# Routing in Switched Networks

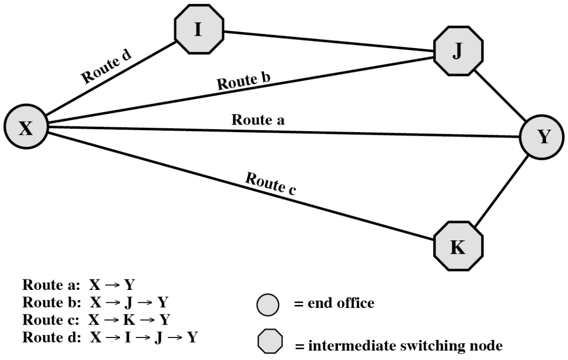
## Routing in Circuit Switched Network

- Many connections will need paths through more than one switch
- Need to find a route
  - —Efficiency
  - —Resilience
- Public telephone switches are a tree structure
  - —Static routing uses the same approach all the time
- Dynamic routing allows for changes in routing depending on traffic
  - —Uses a peer structure for nodes

# Alternate Routing

- Different scenarios
  - —Possible routes between end offices predefined
  - —Originating switch selects appropriate route
  - —Routes listed in preference order
  - —Different sets of routes may be used at different times

# Alternate Routing Diagram



Route a: X → Y
Route b: X → J → Y
Route c: X → K → Y
Route d: X → I → J → Y

○ = end office
⬡ = intermediate switching node

(a) Topology

| Time Period | First route | Second route | Third route | Fourth and final route |
|---|---|---|---|---|
| Morning | a | b | c | d |
| Afternoon | a | d | b | c |
| Evening | a | d | c | b |
| Weekend | a | c | b | d |

(b) Routing table

## Routing in Packet Switched Network

- Complex, crucial aspect of packet switched networks
- Characteristics required
  - —Correctness
  - —Simplicity
  - —Robustness
  - —Stability
  - —Fairness
  - —Optimality
  - —Efficiency

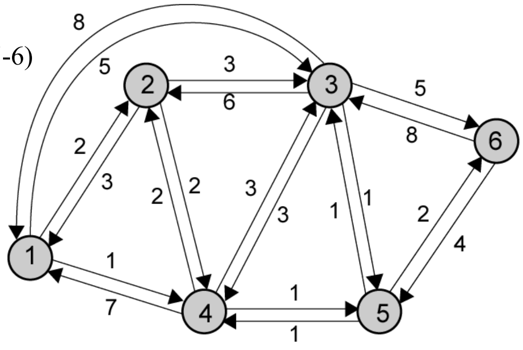
## Performance Criteria

- Used for selection of route
  - —Minimum hop
  - —Least cost
  - —Delay
  - —Throughput

  - —See Stallings appendix 10A for routing algorithms

# Example Packet Switched Network

◆Example
- –communicating nodes: node-1 to node-6
- –what is of interest?
  - »Shortest path (1-3-6)
  - »least cost path (1-4-5-6)



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# Decision Time and Place

- Time
  - —Packet or virtual circuit basis
- Place
  - —Distributed
    - Made by each node
  - —Centralized
    - requires central node
  - —Source
    - originating node

# Network Information Source and Update Timing

- Routing decisions usually based on knowledge of network
  - (not always)
- Distributed routing
  - Nodes use local knowledge
  - May collect info from adjacent nodes
  - May collect info from all nodes on a potential route
- Central routing
  - Collect info from all nodes
- Update timing
  - When is network info held by nodes updated?
    - Fixed - never updated
    - Adaptive - regular updates

    - Continuous
    - Periodic
    - Major load change
    - Topology change

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# Routing Strategies

- We will discuss several strategies:
  - Fixed Routing
  - Flooding Routing
  - Random Routing
  - Adaptive Routing

# Fixed Routing

- Single permanent route for each source-destination pair
- Determine routes using a least cost algorithm (appendix 10A)
- Route fixed, at least until a change in network topology

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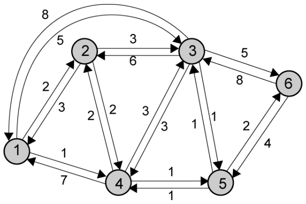
# Fixed Routing Tables



**CENTRAL ROUTING DIRECTORY**

**From Node**

| **To Node** | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | — | 1 | 5 | 2 | 4 | 5 |
| 2 | 2 | — | 5 | 2 | 4 | 5 |
| 3 | 4 | 3 | — | 5 | 3 | 5 |
| 4 | 4 | 4 | 5 | — | 4 | 5 |
| 5 | 4 | 4 | 5 | 5 | — | 5 |
| 6 | 4 | 4 | 5 | 5 | 6 | — |

