Lecture 18: Network Layer
Link State Routing

COMP 332, Spring 2024

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Acknowledgements: materials adapted from Computer Networking: A Top Down Approach 7th edition: ©1996-2016, J.F Kurose and K.W. Ross, All Rights Reserved as well as from slides by Abraham Matta at Boston University, and some material from Computer Networks by Tannenbaum and Wetherall.

Today

Announcements

- Homework 6 due tonight by 11:59p
- Homework 7 posted, due April 22
    - You will need to test your code on Linux VM, for coding part of Homework 7 can work with a partner

Addressing

- usage in routing
- how to get an IP address

Network programming

- raw sockets and byte packing
- bit-wise operations in python

Control plane aka where routing happens

- overview
- link state routing

Addressing

USAGE IN ROUTING

Routers forward traffic to networks not hosts

Forwarding table

- does not contain row for every dest IP address
- instead computes routes between subnets (blocks of addresses)

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

What if address ranges don't divide up nicely?

Longest prefix matching

– use longest address prefix that matches destination address

Destination Address Range	Link interface
11001000 00010111 00010*** *********	0
11001000 00010111 00011000 *********	1
11001000 00010111 00011*** *********	2
otherwise	3

Question

DA: 11001000 00010111 00010110 10100001 which interface?

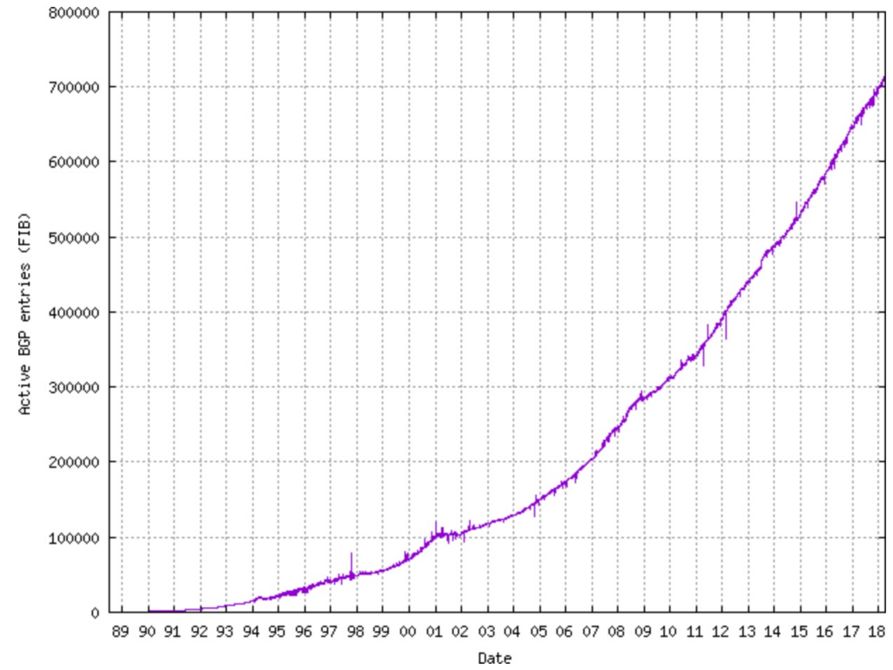
DA: 11001000 00010111 00011000 10101010 which interface?

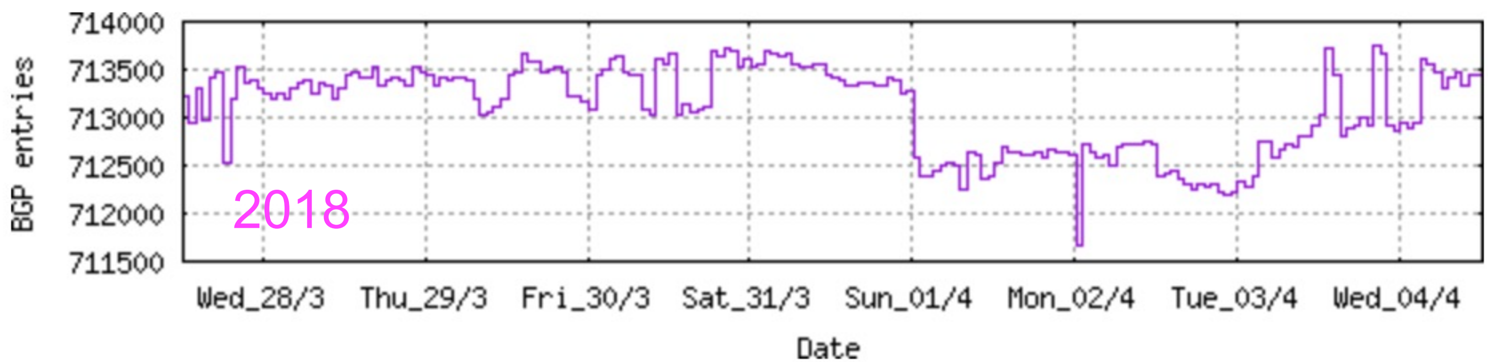
How big is a routing table for a core router?

From http://www.cidr-report.org/as2.0/

Table History

Date	Prefixes	CIDR Aggregated
28-03-18	713318	386580
29-03-18	713461	386983
30-03-18	713175	387365
31-03-18	713602	387141
01-04-18	713267	386331
02-04-18	712612	386192
03-04-18	712224	386045
04-04-18	712855	386936



