Packet Switching

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- Routing algorithms
  - Dijkstra's Algorithm
  - Bellman-Ford Algorithm
- ARPAnet routing

Routing

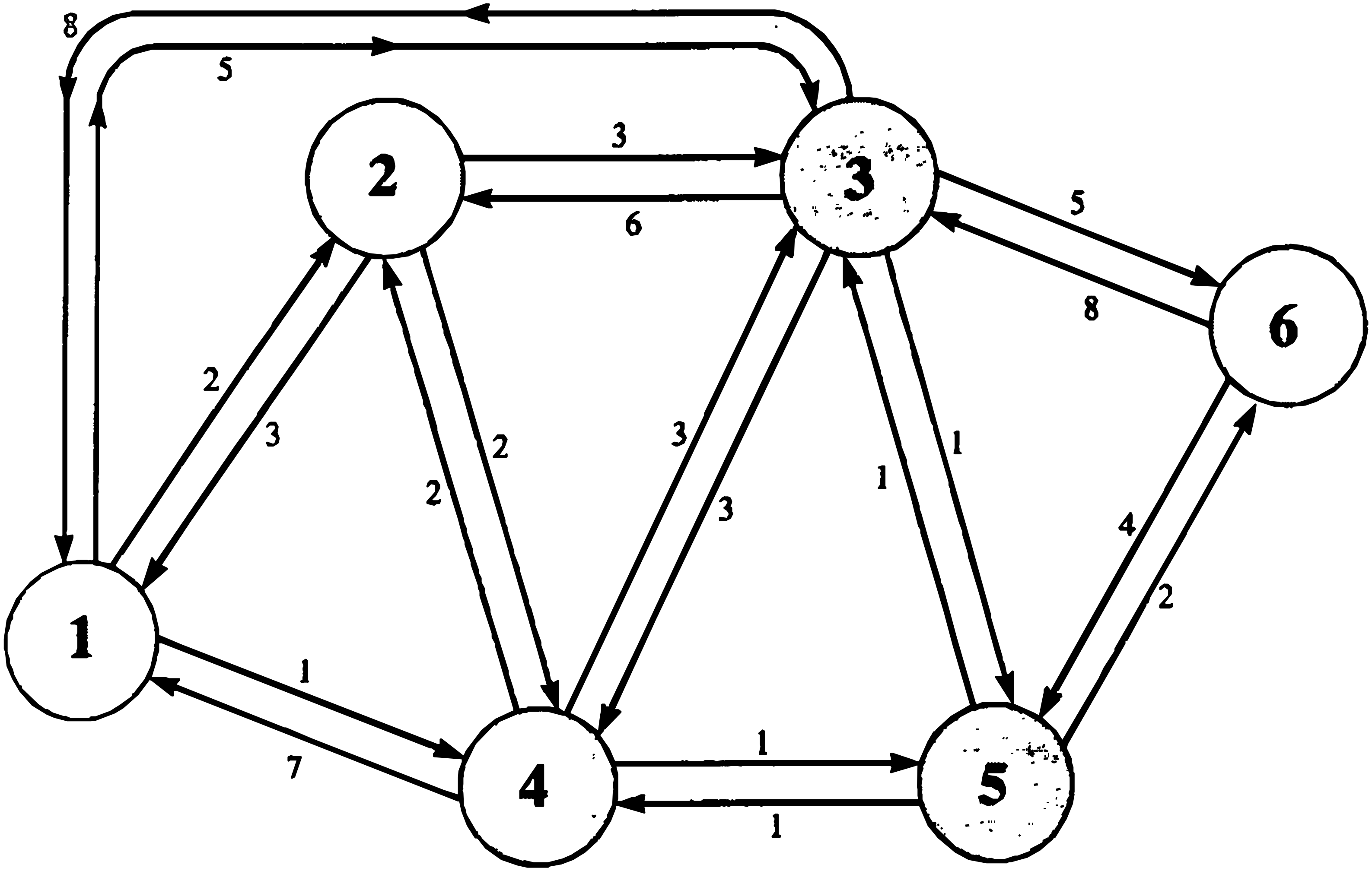


Fig 9.5

Rooting or Routing

- *Rooting* is what fans do at football games, what pics do for truffles under oak trees in the Vaucluse, and what nursery workers intent on propagation do to cuttings from plants.
- *Routing* is how one creates a beveled edge on a table top or sends a corps of infanctrymen into full scale, disorganized retreat

Ref: Piscitello and Chapin, p413

Routeing or Routing

- Routeing: British
- Routing: American
- Since Oxford English Dictionary is much heavier than any other dictionary of American English, British English generally prevalis in the documents produced by ISO and CCITT; wherefore, most of the international standards for routing standards use the routeing spelling.

