EECS 489
Computer Networks

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Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.

Agenda

- 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 @ #6

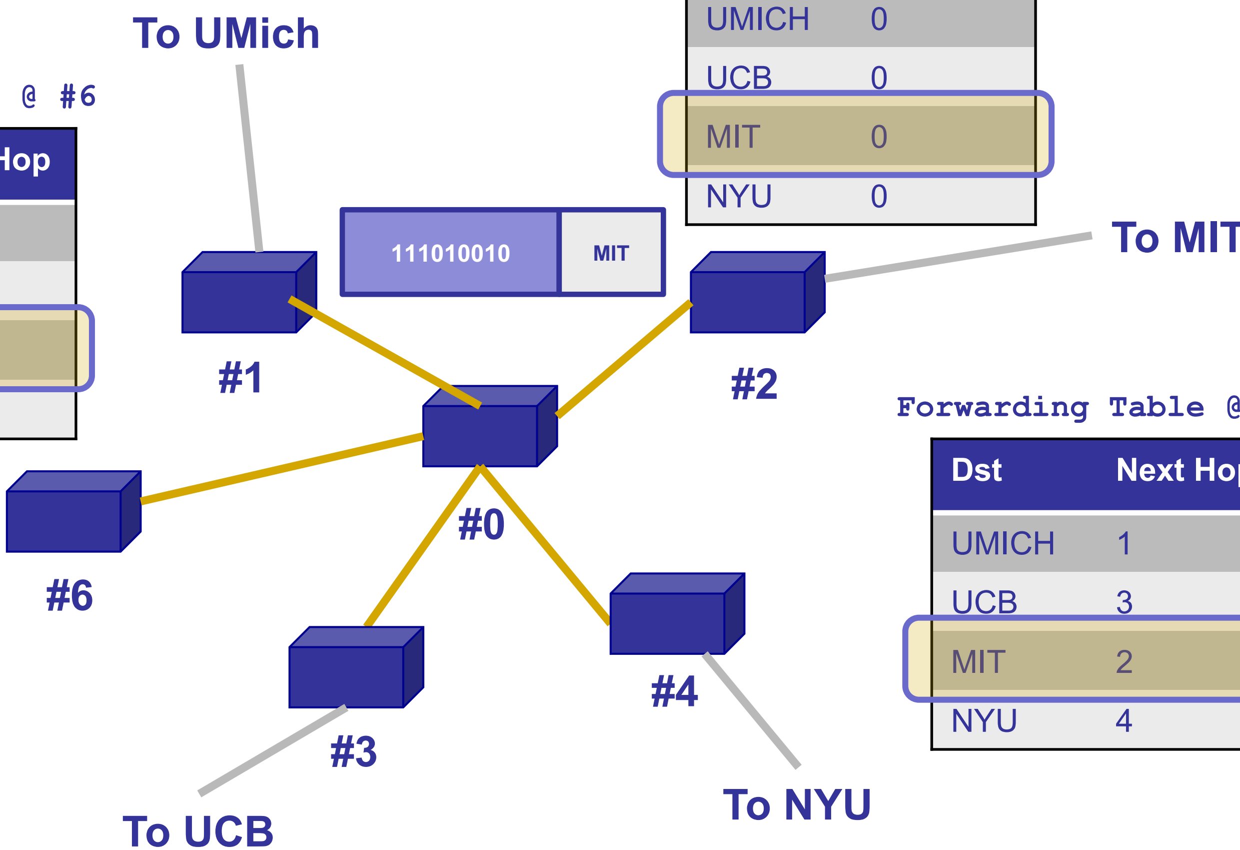
Dst	Next Hop
UMICH	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #2

Dst	Next Hop
UMICH	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #0

Dst	Next Hop
UMICH	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 if 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 @ #6

