EN.601.414/614 Computer Networks

Routing Fundamentals

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Spring 2019 (MW 3:00-4:15pm in Shaffer 301)

JOHNS HOPKINS UNIVERSITY

https://github.com/xinjin/course-net

Research Opportunities

- **You are very welcome!**
  - ➢ Undergraduate: recommendation letters for applying to graduate programs (Berkeley/Princeton/MIT/Stanford/CMU/Harvard, etc.)
  - ➢ Master: join my research group as PhDs
  - ➢ PhD: GBO projects
- **Requirements:**
  - ➢ Get A/A+ from 601.414/614 Computer Networks
  - ➢ Good programming skills in C/C++/Python
  - ➢ Having taken 601.714 Advanced Computer Networks (offered every fall) is a plus

Research Opportunities

- **Projects**
  - Hardware-software co-design: leverage programmable hardware (e.g., programmable switches, GPUs, FPGAs) to improve computation, networking and storage for cloud computing
  - AI & Systems: apply AI to improve systems, and design systems to improve AI
  - Check my publications for details

Assignment 3

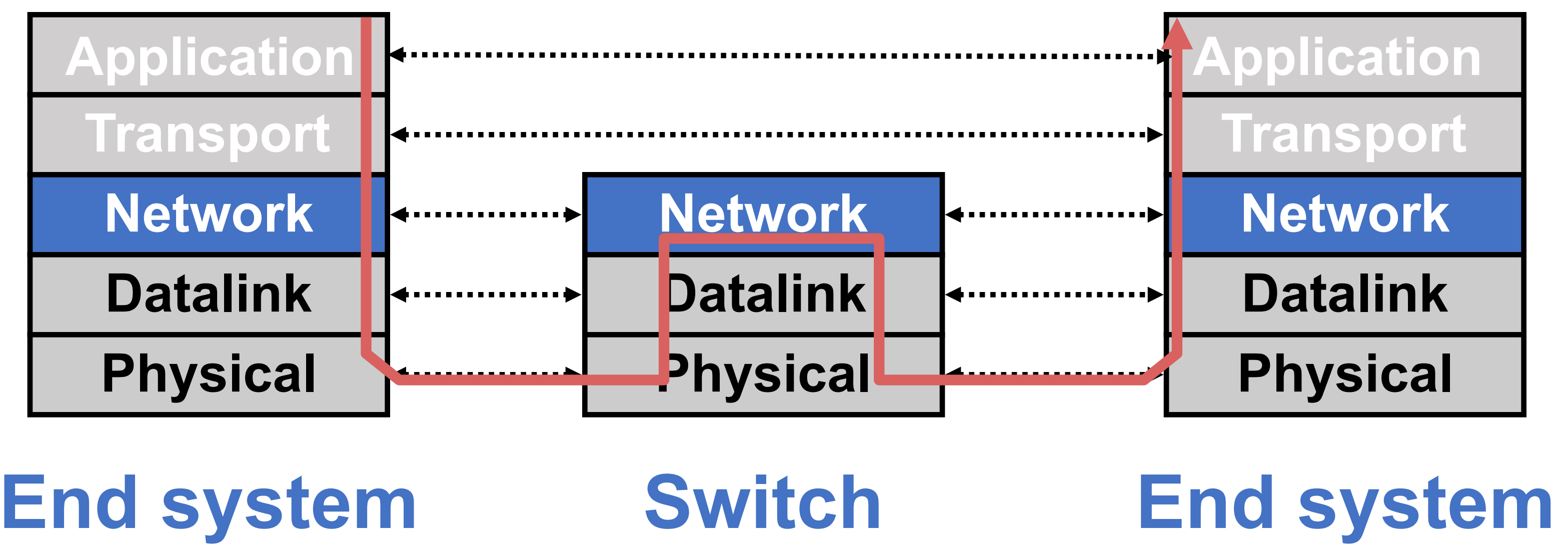
- **Intra-domain routing algorithms**
  - Design and implement simple versions of link state and distance vector protocols by yourself
  - Hands-on experiences on routing protocols: real-world protocols in Cisco routers are just more complicated than the ones you designed and implemented!
- **A preliminary version is online. Not final!**
  - Take a look if you want to get a sense of what to do
- **Will add more hints and scaffolding code**
- **Will formally release and discuss it next Monday**

