Basics of Routing and Link-State Routing

Lecture given by Emmanuel Lochin

ISAE-SUPAERO

Original slides from A. Carzaniga (Univ. Lugano)
Extended/modified by E. Lochin (ISAE-SUPAERO) with author permission Textbook Chap. #3 Sections 4.5 to 4.5.1 and 4.7.1

Outline

- Routing problem
- Graph model
- Classes of routing algorithms
- Broadcast routing
- Link-state routing
- Dijkstra's algorithm

Routing Problem

- Finding paths through a network

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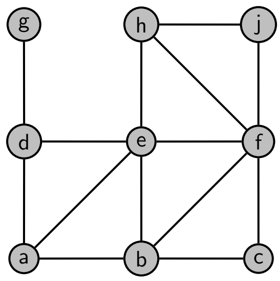
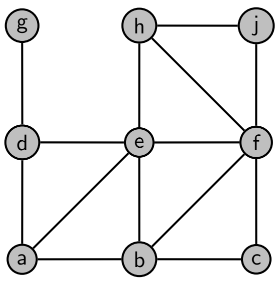


Routing Problem

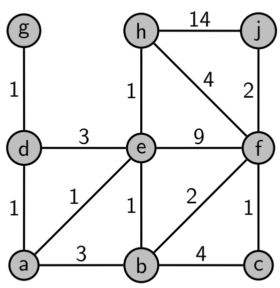
- Finding paths through a network



- Example : $a \rightarrow j$?

Routing Problem

- Finding paths through a network



- Example : $a \rightarrow j$?

Graph Model

- The network is modeled as a graph

$$G = (V, E)$$

  - V is a set of vertices representing the routers
  - $E \subseteq V \times V$ is a set of edges representing communication links
    - e.g., $(u, v) \in E$ iff router u is on the same subnet as v
  - G is assumed to be an undirected graph
    - i.e., $(u, v) \in E \Leftrightarrow (v, u) \in E$ for all $u, v \in N$
  - A cost function $c : E \rightarrow \mathbb{R}$
    - costs are always positive : $c(e) > 0$ for all $e \in E$
    - links are symmetric : $c(u, v) = c(v, u)$ for all $u, v \in N$

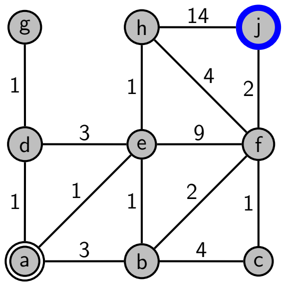
Routing in the Graph Model

- For every router $u \in V$, for every other router $v \in V$, compute the path $P_{u \rightarrow v} = u, x_1, x_2, \ldots, x_n, v$ such that
  - $P_{u \rightarrow v}$ is completely contained in the network graph G. I.e., $(u, x_1) \in V, (x_1, x_2) \in V, \ldots, (x_n, v) \in V$
  - $P_{u \rightarrow v}$ is a **least-cost path**, where the cost of the path is $c(P_{u \rightarrow v}) = c(u, x_1) + c(x_1, x_2) + \ldots + c(x_n, v)$
- Compile u's forwarding table by adding the following entry :

$$A(v) \rightarrow I_u(x_1)$$

  - $A(v)$ is the address (or set of addresses) of router v
  - $I_u(x_1)$ is the interface that connects u to the first next-hop router x_1 in $P_{u \rightarrow v} = u, x_1, x_2, \ldots, x_n, v$

Back To The Example



- Example : $a \rightarrow j$

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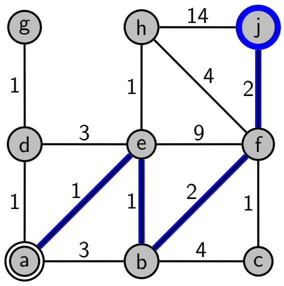

- Example : $a \rightarrow j$
  - least-cost path is $P_{a \rightarrow j} = a, e, b, f, j$

