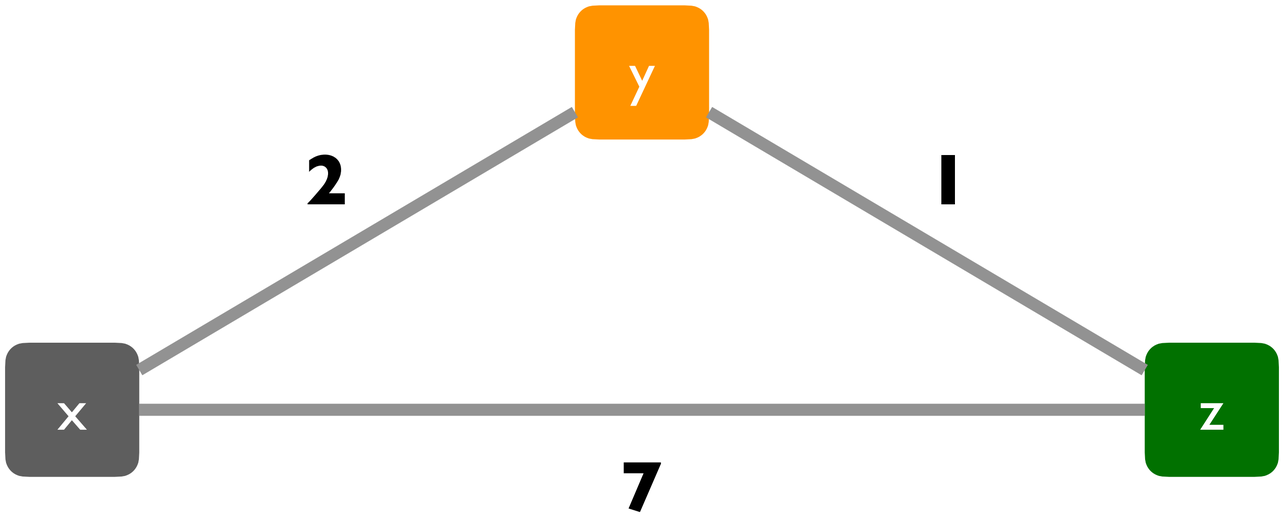
For all neighbors n

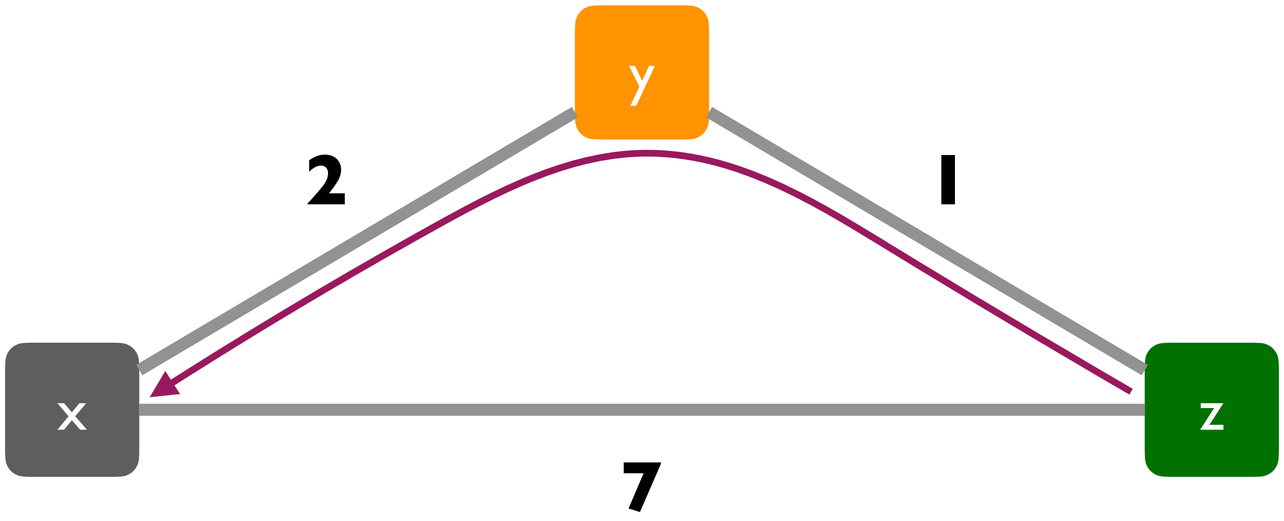
Bellman-Ford Equation

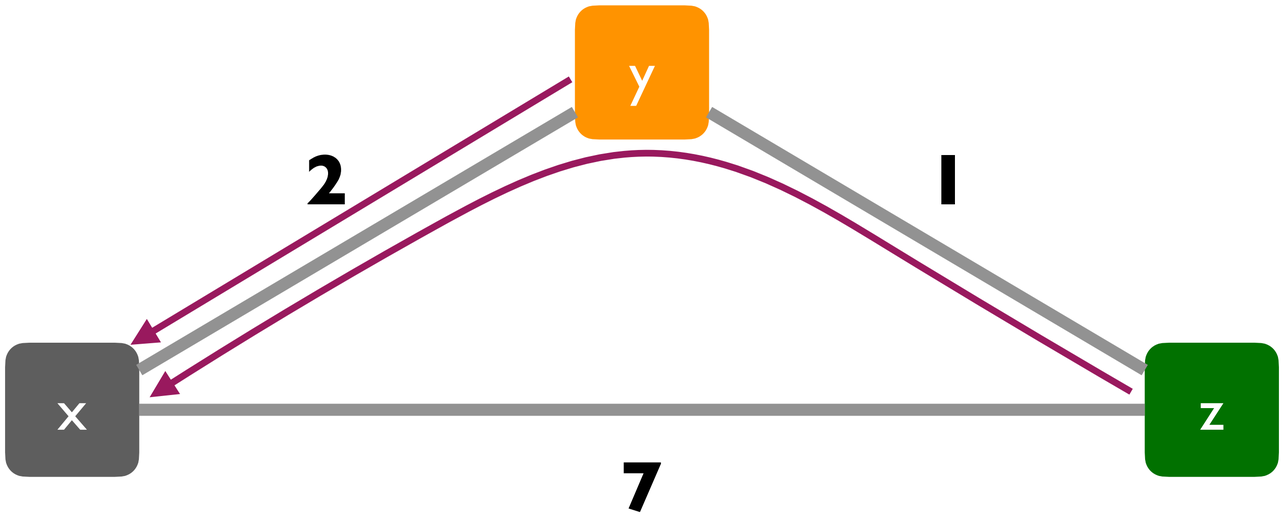
Bellman-Ford Equation

Bellman-Ford Equation

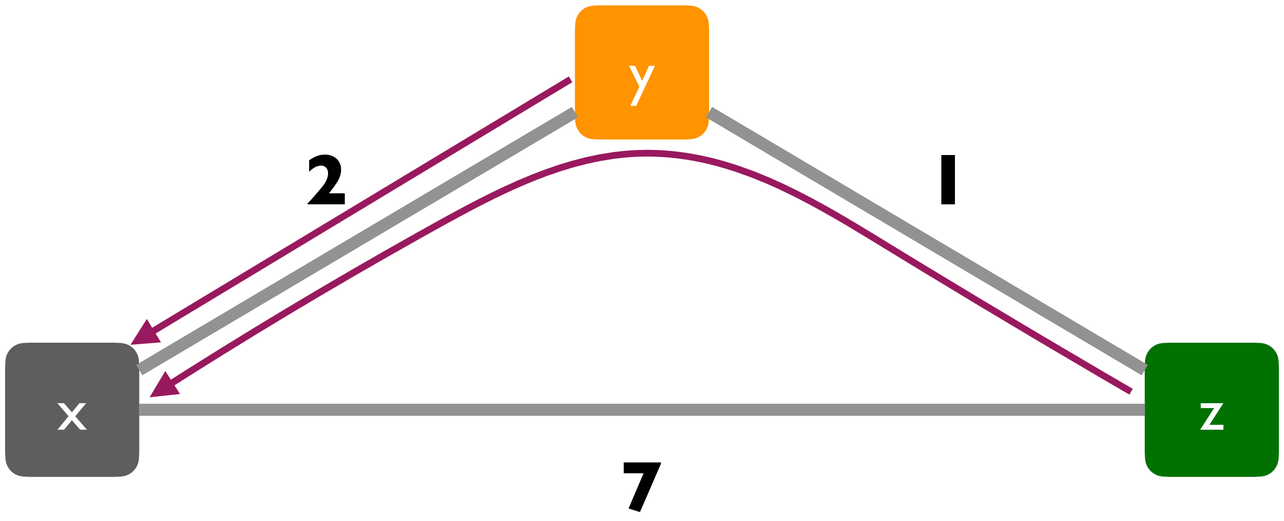
- Formalizes the following decision:
  - *Pick as the next hop for destination z*
    The neighbor that results
    in the least-cost path to z