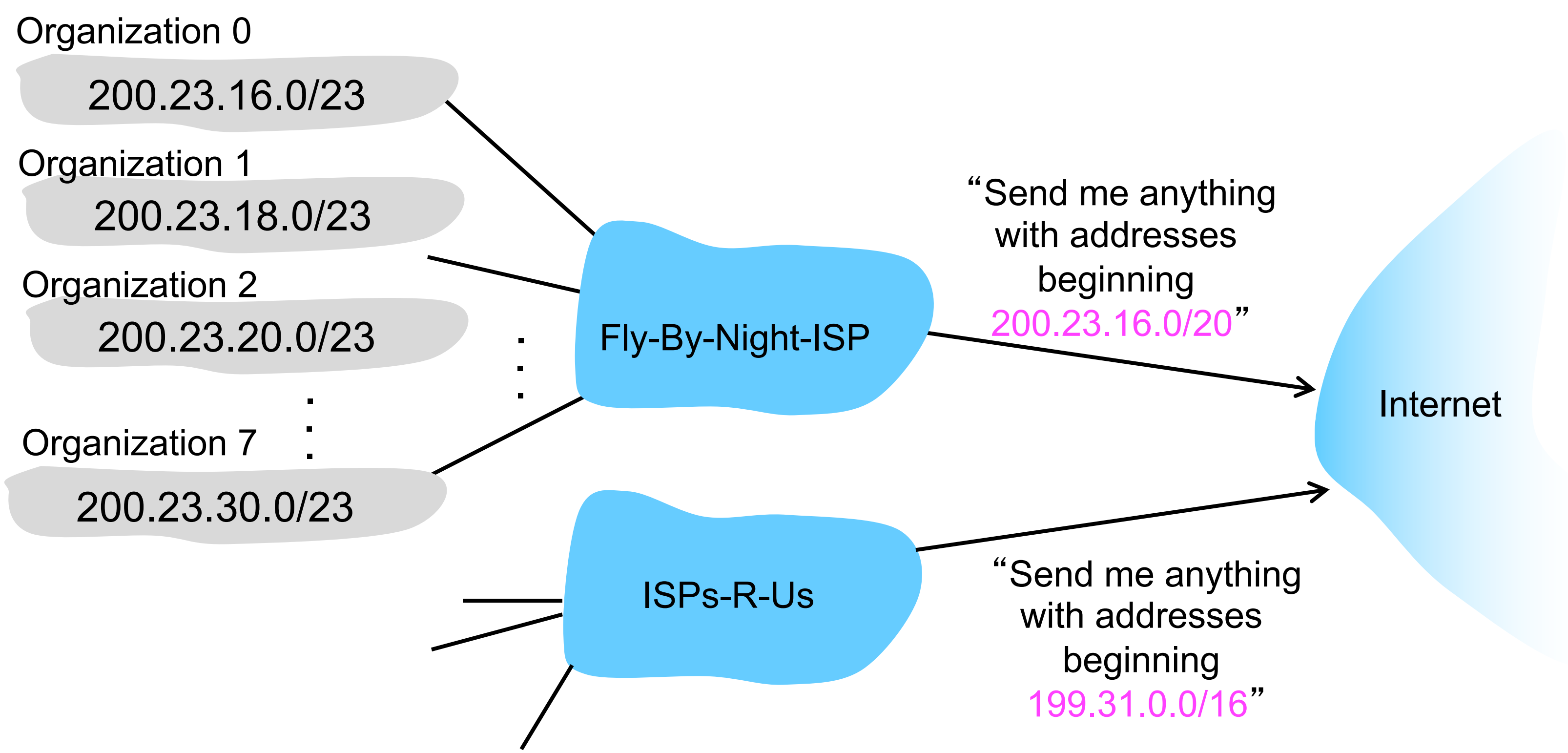


Q: If a core router processes 1million pkts+ per second, how fast does it need to be able to search table?

Hierarchical addressing

Route aggregation

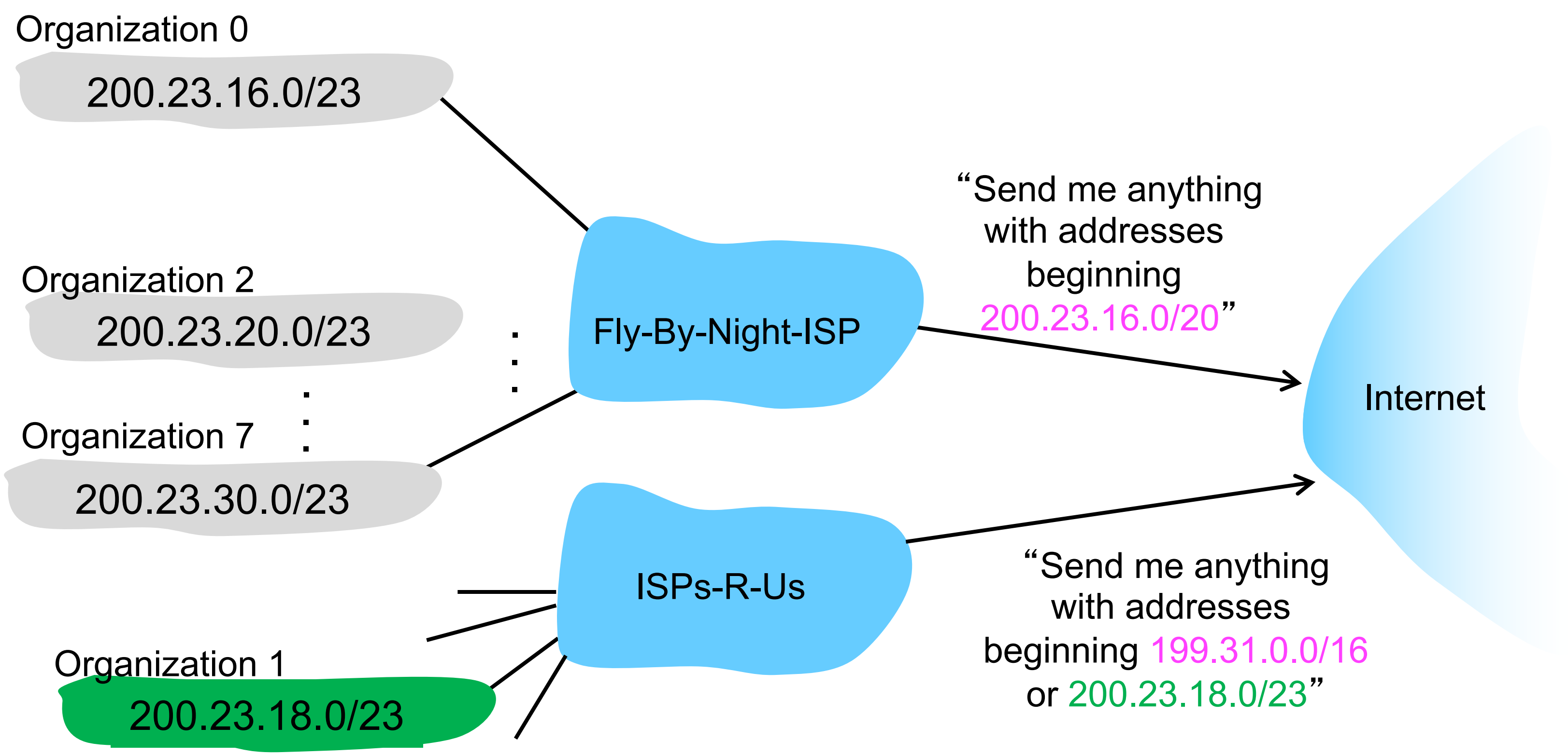
- combine multiple small prefixes into a single larger prefix
- allows efficient advertisement of routing information



Longest prefix matching

More specific routes

- ISPs-R-Us has a more specific route to Organization 1



Addressing

HOW TO GET AN IP ADDRESS?

How does ISP get block of addresses?

ICANN

- Internet Corporation for Assigned Names and Numbers
- http://www.icann.org/

ICANN functions

- allocates addresses
- manages DNS
- assigns domain names, resolves disputes
- …

How does network get net part of IP address?

Allocated portion of its provider ISP's address space

ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20
Organization 0	11001000 00010111 00010000 00000000	200.23.16.0/23
Organization 1	11001000 00010111 00010010 00000000	200.23.18.0/23
Organization 2	11001000 00010111 00010100 00000000	200.23.20.0/23
...	….. ….	….
Organization 7	11001000 00010111 00011110 00000000	200.23.30.0/23

How does host get an IP address?