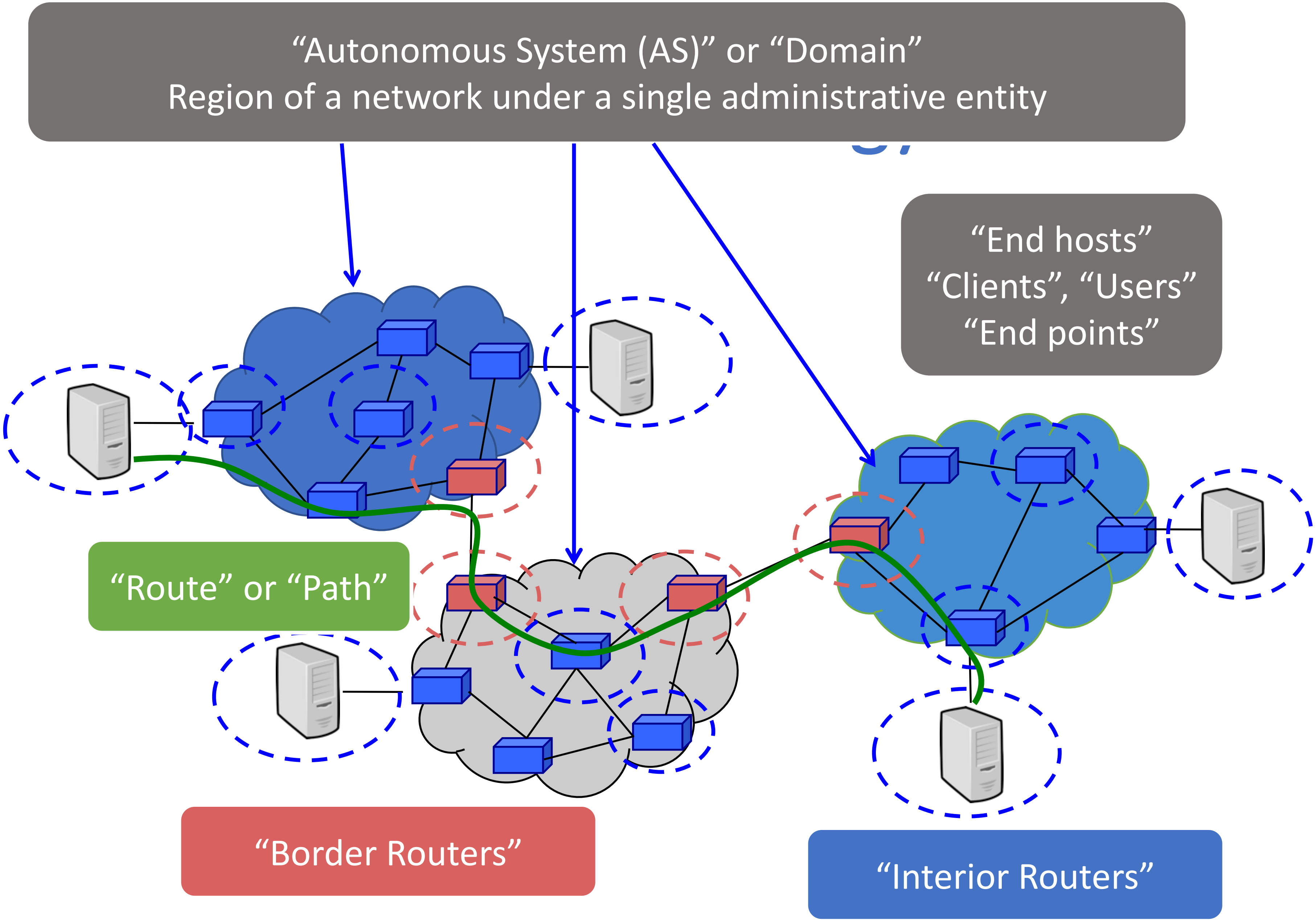
Agenda

- **Network layer recap**
- **Routing fundamentals**

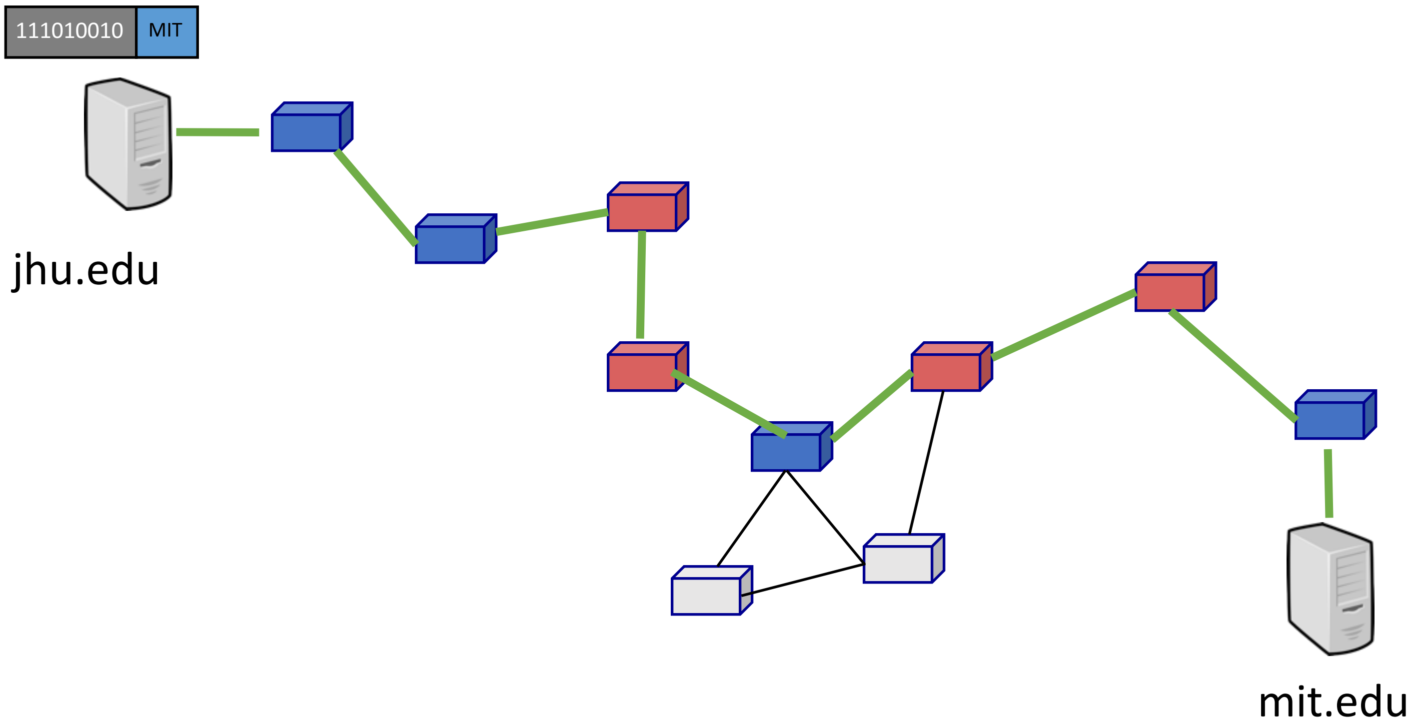
Recap: Network layer

- **Present everywhere**
- **Performs addressing, forwarding, and routing, among other tasks**




"Autonomous System (AS)" or "Domain"
Region of a network under a single administrative entity
"End hosts"
"Clients", "Users"
"End points"
"Route" or "Path"
"Border Routers"
"Interior Routers"

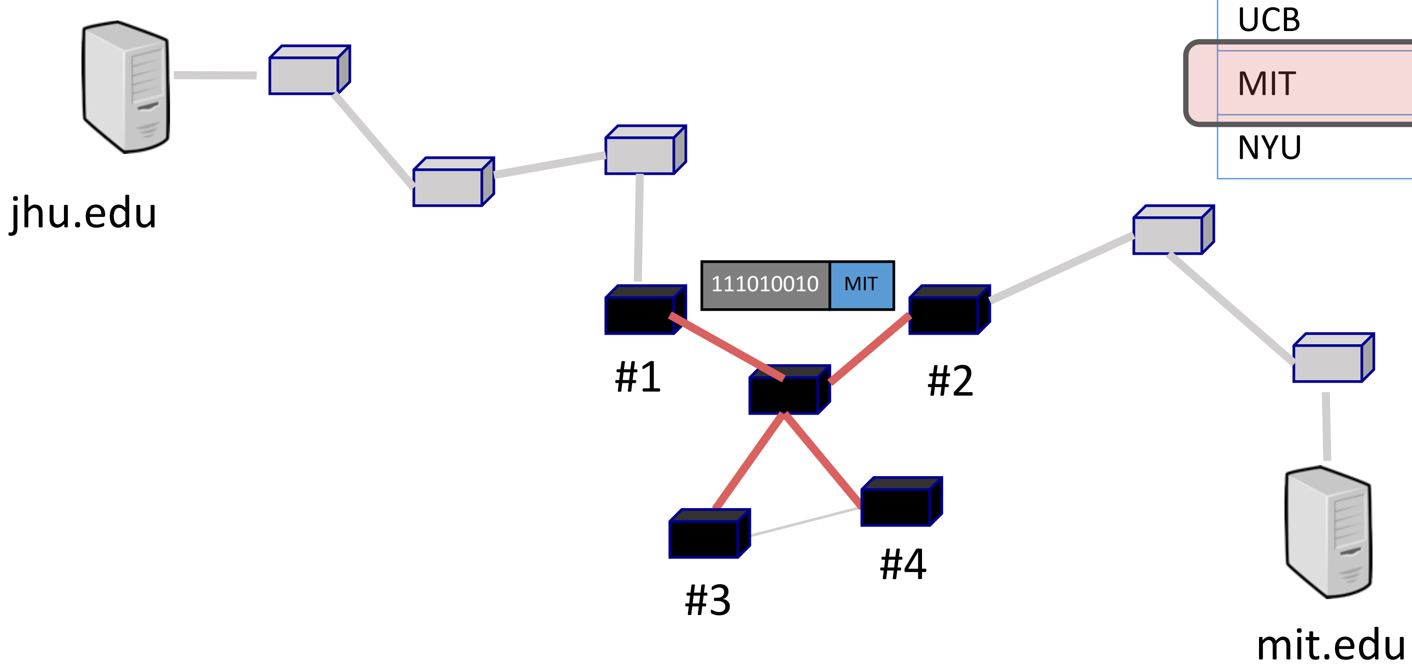
Recap: Forwarding



Recap: Forwarding

Forwarding Table

Destination	Next Hop
JHU	1
UCB	3
MIT	2
NYU	4



Recap: Forwarding

- **Directing a packet to the correct interface so that it progresses to its destination**
  - Local
- **How?**
  - Read address from packet header
  - Search forwarding table