Dst	Next Hop
UMICH	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #2

Dst	Next Hop
UMICH	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #0

Dst	Next Hop
UMICH	1
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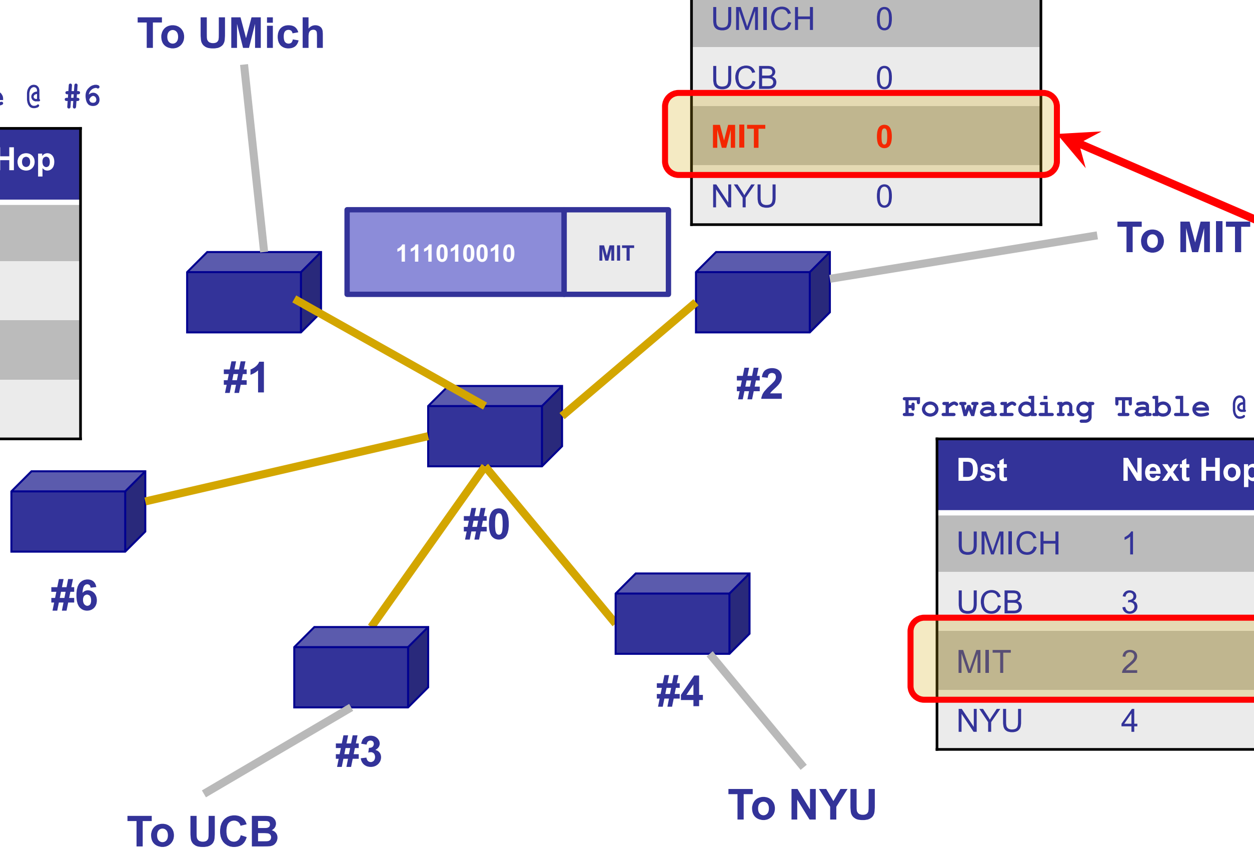