**Node 1 Directory**

| Destination | Next Node |
|---|---|
| 2 | 2 |
| 3 | 4 |
| 4 | 4 |
| 5 | 4 |
| 6 | 4 |

**Node 2 Directory**

| Destination | Next Node |
|---|---|
| 1 | 1 |
| 3 | 3 |
| 4 | 4 |
| 5 | 4 |
| 6 | 4 |

**Node 3 Directory**

| Destination | Next Node |
|---|---|
| 1 | 5 |
| 2 | 5 |
| 4 | 5 |
| 5 | 5 |
| 6 | 5 |

**Node 4 Directory**

| Destination | Next Node |
|---|---|
| 1 | 2 |
| 2 | 2 |
| 3 | 5 |
| 5 | 5 |
| 6 | 5 |

**Node 5 Directory**

| Destination | Next Node |
|---|---|
| 1 | 4 |
| 2 | 4 |
| 3 | 3 |
| 4 | 4 |
| 6 | 6 |

**Node 6 Directory**

| Destination | Next Node |
|---|---|
| 1 | 5 |
| 2 | 5 |
| 3 | 5 |
| 4 | 5 |
| 5 | 5 |

# Flooding

- No network info required
- Packet sent by node to every neighbor
- Incoming packets retransmitted on every link except incoming link
- Eventually a number of copies will arrive at destination
- Each packet is uniquely numbered so duplicates can be discarded
- Nodes can remember packets already forwarded to keep network load in bounds
- Can include a hop count in packets

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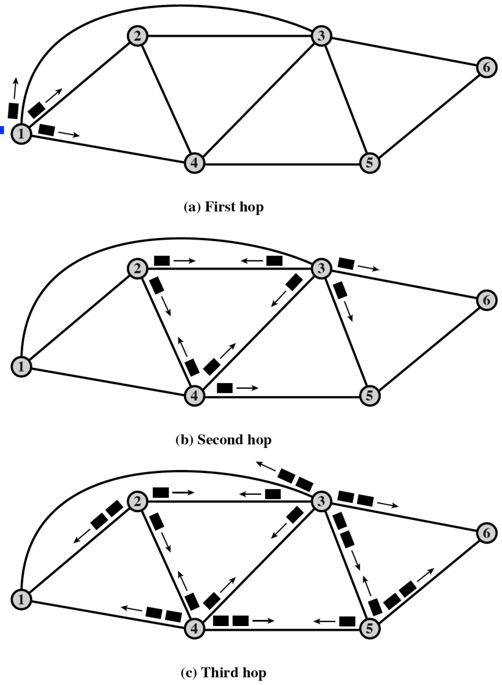
# Flooding Example

Hop Count = 3



## Properties of Flooding

- All possible routes are tried
  - —Very robust
- At least one packet will have taken minimum hop count route
  - —Can be used to set up virtual circuit
- All nodes are visited
  - —Useful to distribute information (e.g. routing)

## Random Routing

- Node selects one outgoing path for retransmission of incoming packet
- Selection can be random or round robin
  - —Can select outgoing path based on probability calculation, i.e.
    - $P_i$ probability of selecting link *i*
    - $R_i$ data rate of link *i*
    - Sum is taken over all outgoing candidate links

$$P_i = \frac{R_i}{\sum_j R_j}$$

- No network info needed
- Route is typically not least cost nor minimum hop

# Adaptive Routing

- **Used by almost all packet switching networks**
- Routing decisions change as conditions on the network change
  - Failure
  - Congestion
- Requires info about network
- Decisions are more complex
- Tradeoff between
  - quality of network info and
  - overhead

# Adaptive Routing - Advantages

- Improved performance
- Aid congestion control
- Complex system
  - May not realize theoretical benefits

## Adaptive Routing - Drawbacks

- routing is more complex
  - —increasing processing burden on network node
- strategies often depend on information that is collected in one place and needed in another
  - —traffic burden on network increases
- adaptive strategy may react too quickly
  - —congestion-produced oscillation
  - —if it reacts too slow, strategy will be irrelevant

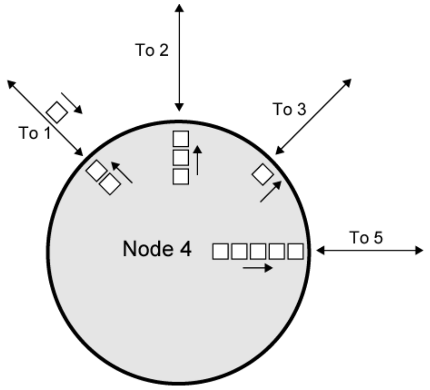
## Classification

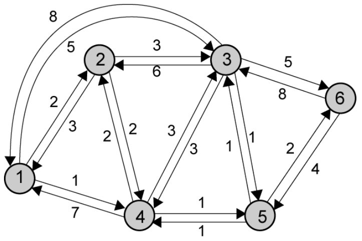
- Based on information sources
  - —Local (isolated)
    - Route to outgoing link with shortest queue
    - Can include bias for each destination
    - Rarely used
  - —Adjacent nodes
  - —All nodes