Ref: Piscitello and Chapin, p413

Routing Techniques Elements

- **Performance criterion**: *Hops*, Distance, *Speed*, Delay, Cost
- **Decision time**: *Packet*, session
- **Decision place**: *Distributed*, centralized, Source
- **Network information source**: None, local, *adjacent nodes*, nodes along route, all nodes
- **Routing strategy**: Fixed, *adaptive*, random, flooding
- **Adaptive routing update time**: Continuous, *periodic*, *topology change*, major load change

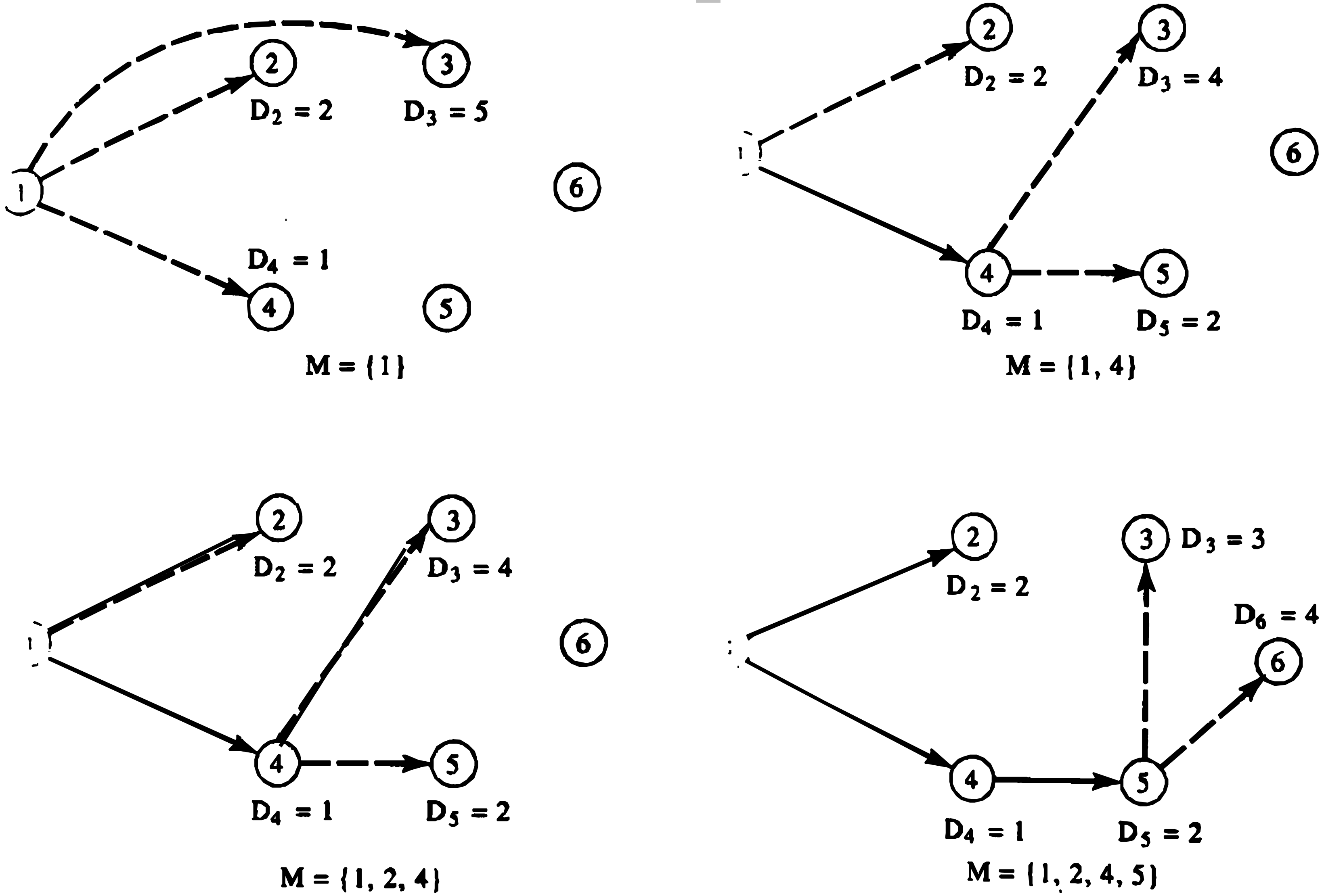
Distance Vector vs Link State

- **Distance Vector**: Each router sends a vector of distances to its neighbors. The vector contains distances to all nodes in the network.
  Older method. Count to infinity problem.
- **Link State**: Each router sends a vector of distances to all nodes. The vector contains only distances to neighbors. Newer method. Used currently in internet.

Dijkstra's Algorithm

- Goal: Find the least cost paths from a given node to all other nodes in the network
- Notation:
  d_{ij} = Link cost from i to j if i and j are connected