y
2
1
x
z
7

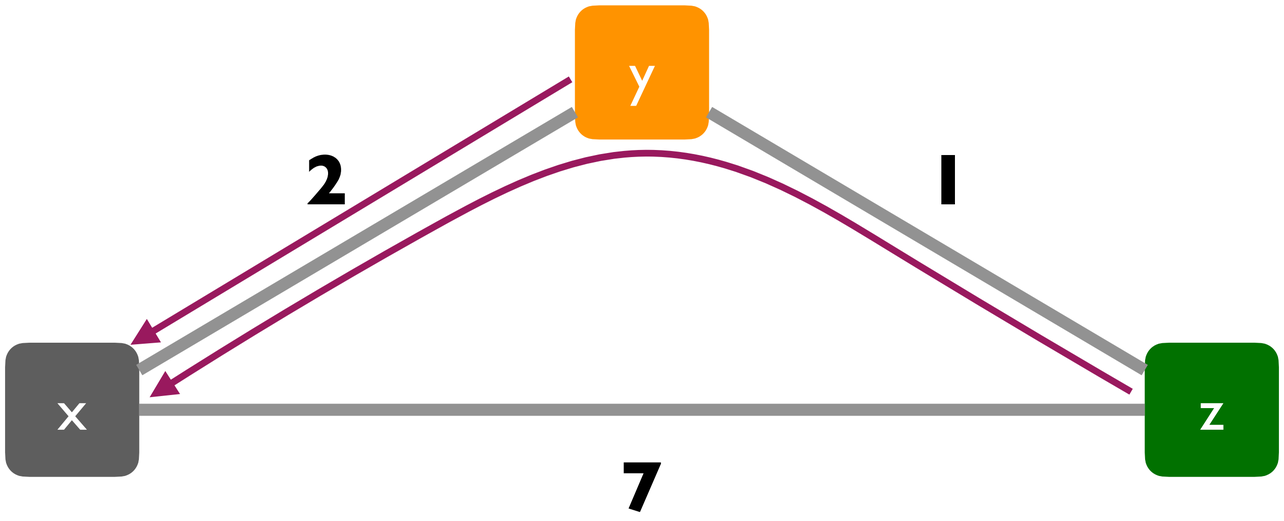

y
2
1
x
z
7


y
2
1
x
z
7

	x	y	z
y	2	0	1
z	3	1	0

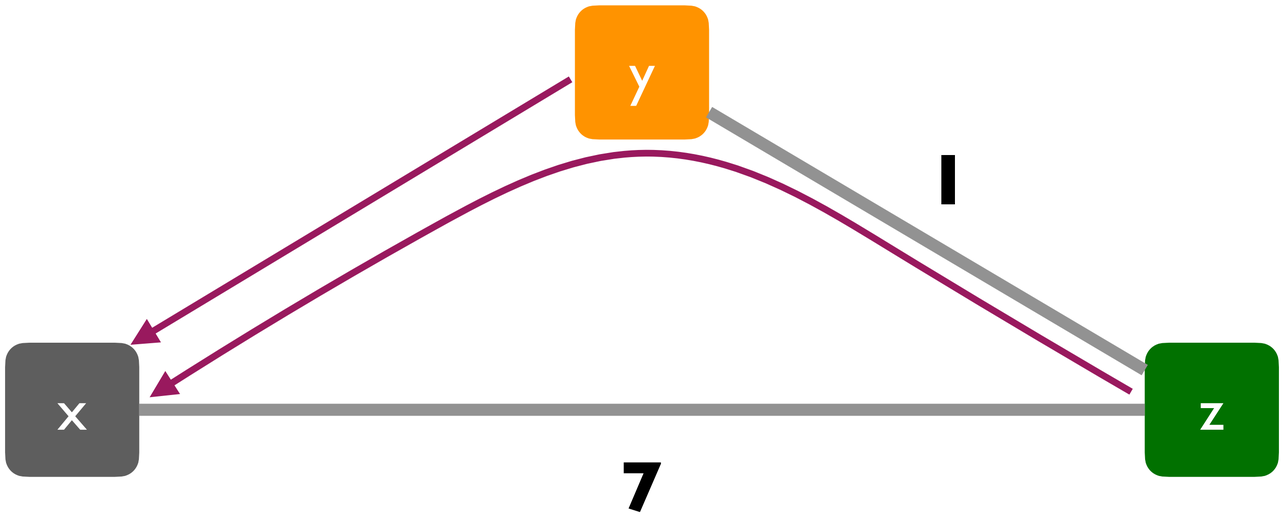


	x	y	z
y	2	0	1
z	3	1	0



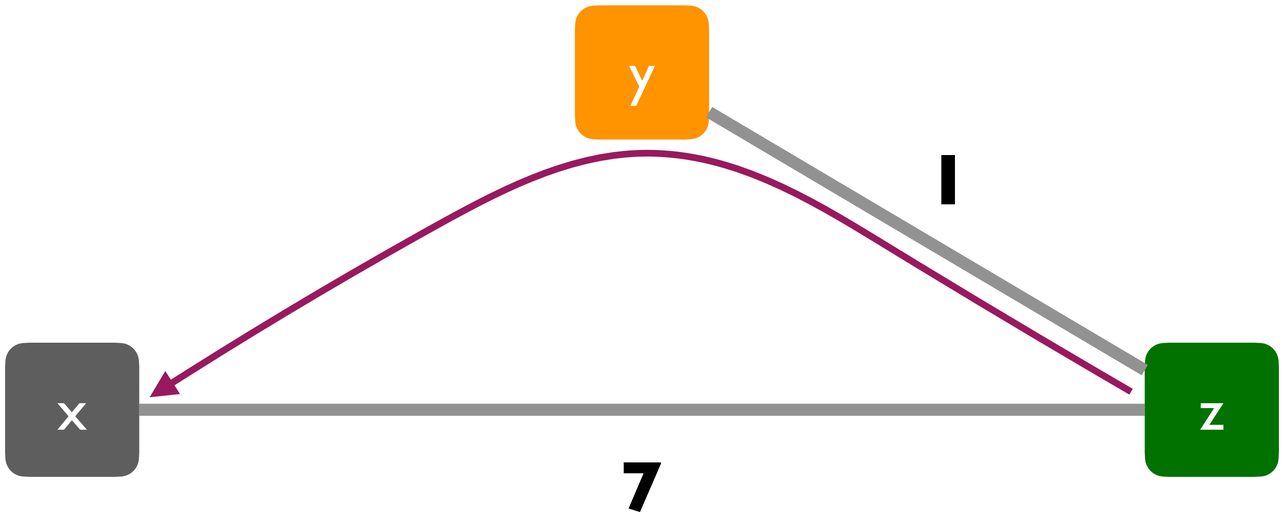
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	2	0	1
z	3	1	0