# Isolated Adaptive Routing

Node 4's Bias
Table for
Destination 6

| Next Node | Bias |
|---|---|
| 1 | 9 |
| 2 | 6 |
| 3 | 3 |
| 5 | 0 |





Algorithm:
minimize $Q + B_i$
where
$Q$ is queue length
$B_i$ is bias for destination $i$

# ARPANET Routing Strategies(1)

- First Generation (1969)
  - —Distributed adaptive
  - —Estimated delay as performance criterion
  - —Bellman-Ford algorithm
  - —Node exchanges delay vector with neighbors
  - —Update routing table based on incoming info
  - —Doesn't consider line speed, just queue length
  - —Queue length not a good measurement of delay
  - —Responds slowly to congestion

# ARPANET Routing Strategies(2)

- Second Generation (1979)
  - —Uses delay as performance criterion
  - —Delay is measured directly
  - —Uses Dijkstra’s algorithm
  - —Good under light and medium loads
  - —Under heavy loads, little correlation between reported delays and those experienced

# ARPANET Routing Strategies(3)

- Third Generation (1987)
  - —Link cost calculations changed
  - —Measure average delay over last 10 seconds
  - —Normalize based on current value and previous results

## Least Cost Algorithms

- Basis for routing decisions
  - Can minimize hop by setting each link cost to unity
  - Can have link value inversely proportional to capacity
- Given network graph
  - Nodes connected by bi-directional links
  - Each link has a cost in each direction
- Define cost of path between two nodes as sum of costs of links traversed
- For each pair of nodes, find a path with the least cost
- Link costs in different directions may be different
  - E.g. length of packet queue

## Dijkstra's Algorithm Definitions

- Find shortest paths from given source to all other nodes, by developing paths in order of increasing path length
- **N** = set of nodes in the network
- s = source node
- **T** = set of nodes so far incorporated by the algorithm
- w(i, j) = link cost from node i to node j
  - w(i, i) = 0
  - w(i, j) = ∞ if the two nodes are not directly connected
  - w(i, j) ≥ 0 if the two nodes are directly connected
- L(n) = cost of least-cost path from node s to node n currently known
  - At termination, L(n) is cost of least-cost path from s to n

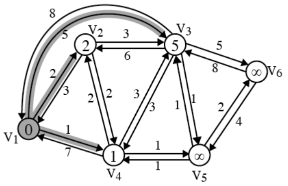
# Dijkstra's Algorithm Method

- Step 1 [Initialization]
  - **T** = {s} Set of nodes so far incorporated consists of only source node
  - L(n) = w(s, n) for n ≠ s
  - Initial path costs to neighboring nodes are simply link costs
- Step 2 [Get Next Node]
  - Find neighboring node *x* not in **T** with least-cost path from s
  - Incorporate node into **T**
- Step 3 [Update Least-Cost Paths]
  - L(n) = min[L(n), L(x) + w(x, n)] for all n ∉ T
  - If latter term is minimum, path from s to n is path from s to x concatenated with edge from x to n
- Algorithm terminates when all nodes have been added to T

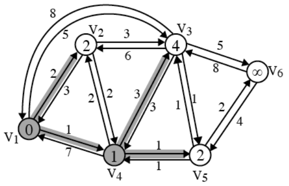
# Dijkstra's Algorithm Notes

- At termination, value L(x) associated with each node x is cost (length) of least-cost path from s to x.
- In addition, T defines least-cost path from s to each other node
- One iteration of steps 2 and 3 adds one new node to T
  - Defines least cost path from s to that node