  D_n = Total path cost from s to n
  M = Set of nodes so far for which the least cost path is known
- Method:
  - Initialize: M={s}, $D_n = d_{sn}$
  - Find node w $\notin$ M, whose Dn is minimum
  - Update D_n

Example


$D_2 = 2$
$D_3 = 5$
$D_4 = 1$
$M = \{1\}$
$D_2 = 2$
$D_3 = 4$
$D_4 = 1$
$D_5 = 2$
$M = \{1, 4\}$
$D_2 = 2$
$D_3 = 4$
$D_4 = 1$
$D_5 = 2$
$M = \{1, 2, 4\}$
$D_2 = 2$
$D_3 = 3$
$D_6 = 4$
$D_4 = 1$
$D_5 = 2$
$M = \{1, 2, 4, 5\}$

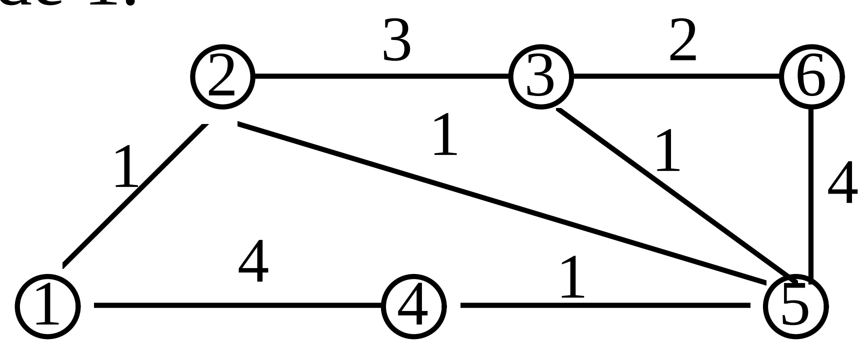
Example (Cont)

	M	D2	Path	D3	Path	D4	Path	D5	Path	D6	Path
1	{1}	2	1-2	5	1-3	1	1-4	∞	-	∞	-
2	{1,4}	2	1-2	4	1-4-3	1	1-4	2	1-4-5	∞	-
3	{1,2,4}	2	1-2	4	1-4-3	1	1-4	2	1-4-5	∞	-
4	{1,2,4,5}	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6
5	{1,2,3,4,5}	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6
6	{1,2,3,4,5,6}	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6

Table 9.4a

Dijkstra's Routing Algorithm

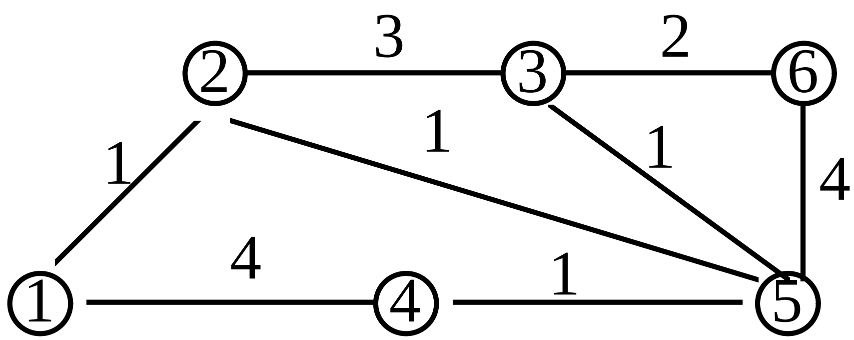
- Apply to the following network and compute paths from node 1.