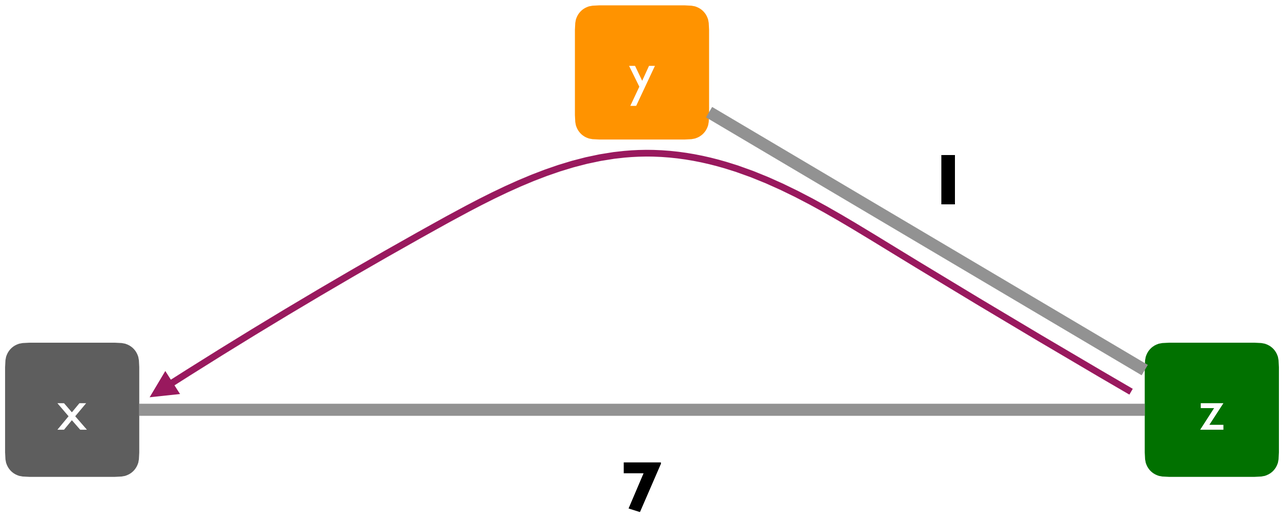
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y		0	1
z	3	1	0



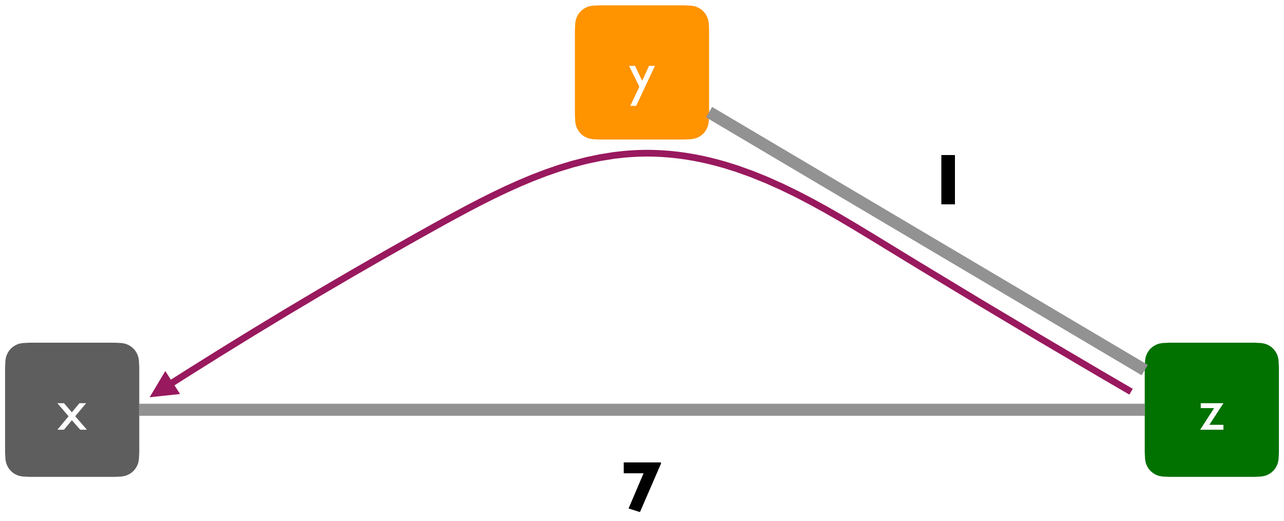
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y		0	1
z	3	1	0



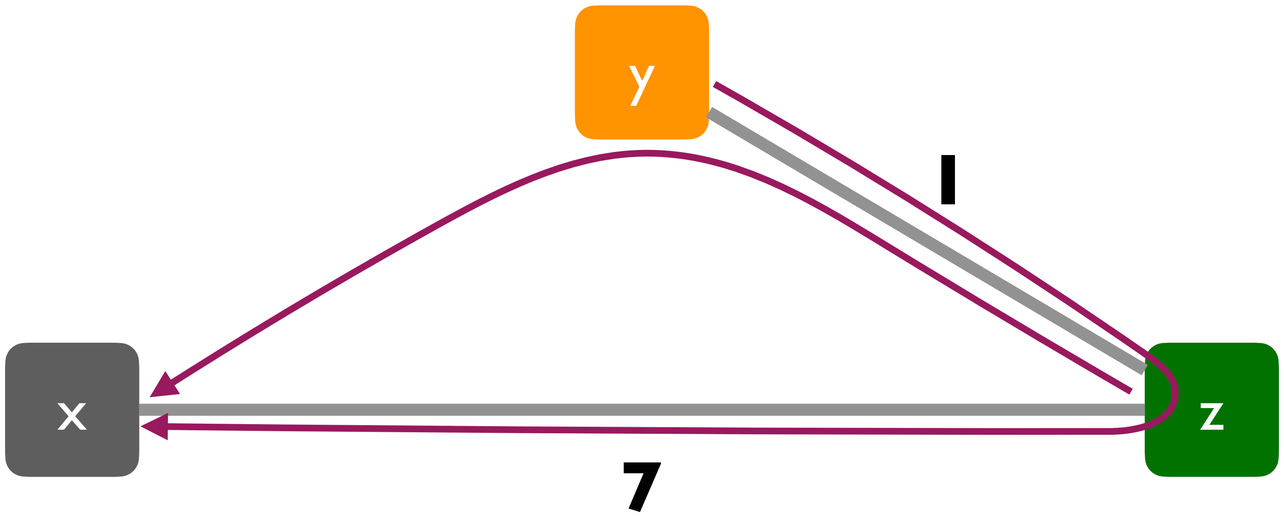
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	4	0	1
z	3	1	0



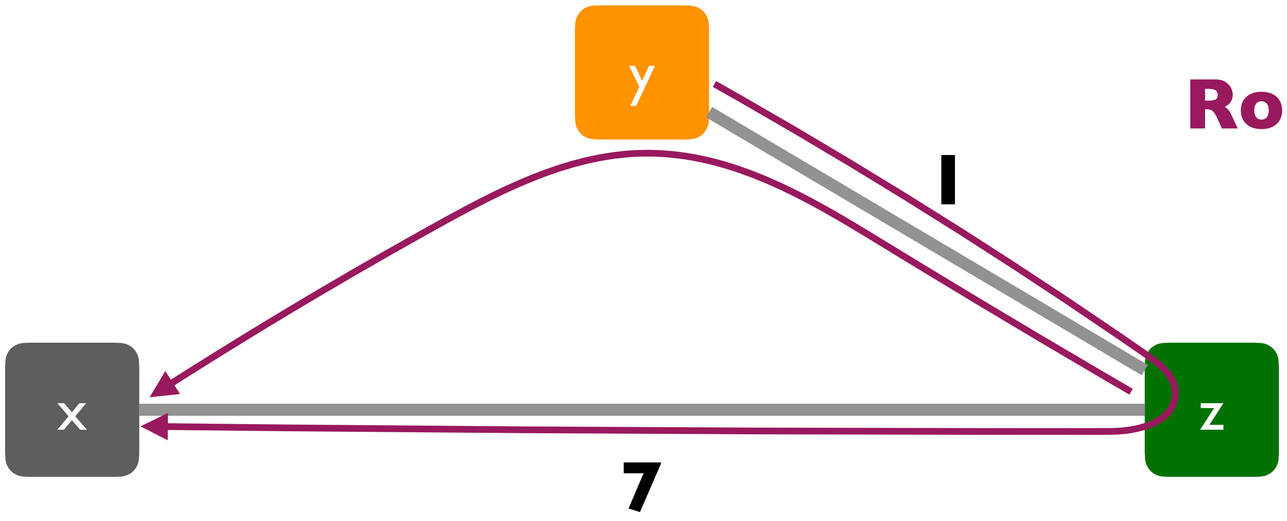
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	4	0	1
z	3	1	0