Recap: Routing

- **Setting up network-wide *forwarding tables* to enable end-to-end communication**
  - ➢Global
- **How?**
  - ➢Using different routing protocols

Recap: Forwarding vs. routing

- **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 algorithm

- **Very different timescales!**

Routing fundamentals

Goal of routing

- **Find a path to a given destination**
- **How do we know that the state contained in forwarding tables meets our goal?**
  - ➢ This is what "validity" of routing state tells us
  - ➢ [This is non-standard terminology]

Local vs. global view of state

- ***Local* routing state is the forwarding table in a single router**
  - By itself, the state in a single router cannot be evaluated
  - It must be evaluated in terms of the global context

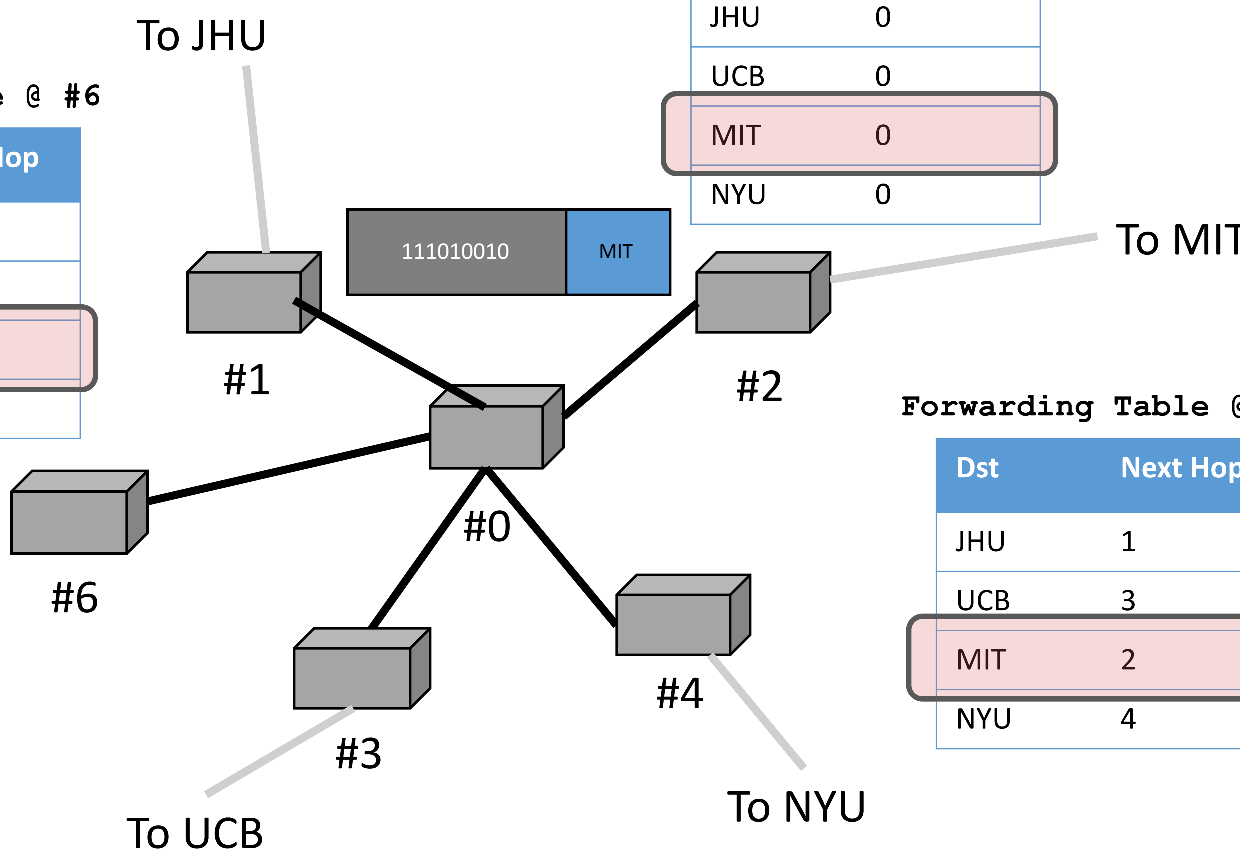
Example:
Local vs. global view of state

Forwarding Table @ #2

Dst	Next Hop
JHU	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #6

Dst	Next Hop
JHU	0
UCB	0
MIT	0
NYU	0



Forwarding Table @ #0

Dst	Next Hop
JHU	1
UCB	3
MIT	2
NYU	4

Local vs. global view of state

- ***Local* routing state is the forwarding table in a single router**
    - ➢ By itself, the state in a single router cannot be evaluated
    - ➢ It must be evaluated in terms of the global context
- ***Global* state refers to the collection of forwarding tables in each of the routers**
    - ➢ Global state determines which paths packets take
    - ➢ (Will discuss later where this routing state comes from)

“Valid” routing state

- **Global state is “valid” if it produces forwarding decisions that always deliver packets to their destinations**
- **Goal of routing protocols: compute valid state**
  - ➢How can we tell if routing state is valid?
- **Need a succinct correctness condition for routing**

Necessary and sufficient condition

- **Global routing state is valid *if and only if*:**
  - ➢There are no dead ends (other than destination)
  - ➢There are no loops
- **A dead end is when there is no outgoing link (next-hop)**
  - ➢A packet arrives, but the forwarding decision does not yield any outgoing link
- **A loop is when a packet cycles around the same set of nodes forever**