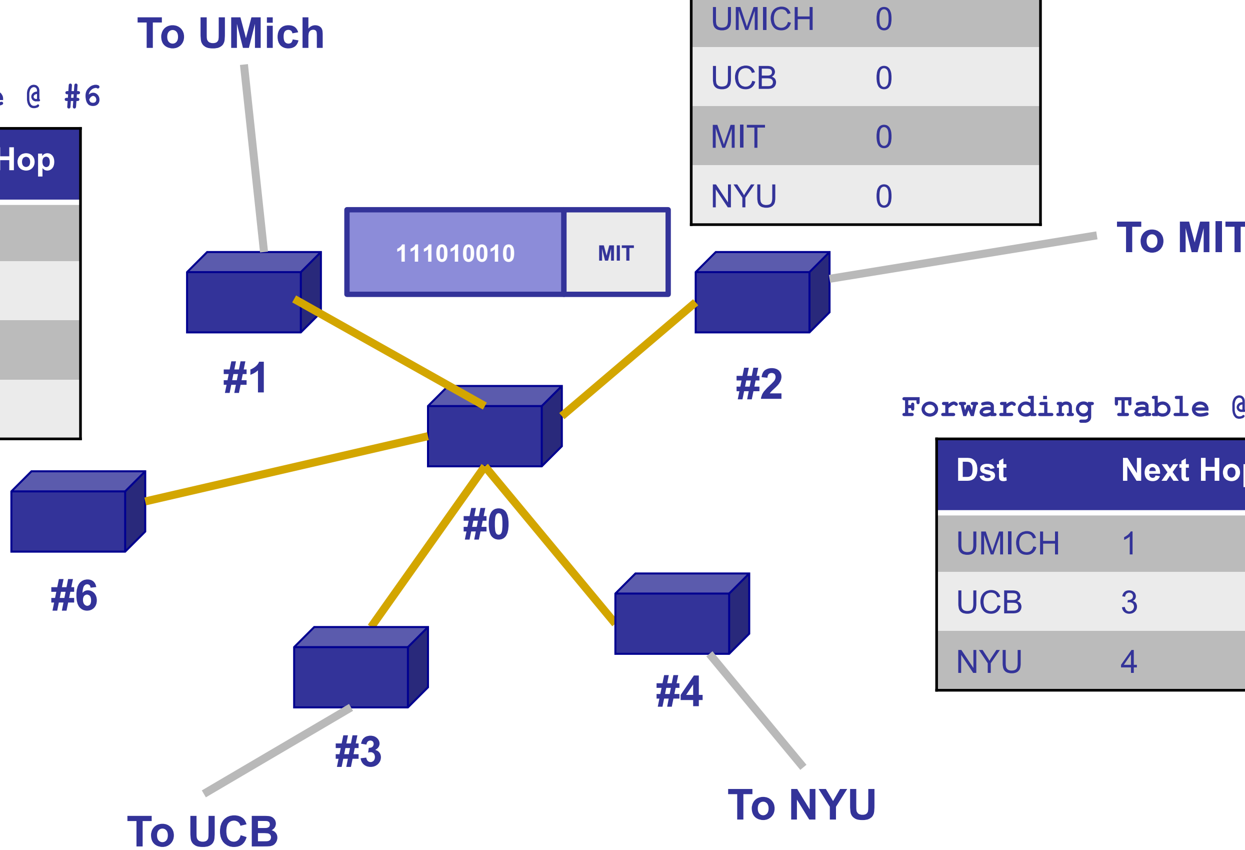
Dead end to MIT @ #0

Forwarding Table @ #6

Dst	Next Hop
UMICH	0
UCB	0
MIT	0
NYU	0

Forwarding Table @ #2

Dst	Next Hop
UMICH	0
UCB	0
MIT	0
NYU	0



Forwarding Table @ #0

Dst	Next Hop
UMICH	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

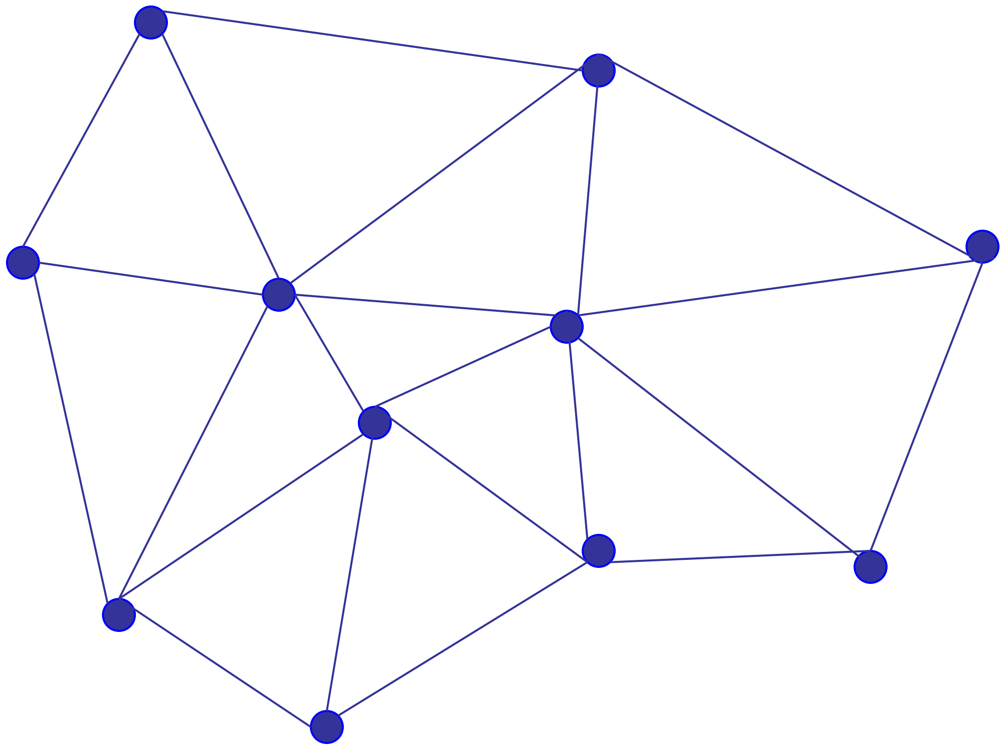
Sufficient (“if”)