Option 1

- hard-coded by system admin in a file on your host

Option 2:

- dynamically get address from a server
  - DHCP: Dynamic Host Configuration Protocol

We're running out of IPv4 addresses

Why?

- inefficient use of address space
  - from pre-CIDR use of address classes (A: /8, B: /16, C: /24)
- too many networks (and devices)
  - Internet comprises 100,000+ networks
  - routing tables and route propagation protocols do not scale

Q: how many IPv4 addresses are there?

- 2^{32}

Solutions

- IPv6 addresses
- DHCP: Dynamic Host Configuration Protocol
- NAT: Network Address Translation

Network Programming

RAW SOCKETS

Raw sockets

Take bytes put into socket and push out of network interface

- no IP or transport layer headers added by operating system!

Q: why have raw sockets? Why are stream/datagram not enough?

Lets you create your own transport and network layer headers

- set field values as you choose
  - e.g., time-to-live fields

You will need to run your code on Linux VM!

Homework 7/8: raw sockets

```
# Create send and receive sockets
send_sock = socket.socket(
        socket.AF_INET, socket.SOCK_RAW, socket.IPPROTO_RAW)
recv_sock = socket.socket(
        socket.AF_INET, socket.SOCK_RAW, socket.IPPROTO_ICMP)

# Set IP_HDRINCL flag so kernel does not rewrite header fields
send_sock.setsockopt(socket.IPPROTO_IP, socket.IP_HDRINCL, 1)

# Set receive socket timeout to 2 seconds
recv_sock.settimeout(2.0)
```

https://docs.python.org/3/library/socket.html

Q: why set a timeout?

Byte packing and structs

How do you create a (packet) header?

```
def create_icmp_header(self):

    ECHO_REQUEST_TYPE = 8
    ECHO_CODE = 0

    # ICMP header info from https://tools.ietf.org/html/rfc792
    icmp_type = ECHO_REQUEST_TYPE       # 8 bits
    icmp_code = ECHO_CODE               # 8 bits
    icmp_checksum = 0                   # 16 bits
    icmp_identification = self.icmp_id # 16 bits
    icmp_seq_number = self.icmp_seqno  # 16 bits

    # ICMP header is packed binary data in network order
    icmp_header = struct.pack('!BBHHH', # ! means network order
    icmp_type,           # B = unsigned char = 8 bits
    icmp_code,           # B = unsigned char = 8 bits
    icmp_checksum,       # H = unsigned short = 16 bits
    icmp_identification, # H = unsigned short = 16 bits
    icmp_seq_number)     # H = unsigned short = 16 bits

    return icmp_header
```

https://docs.python.org/3/library/struct.html

Network Programming

BIT-WISE OPERATIONS IN PYTHON

Bit-wise operations on variables

x << y

- returns x with bits shifted to left by y places
    - new bits on right-hand-side are zeros
    - same as multiplying x by 2^y

x >> y

- returns x with bits shifted to right by y places
    - same as dividing x by 2^y

x & y

- does a bitwise and
    - each bit of output is 1 if corresponding bit of x AND of y is 1, otherwise 0

~ x

- returns complement of x
    - number you get by switching each 1 for 0 and each 0 for 1

E.g.,

- use to pack ip_version and ip header length into 8 bits

https://wiki.python.org/moin/BitwiseOperators
https://www.tutorialspoint.com/python3/bitwise_operators_example.htm

Control Plane
OVERVIEW

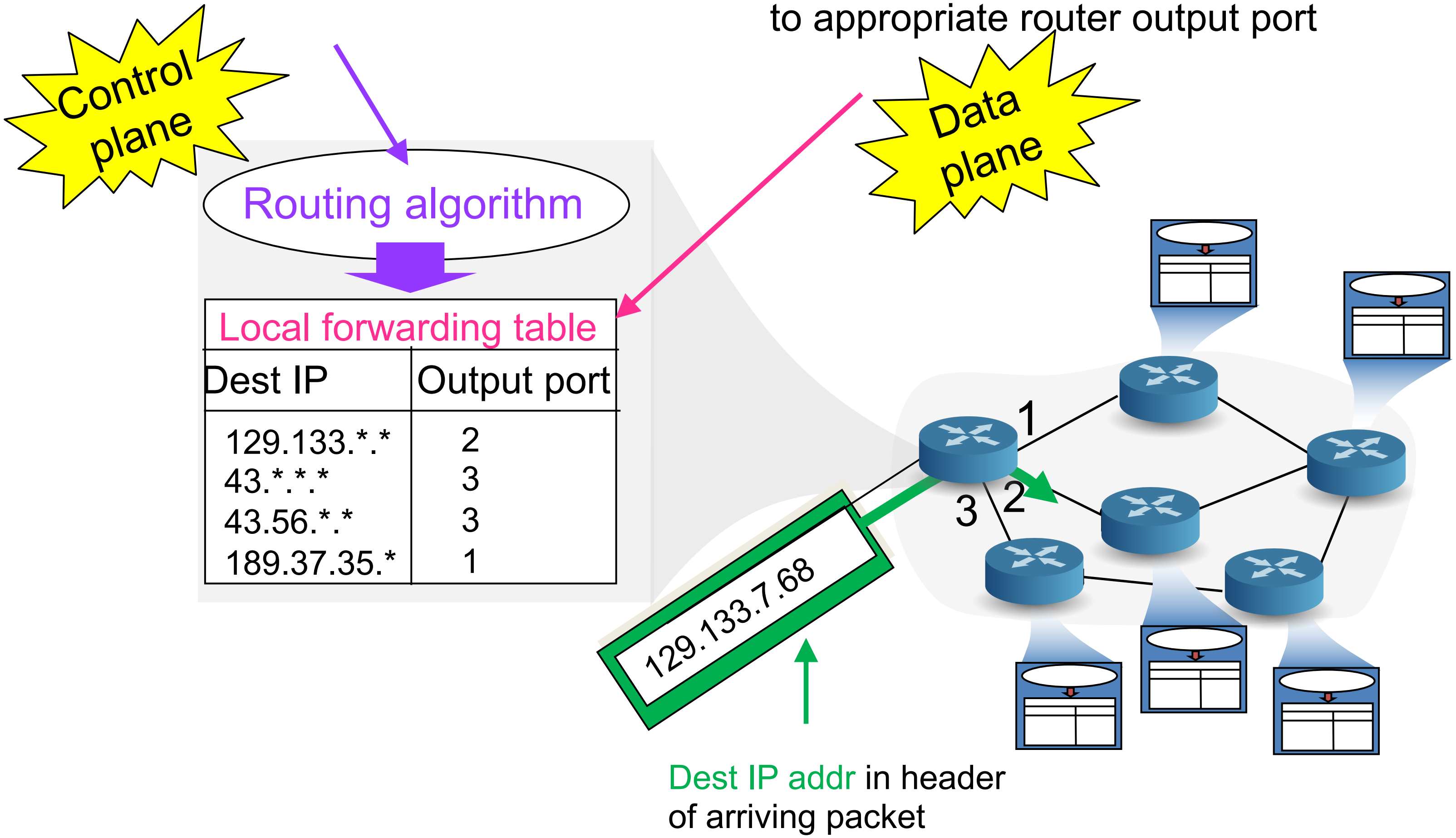
Control vs. data plane functions

Routing (slower time scale)

- determine route taken by packets from source to destination

Forwarding (faster time scale)

- move packets from router's input port to appropriate router output port



Local forwarding table

Dest IP	Output port
129.133.*.*	2
43.*.*.*	3
43.56.*.*	3
189.37.35.*	1

How to get these routes?