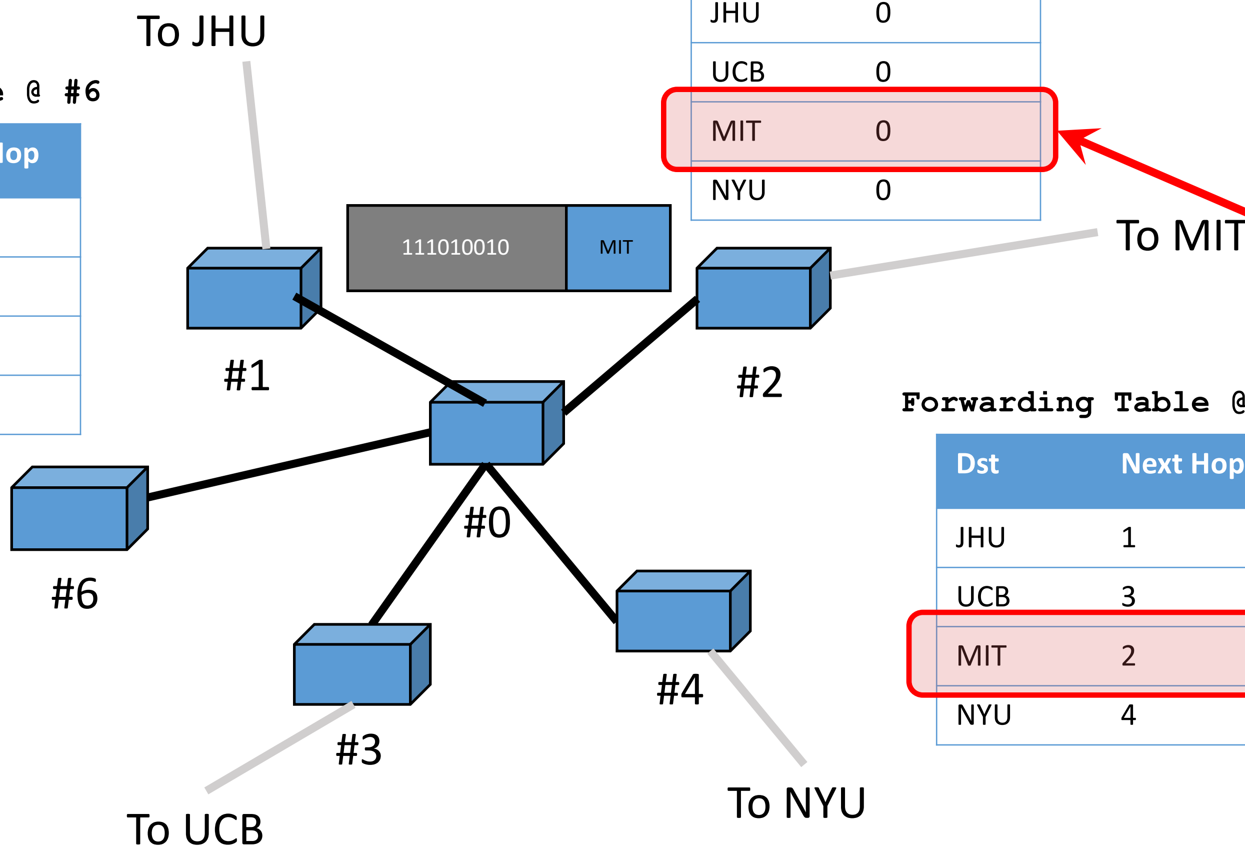
Loop!

Forwarding Table @ #2

Dst	Next Hop
JHU	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #6

Dst	Next Hop
JHU	0
UCB	0
MIT	0
NYU	0



Forwarding Table @ #0

Dst	Next Hop
JHU	1
UCB	3
MIT	2
NYU	4

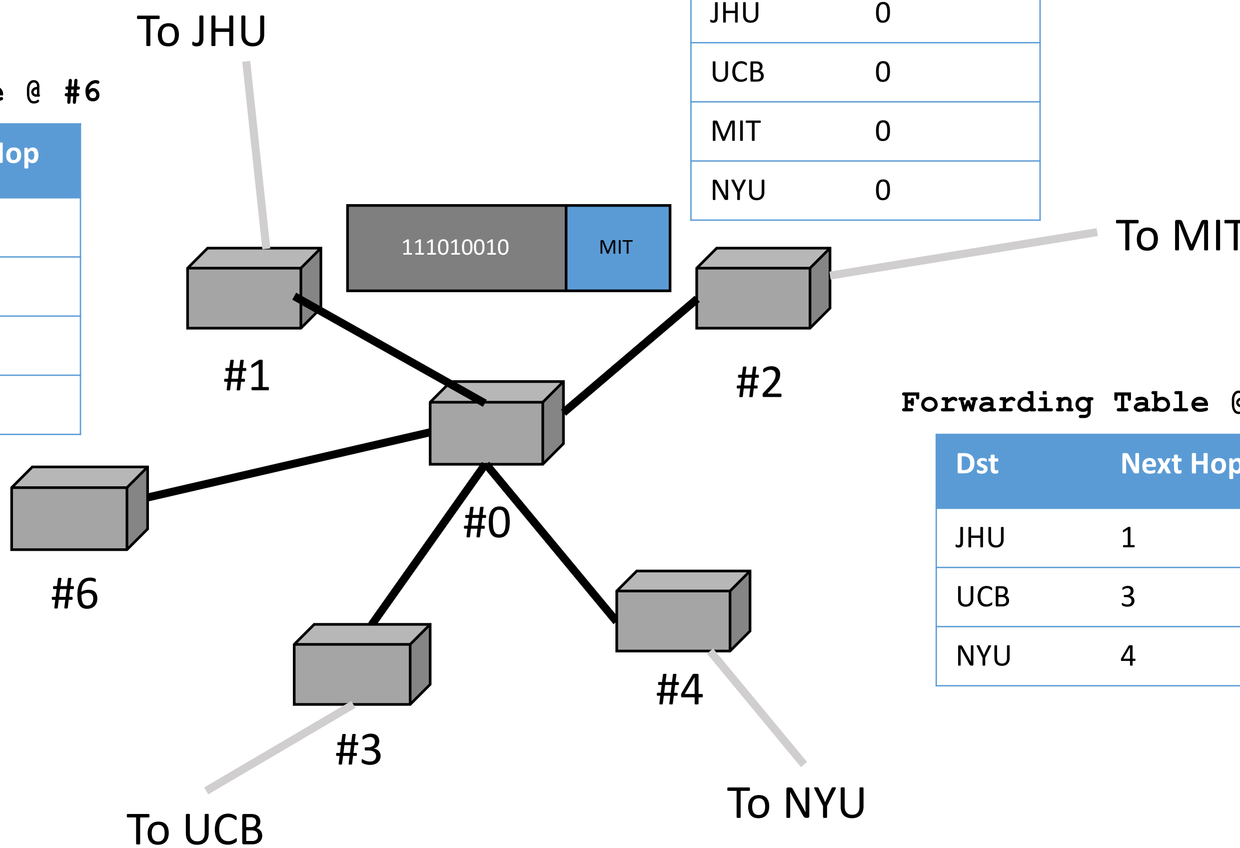
Dead end to MIT @ #0

Forwarding Table @ #6

Dst	Next Hop
JHU	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #2

Dst	Next Hop
JHU	0
UCB	0
MIT	0
NYU	0



Forwarding Table @ #0

Dst	Next Hop
JHU	1
UCB	3
NYU	4

Necessary and sufficient condition

- **Global routing state is valid *if and only if*:**
  - There are no dead ends (other than destination)
  - There are no loops

Necessary (“only if”)