	x	y	z
y	2	0	1
z	3	1	0

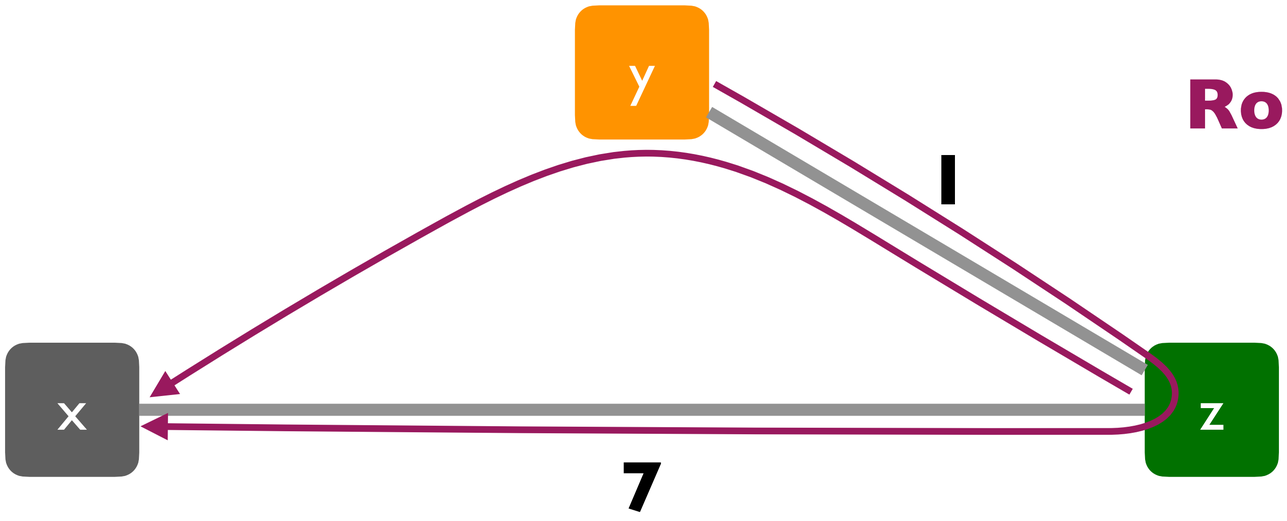
	x	y	z
y	4	0	1
z	3	1	0



Routing loop!

	x	y	z
y	2	0	1
z	3	1	0

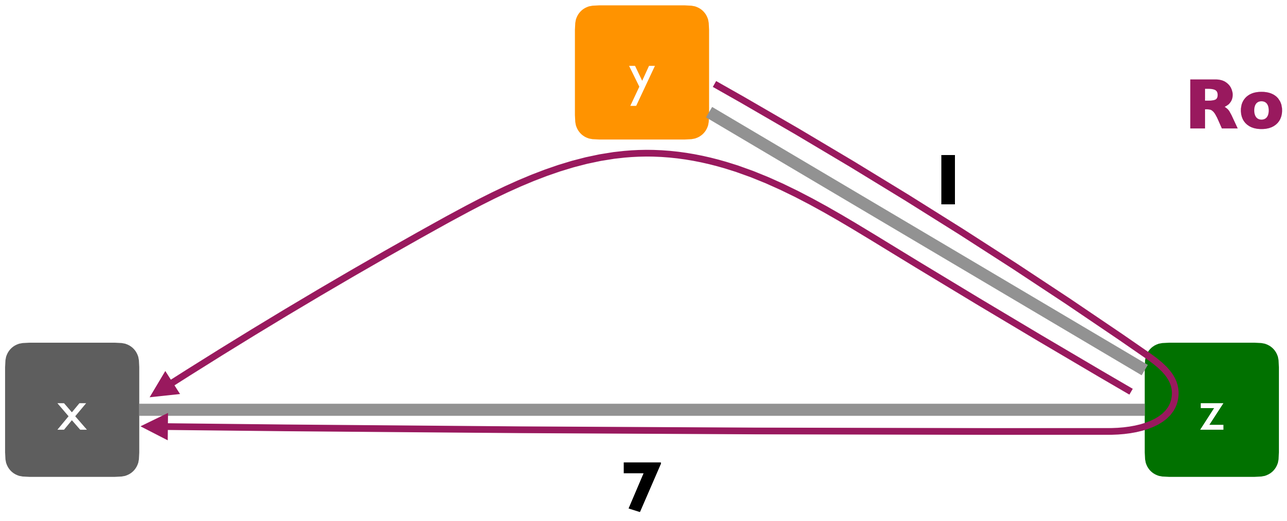
	x	y	z
y	4	0	1
z	3	1	0



Routing loop!

	x	y	z
y	4	0	1
z	3	1	0

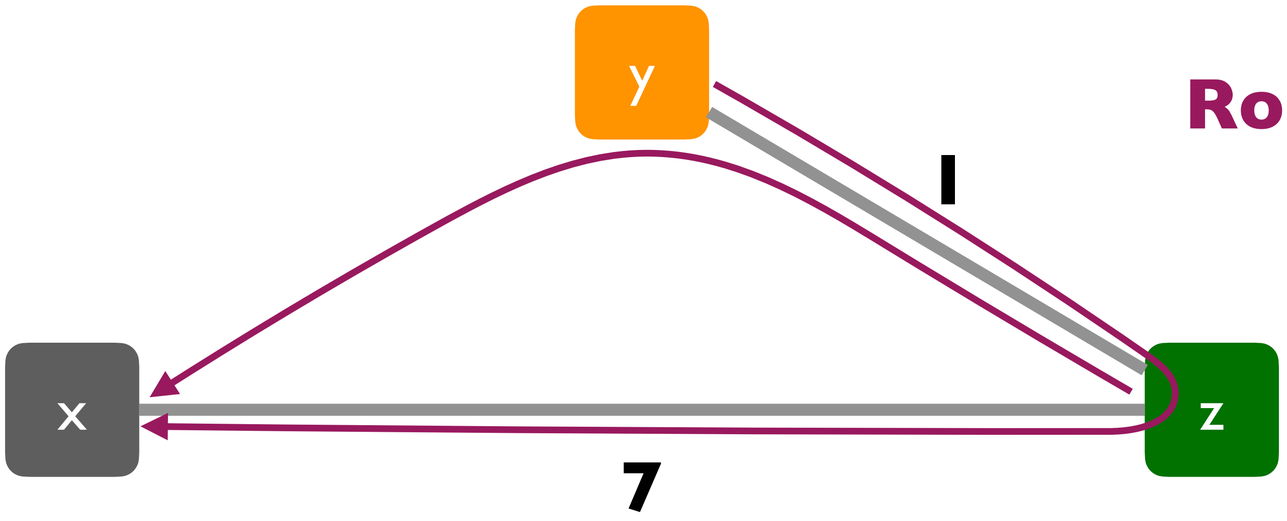
	x	y	z
y	4	0	1
z	3	1	0



Routing loop!

	x	y	z
y	4	0	1
z	3	1	0

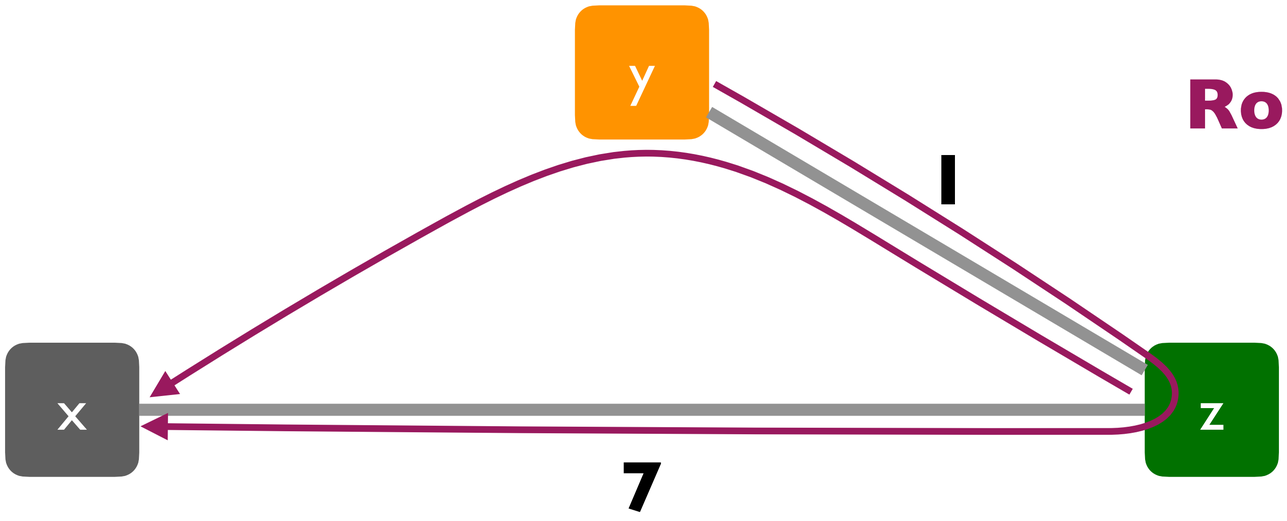
	x	y	z
y	4	0	1
z	3	1	0



Routing loop!

