-컴퓨터 네트워크-

Layer 3 : Routing

2022 Spring
Kyungseop Shin

Course Outline

- IP layer에서의 forwarding table 생성을 위한 기법에 대해 이해
  - Routing algorithm 기본 개념에 대해 이해
    - Link-state algorithm, Distance-Vector algorithm에 대한 개념 이해
- Internet에서의 routing 메커니즘에 대해 이해

Routing Control Plane

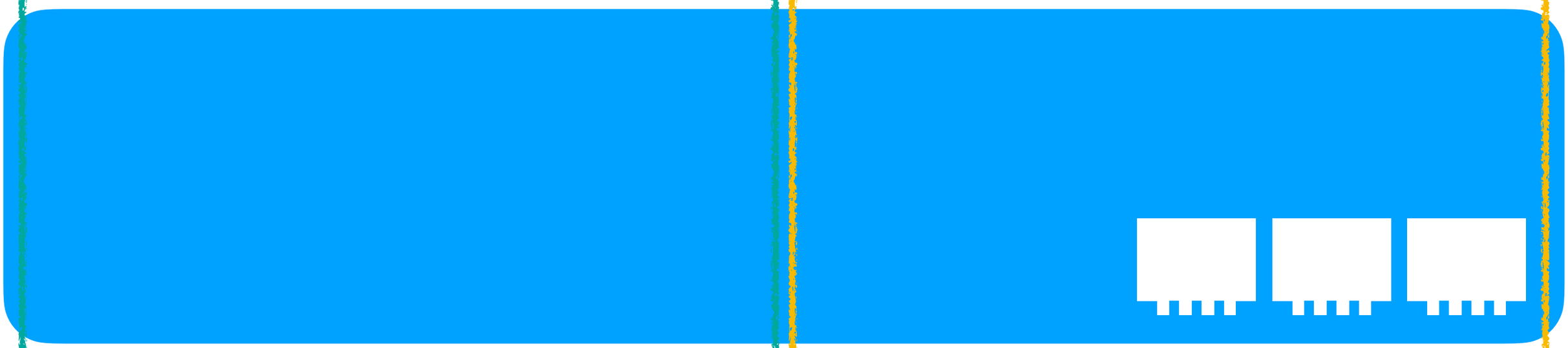
- Router 내의 data/control plane
    - 동작 성격 (Data forwarding / routing)에 따라 기능이 나뉘어짐

Data plane

- **IP header 분석**
- **Datagram forwarding**
- **Fragmentation**

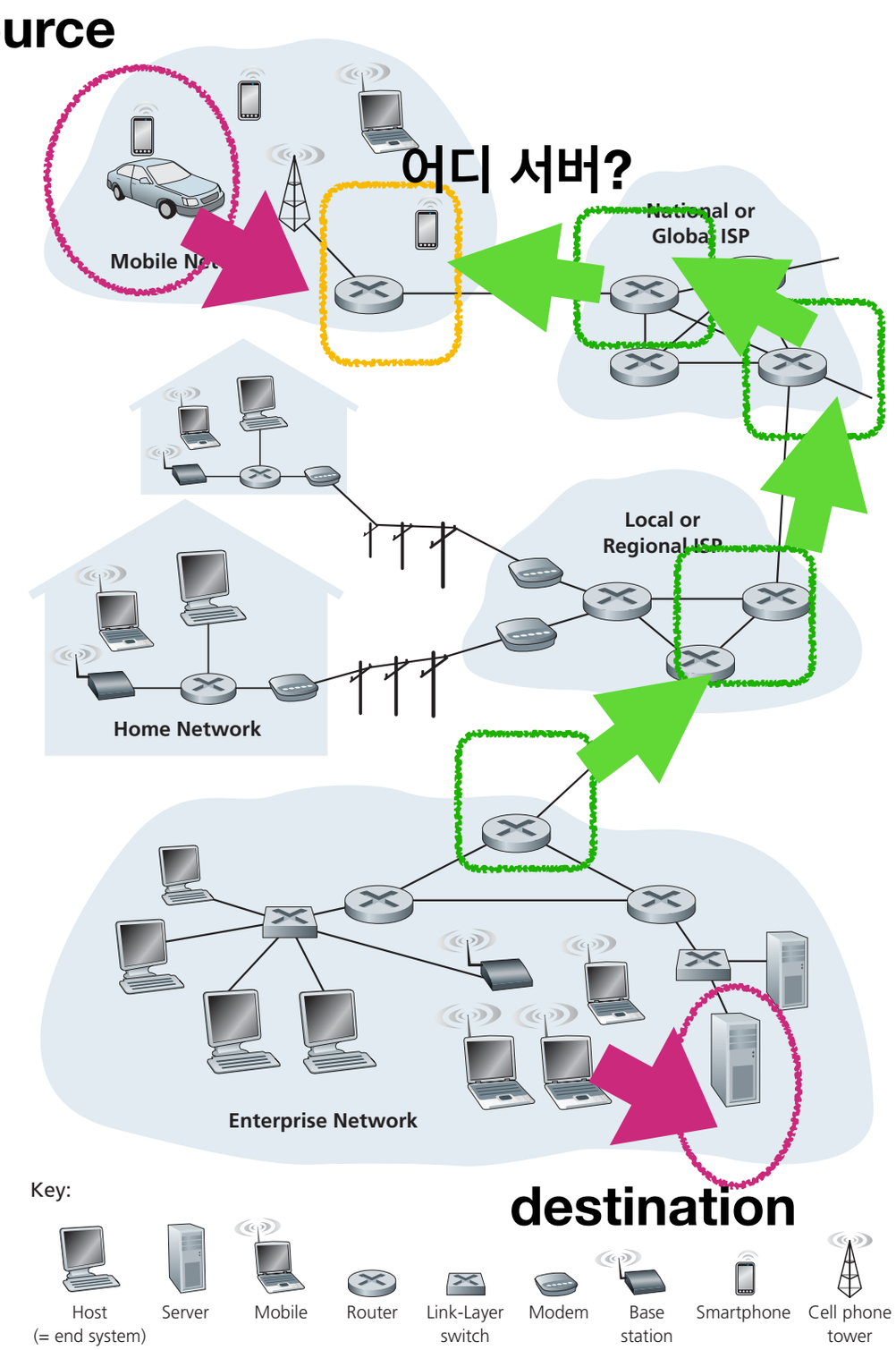
Control plane

- **Routing algorithm**
- **ICMP**



Routing Algorithm

- Router의 forwarding table
  - 입력datagram에 대한 출력 port를 정하기 위해 각 router가 보유한 표
- Routing algorithm
  - Routing table을 만들기 위한 각 router의 동작
  - decentralized