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

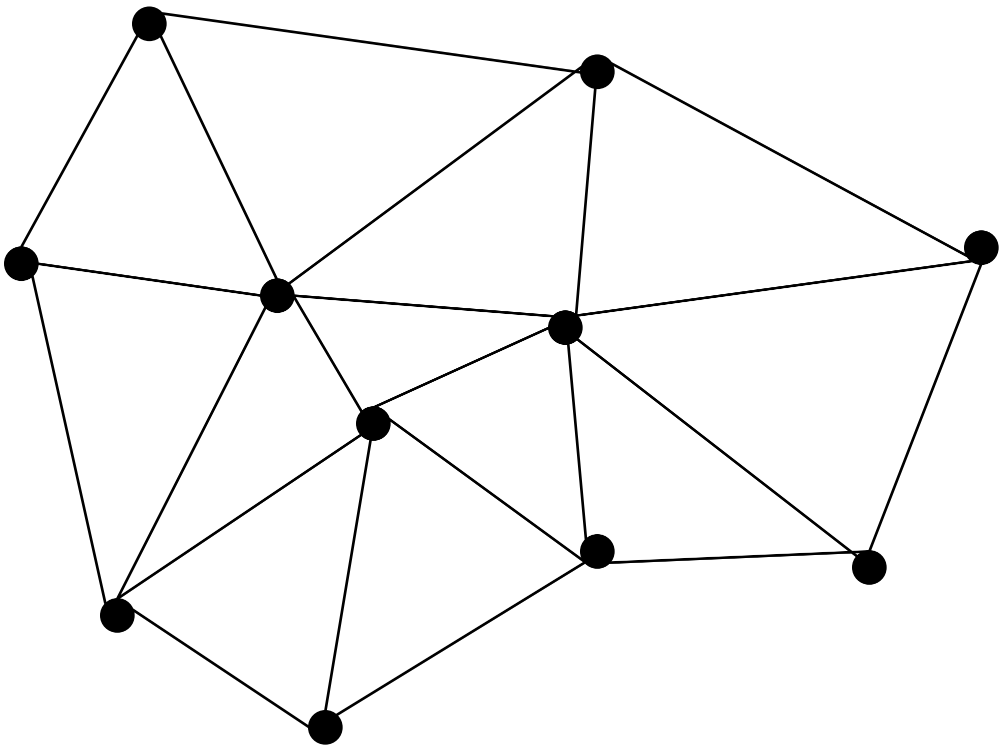
Sufficient ("if")

- **Assume there are no dead ends and no loops**
- **Packet must keep wandering, but without repeating**
  - If ever enter same switch from same link, will loop
- **Only a finite number of possible links for it to visit**
  - It cannot keep wandering forever without looping
  - Must eventually hit destination

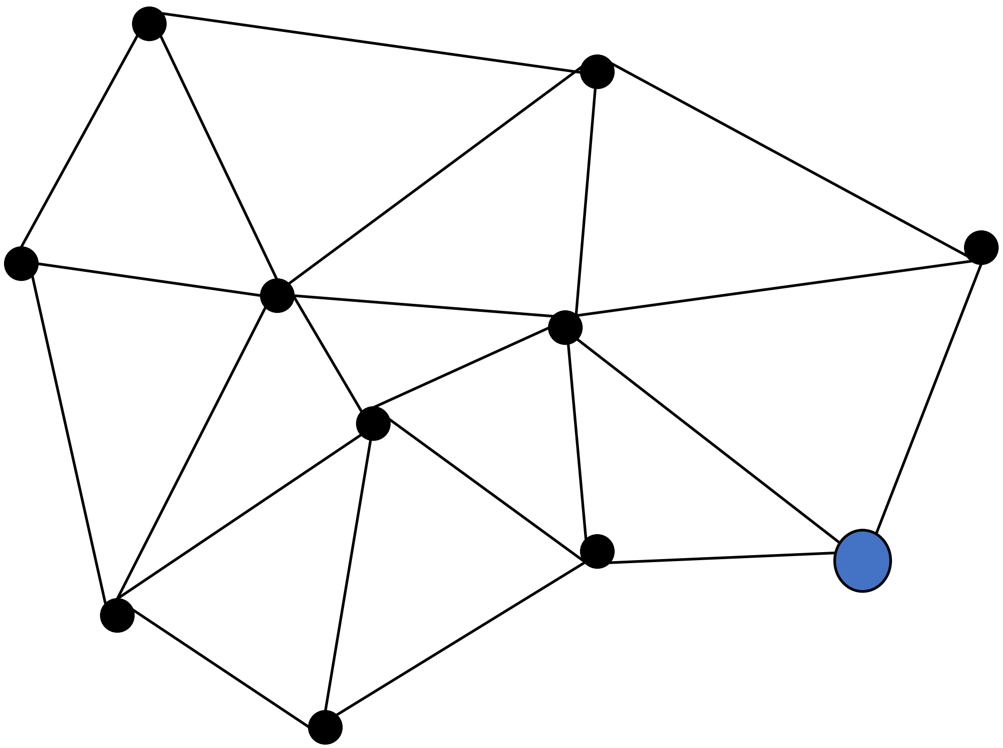
Checking validity of routing state

- **Focus only on a single destination**
  - Ignore all other routing state
- **Mark outgoing link (“next hop”) with arrow**
  - There is only one at each node
- **Eliminate all links with no arrows**
- **Look at what’s left**