	M	D2	Path	D3	Path	D4	Path	D5	Path	D6	Path
1											
2											
3											
4											
5											
6											

Dijkstra's routing algorithm

- Apply to the following network and compute paths from node 1.



	M	D2	Path	D3	Path	D4	Path	D5	Path	D6	Path
1	{1}	1	1-2	∞	-	4	1-4	∞	-	∞	-
2	{1,2}	1	1-2	4	1-2-3	4	1-4				
3	{1,2,3}	1	1-2	4	1-2-3	4	1-4	2	1-2-5	6	1-2-3-6
4	{1,2,3,5}	1	1-2	4	1-2-3	3	1-2-5-1	2	1-2-5	6	1-2-3-6
5	{1,2,3,4,5}	1	1-2	4	1-2-3	3	1-2-5-1	2	1-2-5	6	1-2-3-6
6	{1,2,3,4,5,6}	1	1-2	4	1-2-3	3	1-2-5-1	2	1-2-5	6	1-2-3-6

Bellman-Ford Algorithm

- Notation:
  h = Number of hops being considered
  $D^{(h)}_n$ = Cost of h-hop path from s to n
- Method: Find all nodes 1 hop away
  Find all nodes 2 hops away
  Find all nodes 3 hops away
  - Initialize: $D^{(h)}_n = \infty$ for all $n \neq s$; $D^{(h)}_n = 0$ for all h
  - Find jth node for which h+1 hops cost is minimum
    $D^{(h+1)}_n = \min_j [D^{(h)}_j + d_{jn}]$