Routing protocols

Goal

- determine "good" path from sending hosts to receiving host, through network of routers

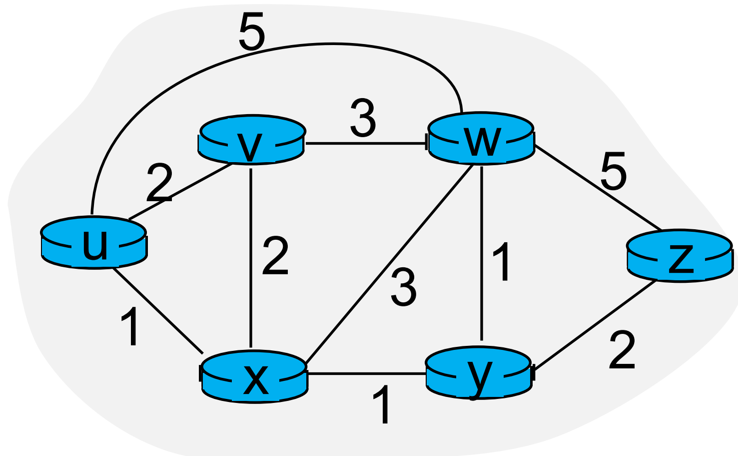
Path

- sequence of routers packets will traverse in going from given initial source host to given final destination host

"Good"

- least "cost", "fastest", "least congested", …
- correctness constraints
  - no loops
  - no dead-ends

Abstract network as a graph



Graph: G = (N,E)

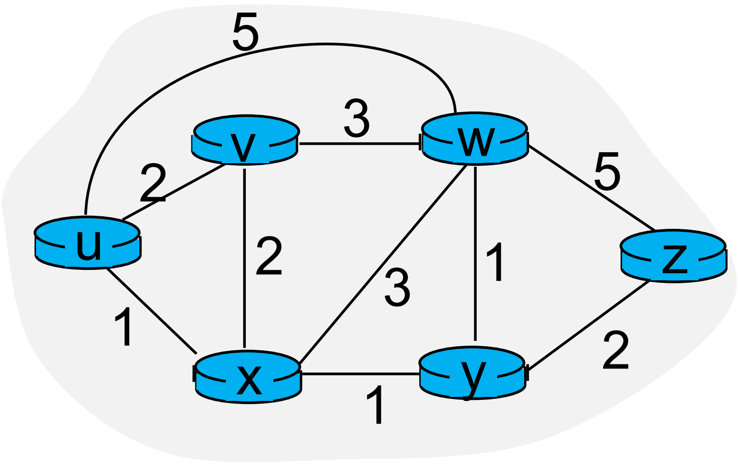
Q: What are the routers? I.e., nodes?

N = set of routers
= { u, v, w, x, y, z }

Q: What are the links? I.e., edges?

E = set of links
={ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

Link costs



$c(x_i,x_j)$ = cost of link (x_i,x_j)
$c(w,z) = 5$
What is cost c(x,y)?

Q: how to set cost?

- Always 1
- Related to bandwidth
- Inversely related to congestion
- Actual cost for ISP to use link
- …

Q: What's the least-cost path between u and z?

$c(u,x) + c(x,y) + c(y,z)$

Cost of path $(x_1, x_2, x_3,\ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

Routing algorithm: algorithm that finds least-cost path

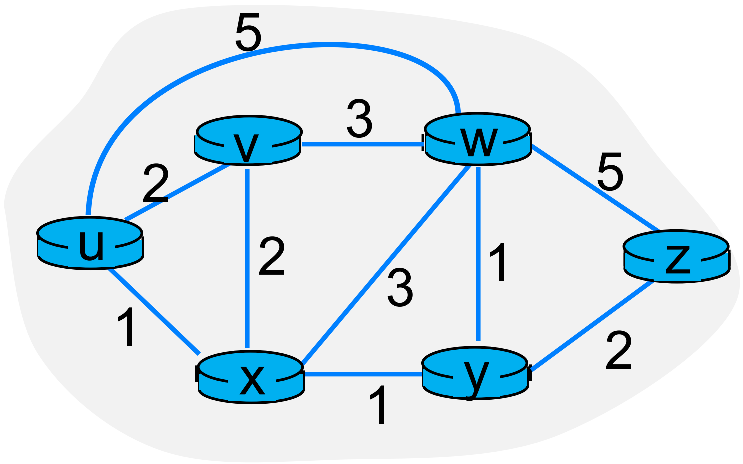
Classifying routing algorithms

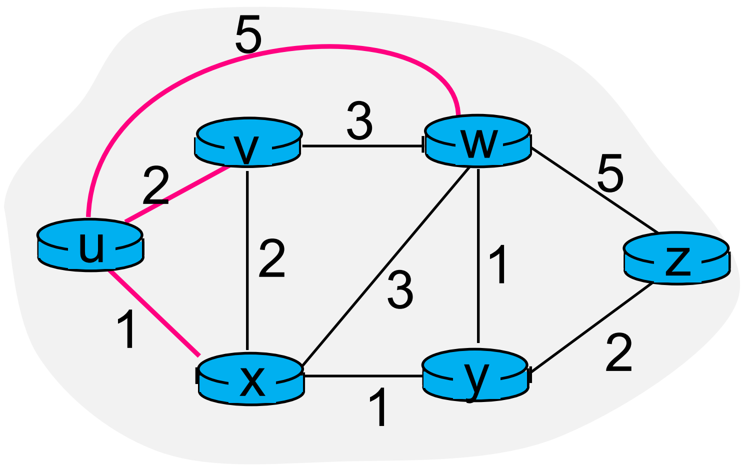
Global information

- global link state algorithms
- all routers have complete topology, link cost info
- *exchange info only about neighbors but with all nodes*

Local/decentralized information

- decentralized distance vector algorithms
- router knows only physically-connected neighbors, link costs to neighbors
- iterative computation
- *exchange info about all nodes but only with neighbors*





Both are used on Internet. First cover abstractly and then talk about specific Internet protocols (OSPF, BGP, RIP, …)

Control Plane

LINK STATE ROUTING

Dijkstra's algorithm

Link state: i.e., network topology, link costs

- known to all nodes, accomplished via link state broadcast
  - msg about a node's neighbors sent to every other node in network
- all nodes have same global info

Computes least cost paths

- from one "source" node to all other nodes
- obtain forwarding table for that node

Given path, put 1st hop router for each dst in forwarding table

Iterative

- after k iterations, know least cost path to k destinations
  - if n nodes, loop n times