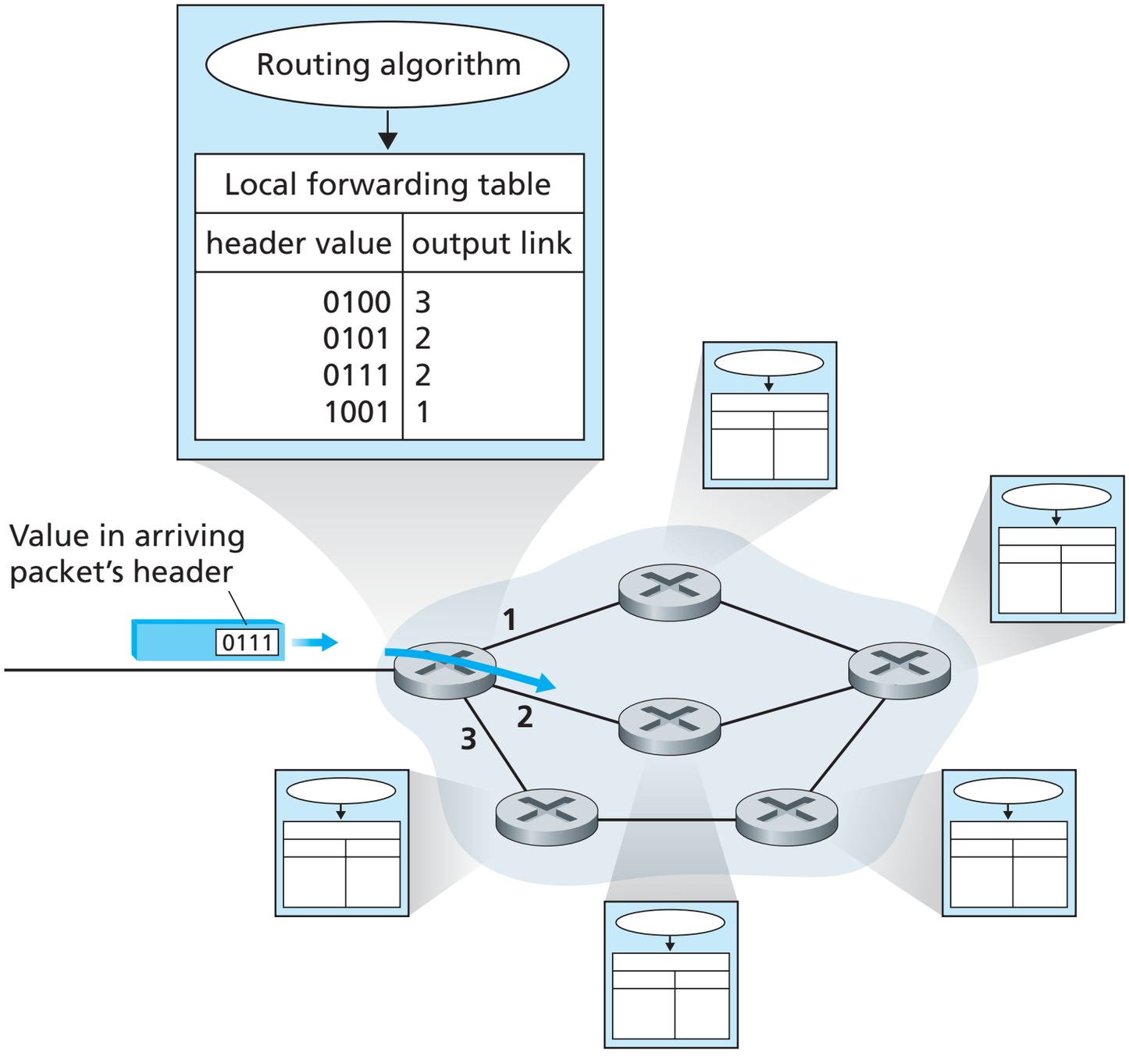


Routing Algorithm

- Control plane (routing algorithm)에 의해 forwarding table 생성

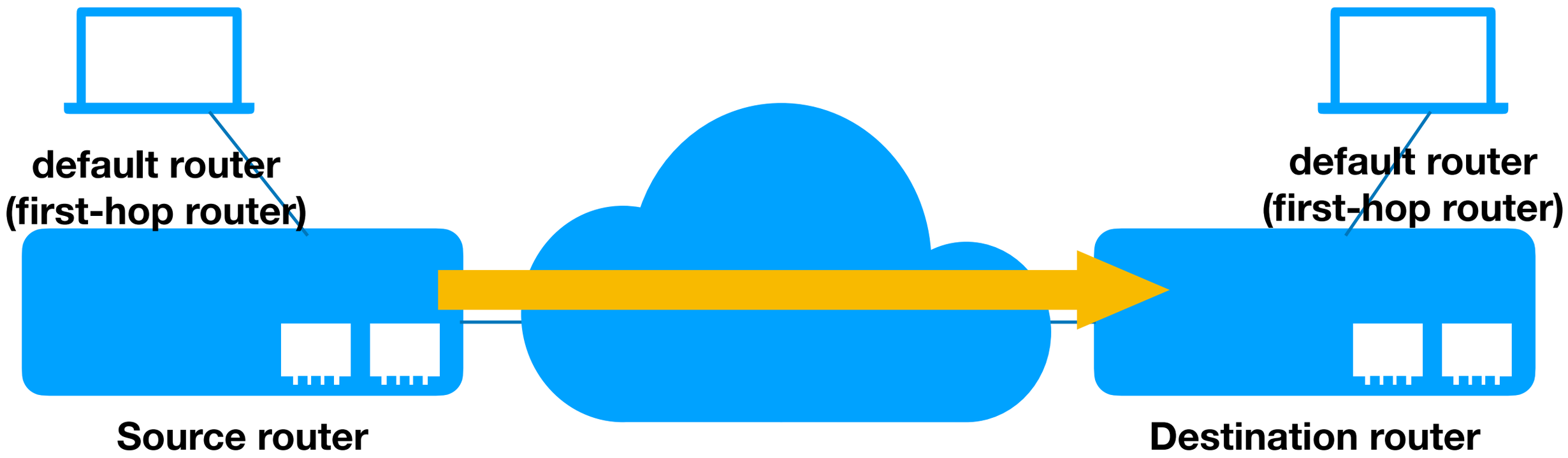
- Data plane에서는 forwarding table을 이용해서 동작

  - 이 IP address 목적지는 어느 port 로 내보내야 궁극적으로 도달하는가?