Example

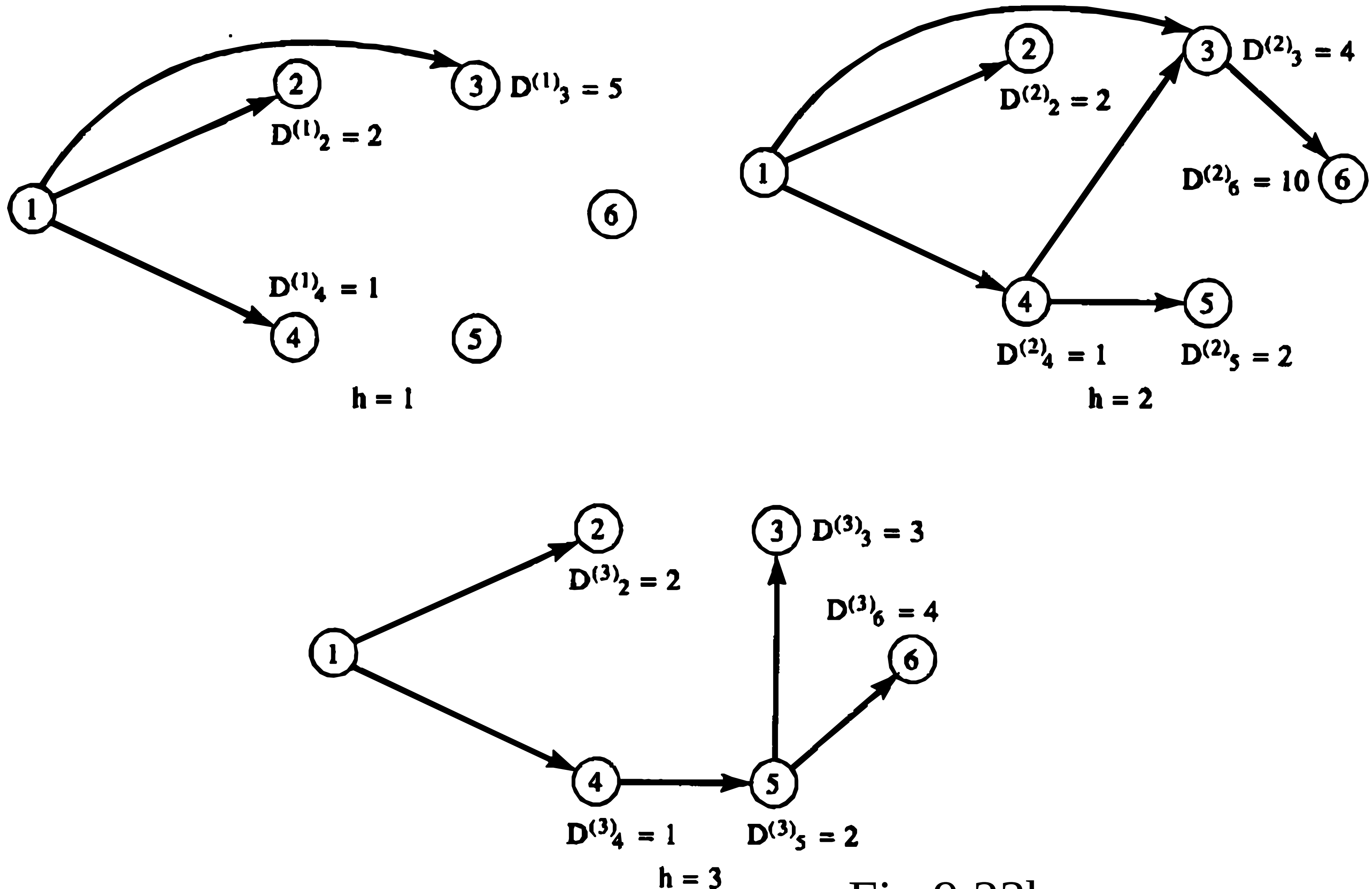


Fig 9.23b

Example (Cont)

h	$D(h_2)$	Path	$D(h_3)$	Path	$D(h_4)$	Path	$D(h_5)$	Path	$D(h_6)$	Path
0	∞	-	∞	-	∞	-	∞	-	∞	-
1	2	1-2	5	1-3	1	1-4	∞	-	∞	-
2	2	1-2	4	1-4-3	1	1-4	2	1-4-5	10	1-3-6
3	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6
4	2	1-2	3	1-4-5-3	1	1-4	2	1-4-5	4	1-4-5-6