	x	y	z
y	4	0	1
z	5	1	0

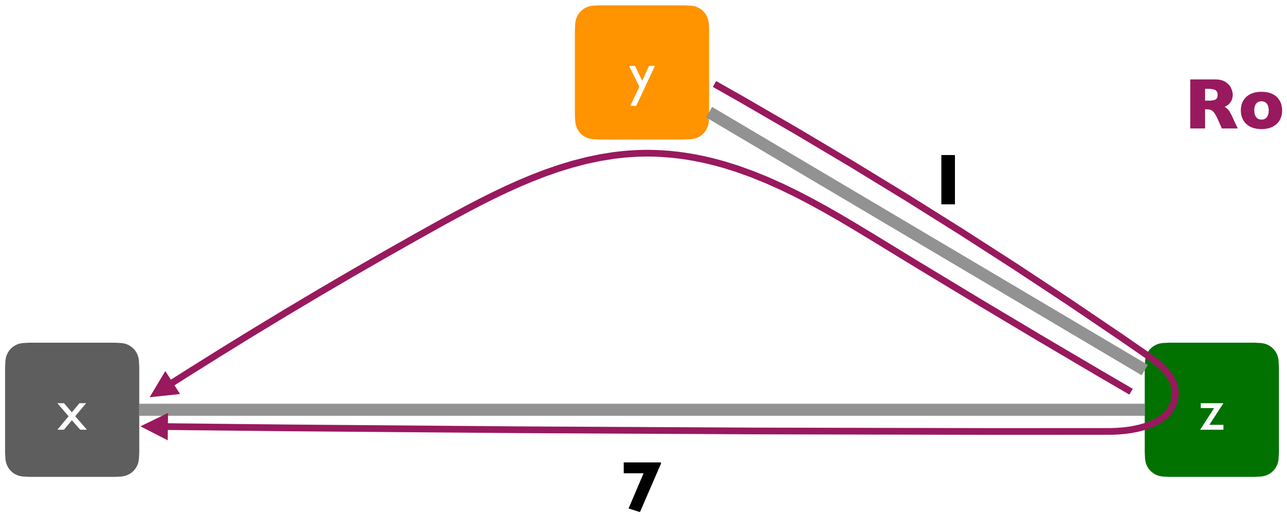
	x	y	z
y	4	0	1
z	5	1	0



Routing loop!

	x	y	z
y	4	0	1
z	5	1	0

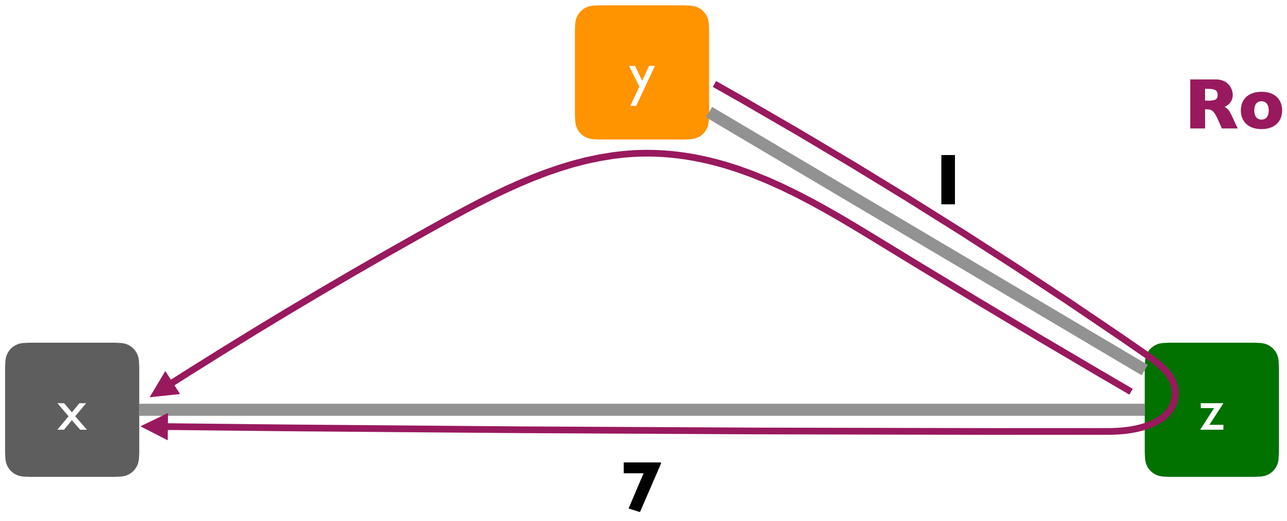
	x	y	z
y	4	0	1
z	5	1	0



Routing loop!

	x	y	z
y	4	0	1
z	5	1	0

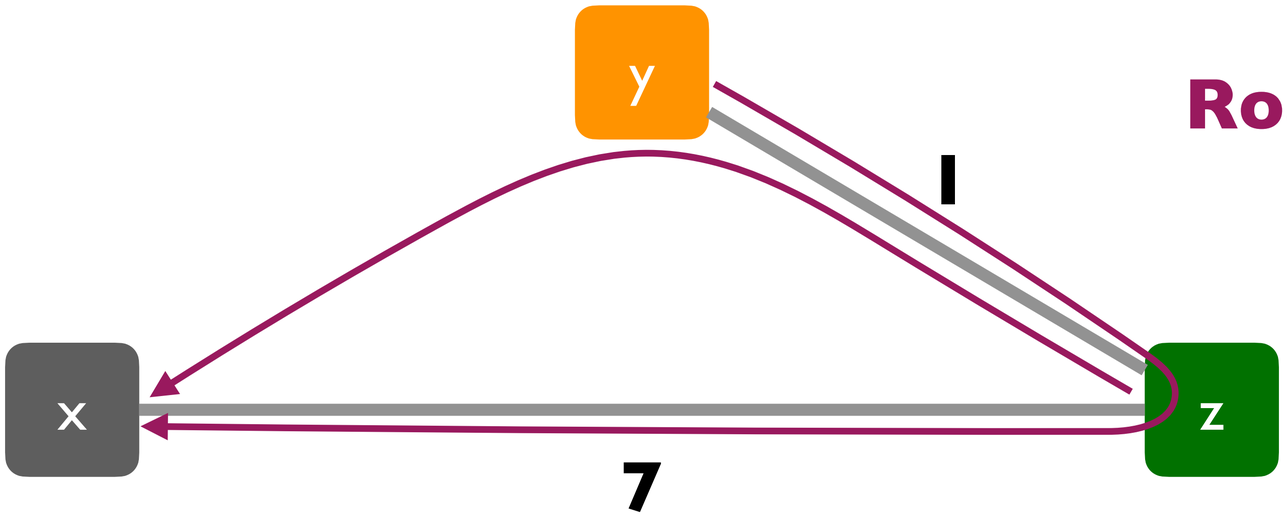
	x	y	z
y	6	0	1
z	5	1	0



Routing loop!

	x	y	z
y	4	0	1
z	5	1	0

	x	y	z
y	6	0	1
z	5	1	0



Routing loop!

