University of Freiburg, Germany
Department of Computer Science

Distributed Systems

Chapter 5 Distributed Routing

Christian Schindelhauer

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5.1: Introduction

- One of the most important prevalent problems in distributed systems

The Internet

- no central entity
- $>$ 400,000 routers of AS (autonomous systems) use BGP (border gateway protocol) to determine routes between AS
- within AS distributed routing protocols update routing tables

Mobile Ad-Hoc Networks

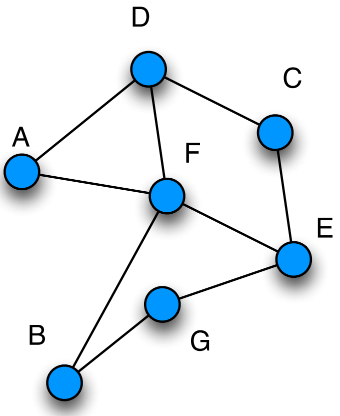
- no central control
- dynamic wireless nodes
- connections appear and disappear at any time

5.2: Routing in the Internet

- Packet forwarding and route selection
- Packet forwarding algorithm
  - each node has a routing table
  - when a packet needs to be processed, choose the best choice from the table
  - decrease TTL (time to live counter)
  - if TTL $= 0$ then delete packet
- Route selection
  - programming of the routing table
  - originally: static (manually)
  - always single-path
  - flat versus hierarchical
  - intradomain and interdomain

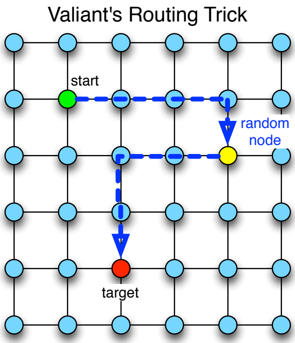
5.3: Routing Paradigms

- Optimization goals
  - delay
  - hop count
  - throughput
  - reliability
  - monetary cost
- Routing decisions
  - Distributed routing
    - routers decide
    - BGP, Distance-Vector, Link-State Routing
  - Source routing
    - senders decide
    - DSR (Dynamic Source Routing), Onion Routing (TOR)
  - Centralized routing
    - one (possibly external) instance decides all routing
    - (mobile) phone network, static routing



Adaptivity

- Deterministic routing algorithm
  - optimizes the path (usually the hop count)
  - each packet is using the same route
- Oblivious routing algorithms
  - oblivious to the status of the network
  - Valiant has proved that in a two-dimensional network randomized oblivious routing optimizes the throughput
  - packets are routed in random or cyclic directions
- Adaptive routing algorithms
  - use information about network traffic / channel status
  - avoid congested areas
  - avoid unreliable links



Switching Techniques

- Circuit Switching
  - First, determine a path and reserve the router nodes
  - Then, send the packets on this path exclusively reserved for this connection
- Packet Switching
  - store-and- forward switchings
  - each packet is *individually* routed from source to target
- Virtual cut-through switching (VCT)
  - Messages are split into packets
  - if the channel to the next router is free, the packet is immediately forwarded
  - otherwise the packets are buffered in the router with the first blockade and sent if the channel is free again
- Wormhole (WH) switching
  - like VCT but routers have small buffers
  - packet string is stored on buffers like a snake

5.4: Bellman Ford

- The Bellman-Ford Algorithm computes the shortest path problem towards t from each node in graph $G = (V, E)$ with weights $w(u, v)$

Bellman-Ford(G, w, s)

- **Init-Target**(G, w)
- loop $|V| - 1$ times:
  - for all $(u, v) \in E$ do
    - **Relax**(u, v)
- for all $(u, v) \in E$ do
  - if $d(u) > d(v) + w(u, v)$ then return false

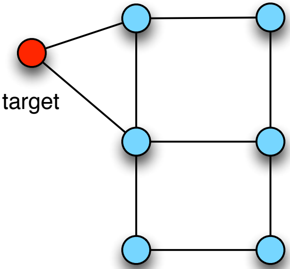
Init-Target(G, w, t)