- 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

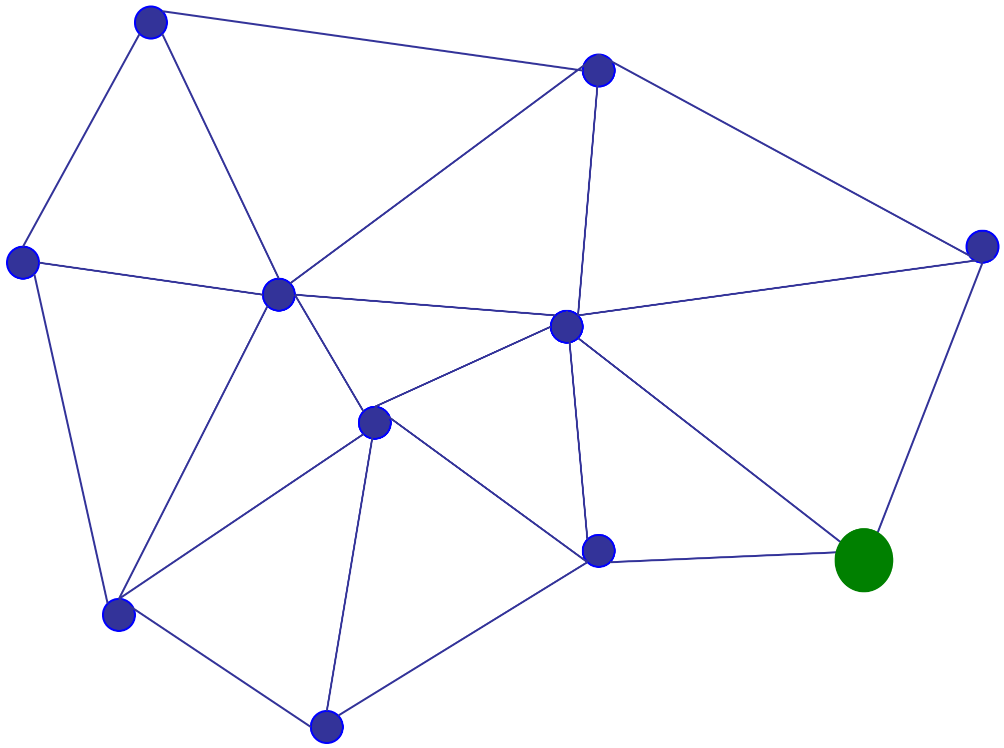
Checking validity of routing state

- 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

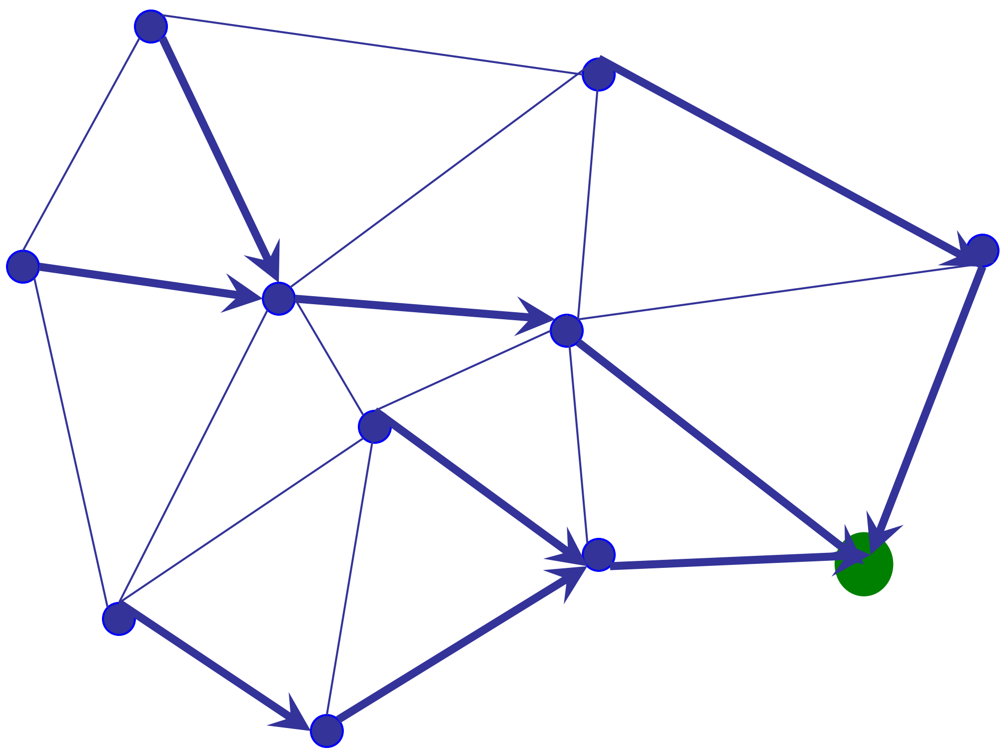
Example 1



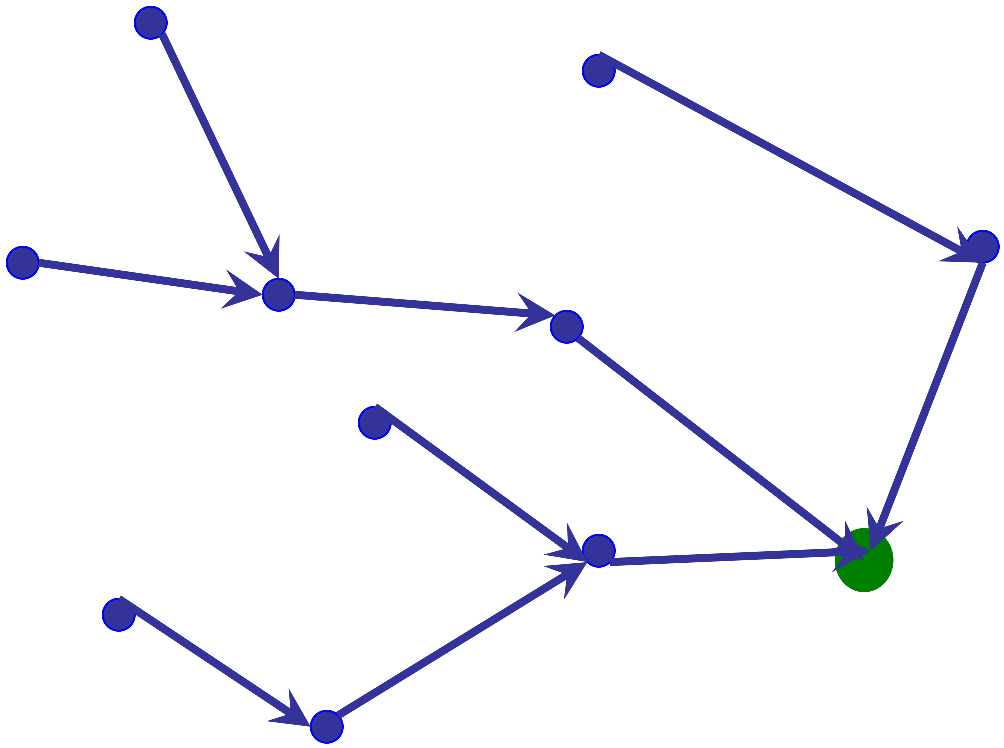
Pick destination



Put arrows on outgoing links (to green dot)