	x	y	z
y	6	0	1
z	5	1	0

	x	y	z
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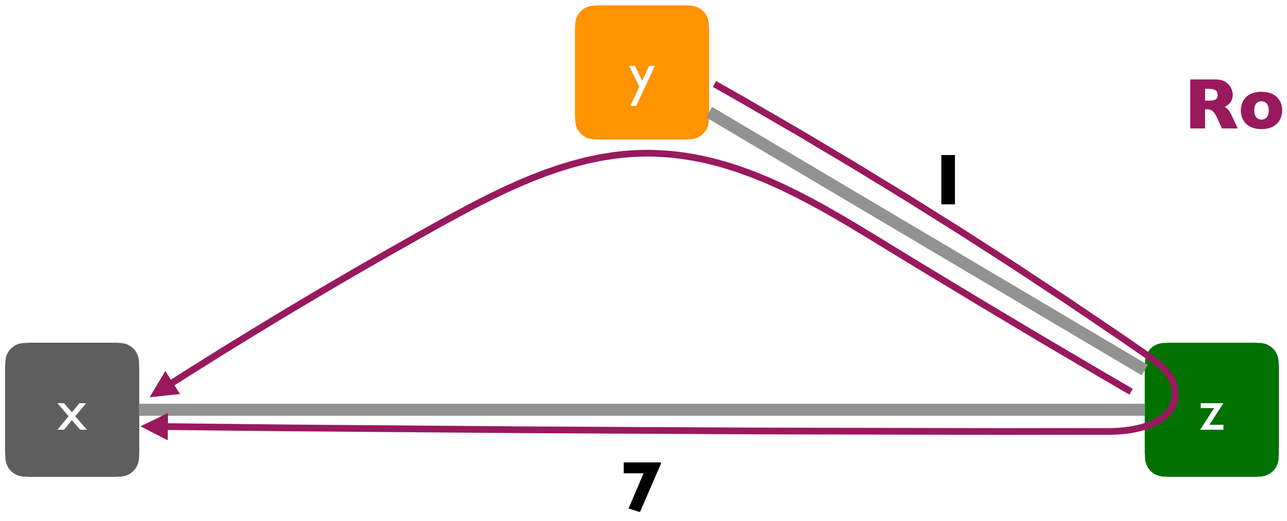

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	x	y	z
y	6	0	1
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	x	y	z
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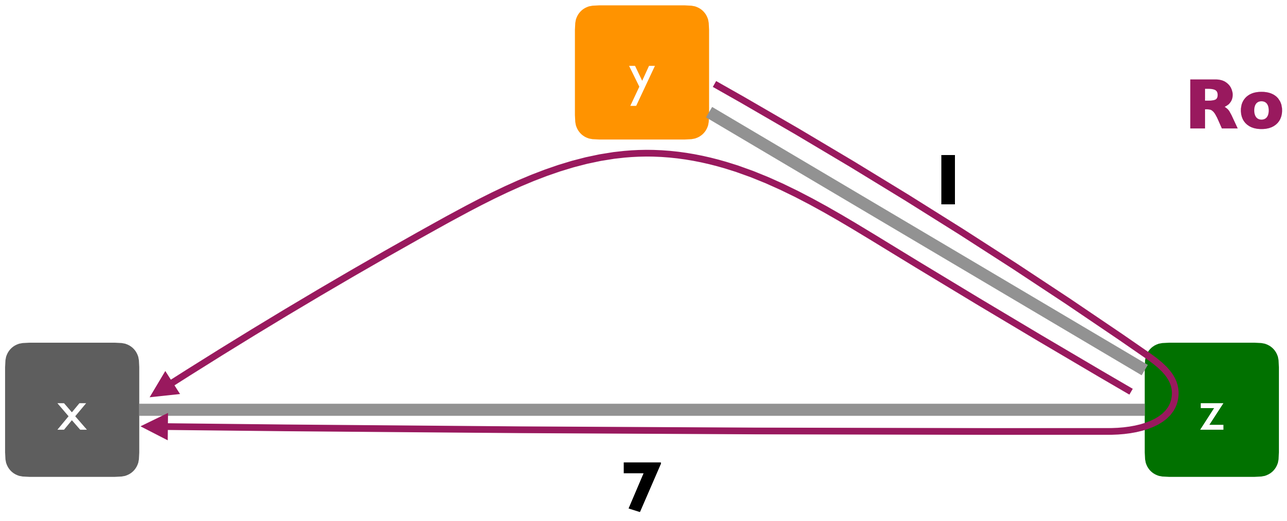
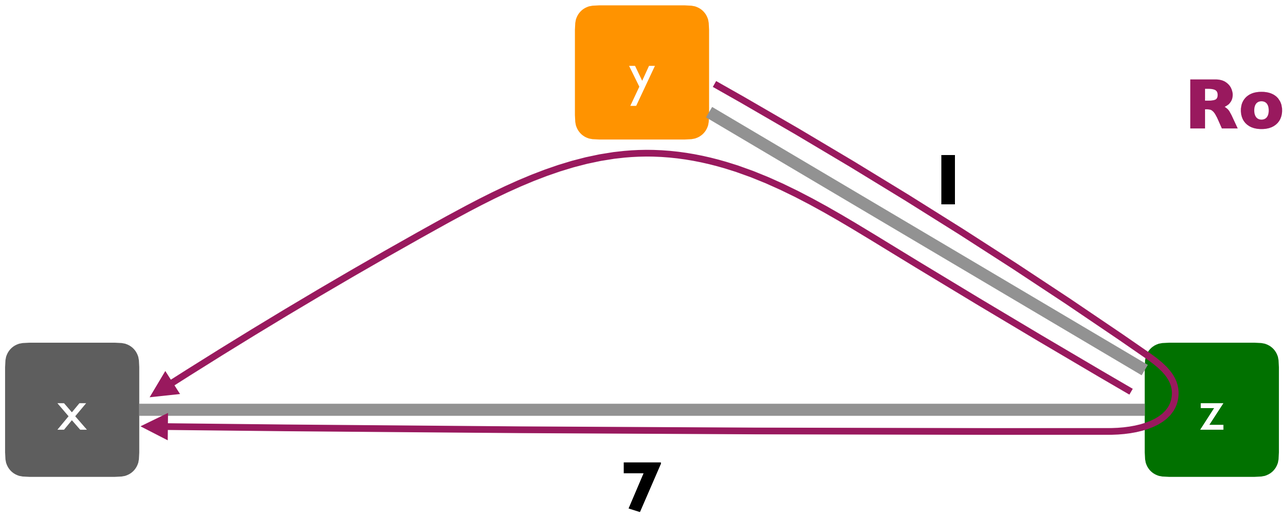


Routing loop!

	x	y	z
y	6	0	1
z	7	1	0

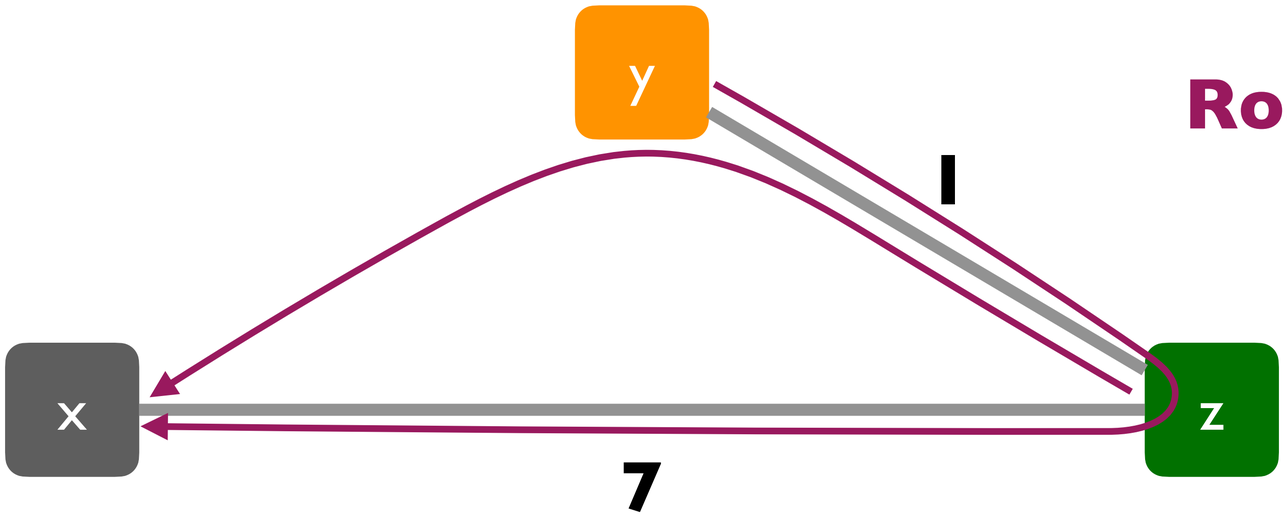
	x	y	z
y	6	0	1
z	7	1	0



Routing loop!