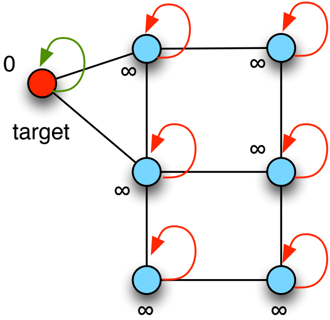
- **Init-Target**(G, w)
- for all $v \in V$ do
  - $d(v) \leftarrow \infty$
  - $\pi(v) \leftarrow v$
- $d(t) \leftarrow 0$

Relax(u, v)

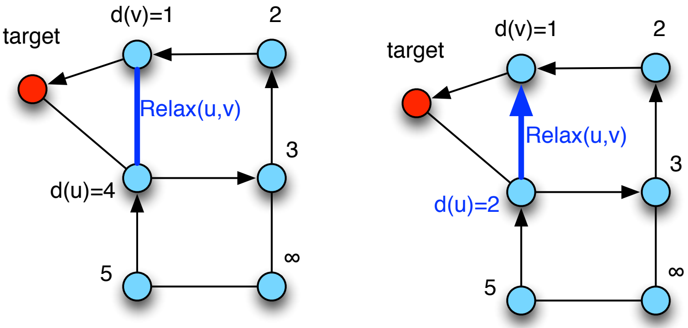
- **Relax**(u, v)
- if $d(u) > w(u, v) + d(v)$ then
  - $d(u) \leftarrow w(u, v) + d(v)$
  - $\pi(u) \leftarrow v$