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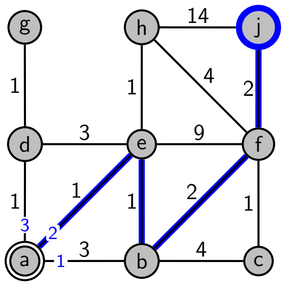


- Example : $a \rightarrow j$
  - least-cost path is $P_{a \rightarrow j} = a, e, b, f, j$
  - a's forwarding table will contain an entry $\boxed{j \rightarrow 2}$ since $l_a(e) = 2$

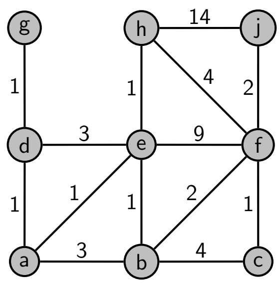
Two General Strategies

- There are two main strategies to implement a routing algorithm
- Link-state routing
  - global view of the network
  - local computation of least-cost paths
- Distance-vector routing
  - local view of the network
  - global computation of least-cost paths

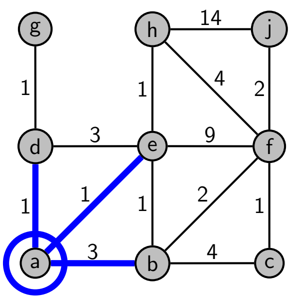
Link-State Routing

- Router u maintains a complete view of the network graph G (including all links and their costs)
  - every router v advertises its adjacent links (their costs) to every other router in the network ; this information is called **link state**
  - link-state advertisements (LSAs) are broadcast through the entire network
  - routers collect link-state advertisements from other routers, and they use them to compile and maintain a complete view of G
- Using its local representation of G, router u computes the least-cost paths from u to every other router in the network
  - the computation is local

Link-State Advertisements

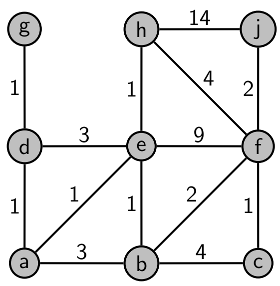


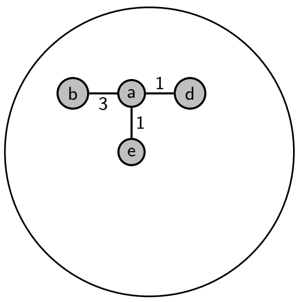
Link-State Advertisements



$LSA_a = \{(a, b, 3), (a, e, 1), (a, d, 1)\}$

Link-State Advertisements





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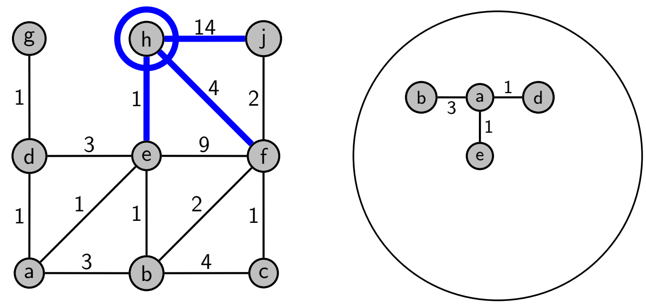
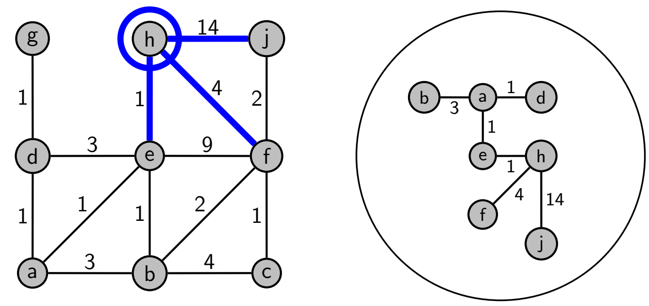