	x	y	z
y	6	0	1
z	7	1	0

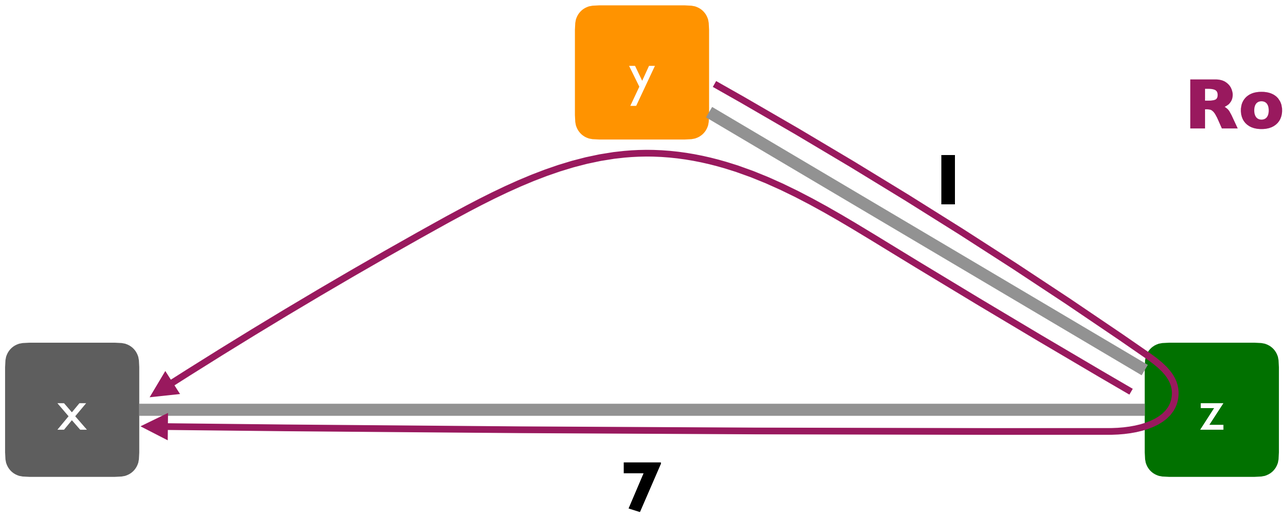
	x	y	z
y	6	0	1
z	7	1	0



Routing loop!

	x	y	z
y	6	0	1
z	7	1	0

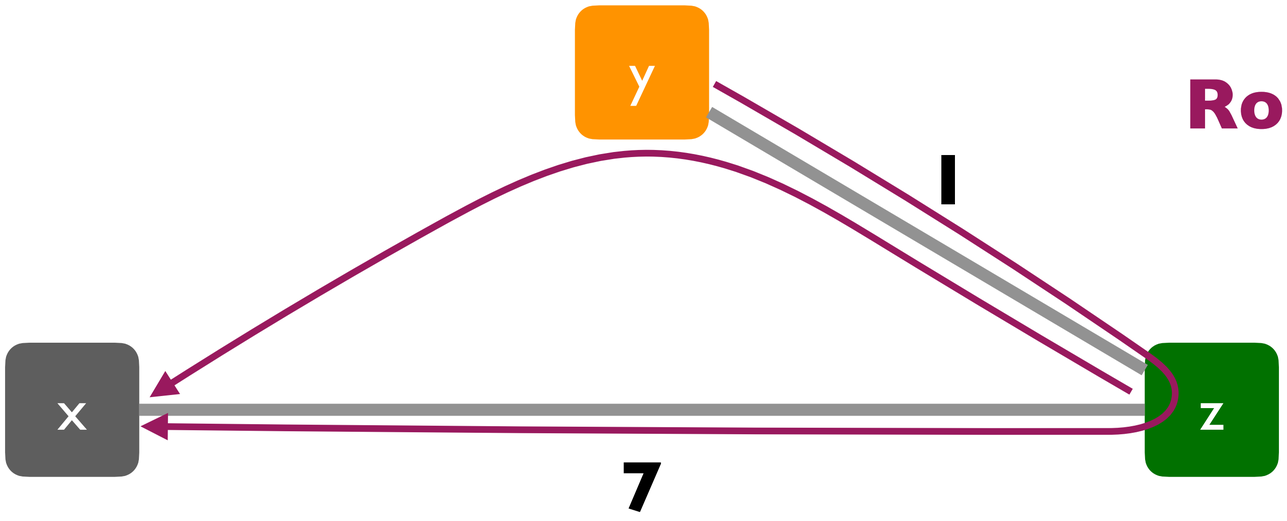
	x	y	z
y	8	0	1
z	7	1	0



Routing loop!

	x	y	z
y	6	0	1
z	7	1	0

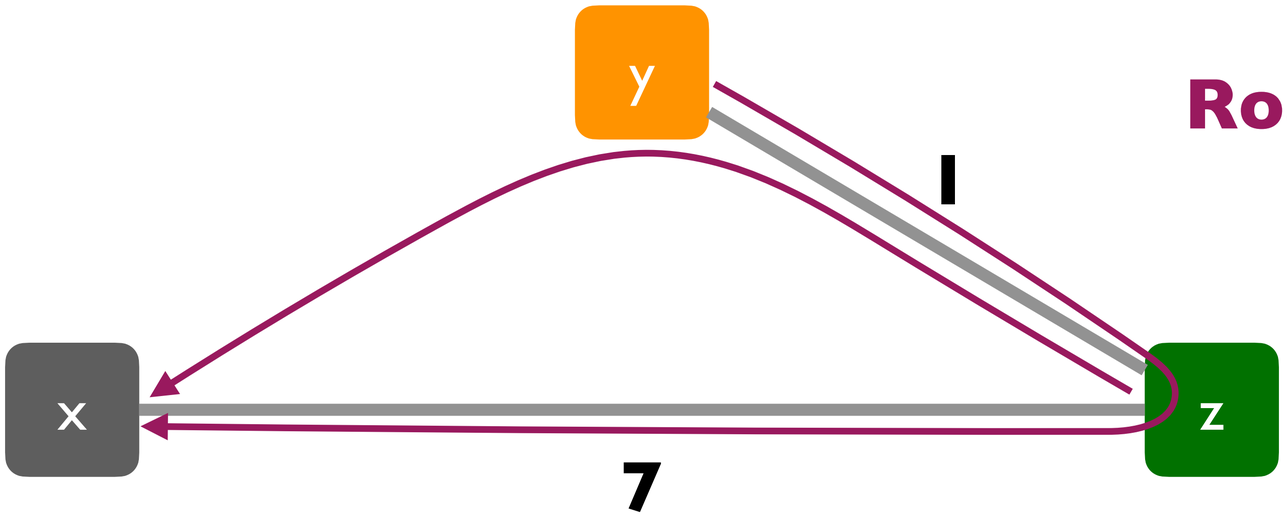
	x	y	z
y	8	0	1
z	7	1	0



Routing loop!

	x	y	z
y	8	0	1
z	7	1	0

	x	y	z
y	8	0	1
z	7	1	0



Routing loop!