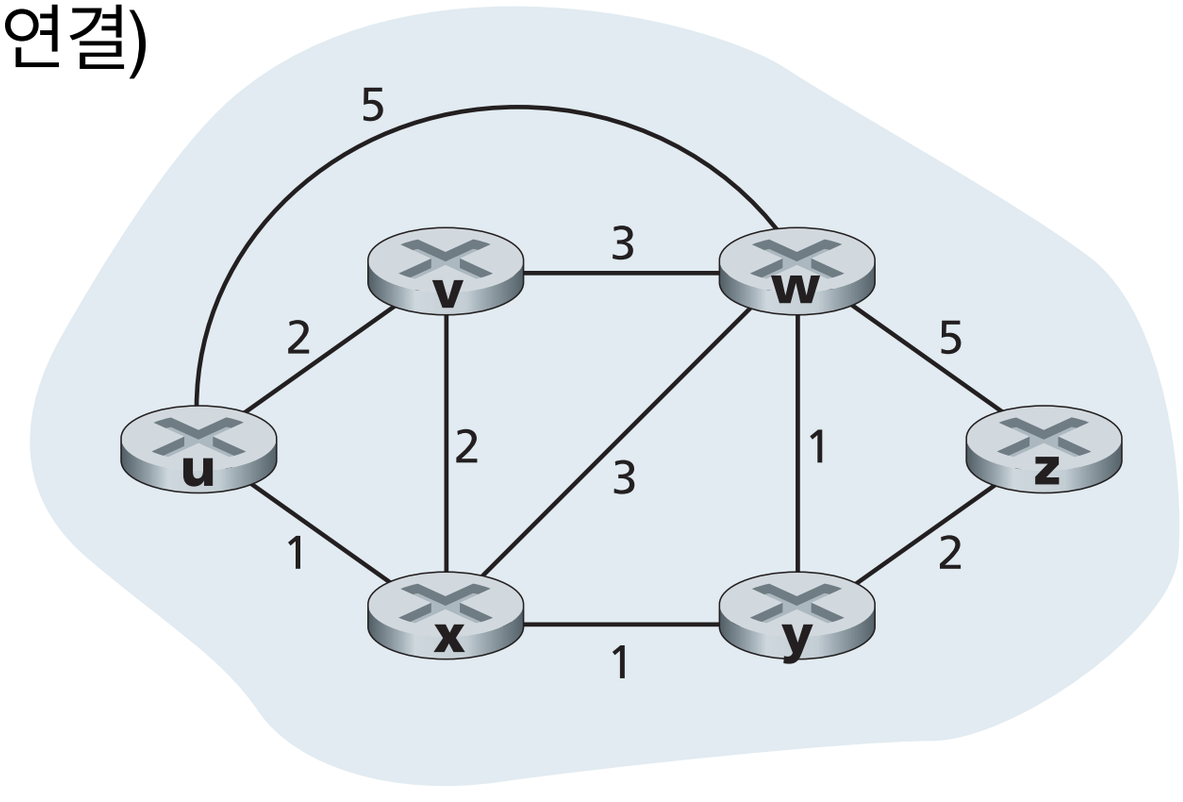
Routing Algorithm

- Routing algorithm의 최종 목적
  - Source router - destination router 간 가장 최적의 경로를 찾는 것



Background

- Routing algorithm은 graph theory를 기본적으로 활용
  - Graph G = (N,E)
    - N : node들의 집합 (router)
    - E : edge들의 집합 (router간 연결)
    - Weight : cost = c(x,y)
      - x,y는 Neighbor
- Path : $(x_1, x_2, \ldots, x_p)$

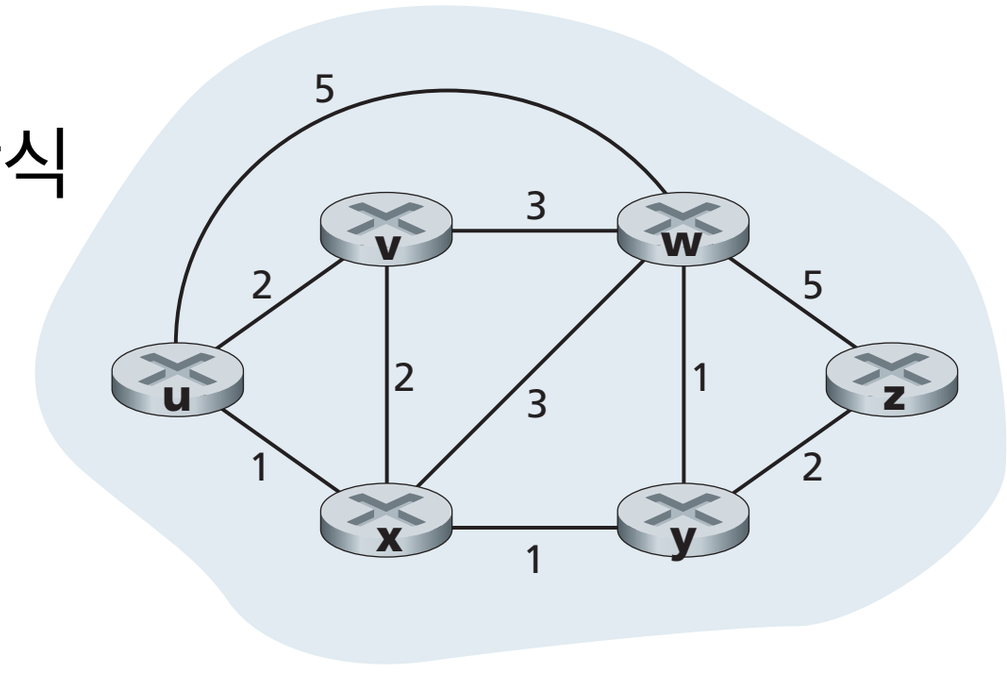


Routing Path

- Least-cost path
  - cost의 합이 최소인 경로 $c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$
    - 앞의 그림에서 u-w의 경우 u-x-y-w
- Shortest path
  - cost를 고려하지 않고 가장 짧은 path
  - 모든 cost가 같은 경우의 least-cost path

Routing Path

- u - z 간 least-cost path를 구하고자 하면
  - 17가지 모든 경우의 수에 대해 해보면 답을 구할 수 있음
    - = Centralized routing algorithm
    - One location, complete information
- Decentralized : router들이 하는 방식