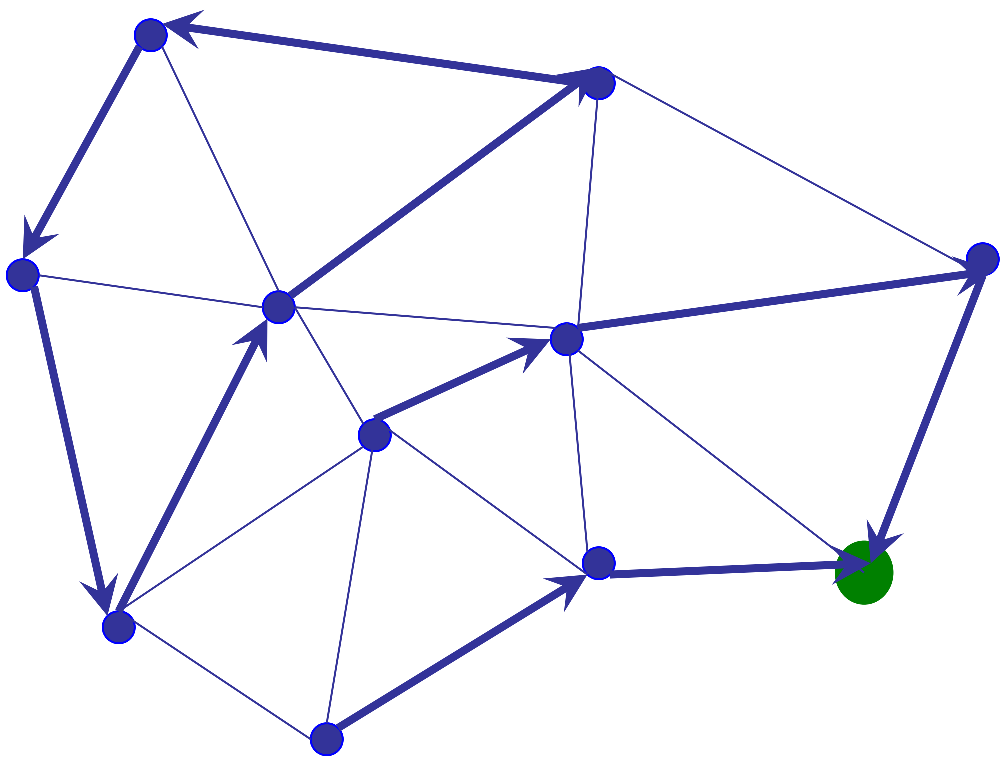


Remove unused links



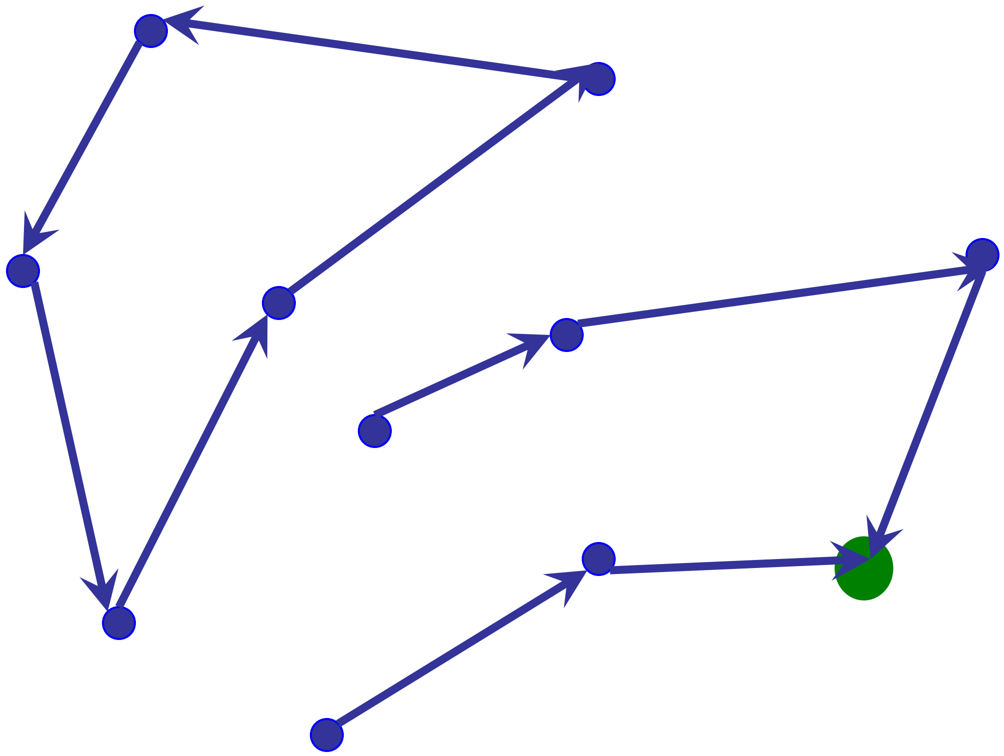
Leaves spanning tree: Valid