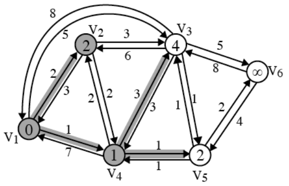
# Example of Dijkstra's Algorithm



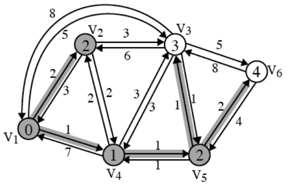
T = {1}



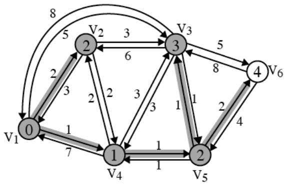
T = {1, 4}



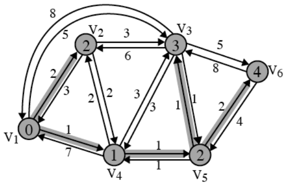
T = {1, 2, 4}



T = {1, 2, 4, 5}



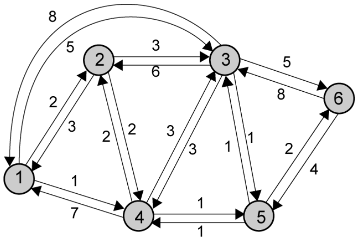
T = {1, 2, 3, 4, 5}



T = {1, 2, 3, 4, 5, 6}

# Results of Example Dijkstra's Algorithm

| Iteration | *T* | *L*(2) | Path | *L*(3) | Path | *L*(4) | Path | *L*(5) | Path | *L*(6) | 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 |



# Bellman-Ford Algorithm Definitions

- Essential idea
  - first, find shortest paths from given node subject to the constraint that the paths contain at most 1 link
  - next, find the shortest paths with a constraint of paths of at most 2 links
  - and so on

- Definitions
  - $s$ = source node
  - w(i, j) = link cost from node i to node j
    - $w(i, i) = 0$
    - $w(i, j) = \infty$ if the two nodes are not directly connected
    - $w(i, j) \geq 0$ if the two nodes are directly connected
  - $h$ = maximum number of links in path at current stage of the algorithm
    - i.e. $h$ = max length of a path currently considered
  - $L_h(n)$ = cost of least-cost path from $s$ to n under constraint of no more than $h$ links

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# Bellman-Ford Algorithm Method

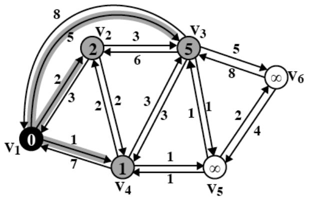
- Step 1 [Initialization]
  - $L_0(n) = \infty$, for all $n \neq s$
  - $L_h(s) = 0$, for all $h$

- Step 2 [Update]
  - For each successive $h \geq 0$
    - For each $n \neq s$, compute

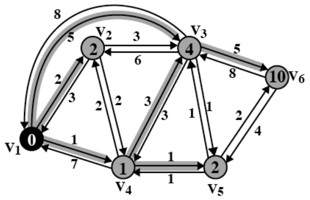
$$L_{h+1}(n) = \min_j [L_h(j) + w(j,n)]$$

  - Connect $n$ with predecessor node $j$ that achieves minimum
  - Eliminate any connection of $n$ with different predecessor node formed during an earlier iteration
  - Path from $s$ to $n$ terminates with link from $j$ to $n$

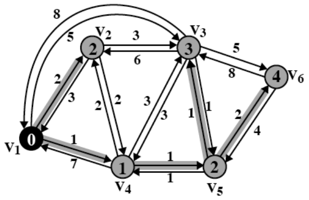
# Example of Bellman-Ford Algorithm



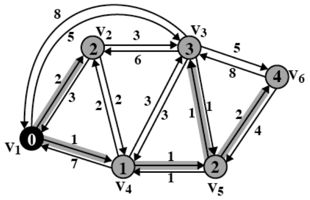
h = 1



h = 2



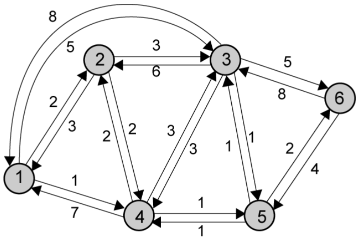
h = 3



h = 4

# Results of Bellman-Ford Example

| *h* | $L_h(2)$ | Path | $L_h(3)$ | Path | $L_h(4)$ | Path | $L_h(5)$ | Path | $L_h(6)$ | 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 |



# Comparison

- Results from two algorithms agree
- Information gathered
  - Bellman-Ford
    - Calculation for node n involves knowledge of link cost to all neighboring nodes plus total cost to each neighbor from s
    - Each node can maintain set of costs and paths for every other node
    - Can exchange information with direct neighbors
    - Can update costs and paths based on information from neighbors and knowledge of link costs
  - Dijkstra
    - Each node needs complete topology
    - Must know link costs of all links in network
    - Must exchange information with all other nodes

# Evaluation

- Dependent on processing time of algorithms
- Dependent on amount of information required from other nodes
- Implementation specific
- Both converge under static topology and costs
- Converge to same solution
- If link costs change, algorithms will attempt to catch up
- If link costs depend on traffic, which depends on routes chosen, then feedback
  - May result in instability

## Summary

- routing in packet-switched networks
- routing strategies
    - fixed, flooding, random,adaptive
- ARPAnet examples
- least-cost algorithms
    - Dijkstra, Bellman-Ford