Dijkstra's algorithm

c(i,j): **link cost** from node i to node j

D(k): **current cost** from source u to destination node k

p(k): **predecessor node** along path from source u to k

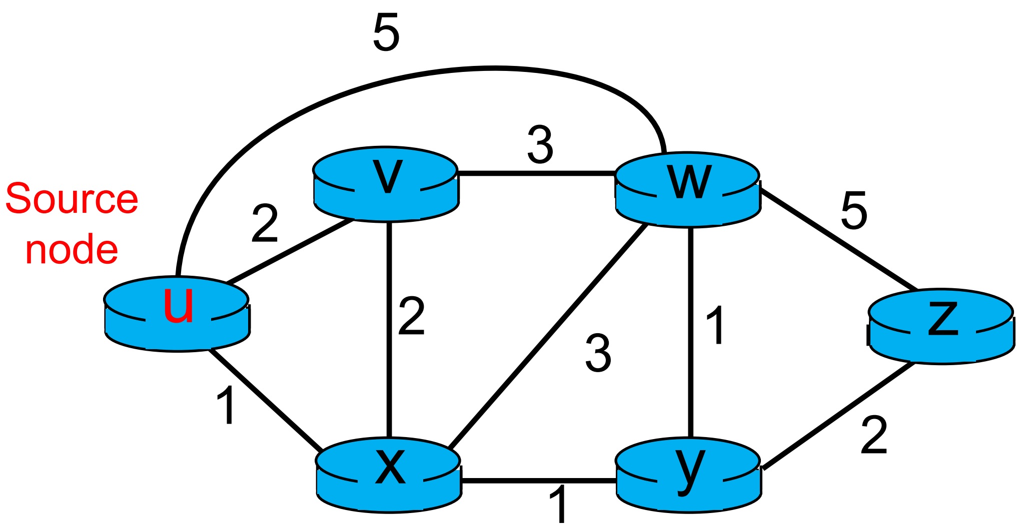
N': set of nodes whose least cost path is **definitively known**

i and j are arbitrary nodes in graph

u will be our starting (aka source) node
k is any arbitrary node

At a give node on path to k, what is node before that node on path?

We don't just know a path to these destinations, we know definitively the least cost path. Essentially building shortest path tree



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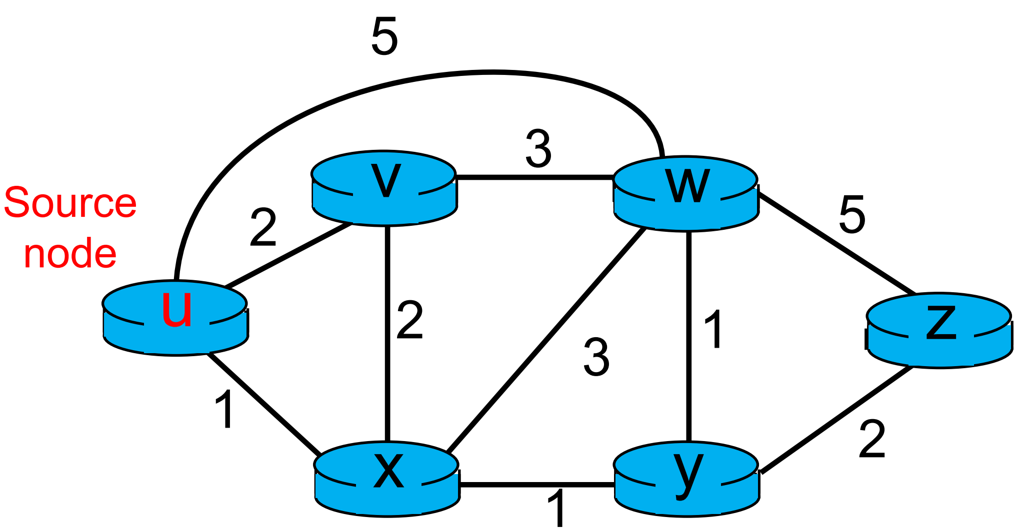

Initialization

N' = {u}

for all nodes j

  if j adjacent to u

   then D(j) = c(u,j)

  else D(j) = ∞

Dijkstra's algorithm

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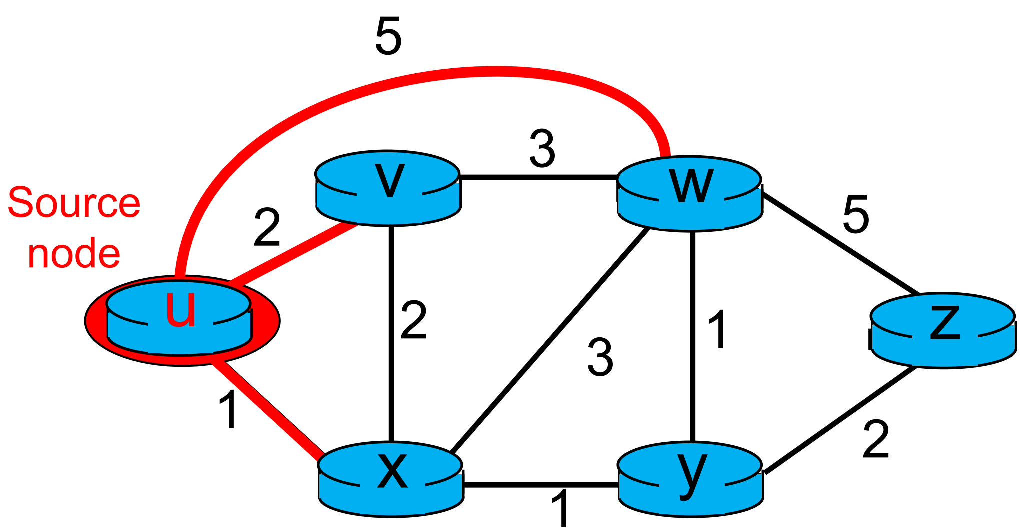
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u					
1						
2						
3						
4						
5						



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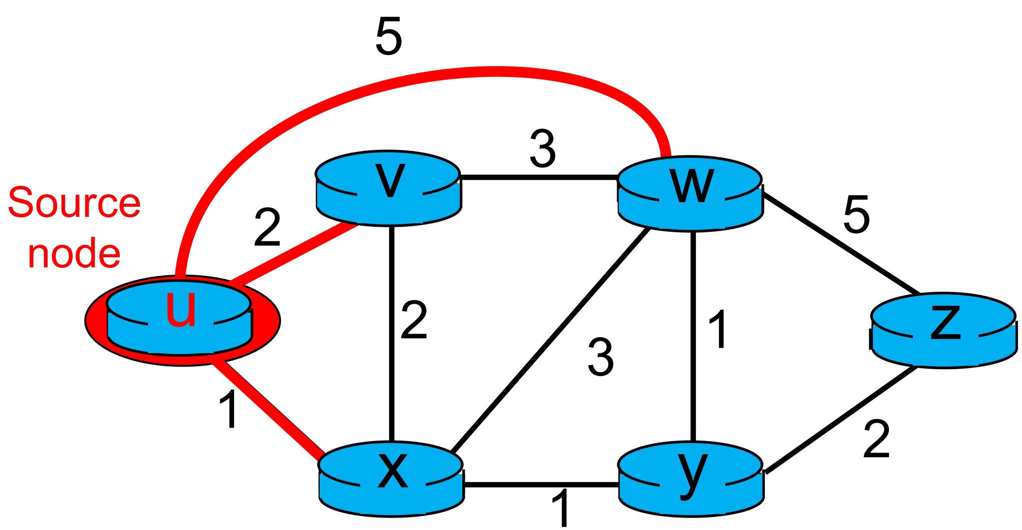
0	u	2,u	5,u	1,u	∞	∞
1						
2						
3						
4						
5						