	x	y	z
y	8	0	1
z	7	1	0

	x	y	z
y	8	0	1
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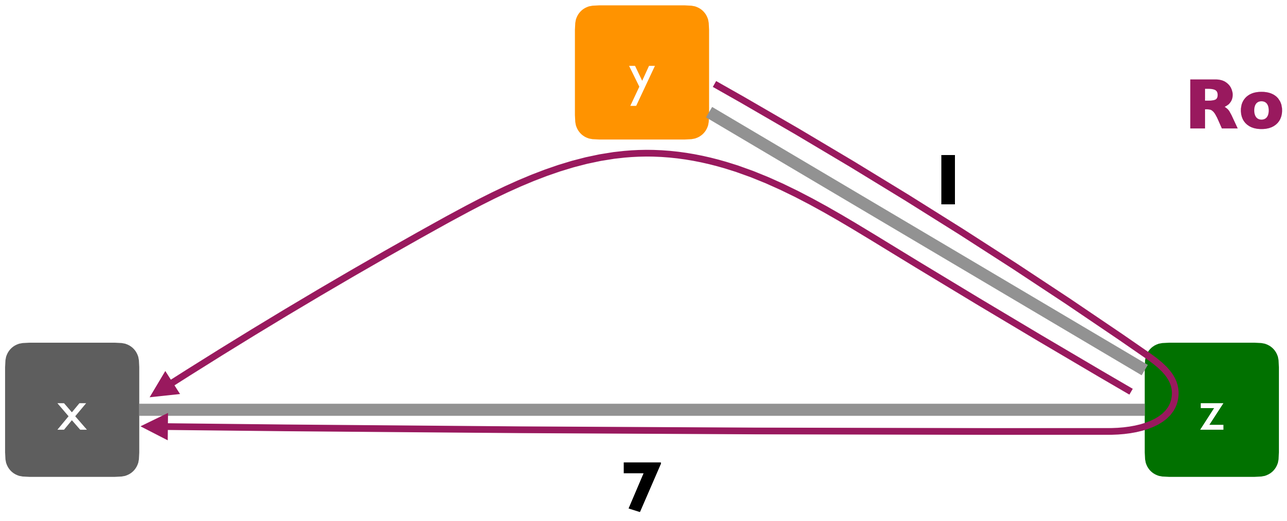

Routing loop!

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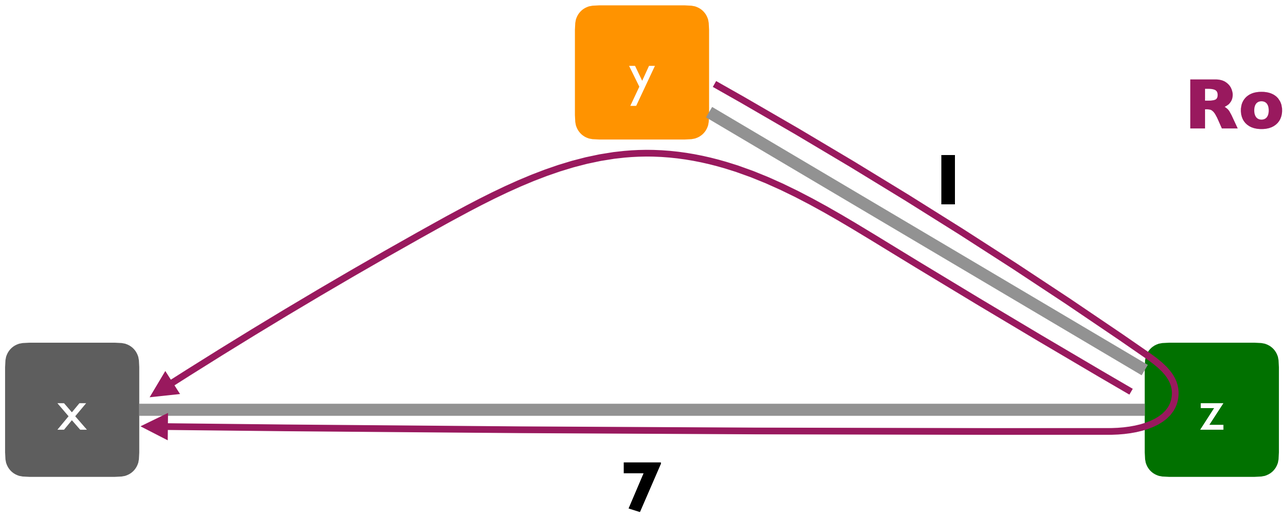
z	7	1	0

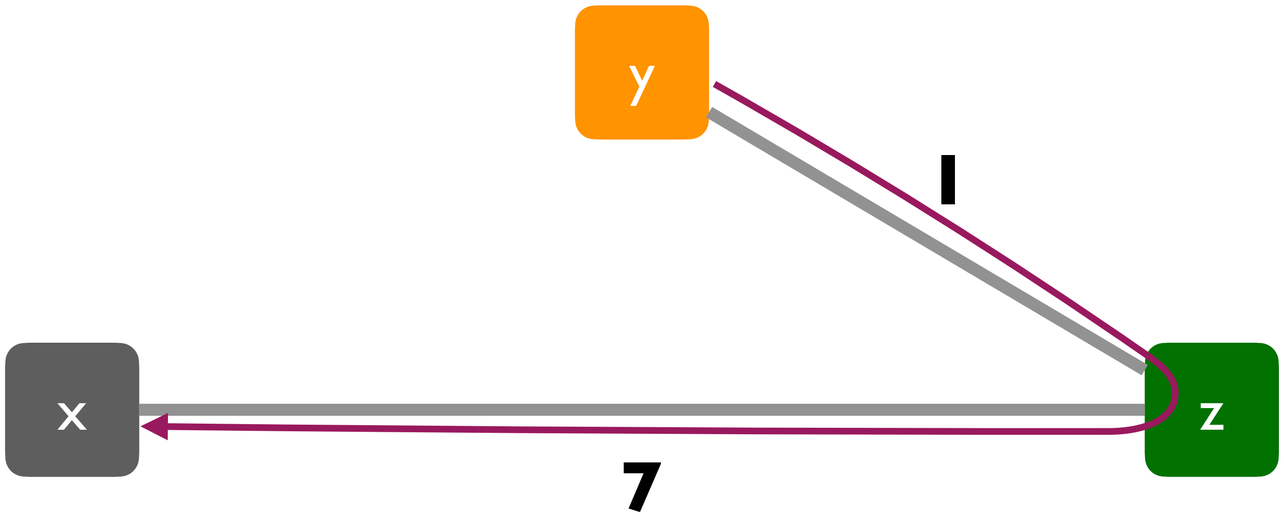
	x	y	z
y	8	0	1
z	7	1	0



Routing loop!

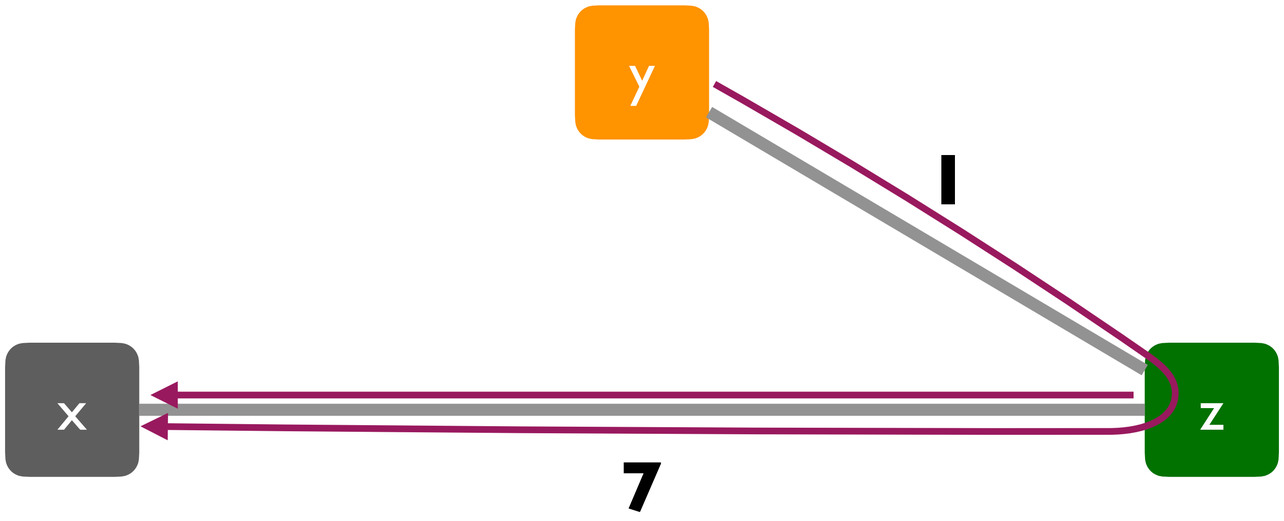
	x	y	z
y	8	0	1
z	7	1	0

	x	y	z
y	8	0	1
z	7	1	0



	x	y	z
y	8	0	1
z	7	1	0

	x	y	z
y	8	0	1
z	7	1	0



	x	y	z
y	8	0	1
z	7	1	0

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- Solution?
  - *Next time…*