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

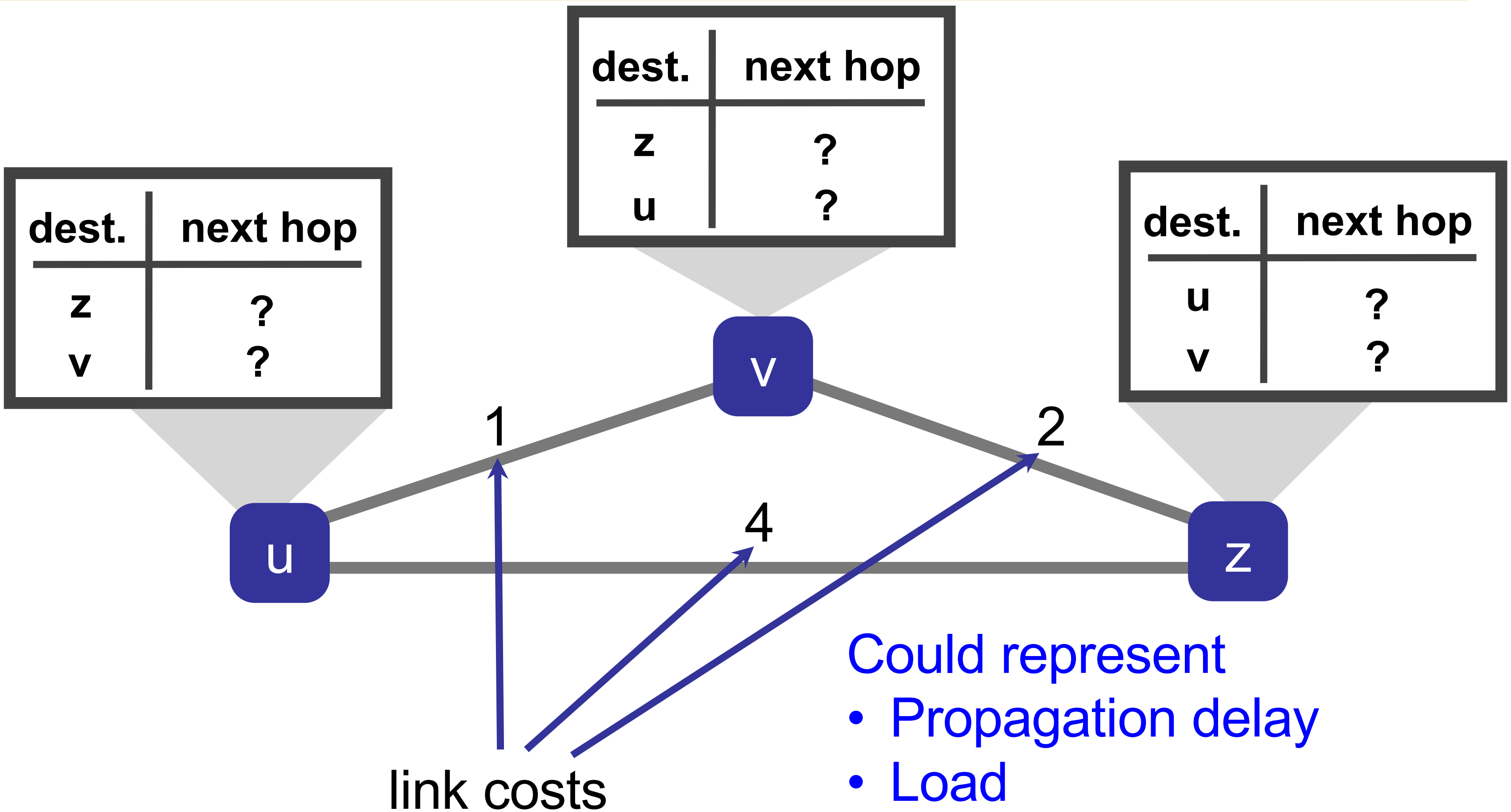
5-MINUTE BREAK!