Routing Algorithm 종류 : Global vs. Decentralized

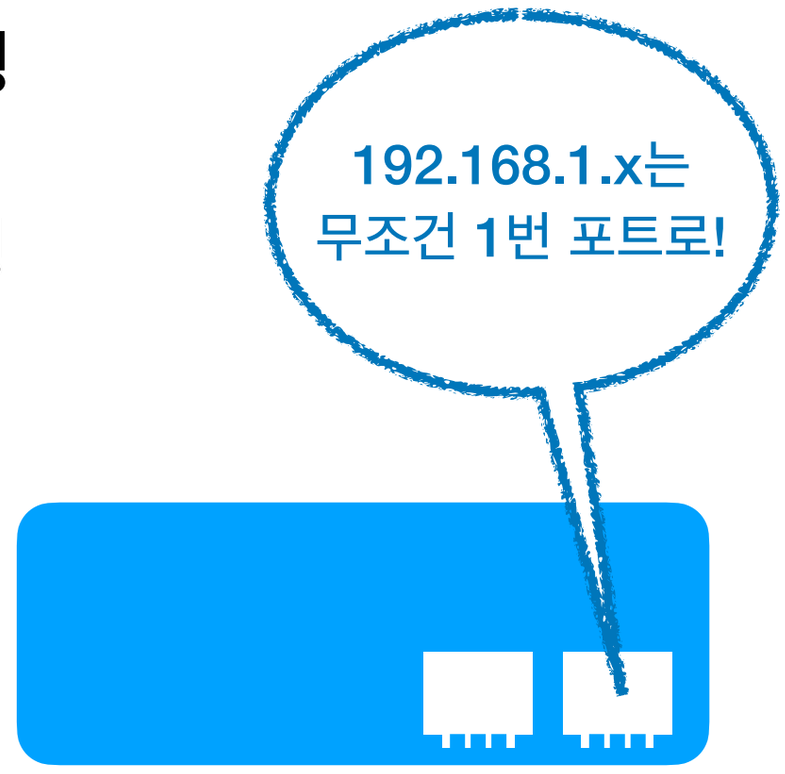
- Global routing algorithm
  - complete/global knowledge about network
    - connectivity, link에 대한 정보
    - Link-state(LS) algorithm
- Decentralized routing algorithm
  - Iterative, distributed manner
  - 특정 node가 모든 link에 대한 정보를 완벽하게 가지지 않으며, 주로 자신과 연결된 link에 대한 정보만 가지고 단계적으로 동작
  - Distance-vector(DV) algorithm

Routing Algorithm 종류 : Static vs. Dynamic

- Static routing algorithms
  - Routing table이 시간에 따라 변하지 않거나 거의 변하지 않음
    - 주로 사람의 조작에 의해서만 변함
- Dynamic routing algorithms
  - Traffic load 및 topology 변화에 의해 자동으로 routing table 이 변함
  - 잘못하면 Routing loop, oscillation 문제가 발생할 여지가 있음

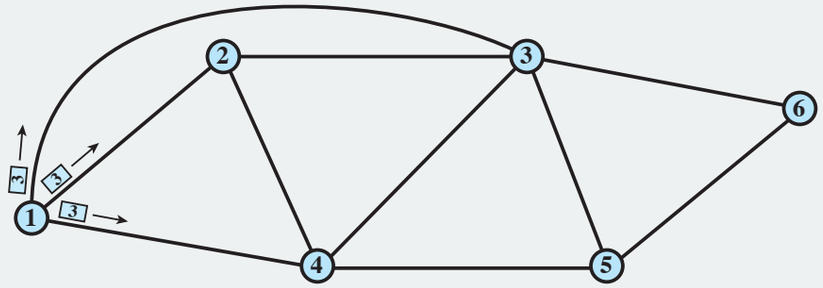
Fixed Routing

- Permanent route : 고정으로 routing 규칙을 지정
  - IP address 특정 대역 등에 대해 out-port 지정
- 활용 시점
  - 전체 관리가 사람에 의해 이루어질 때
  - 부분적으로 고정된 규칙을 적용하고 싶을 때
- 간단하지만 flexibility가 적고 수고가 많이 듬
  - Network failure, congestion 등의 dynamic한 상황에 취약함

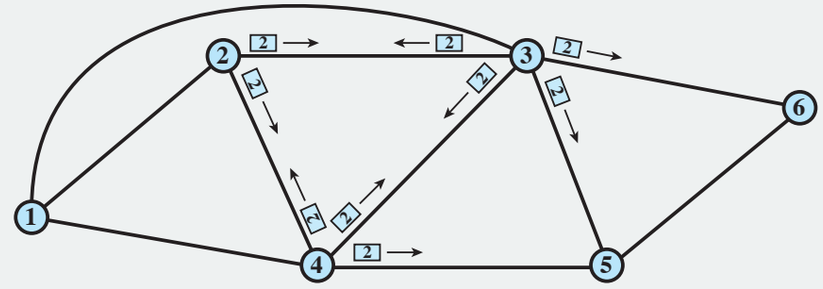


Flooding

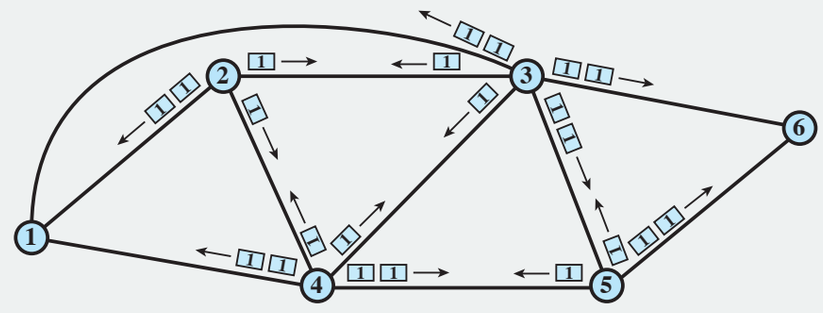
- 모든 neighbor들에게 packet을 무조건 뿌림
- 궁극적으로 destination은 multiple copy 형태로 수신
    - Sequence number를 통해 duplication 방지 가능
- 단순하면서 무식한 방법
    - Routing protocol이나 table등이 필요 없으므로, control plane관점에서 simple함
    - traffic load가 불필요하게 너무 크며 재전송에 대한 제어가 필요



(a) First hop



(b) Second hop



(c) Third hop

Figure 19.3 Flooding Example (hop count = 3)

Link State Routing

- Topology 및 모든 link cost를 파악하고 routing table 생성
  - Link-state broadcast algorithm을 통해 활용
    - 각자의 Identity와 link 별 cost 정보를 neighbor에게 전달
      - 모든 node가 동일한 routing 정보를 공유할 수 있음
- Dijkstra’s algorithm : least-cost path를 iterative하게 파악
  - $D(v)$: cost of the least-cost path from the source node to destination v as of this iteration of the algorithm.
  - $p(v)$: previous node (neighbor of v) along the current least-cost path from the source to v.
  - N' : subset of nodes; v is in N' if the least-cost path from the source to v is definitively known.