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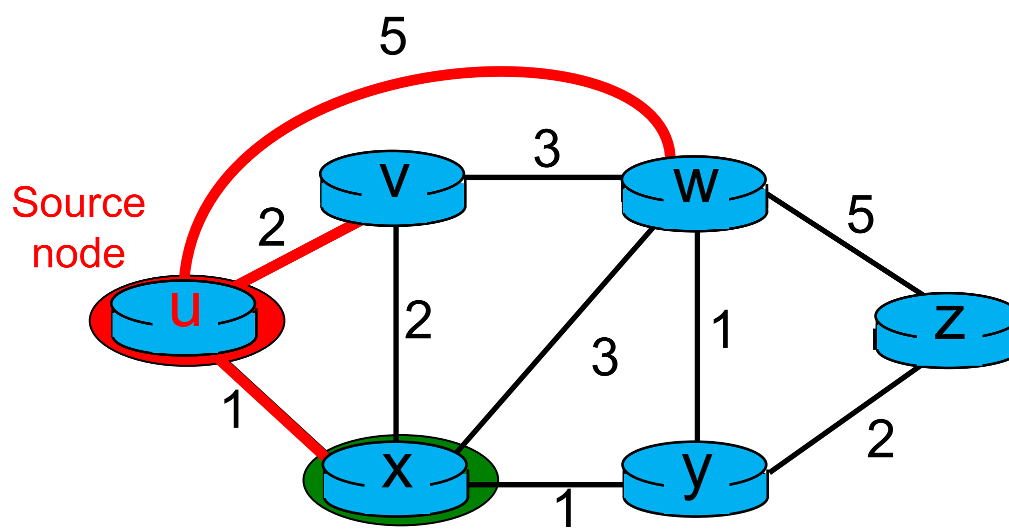
0	u	2,u	5,u	1,u	∞	∞
1	ux					
2						
3						
4						
5						

x is not in N', and D(x) is lowest



Loop

Find j ∉ N' s.t. D(j) is min

Add j to N'

Now we know the *lowest cost path from u to x.* Why?

Any other path from u to x must go through *neighbor of u to get to x.* But we just looked at all neighbors of u

Dijkstra's algorithm

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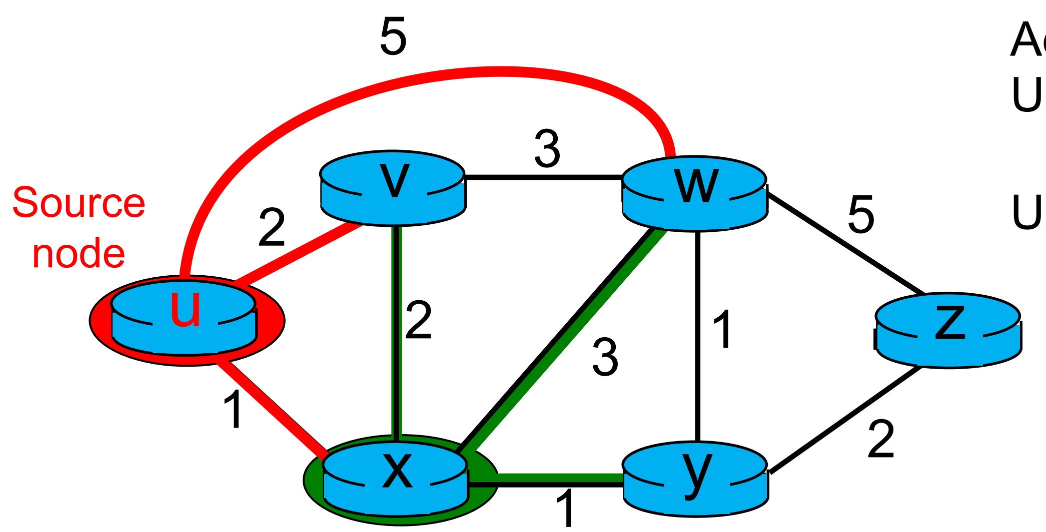
1	ux					
2						
3						
4						
5						



Loop

Find j ∉ N' s.t. D(j) is min

Add j to N'

Update D(k) for all neighbors k ∉ N' of j

D(k) = min(D(k), D(j)+c(j,k))

Until all nodes in N'

Now we check whether any *neighbors of x that are not in N'* can be reached with lower cost path by *first going through x*

Dijkstra's algorithm

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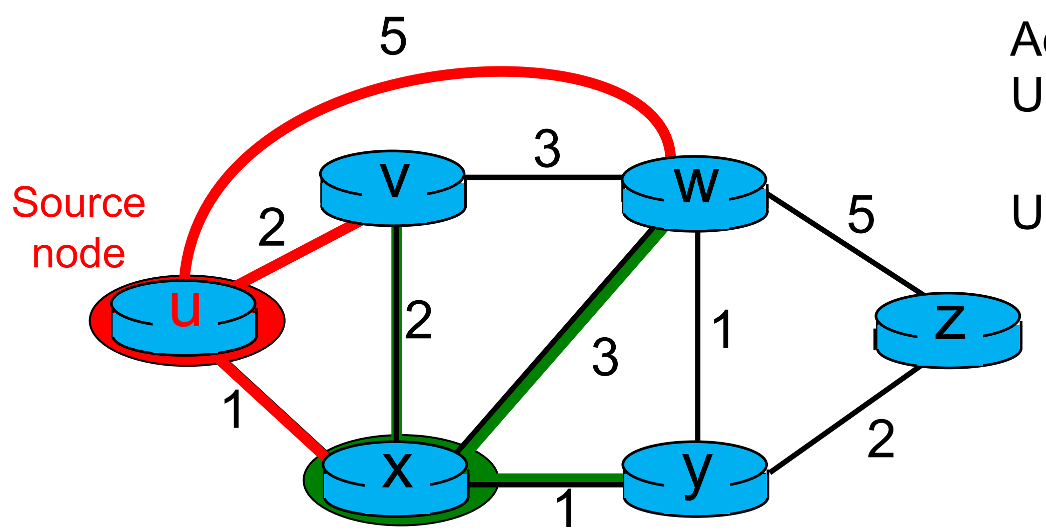
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u				
2		D(v)				
3		= min(D(v), D(x)+c(x,v))				
4		= min(2, 1+2)				
5						