Init-Target

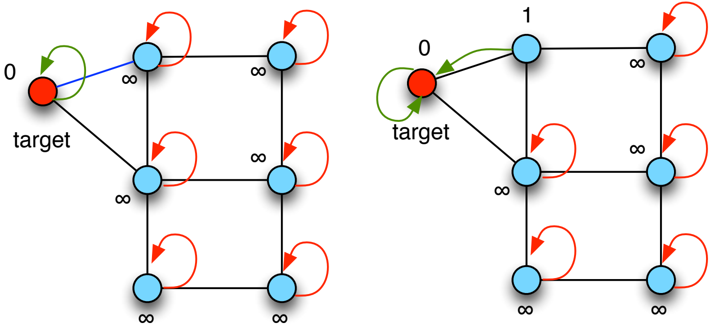




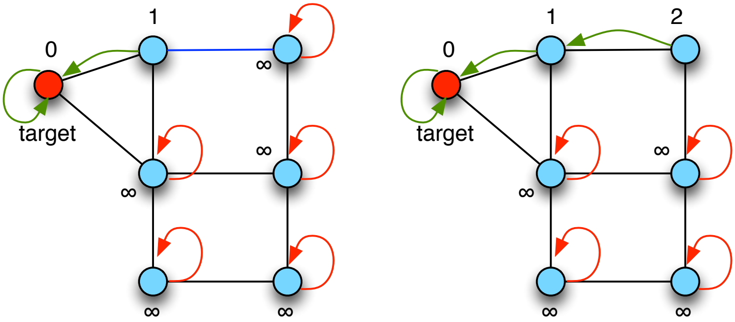
Relax



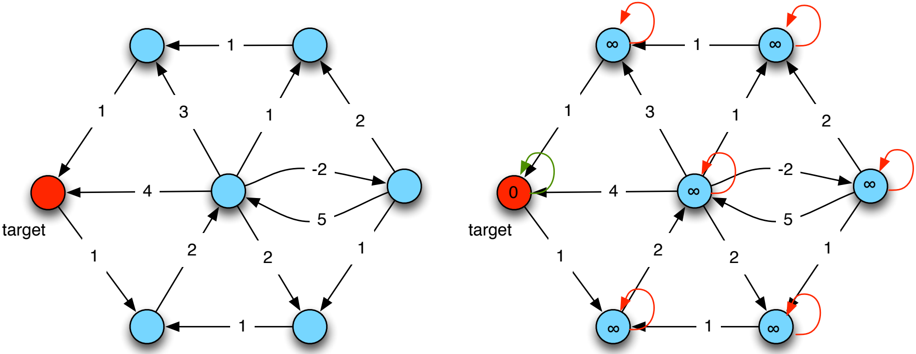
Relax



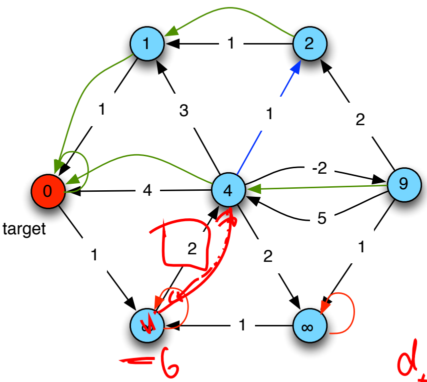
Relax

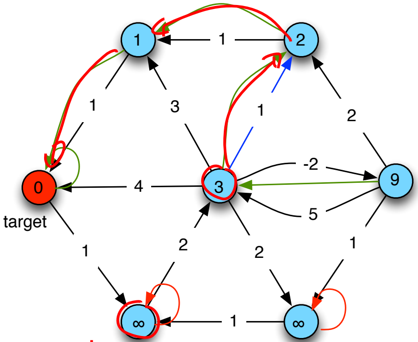


Init-Target for Directed Graphs



Relax for Directed Graphs



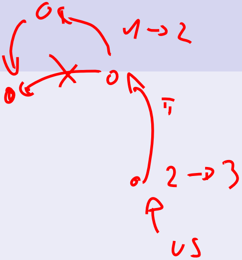


$d_t(u)$:= distance to t

$\pi_t(u)$:= next hop to t

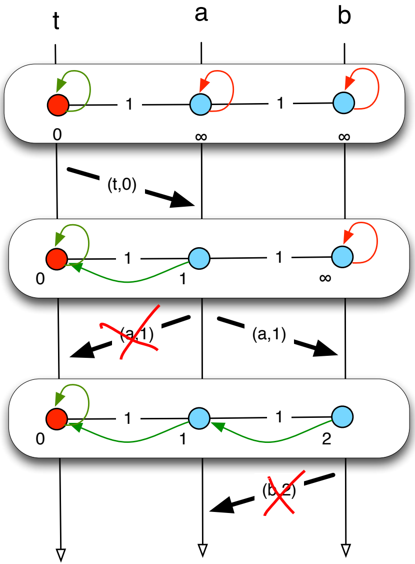
Compute for each (target) node of the network the following.

Distributed Bellman Ford for target t (Distance-Vector Routing)



- If node is t then $d(t) \leftarrow 0$; $\pi(t) \leftarrow t$
- If a message from u to $\pi(u)$ fails then
  - $d(u) \leftarrow \infty$
- If u detects a new neighbor v then
  - send $(u, d(u))$ to v
- If u receives $(v, d(v))$ from v
  - if $d(u) > d(v) + w(u, v)$ or $v = \pi(u)$ then
    - $d(u) \leftarrow d(v) + w(u, v)$
    - $\pi(u) \leftarrow v$
- if $d(u) = \infty$ then $\pi(u) \leftarrow u$
- Every time $d(u)$ or $\pi(u)$ has changed u sends $(u, d(u))$ to all neighbors