Link State Routing

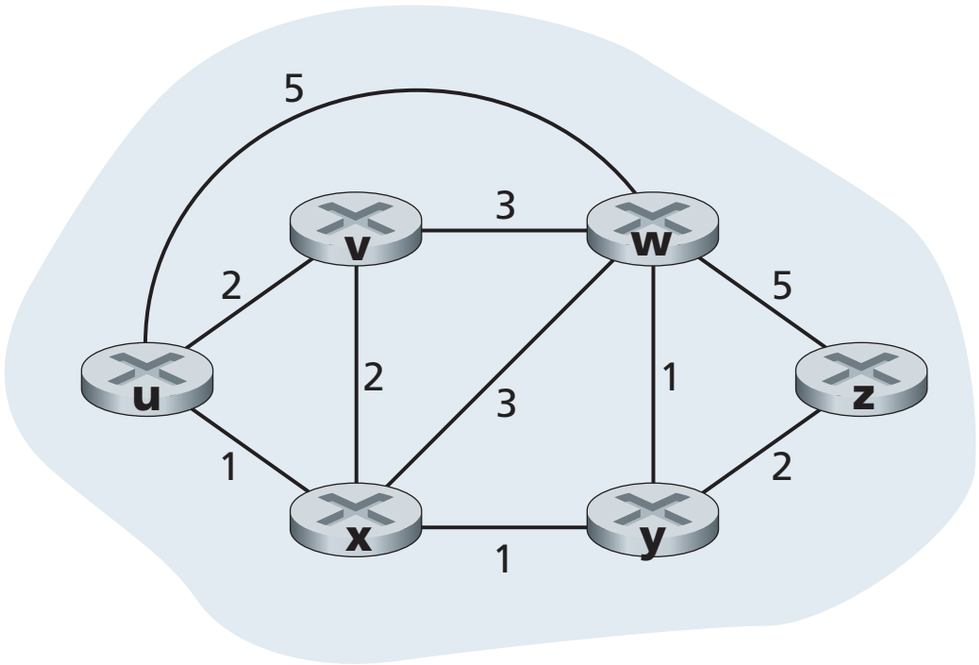
- 순차적으로 node를 넣고 least-cost path를 갱신

Link-State (LS) Algorithm for Source Node *u*

```
1   Initialization:
2     N' = {u}
3     for all nodes v
4       if v is a neighbor of u
5         then D(v) = c(u,v)
6       else D(v) = ∞
7
8   Loop
9     find w not in N' such that D(w) is a minimum
10    add w to N'
11    update D(v) for each neighbor v of w and not in N':
12          D(v) = min( D(v), D(w) + c(w,v) )
13    /* new cost to v is either old cost to v or known
14     least path cost to w plus cost from w to v */
15  until N'= N
```

Link State Routing

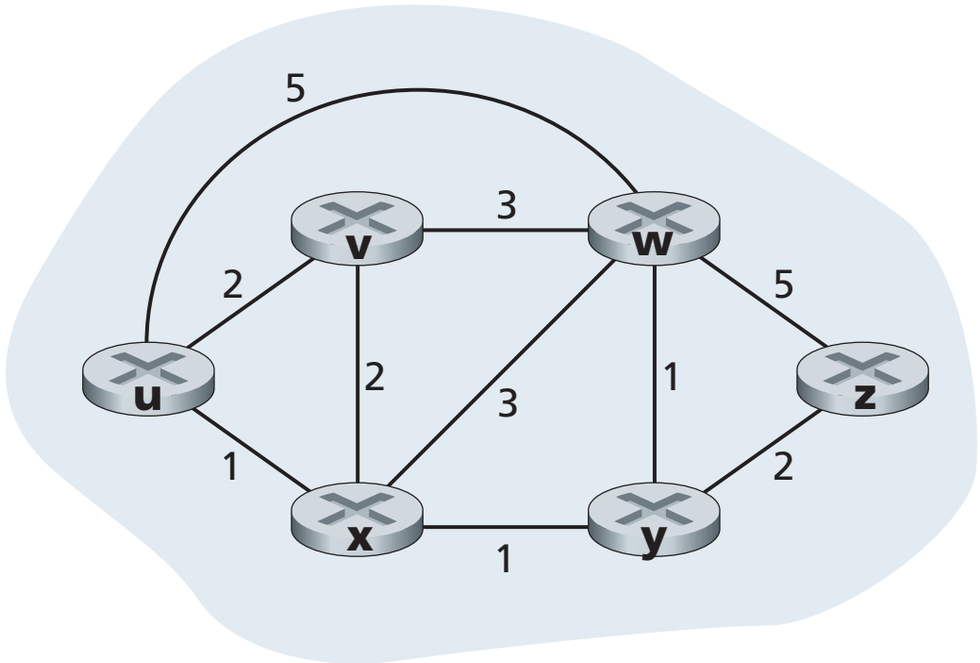
- 예시
  - node가 늘어날수록 D() 값이 줄어듬
  - p를 추적하면 path를 찾을 수 있음

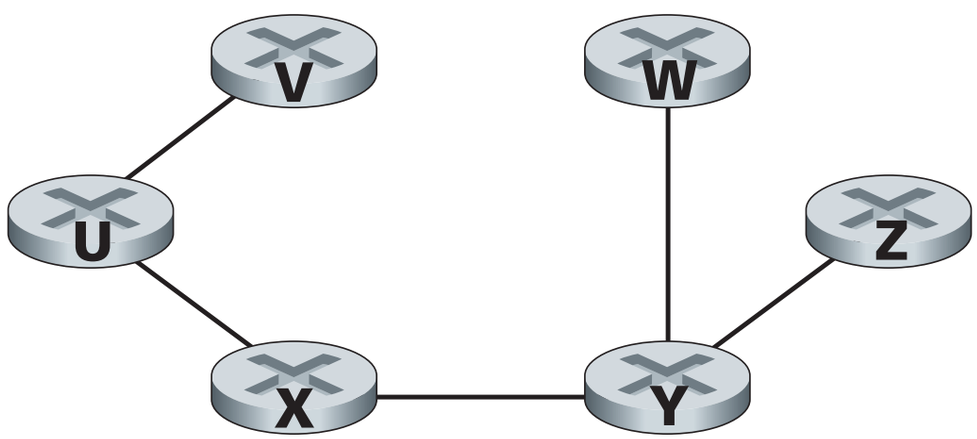


step	N′	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

Link State Routing

- Forwarding table 결과
  - Routing path를 고려하여 destination 별로 out-port 지정

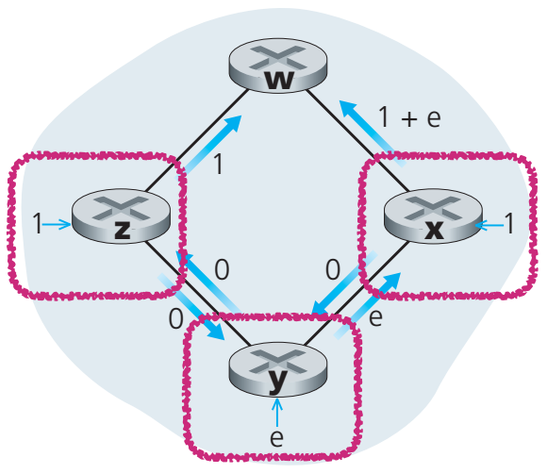




Destination	Link
v	(u, v)
w	(u, x)
x	(u, x)
y	(u, x)
z	(u, x)