Announcements

Goal of routing

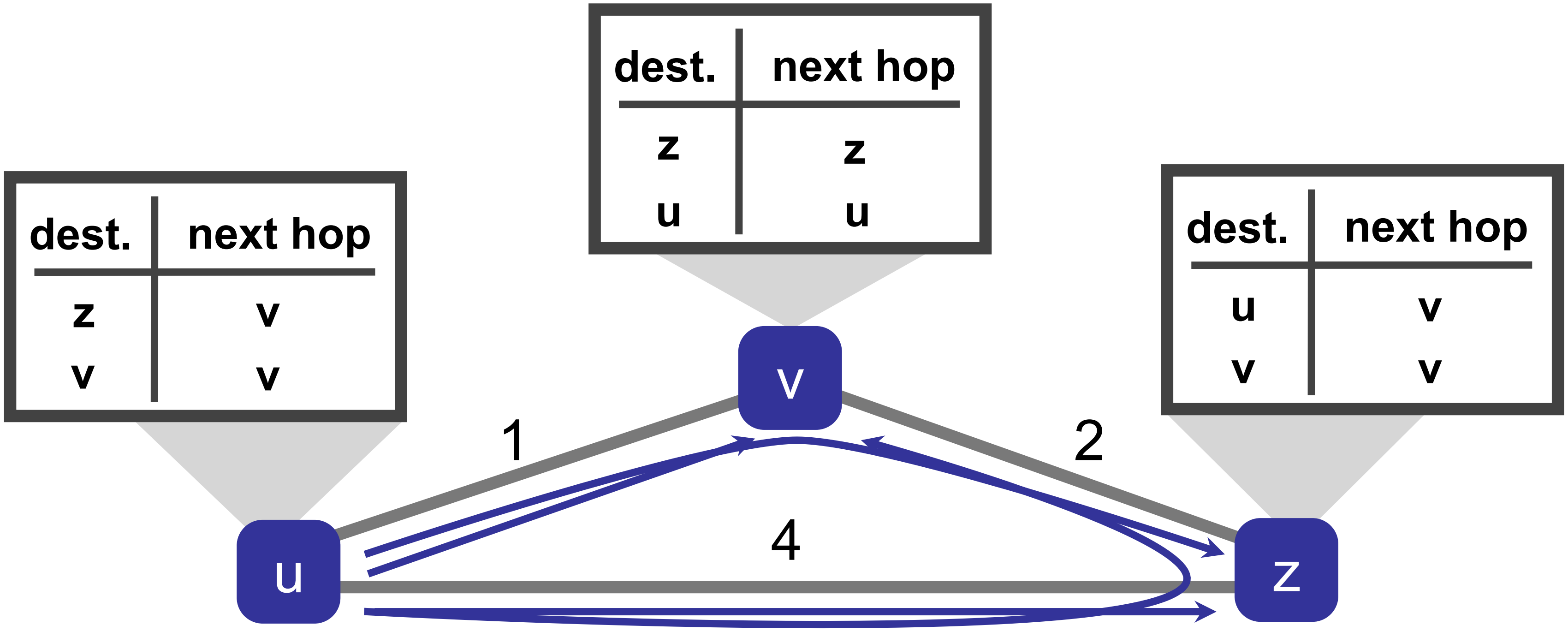
- v1: Find a path to a given destination
- v2: Find a *least-cost path* to a given destination