Table 9.4b

Flooding

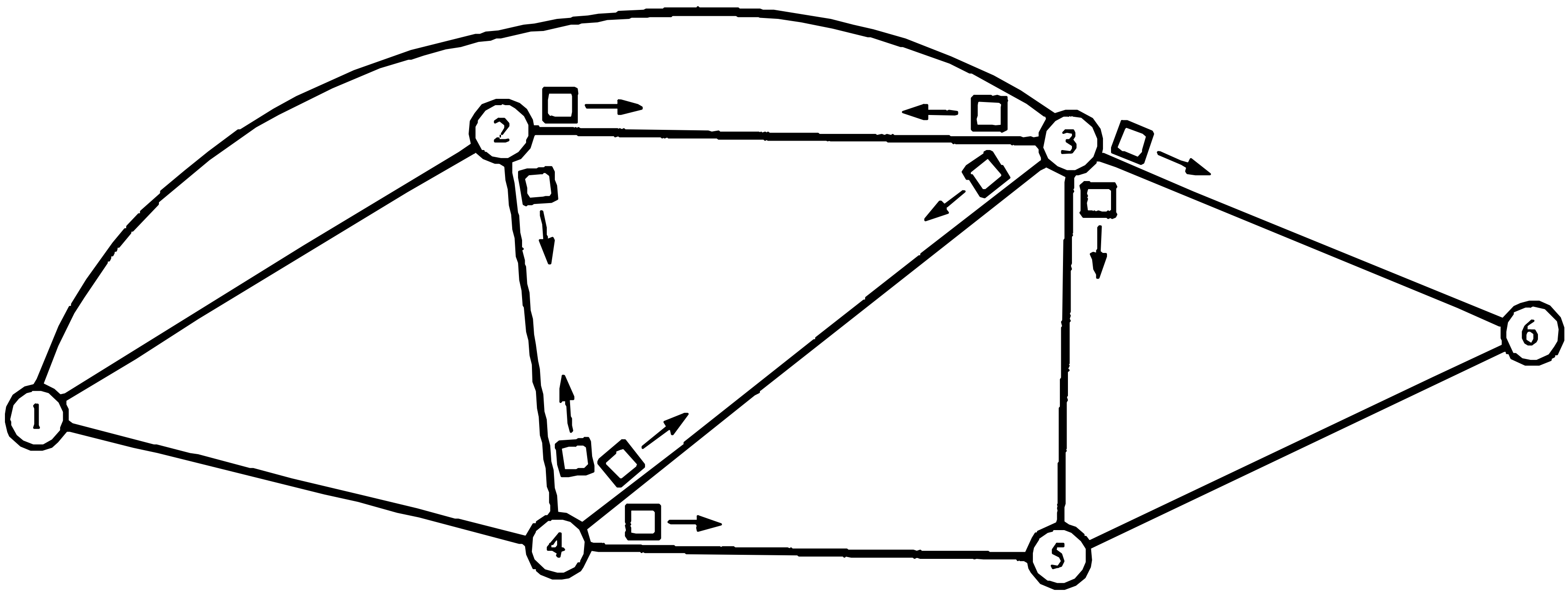


Fig 8.11b

Flooding

- Uses all possible paths
- Uses minimum hop path Used for source routing

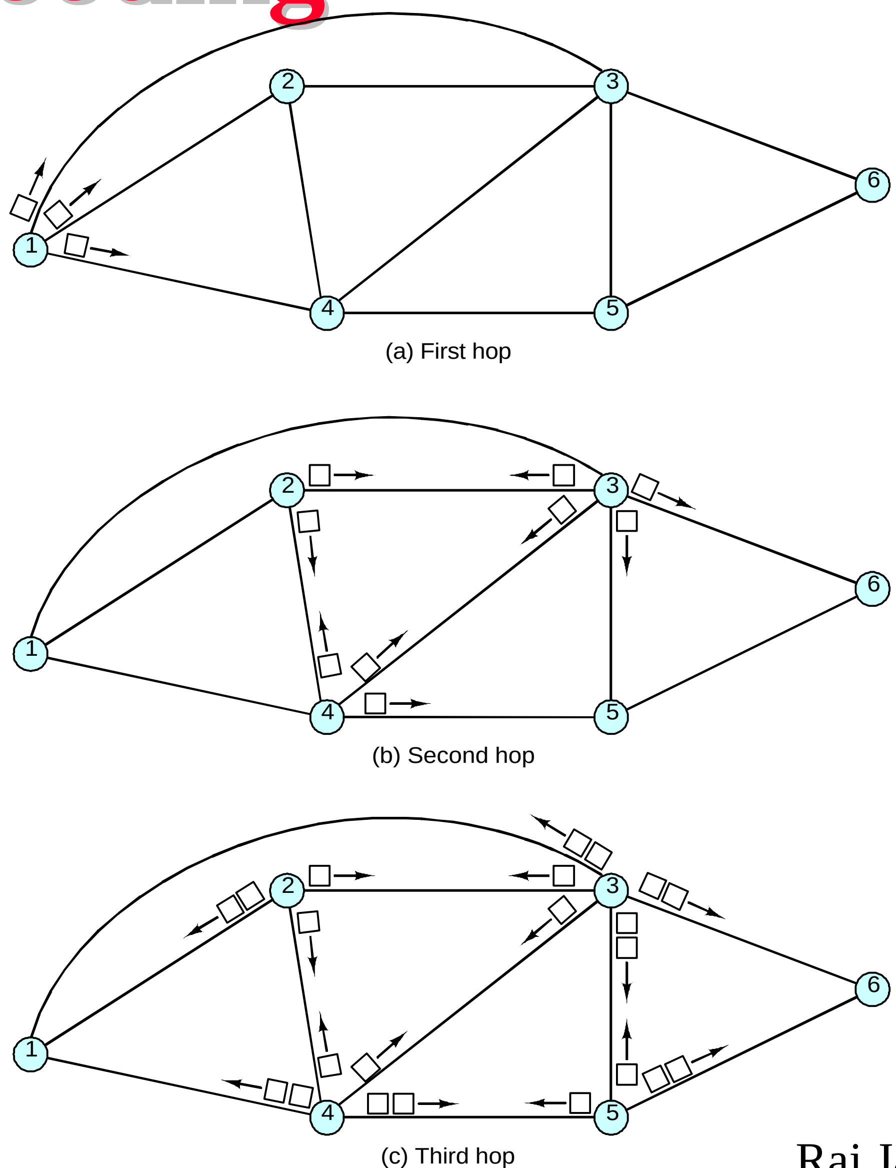


Fig 9.7

ARPAnet Routing (1969-78)

- Features: Cost=Queue length,
- Each node sends a vector of costs (to all nodes) to neighbors. Distance vector
- Each node computes new cost vectors based on the new info using Bellman-Ford algorithm

ARPAnet Routing Algorithm

Destination	Delay	Next node
1	0	Ñ
2	2	2
3	5	3
4	1	4
5	6	3
6	8	3
	D_1	S_1

(a) Node 1ås routing table before update

D_2	D_3	D_4
2	3	1
0	3	2
3	0	2
2	2	0
3	1	1
5	3	3

(b) Delay vectors sent t neighbor nodes

Destination	Delay	Next node
1	0	Ñ
2	2	2
3	3	4
4	1	4
5	2	4
6	4	4

$1^{1,2}$ = 2

$1^{1,3}$ = 5

$1^{1,4}$ = 1

(c) Node 1ås routing table after update and link c