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3 min: compute the updated values of D(v), D(w), D(y)

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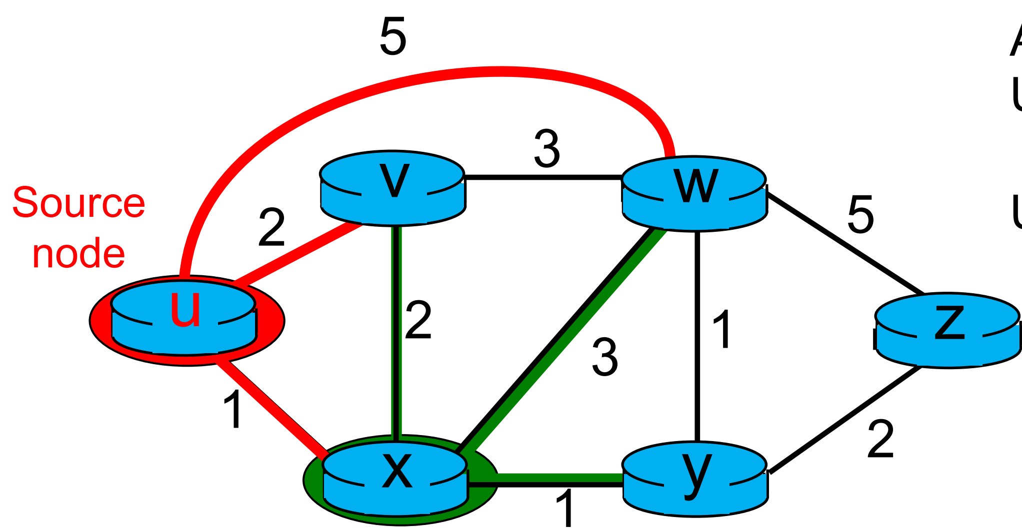
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x			
2						
3						
4						
5						

D(w)
= min(D(w), D(x)+c(x,w))
= min(5, 1+3)



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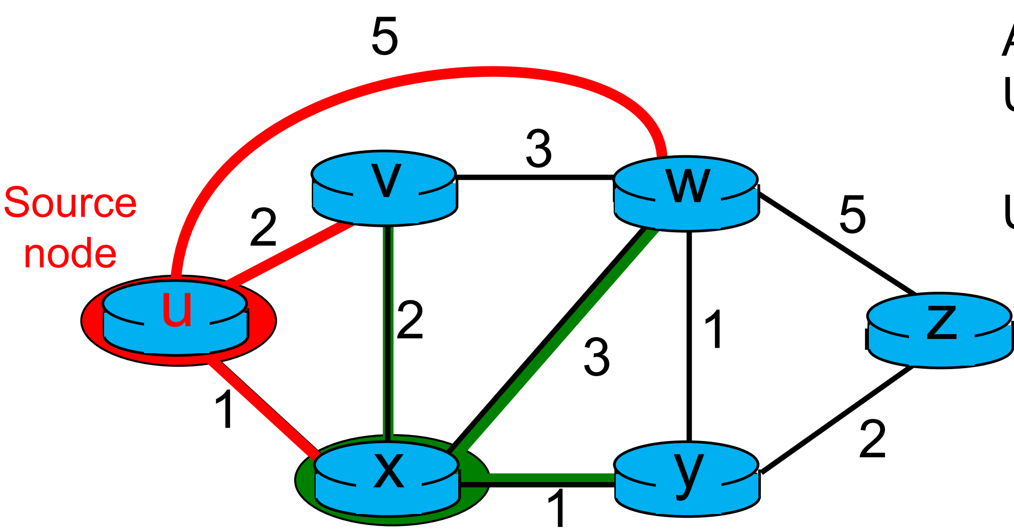
2				x is in N', don't update		
3						
4						
5						



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1	ux	2,u	4,x		2,x	
2						
3						
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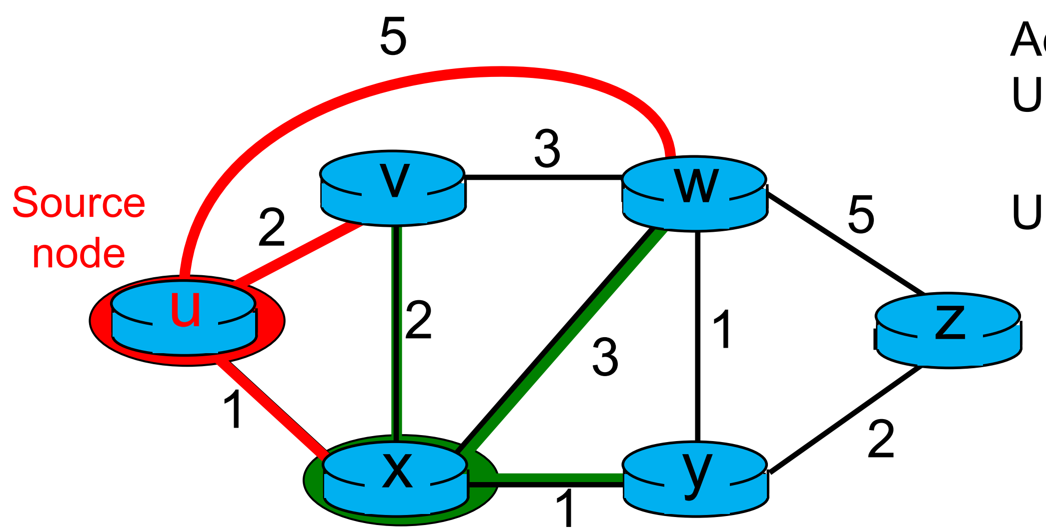
5						

D(y)
= min(D(y), D(x)+c(x,y))
= min(∞, 1+1)



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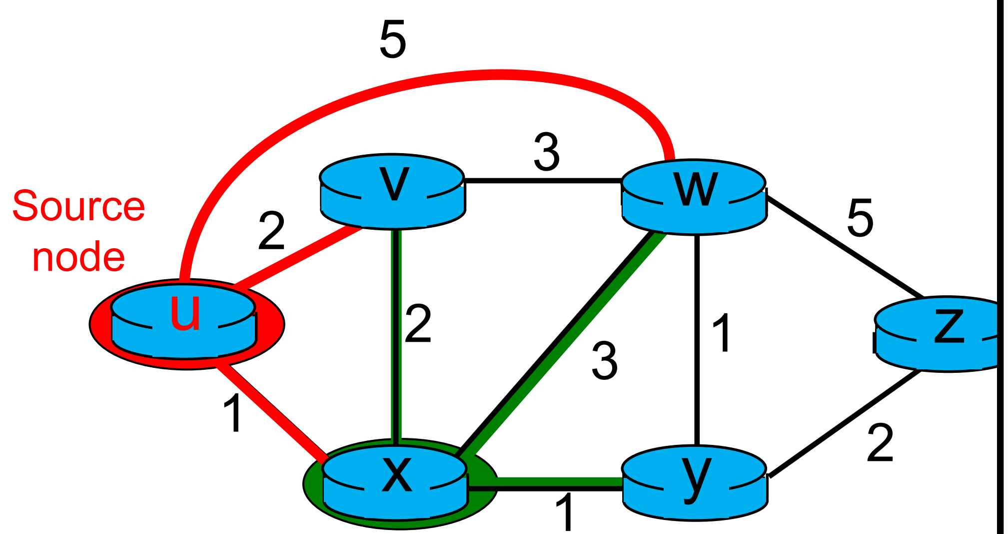
D(z): z is not a neighbor of x so don't update



Now we know the *lowest cost path from u to y.* Why?