$LSA_a = \{(a, b, 3), (a, e, 1), (a, d, 1)\}$
$LSA_h = \{(h, e, 1), (h, f, 4), (h, j, 14)\}$

Link-State Advertisements



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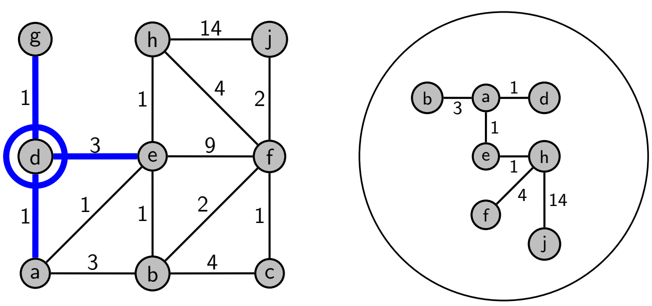

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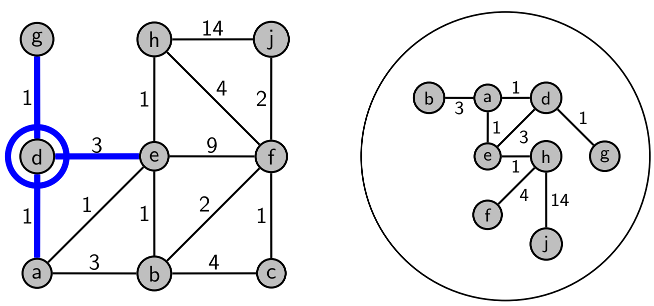

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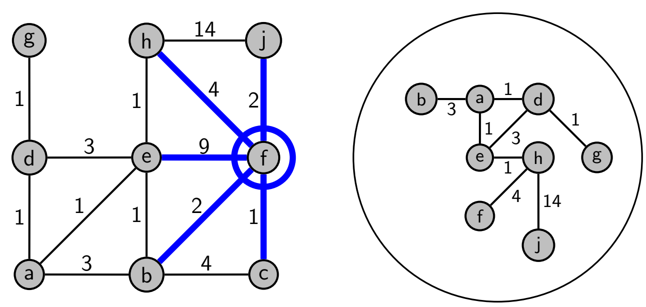

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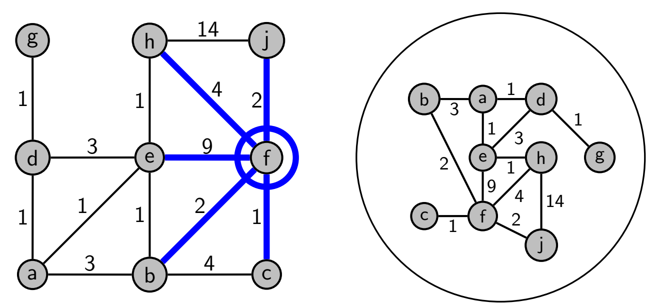
$LSA_d = \{(d, a, 1), (d, g, 1), (d, e, 3)\}$
$LSA_f = \{(f, c, 1), (f, b, 1), (f, e, 3), (f, h, 4), (f, j, 2)\}$

Link-State Advertisements



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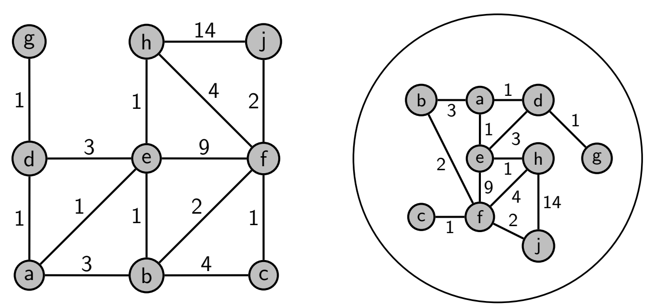

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...

Link-State Routing Ingredients

What do we need to implement link-state routing ?