Fig 9.9

ARPAnet Routing (1979-86)

- Problem with earlier algorithm: Thrashing (packets went to areas of low queue length rather than the destination), Speed not considered
- Solution: Cost=Measured delay over 10 seconds
- Each node floods a vector of cost to neighbors. Link-state. Converges faster after topology changes.
- Each node computes new cost vectors based on the new info using Dijkstra's algorithm

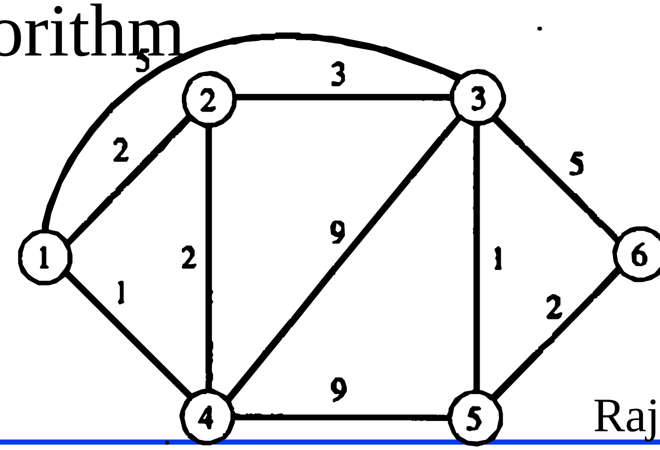


Fig 9.10

ARPAnet Routing (1987+)

- Problem with 2nd Method: Correlation between delays reported and those experienced later : High in light loads, low during heavy loads
  ⇒ Oscillations under heavy loads
  ⇒ Unused capacity at some links, over-utilization of others, More variance in delay more frequent updates More overhead