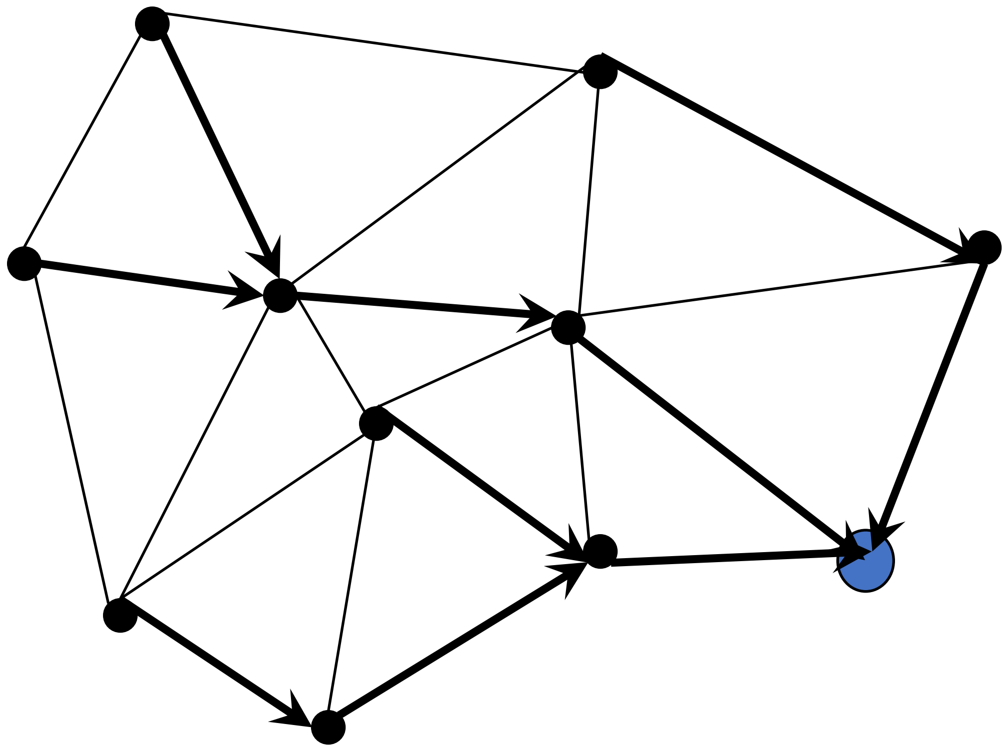
Example 1



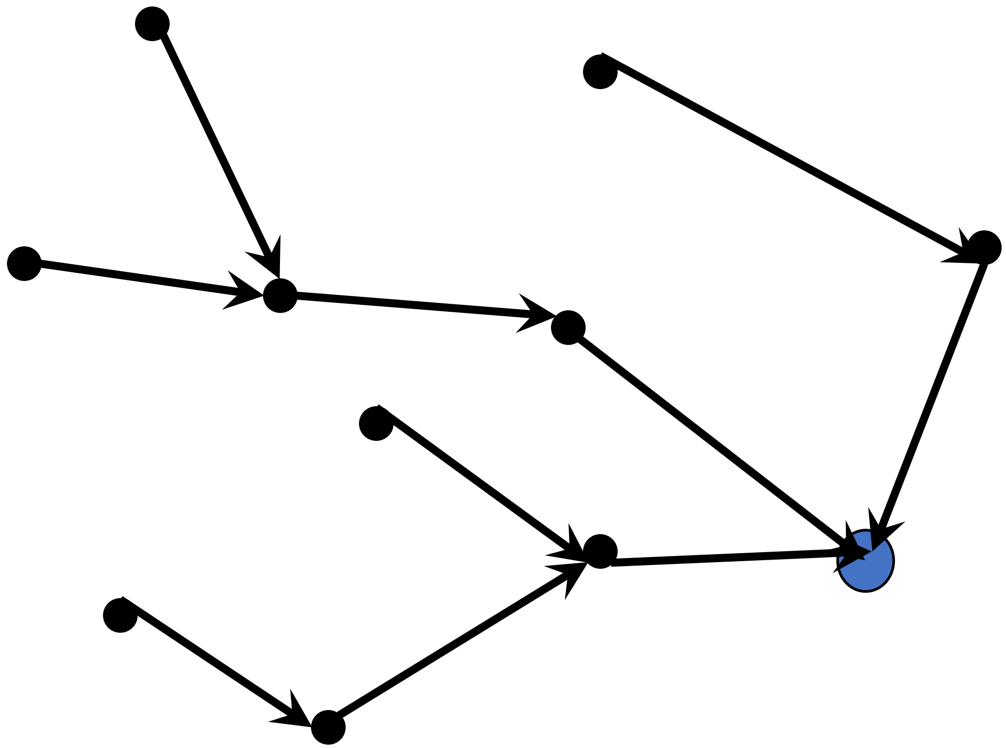
Pick destination



Put arrows on outgoing links (to blue dot)

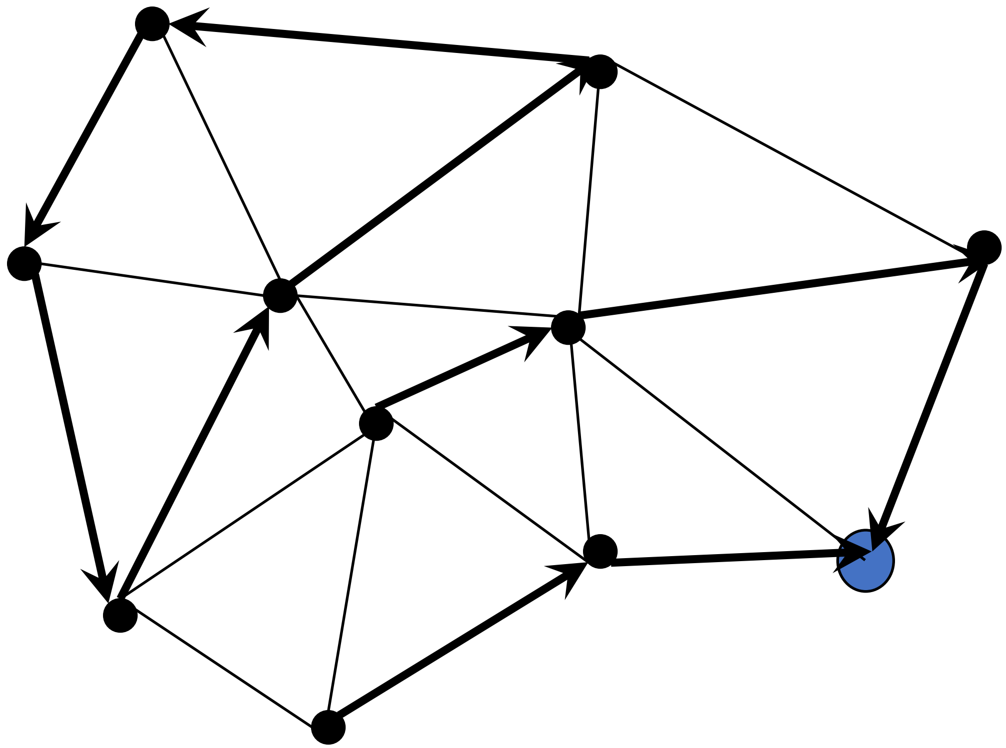


Remove unused links



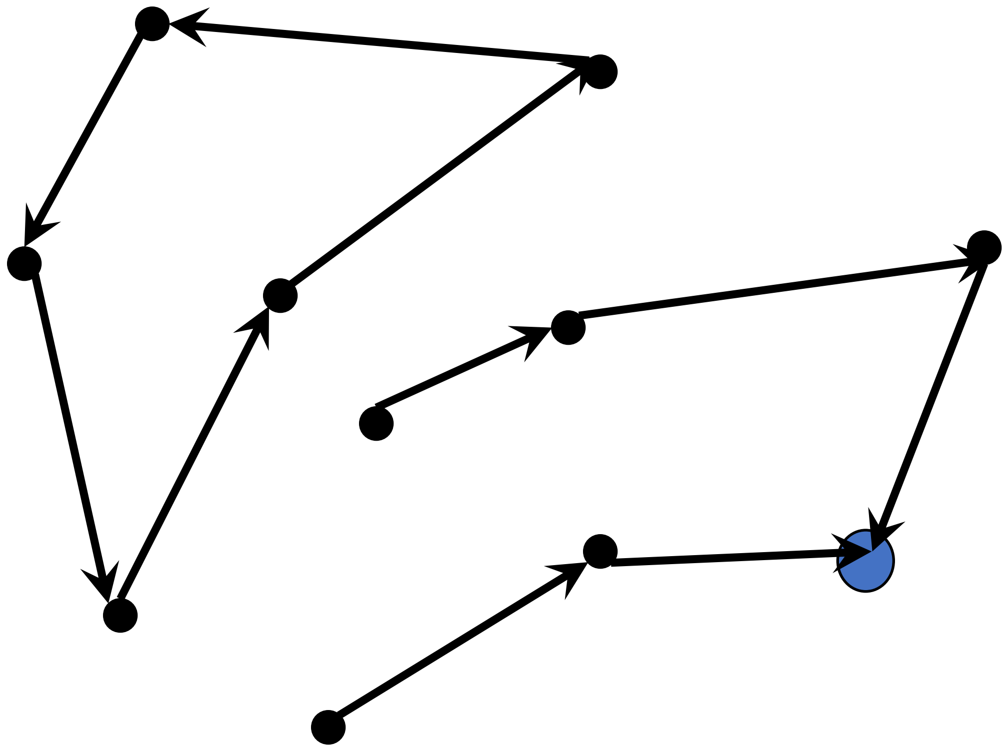
Leaves spanning tree: Valid

Example 2



Is this valid?