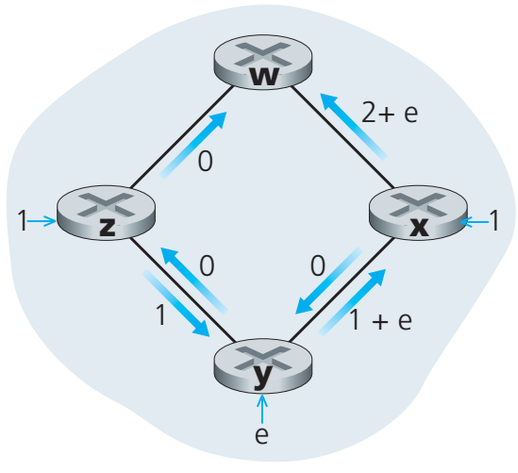
Link State Routing

- Congestion-sensitive routing 과정에서의 oscillation
  - Link cost를 traffic load로 가정하면
- Traffic 상태에 따라 Routing 경로가 안정적이지 못하고 왔다갔다 할수 있음

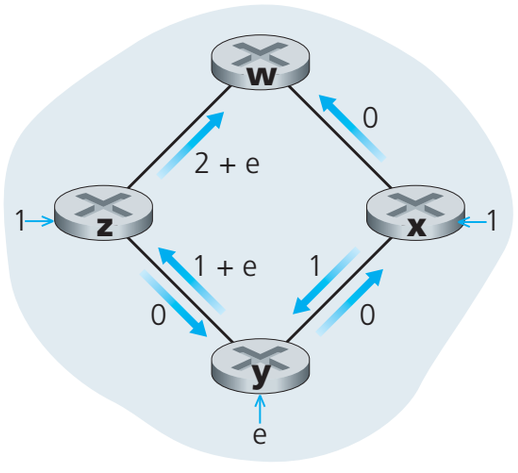


a. Initial routing

b. *x*, *y* detect better path to *w*, clockwise



c. *x*, *y*, *z* detect better path to *w*, counterclockwise



d. *x*, *y*, *z*, detect better path to *w*, clockwise

Distance-Vector Routing

- LS routing과는 다르게 asynchronous / distributed 함
  - Neighbor node끼리만 정보를 주고 받으면서 routing 계산
  - 더이상 neighbor node끼리 정보를 주고 받을 일이 없을 때 까지 iterative하게 정보 교환 / 계산을 반복
  - 각 node가 알아서 정보 교환을 하고 계산 수행
- Bellman-Ford equation 활용

$$d_x(y) = \min_v\{c(x,v) + d_v(y)\},$$

v는 x의 neighbor

→ **Node y에 대한 packet의 forwarding table element**

Distance-Vector Routing

- 기본적인 routing algorithm 방향
  - 각 node x는 Dx(y) 값을 특정 초기값으로 적절히 설정하고
  - Distance vector $\mathbf{D_x}$에 대해 아래 정보를 통해 지속적으로 update

- For each neighbor v, the cost $c(x,v)$ from x to directly attached neighbor, v
- Node x's distance vector, that is, $\boldsymbol{D}_x = [D_x(y): y \text{ in } N]$, containing x's estimate of its cost to all destinations, y, in N
- The distance vectors of each of its neighbors, that is, $\boldsymbol{D}_v = [D_v(y): y \text{ in } N]$ for each neighbor v of x

Distance-Vector Routing

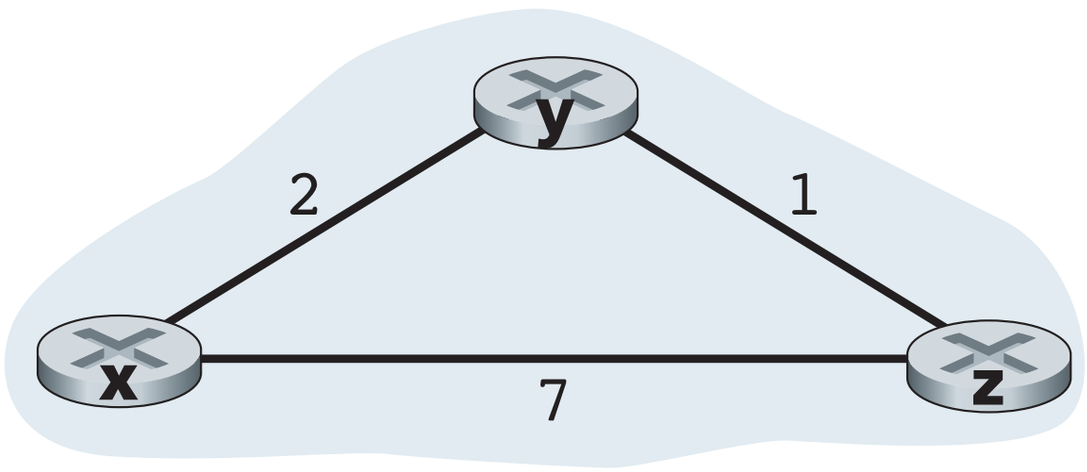
- Neighbor node v로부터 DV를 받으면
  - Bellman-Ford equation에 의해 자신의 DV를 갱신