- Every router sends its LSA to every other router in the network, so we need a broadcast routing scheme
- Once we have all the LSAs from every router, and therefore we complete knowledge of G, we need an algorithm to compute least-cost paths in a graph

Broadcast Routing

- Flooding
  - every router forwards a broadcast packet to every adjacent router, except the one that sent the packet
- Simple and elegant
- Correct w.r.t. the broadcast requirement : a broadcast packet will eventually reach every router
- Any problem with this solution ?
  - cycles in the network create **packet storms**

Broadcast Routing (2)

- Reverse-path broadcast
  - every router forwards a broadcast packet to every adjacent router, except the one where it received the packet router
  - a router u accepts a broadcast packet p originating at router s only if p arrives on the link that is on the direct (unicast) path from u to s
- Correct w.r.t. the broadcast requirement : a broadcast packet will eventually reach every router
- No packet storms even in the presence of cycles in G
- Any problem with this solution ?
  - it requires (unicast) routing information
  - so it is obviously useless to implement a routing algorithm

Broadcast Routing (3)

- Sequence-number controlled flooding
  - the originator s of a broadcast packet marks the packet with a sequence number n_s
  - every router u stores the most recent sequence number seen from each source router. Let's assume that u has seen sequence numbers from s up to n_s
  - a router accepts a broadcast packet p originating at s only if p carries a sequence number $seq(p)$ that is higher than the most recent one seen from s : $seq(p) > n_s$
  - accepted packets are forwarded to every adjacent router, except the previous-hop router
  - u updates its table of sequence numbers $n_s \leftarrow seq(p)$

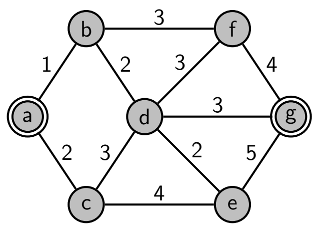
Dijkstra's Algorithm

- Executing locally at node u
- Variables storing values known at each iteration
  - $D[v]$, cost of the least-cost path from u to v
  - $p[v]$, node preceding v (neighbor of v) on the least-cost path from u to v
  - N, nodes of G whose least-cost path from u is definitely known

Dijkstra's Algorithm

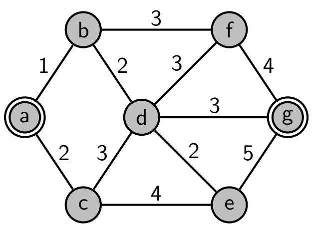
```
DIJKSTRA(G = (V, E), u)
  N = {u}
  for all v ∈ V
      if v ∈ neighbors(u)
          D[v] = c(u, v)
          p[v] = u
      else D[v] = ∞
  while N ≠ V
      find w ∉ N such that D[w] is minimum
      N = N ∪ {w}
      for all v ∈ neighbors(w) \ N
          if D[w] + c(w, v) < D[v]
              D[v] = D[w] + c(w, v)
              p[v] = w
```


Example



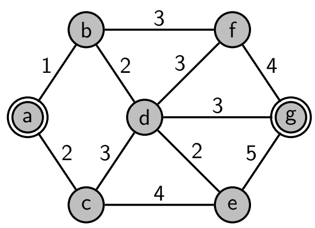
A	B	C	D	E	F	G	steps
o							1
x							2
x							3
x							4
x							5
x							6
x							7

Example



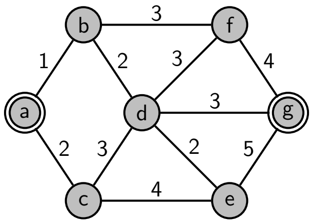
A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x							2
x							3
x							4
x							5
x							6
x							7

Example



A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A						2
x	x						3
x	x						4
x	x						5
x	x						6
x	x						7

Example



A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x						3
x	x						4
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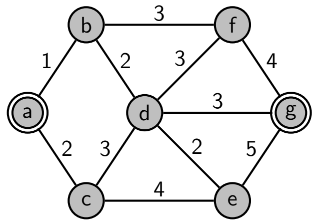
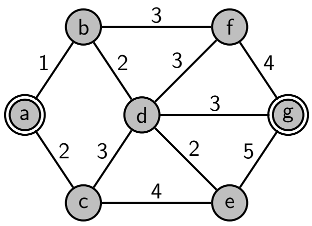
Example