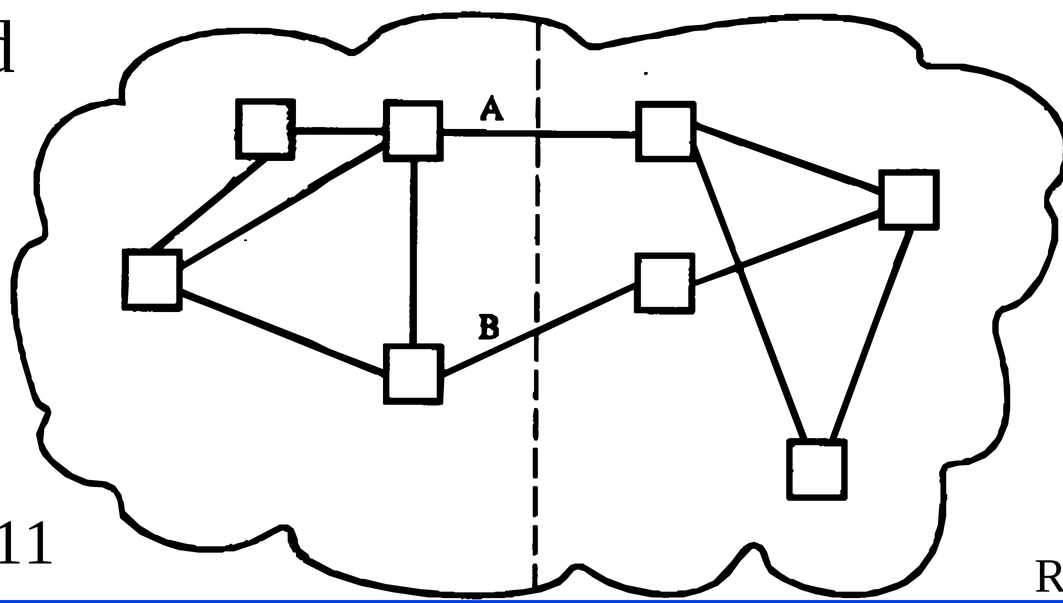


Fig 9.11

Routing Algorithm

- Delay is averanged over 10 s
- Link utilization = r = 2(s-t)/(s-2t)
  where t=measured delay,
  s=service time per packet (600 bit times)
- Exponentially weighted average utilization
  U(n+1) = α U(n)+(1-α)r(n+1)
  =0.5 U(n)+0.5 r(n+1) with α = 0.5
- Link cost = fn(U)

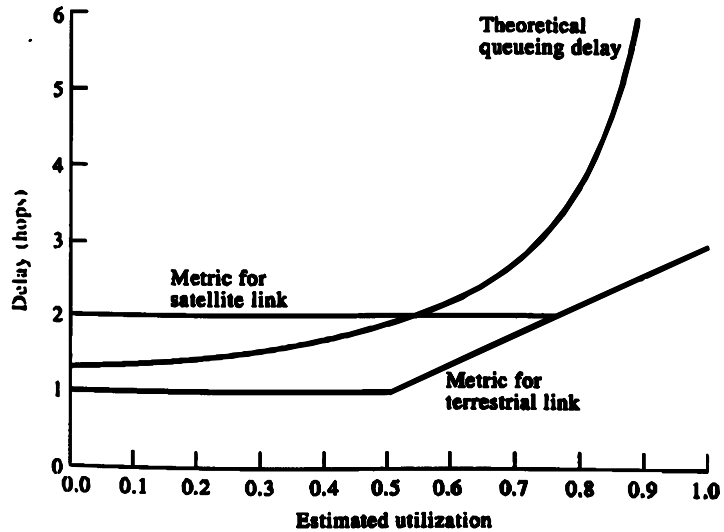
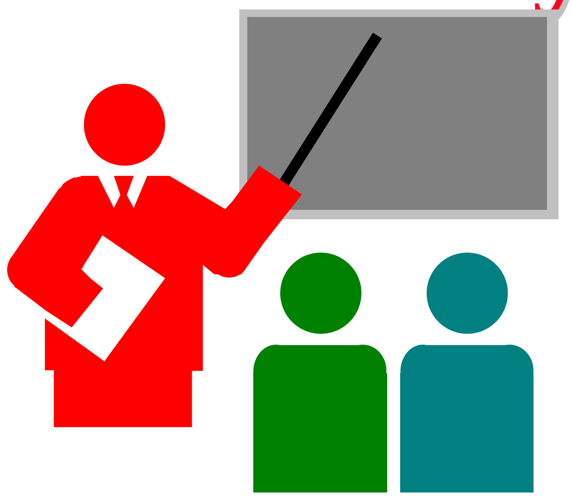


Fig 9.12

Summary



- Distance Vector and Link State
- Routing: Least-cost, Flooding, Adaptive
- Dijkstra's and Bellman-Ford algorithms
- ARPAnet

Homework

- Read Sections 10.1, 10.2, and **Appendix 10A** of Stallings' sixth edition.
- Submit answer to Excercise 10.4 (in b assume a unidirectional single loop), 10.10, and 10.16
- Due: Next class