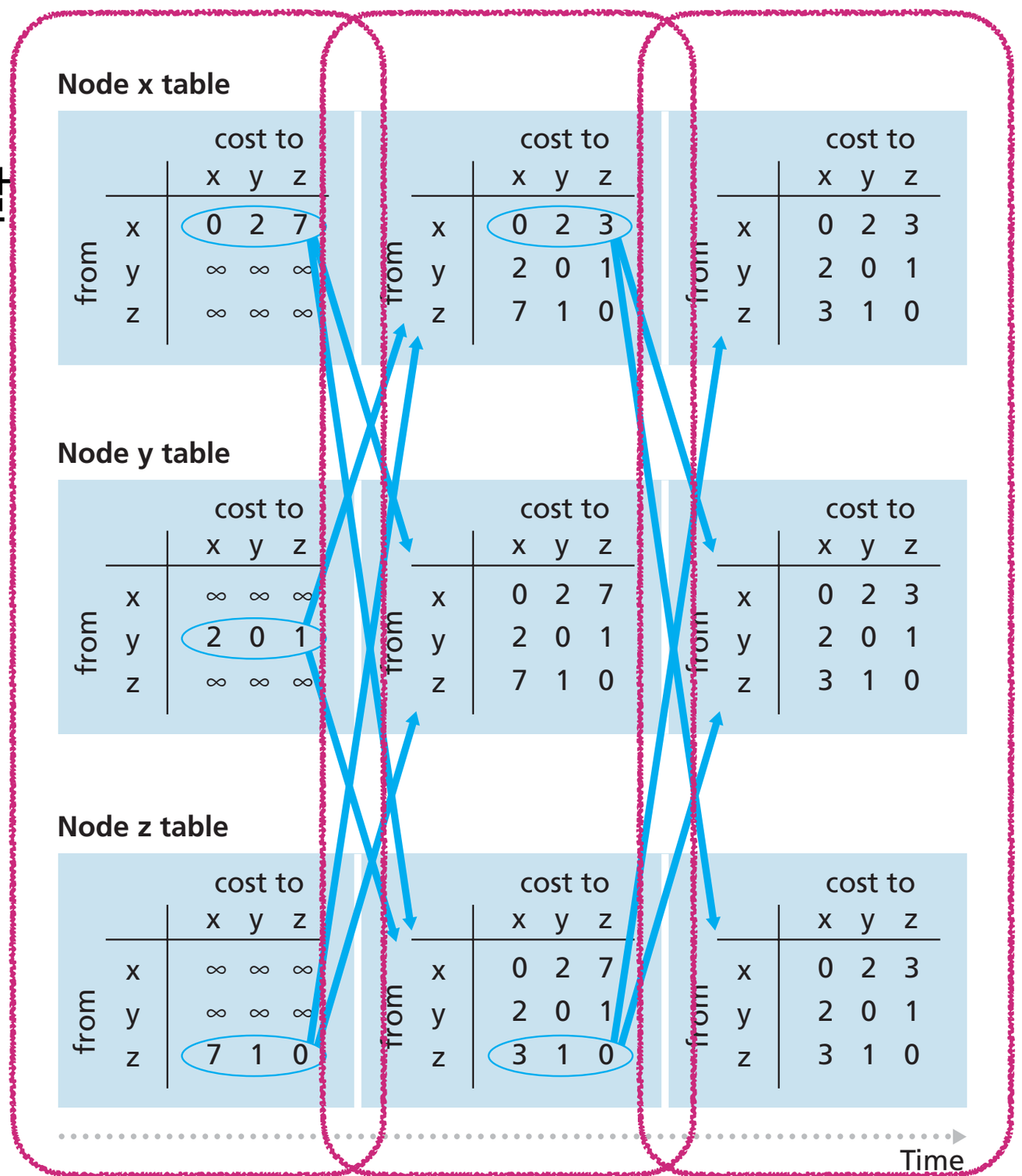
```
1  Initialization:
2     for all destinations y in N:
3        D_x(y) = c(x,y)   /* if y is not a neighbor then c(x,y) = ∞ */
4     for each neighbor w
5        D_w(y) = ? for all destinations y in N
6     for each neighbor w
7        send distance vector D_x = [D_x(y): y in N] to w
8
9  loop
10    wait (until I see a link cost change to some neighbor w or
11          until I receive a distance vector from some neighbor w)
12
13    for each y in N:
14       D_x(y) = min_v{c(x,v) + D_v(y)}
15
16    if D_x(y) changed for any destination y
17       send distance vector D_x = [D_x(y): y in N] to all neighbors
18
19 forever
```

Distance-Vector Routing

- 이웃의 DV정보만 이용하며 DV 정보 교환을 각 node가 알아서 asynchronous하게 함

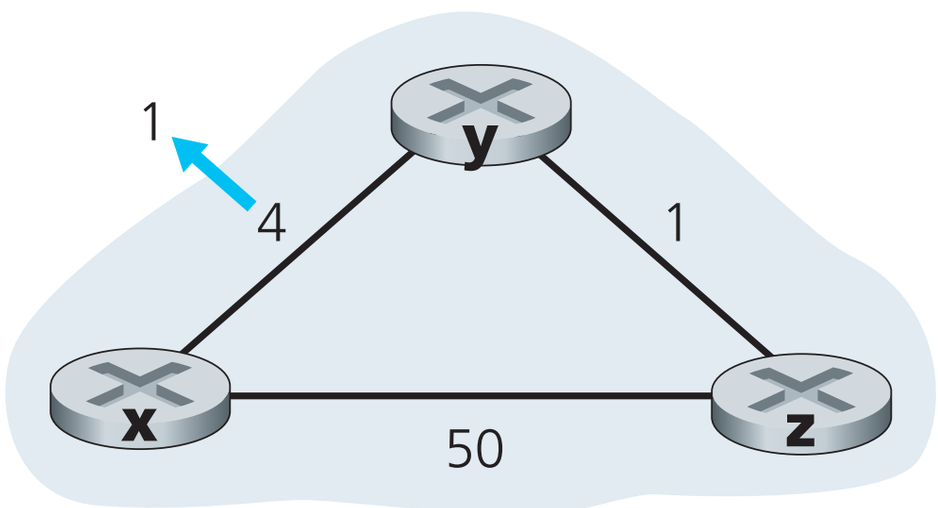
- 예시





Distance-Vector Routing

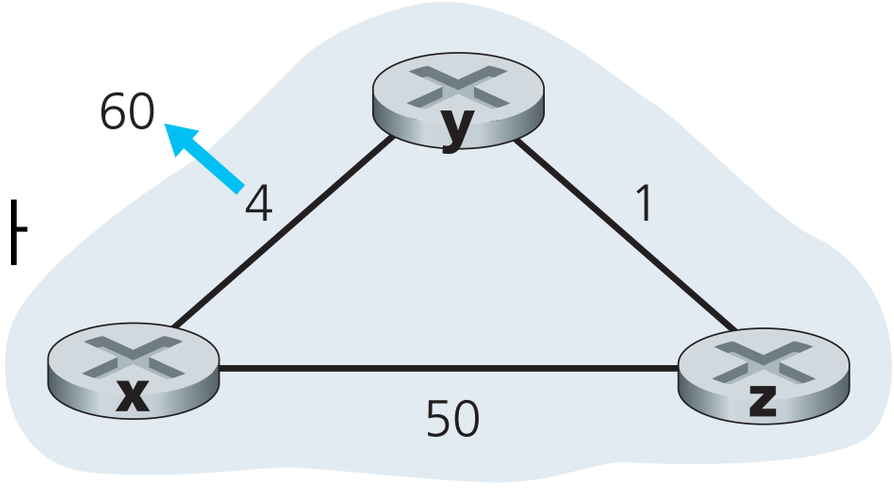
- Link-cost change 1 : cost reduced
  - t_0 : y detects cost change (4 -> 1)
  - t_1 : z receives update ($D_z(x)$: 5 -> 2)
  - t_2 : y receives update (no change)



a.

Distance-Vector Routing

- Link-cost change 2 : cost increased $, D_y(x) = 4, D_y(z) = 1, D_z(y) = 1, \text{ and } D_z(x) = 5$
  - t_0 : y detects (4 -> 60), $D_y(x) = D_y(z) + D_z(x) = 6$
  - t_1 : z receives update ($D_z(x)$: 5 -> 7)
    - Routing loop
- t_2 : y receives update ($D_y(x)=7$)
- 이후 link cost가 50이 될 때까지 1씩 증가
  - ==> To much iterations



b.