Any other path from u to y must go through *neighbor of u but x is lowest cost neighbor.*

And adding on cost from x to y still gives *lower (same) cost than even to just go to other neighbors of u.*

Dijkstra's algorithm

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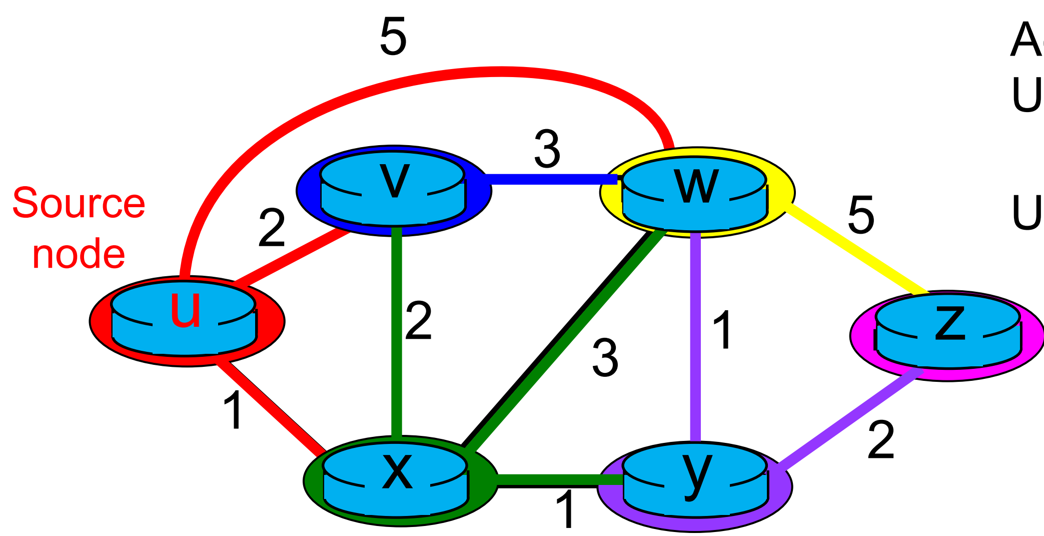
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					



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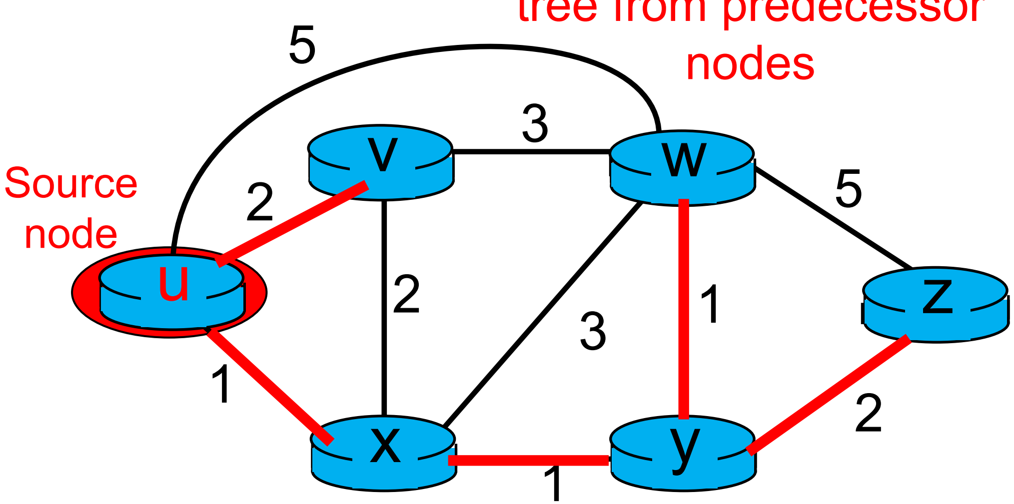
Dijkstra's algorithm

c(i,j): **link cost** from node i to node j
D(k): **current cost** from source u to destination node k
p(k): **predecessor node** along path from source u to k
N': set of nodes whose least cost path is **definitively known**

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

1. Build shortest path tree from predecessor nodes



2. Build forwarding table at u

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

Algorithm complexity with n nodes

Each iteration: need to check all nodes not in N'

- n in 1st iteration, n-1 in 2nd iteration, n-2 in 3rd iteration …
- n(n+1)/2 comparisons: $O(n^2)$, more efficient implementations possible

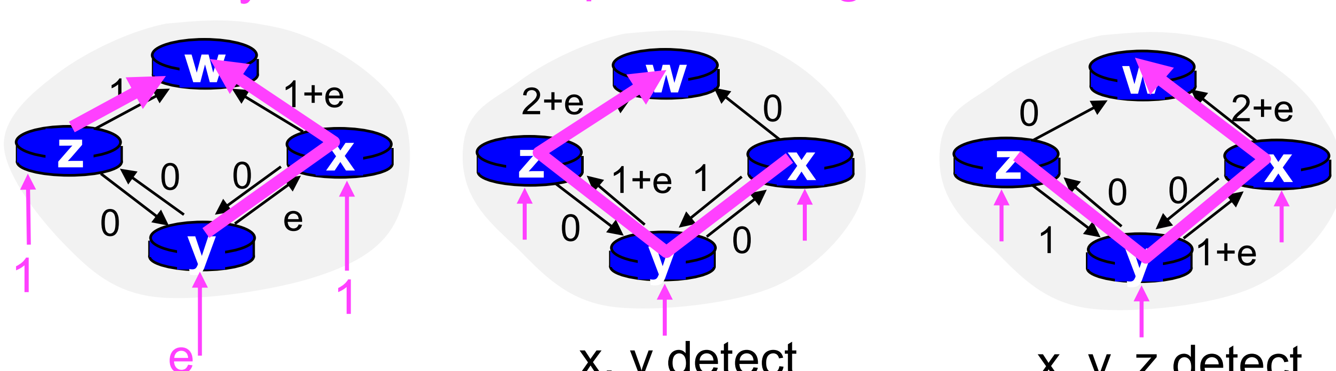
Network is dynamic

- link goes down: link state broadcast
- router goes down: remove link and all nodes recompute

Oscillations possible

- when congestion or delay-based link cost

initially … recompute routing … recompute



x, y detect better path to w

x, y, z detect better path to w

Need to prevent routers from synchronizing computations:
Have routers randomize when they send out link advertisements