Distance Vector



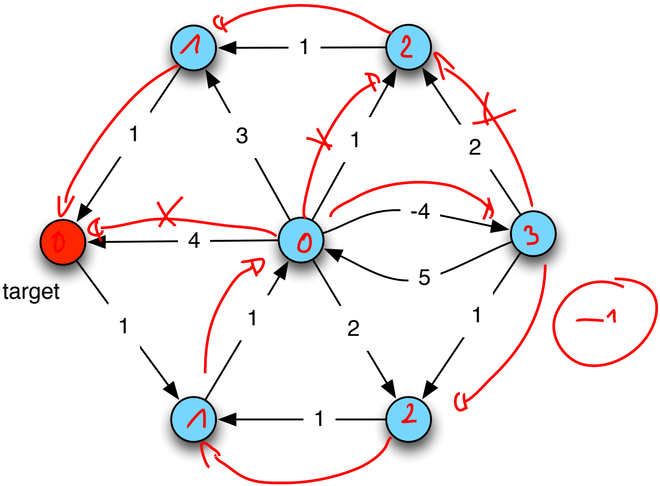
Correctness

- Let $|u, v|$ be the distance from u to v
- Assume that the weights are constant
- Then, at each time of the operation $d(u) > |u, t|$
- If the shortest path from u to t is $(u, v_1, v_2, \ldots, v_n, t)$ and
  - a message is sent from t to v_n and then from v_n to v_{n-1}, etc.
  - then $d(v_n) = |v_n, t|$, $d(v_{n-1}) = |v_{n-1}, t|$, ..., $d(u, t) = |u, t|$
- So, for each shortest path of finite length eventually Distributed Bellman Ford converges

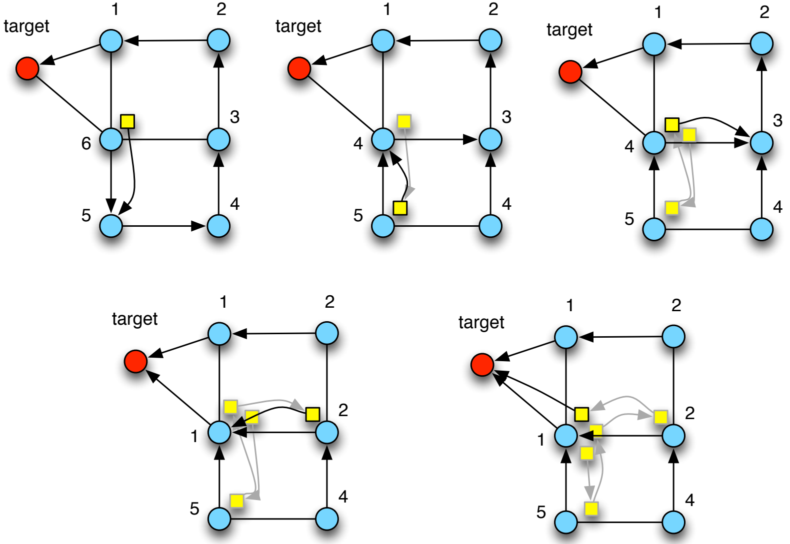
Problems of Distributed Bellman Ford

- Negative path cycles
  - Bellman-Ford works fine as long as the shortest path is finite
  - if a negative path cycle exist, then the shortest path is infinite
- Dynamic graphs
  - Temporarily wrong routes
    - During the distributed computation messages might take wrong directions
    - could even revisit the same node more than once
  - Lost connections
    - Bad news travels slowly (or not at all)
    - If the distance increases then no messages are produced
    - Old an wrong information is preserved
- Temporarily undefined routes
  - For speeding up store last message of each neighbor
  - Use this information when new messages arrive
- Count-to-Infinity Problem
  - If the target is not reachable and at least two nodes remain connected
  - then the distance is updated towards infinity