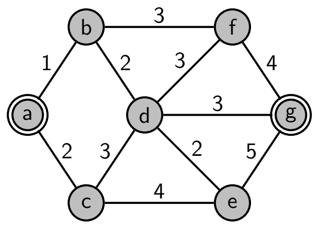
A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A					3
x	x	x					4
x	x	x					5
x	x	x					6
x	x	x					7

Example



A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A	5-C	6-C			3
x	x	x					4
x	x	x					5
x	x	x					6
x	x	x					7

Example



A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A	5-C	6-C			3
x	x	x	3-B				4
x	x	x	x				5
x	x	x	x				6
x	x	x	x				7

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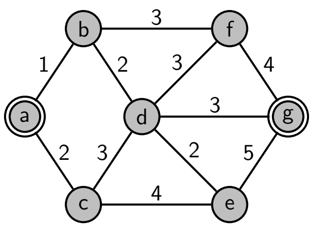
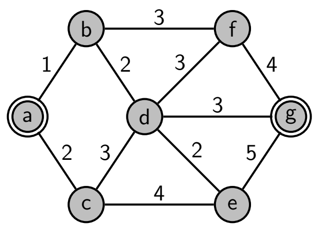


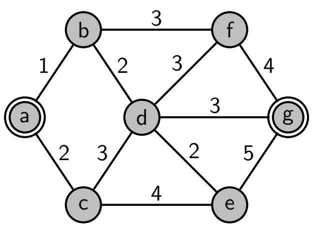
A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A	5-C	6-C			3
x	x	x	3-B	5-D	6-D	6-D	4
x	x	x	x				5
x	x	x	x				6
x	x	x	x				7

Example



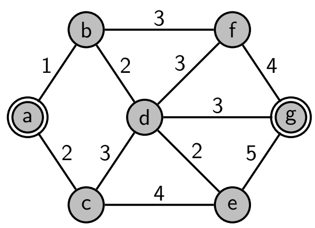
A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A	5-C	6-C			3
x	x	x	3-B	5-D	6-D	6-D	4
x	x	x	x		4-B		5
x	x	x	x		x		6
x	x	x	x		x		7

Example



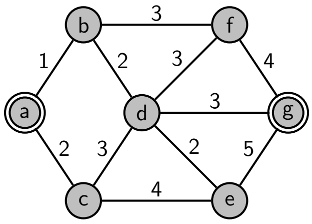
A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A	5-C	6-C			3
x	x	x	3-B	5-D	6-D	6-D	4
x	x	x	x		4-B	8-F	5
x	x	x	x		x		6
x	x	x	x		x		7

Example



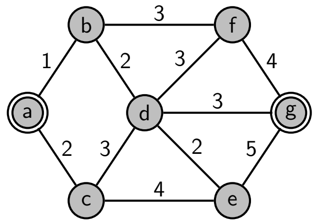
A	B	C	D	E	F	G	steps
o	1-A	2-A					1
x	1-A		3-B		4-B		2
x	x	2-A	5-C	6-C			3
x	x	x	3-B	5-D	6-D	6-D	4
x	x	x	x		4-B	8-F	5
x	x	x	x	5-D	x		6
x	x	x	x	x	x		7

Example



A	B	C	D	E	F	G	steps
o	1-A	2-A					1
×	1-A		3-B		4-B		2
×	×	2-A	5-C	6-C			3
×	×	×	3-B	5-D	6-D	6-D	4
×	×	×	×		4-B	8-F	5
×	×	×	×	5-D	×	10-E	6
×	×	×	×	×	×		7

Example



A	B	C	D	E	F	G	steps
							1
	1-A						2
							3
			3-B				4
							5
							6
						6-D	7