Link State vs. Distance-Vector

- DV : 인접 node끼리만 정보 교환, 정보 내용은 모든 node에 대한 cost
- LS : 모든 node와 정보 교환, 정보 내용은 인접 node에 대한 cost
- Message complexity
    - LS 는 많은 메시지 전송이 필요, DV는 link cost 변화 빈도에 따라 메시지 전송 횟수 증가
- Speed of convergence : DV가 convergence 속도가 느림
- Robustness : LS는 각자 routing을 계산하는 방식이라 더 안정적임

Hierarchical Routing

- 실제 Internet은 sub-network와 gateway router 형태로 계층적으로 네트워크를 형성
  - Subnet간 packet routing은 gateway router를 통해서만 이루어짐
- Autonomous System (AS) : 한 기관이 관리하는 router 및 network 모음
  - 동일한 routing protocol에 의해 밀접하게 동작
- Intra vs. inter-AS routing

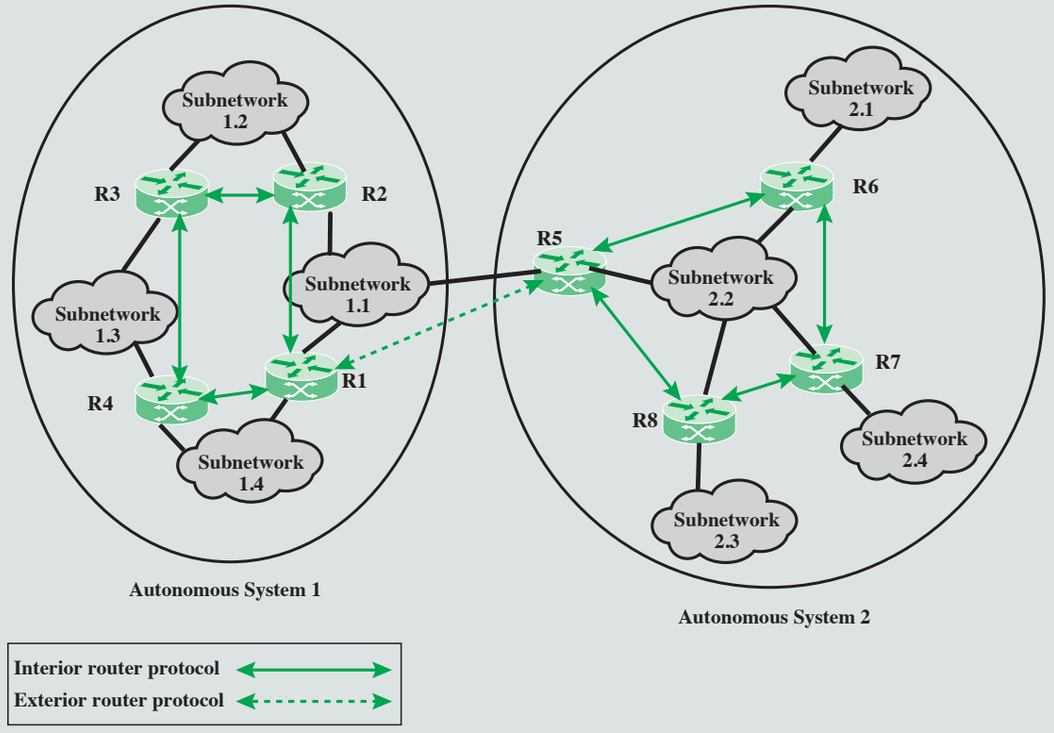
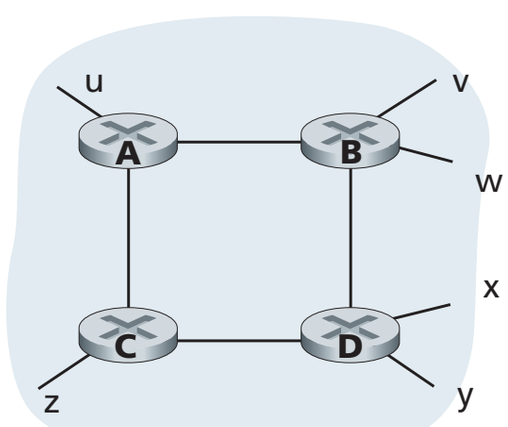


Figure 19.9 Application of Exterior and Interior Routing Protocols

Routing Information Protocol (RIP)

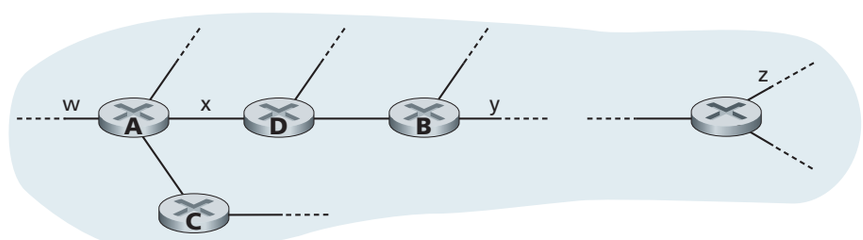
- intra-AS routing에 주로 활용되는 routing algorithm
- Distance-vector protocol에 속하며, link cost가 모두 1
  - Hop count가 cost metric임 (max cost : 15)
- RIP response/advertisement message (30초에 한번 전송)



Destination	Hops
u	1
v	2
w	2
x	3
y	3
z	2

Routing Information Protocol (RIP)

- Routing table : distance vector 및 forwarding table
- Routing advertisement message 수신 후
  - Routing 정보 갱신



Destination Subnet	Next Router	Number of Hops to Destination
z	C	4
w	—	1
x	—	1
. . . .	. . . .	. . . .

Destination Subnet	Next Router	Number of Hops to Destination
w	A	2
y	B	2
z	B	7
x	—	1
. . . .	. . . .	. . . .

Destination Subnet	Next Router	Number of Hops to Destination
w	A	2
y	B	2
z	A	5
. . . .	. . . .	. . . .

Routing Information Protocol (RIP)

- 180초 이상 routing advertisement message 수신이 없으면
  - No longer reachable이라 판단
    - Routing table 을 수정하고 advertisement를 보냄
- RIP request message : 특정 destination에 대한 neighbor’s cost를 요청 (UDP, port 520)

Open Shortest Path First (OSPF)

- RIP의 다음 버전이며, 여러가지 개선된 기능을 가짐
- Dijkstra least-cost path algorithm 기반이며, link state에 대한 flooding 활용
    - Complete topological map을 기반으로 모든 subnet에 대한 shortest-path 계산
    - Link cost는 network administrator가 지정하기 나름이며, 모든 link cost를 1로 설정하면 minimum-hop routing이 됨
- 모든 router에게 link state information을 broadcasting함
    - robustness를 위해서 link change가 없어도 최소한 30분에 한번 수행

Border Gateway Protocol (BGP)

- Internet에서의 Exterior router protocol
  - AS 간 routing을 위한 protocol
- 아래 세가지 역할 수행
  - 인접 AS간 subnet reachability information 교환
  - Reachability 정보에 대해 AS내 router에게 전달
  - subnet에 대한 routing 결정

Key Design Issue

- Routing performance
  - Correctness, Optimality
- Low control overhead
  - Simplicity, Efficiency
- Robustness, Stability, Fairness