Not valid: Contains loop!



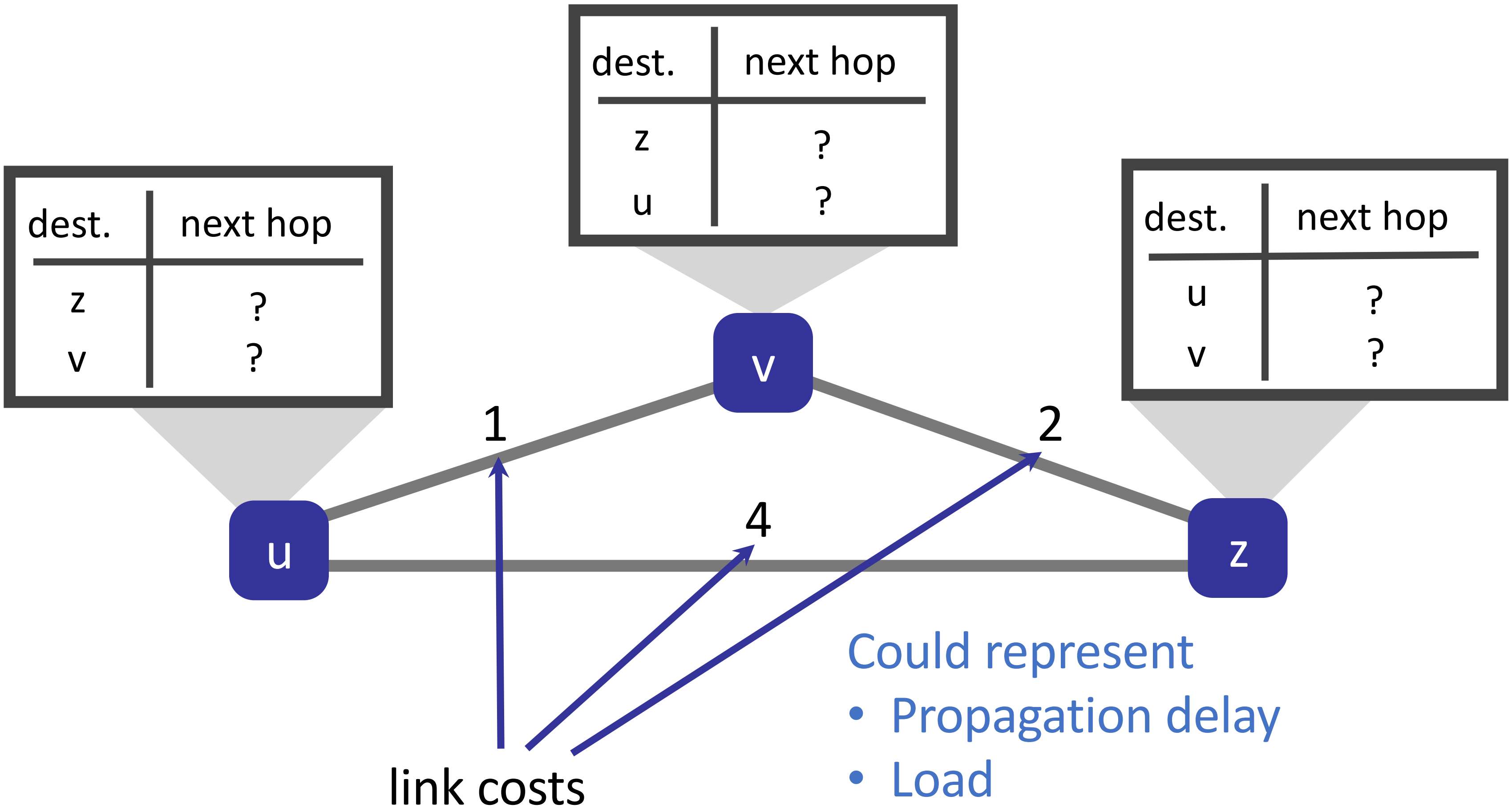
Routing validity

- **Very easy to check validity of routing state for a particular destination**
- **Dead ends are nodes without outgoing arrow**
- **Loops are obvious too**
  - Disconnected from rest of graph

Goal of routing

- **v1: Find a path to a given destination**
- **v2: Find a *least-cost path* to a given destination**

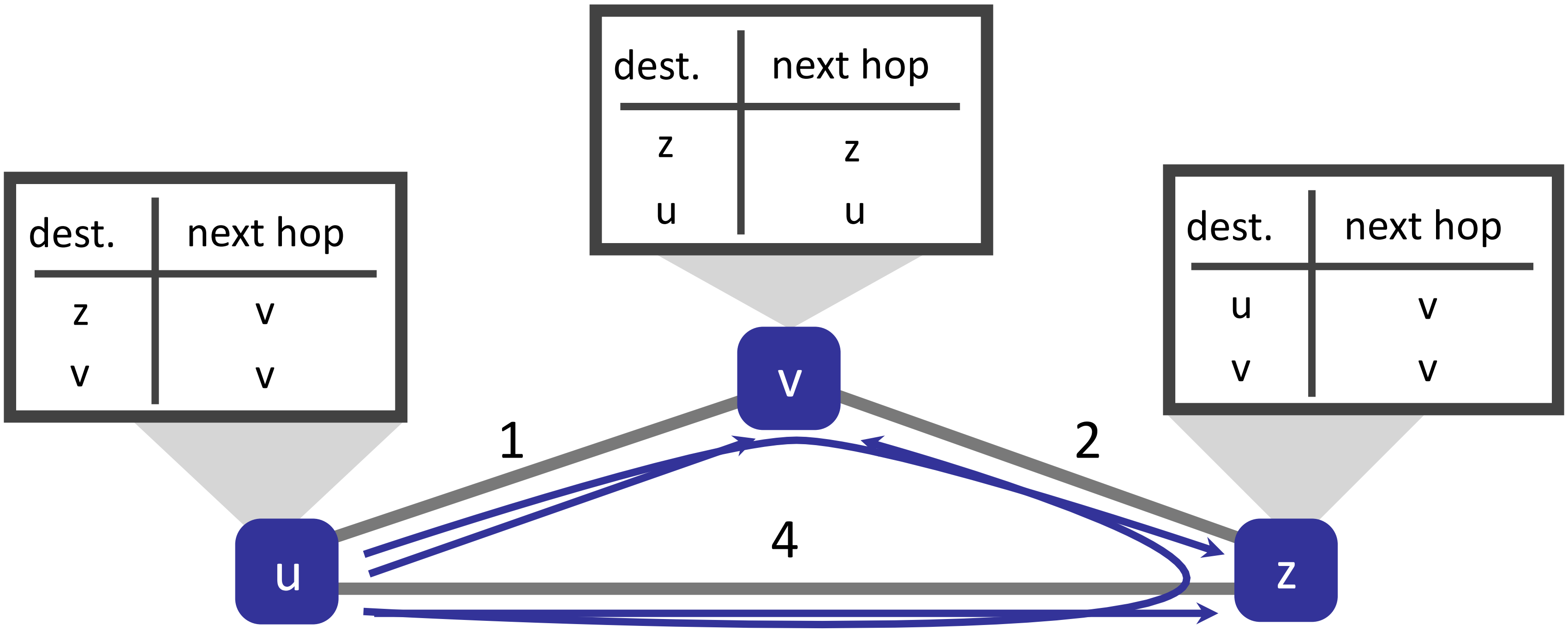
Example



Could represent

- Propagation delay
- Load
- Cost

Example



least-cost path from u to z: u v z

least cost path from u to v: u v

Least-cost path routing

- **Given:** **router graph & link costs**
- **Goal:** **find least-cost path**
  - ➢From each source router to each destination router