Negative Path Cycles

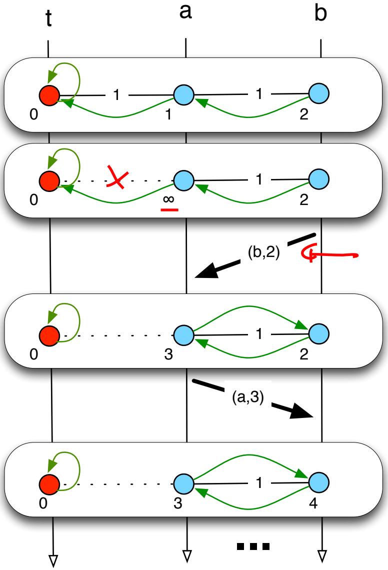


Temporarily Wrong Routes



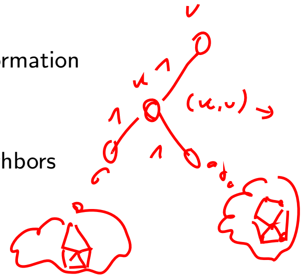
Count to Infinity Problem

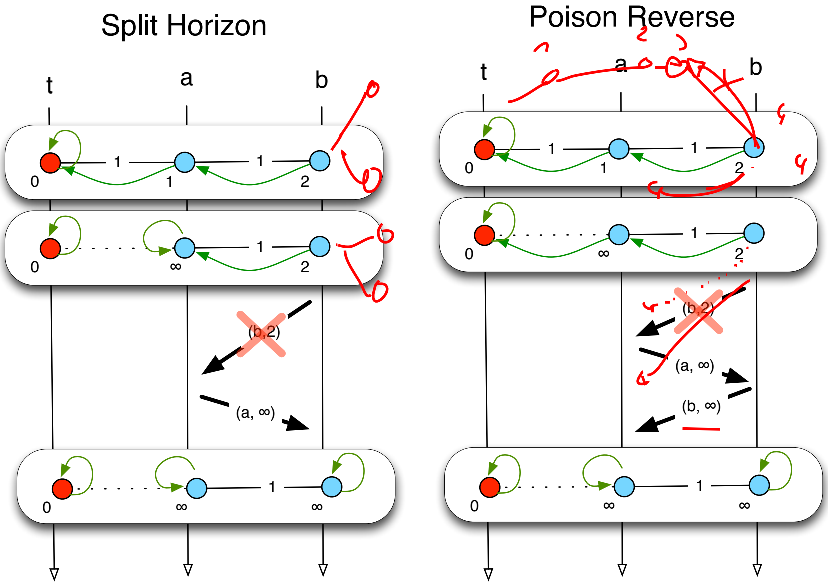
- If the target is not reachable and at least two nodes remain connected
- then the distance is updated towards infinity



Solutions to the Count-to-Infinity Problem

- Split Horizon
  - A node does not advertise routes to nodes on its path to the target
- Poison reverse
  - A variant of split horizon
  - A node does not advertise routes to nodes on its path to the target
  - With the exception of a value of ∞ is advertised immediately towards target
- Link State Routing
  - all link information is broadcast in the network
  - each node computes the shortest path on this information
- Path Vector Protocol
  - instead of only storing the next link
  - store the complete path and forward it to the neighbors
  - used in BGP




Split Horizon
t
a
b
1
1
0
1
2
0
∞
2
(b,2)
(a, ∞)
0
∞
∞
Poison Reverse
t
a
b
1
1
0
1
2
0
∞
2
(b,2)
(a, ∞)
(b, ∞)
0
∞
∞

Distance-Vector Routing with Split Horizon for target t

- If node is t then $d(t) \leftarrow 0$; $\pi(t) \leftarrow t$
- If a message from u to $\pi(u)$ fails then
  - $d(u) \leftarrow \infty$
  - $\pi(u) \leftarrow u$
- If u detects a new neighbor v then
  - send $(u, d(u))$ to v
- If u receives $(v, d(v))$ from v
  - if $d(u) > d(v) + w(u, v)$ or $v = \pi(u)$ then
    - $d(u) \leftarrow d(v) + w(u, v)$
    - $\pi(u) \leftarrow v$
- Periodically and every time $d(u)$ or $\pi(u)$ has changed u sends $(u, d(u))$ to all neighbors except for $\pi(u)$