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

EECS 281: 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

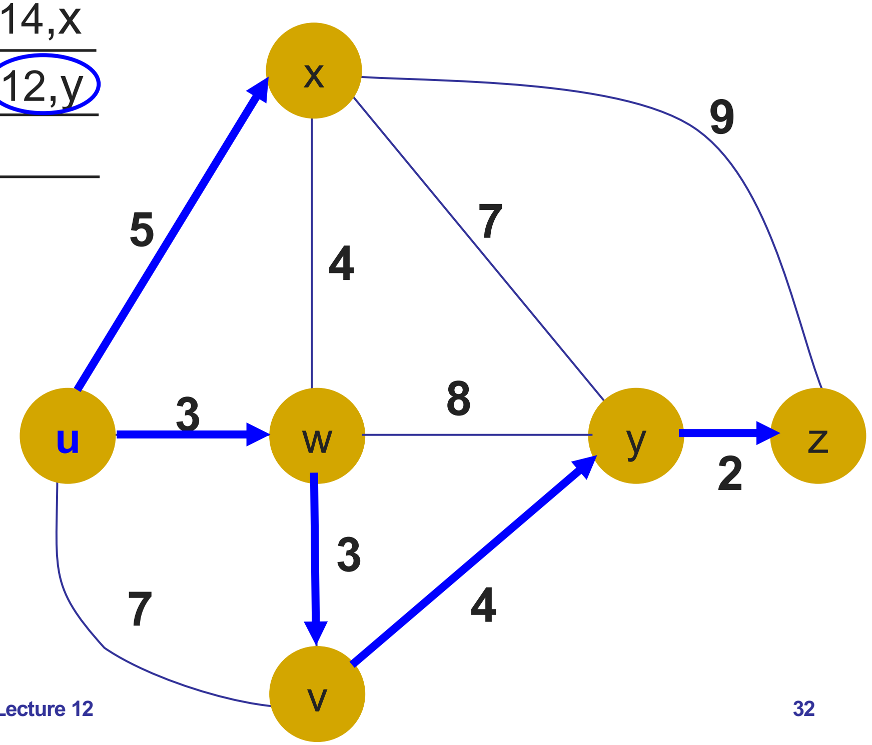
```
Initialization:
  N' = {u}; D(u) = 0
  for all nodes v
    if v adjacent to u
      then D(v) = c(u,v)
    else D(v) = ∞
Loop
  find w not in N' such that D(w) is a minimum
  add w to N'
  update D(v) for all v adjacent to w and not in N':
      D(v) = min( D(v), D(w) + c(w,v) )
      /* new cost 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)

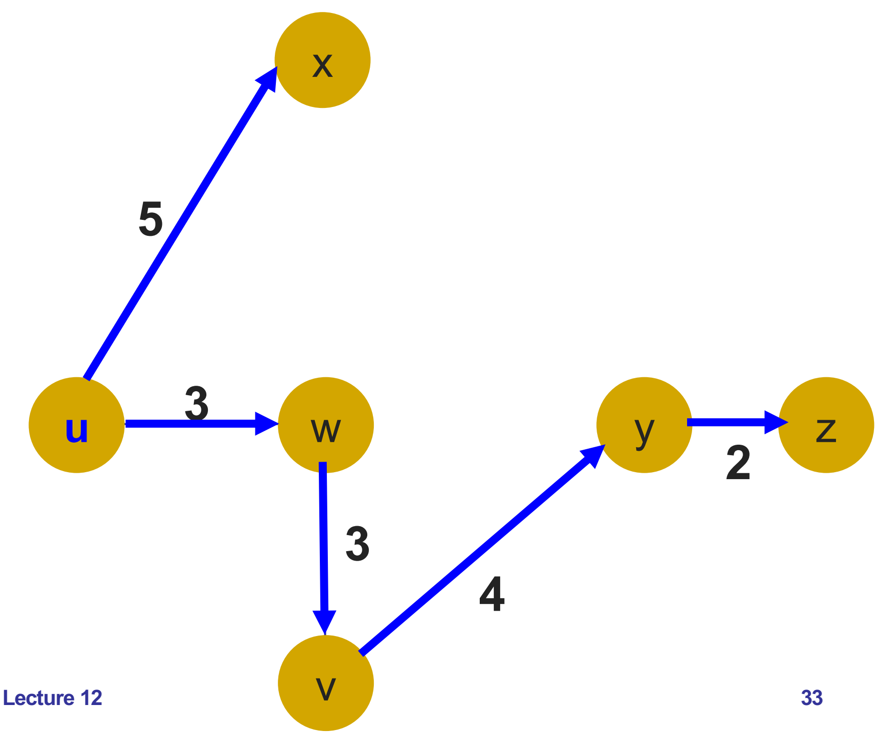


Dijkstra's algorithm: Example

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