Least-cost routes

- **Least-cost routes provide an easy way to avoid loops**
  - No reasonable cost metric is minimized by traversing a loop
- **Least-cost paths form a spanning tree for each destination rooted at that destination**

Dijkstra’s algorithm

- **Network topology, link costs known to all nodes**
  - All nodes have same info
- **Computes least-cost paths from one node (“src”) to all other nodes**
  - After k iterations, know least-cost path to k destinations

- **Notations**
  - c(x,y): link cost from x to y;
    - ∞ if not direct neighbors
  - D(v): current value of cost of path from src to dst v
  - p(v): predecessor node along path from source to v
  - N': set of nodes whose least-cost path definitively known

Dijkstra's algorithm

```
Initialization:
  N' = {u}; D(u) = 0
  for all nodes v
    if v adjacent to u
      then D(v) = c(u,v)
    else D(v) = ∞
```

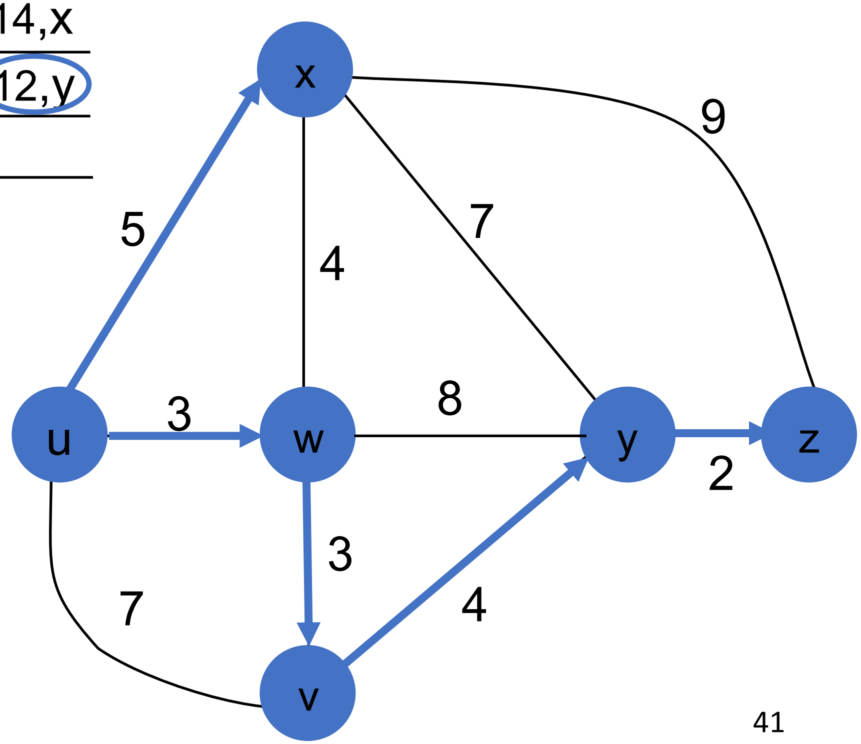
Dijkstra's algorithm

```
Initialization:
  N' = {u}; D(u) = 0
  for all nodes v
    if v adjacent to u
      then D(v) = c(u,v)
    else D(v) = ∞

Loop
  find w not in N' such that D(w) is a minimum
  add w to N'
  update D(v) for all v adjacent to w and not in N':
      D(v) = min( D(v), D(w) + c(w,v) )
      /* new cost to v is either old cost to v or known
       least path cost to w plus cost from w to v */
until all nodes are in N'
```

Dijkstra's algorithm: Example

Step	N'	D(v) p(v)	D(w) p(w)	D(x) p(x)	D(y) p(y)	D(z) p(z)
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					



Notes:

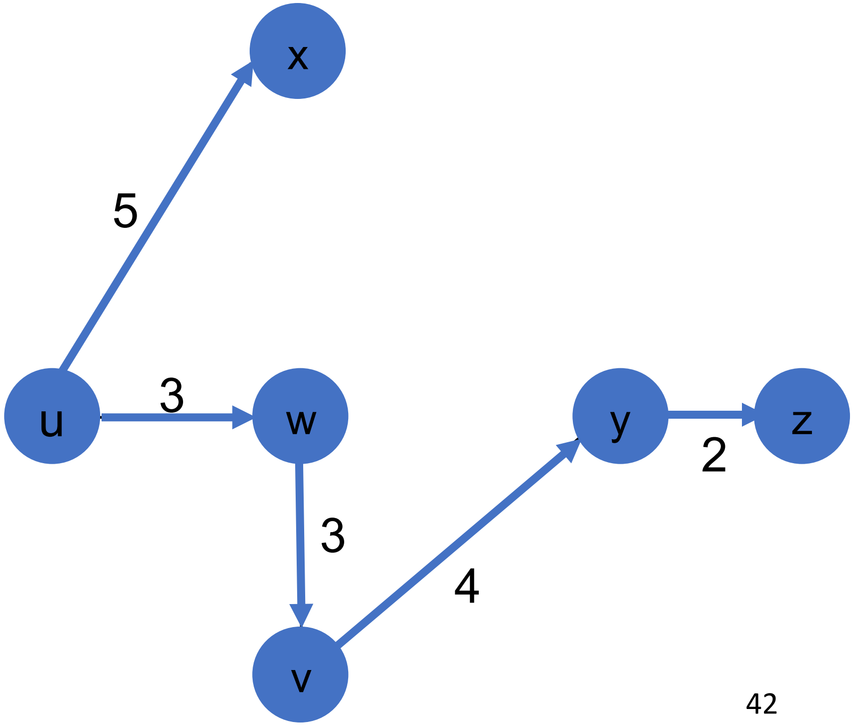
- Construct shortest path tree by tracing predecessor nodes
- Ties can exist (can be broken arbitrarily)

Dijkstra’s algorithm: Example

Resulting forwarding table in u

destination	link
v	(u, w)
w	(u, w)
x	(u, x)
y	(u, w)
z	(u, w)

Resulting least-cost tree from u



Summary

- **Network layer control plane calculates valid routes and sets up forwarding table**
  - Avoiding loops and dead ends
- **Least-cost routes can be calculated using Dijkstra's algorithm**

- **Next lecture: Routing protocols**

Thanks!
Q&A