  Split horizon rule: information is not sent towards target

Distance-Vector Routing with Poison Reverse for target t

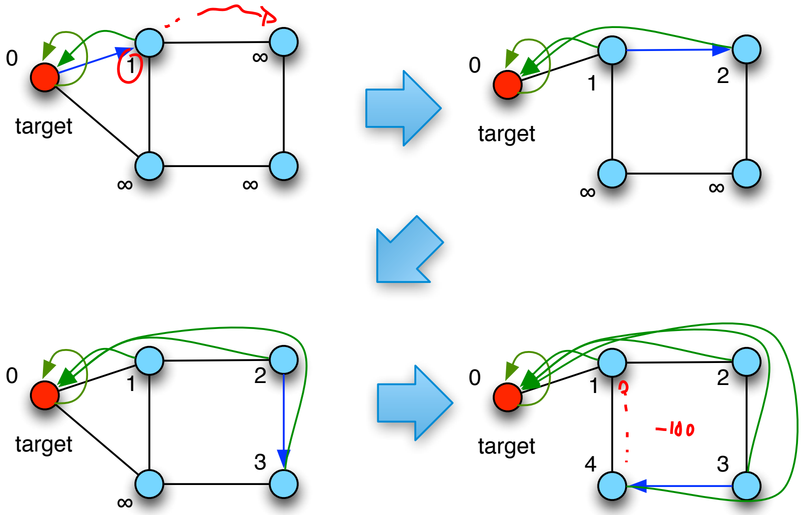
- If node is t then $d(t) \leftarrow 0$; $\pi(t) \leftarrow t$
- If a message from u to $\pi(u)$ fails then
  - $d(u) \leftarrow \infty$
  - $\pi(u) \leftarrow u$
- If u detects a new neighbor v then
  - send $(u, d(u))$ to v
- If u receives $(v, d(v))$ from v
  - if $d(u) > d(v) + w(u,v)$ or $v = \pi(u)$ then
    - $d(u) \leftarrow d(v) + w(u,v)$
    - $\pi(u) \leftarrow v$
- Periodically and every time $d(u)$ or $\pi(u)$ has changed send $(u, d(u))$ to all neighbors except for $\pi(u)$
- If $d(u)$ has changed to ∞ then send $(u, d(u))$ to $\pi(u)$
  Poison reverse: remove loops before they can propagate

Path Vector Protocol for target t

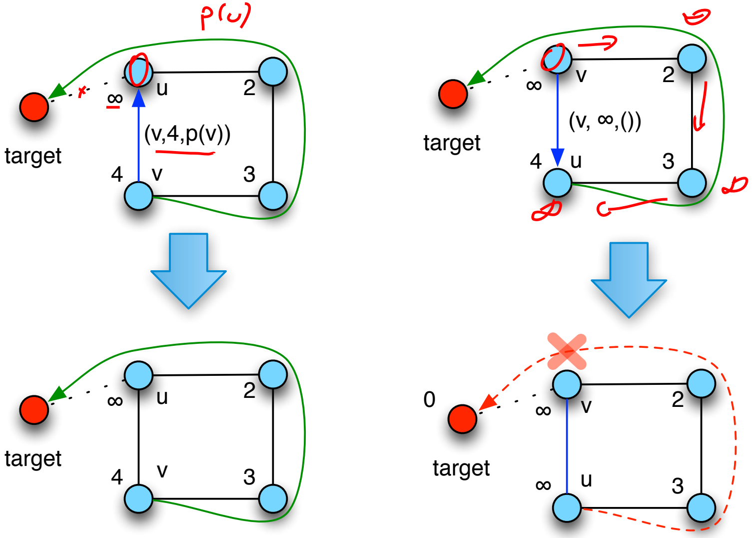
$d(u)$ distance to target
$p(t)$ path to target

- $d(t) \leftarrow 0$; $p(t) \leftarrow (t)$
- t sends $(t, d(t), p(t))$ to all neighbors once
- If a message from u to the first node of $p(u)$ fails then
  - $d(u) \leftarrow \infty$
  - $p(u) \leftarrow ()$
- If u detects a new neighbor v then
  - send $(u, d(u), p(u))$ to v
- If u receives $(v, d(v), p(v))$ from v
  - if $d(v) = \infty$ and $v \in p(u)$ then — u's route has vanished
    - $d(u) \leftarrow \infty$
    - $p(u) \leftarrow ()$
  - if $u \notin p(v)$ and $d(u) > d(v) + w(u, v)$ then — only if u is not in the path to t relax distance (prevents cycles)
    - $d(u) \leftarrow d(v) + w(u, v)$
    - $p(u) \leftarrow (u, p(v))$ — append u to path from v to t
- Periodically and every time $d(u)$ or $p(u)$ has changed send $(u, d(u), p(u))$ to all neighbors

Relax in Path Distance Vector



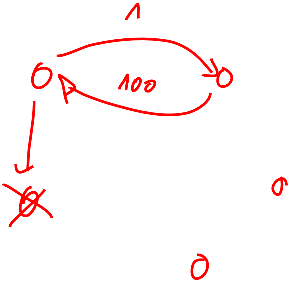
Lost Target in Path Distance Vector

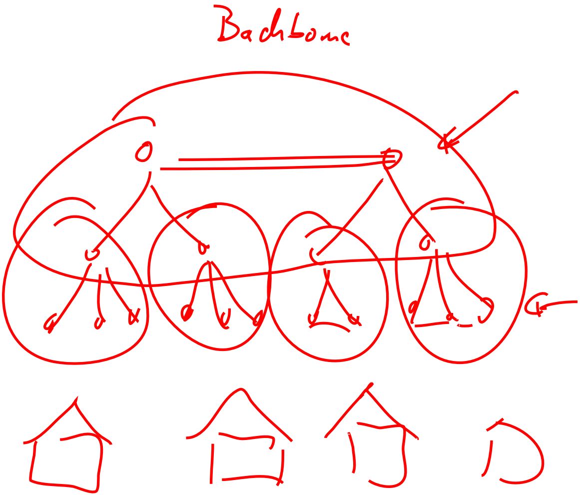


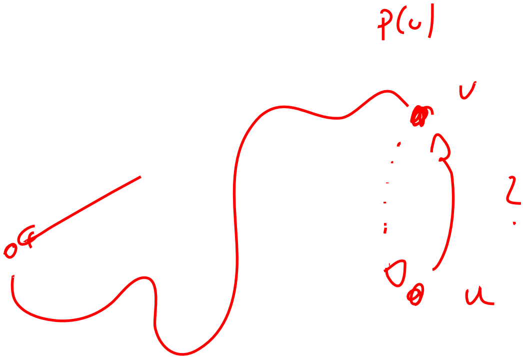
Applications of Routing Algorithms

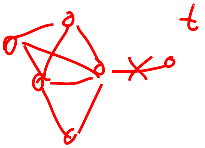
- Mobile Ad Hoc Networks
  - reactive versus proactive protocols
  - proactive protocols like DV construct routing tables even without packets
  - when the network is too dynamic this is an overhead
  - then reactive protocols like Flooding, DSR, AODV are more adequate
- DV routing is used in Intra-Domain Routing
  - RIP (Routing Information Protocol)
  - EIGRP (Enhanced Interior Gateway Routing Protocol)
- main alternative for Intra-Domain Routing is Link-State-Routing used in
  - OSPF (Open Shortest Path First)
  - IS-IS (Intermediate System to Intermediate System Protocol)
- Path-Vector-Protocol is the worldwide standard in Inter-Domain Routing
  - BGP (Border Gateway Protocol)

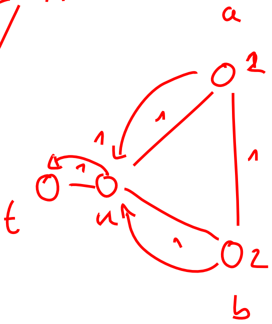
End of Section 5

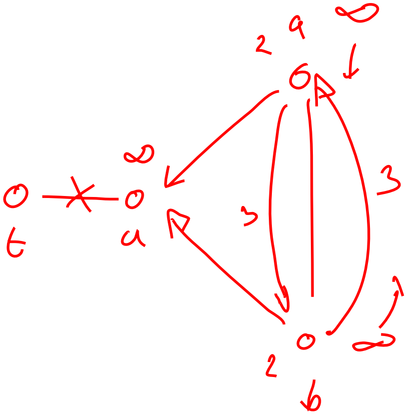



Backbone


p(v)
v
u


t


a
1
1
1
1
1
t
0
u
1
2
b


2
a
∞
6
∞
0
t
u
3
3
2
b
∞