Formal Methods for Wireless Mesh Networks

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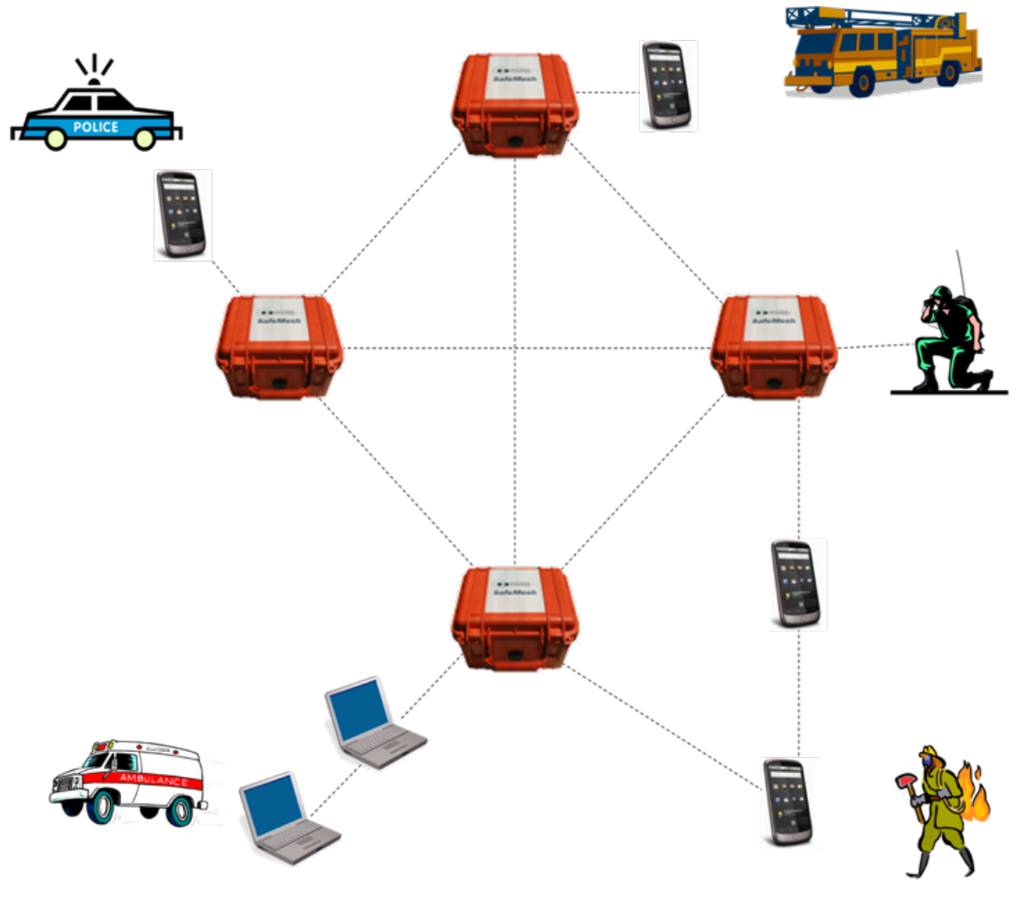
Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

NICTA Members

NICTA Partners

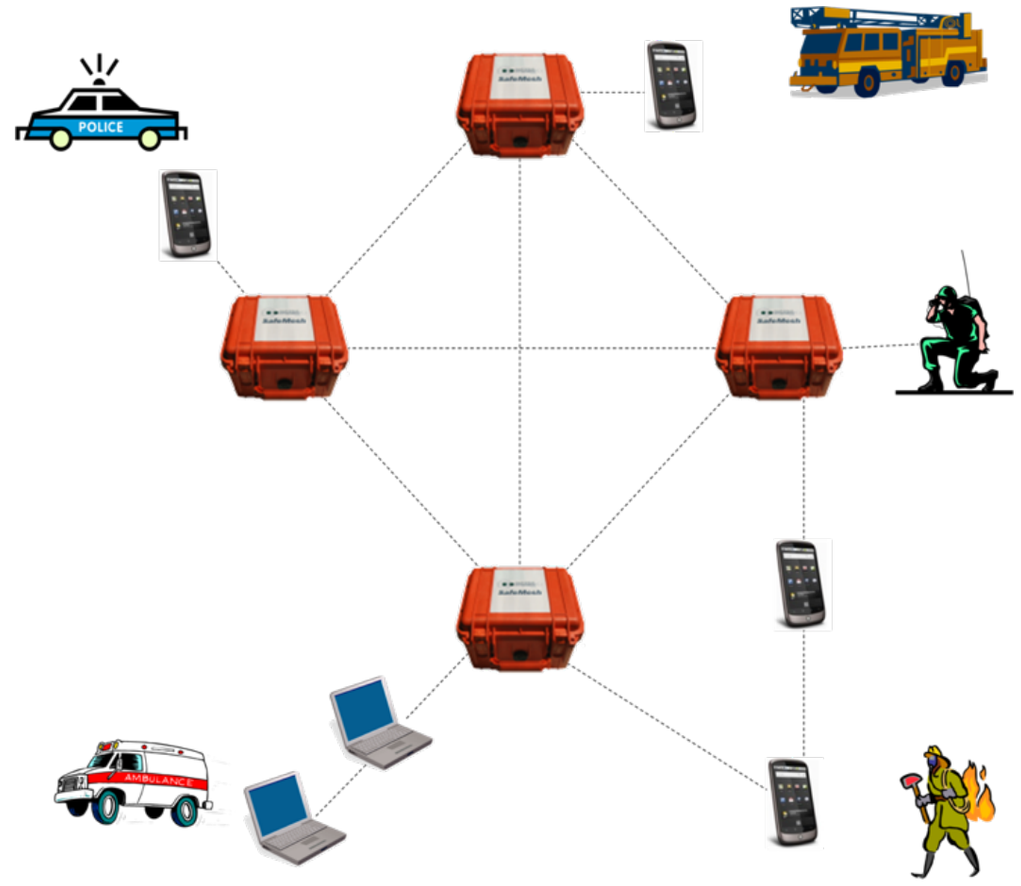
What is the Problem?

- Wireless Mesh Networks (WMNs)
  - key features: mobility, dynamic topology, wireless multihop backhaul
  - quick and low cost deployment
- Applications
  - public safety
  - emergency response, disaster recovery
  - transportation
  - mining
  - smart grid
  - ...



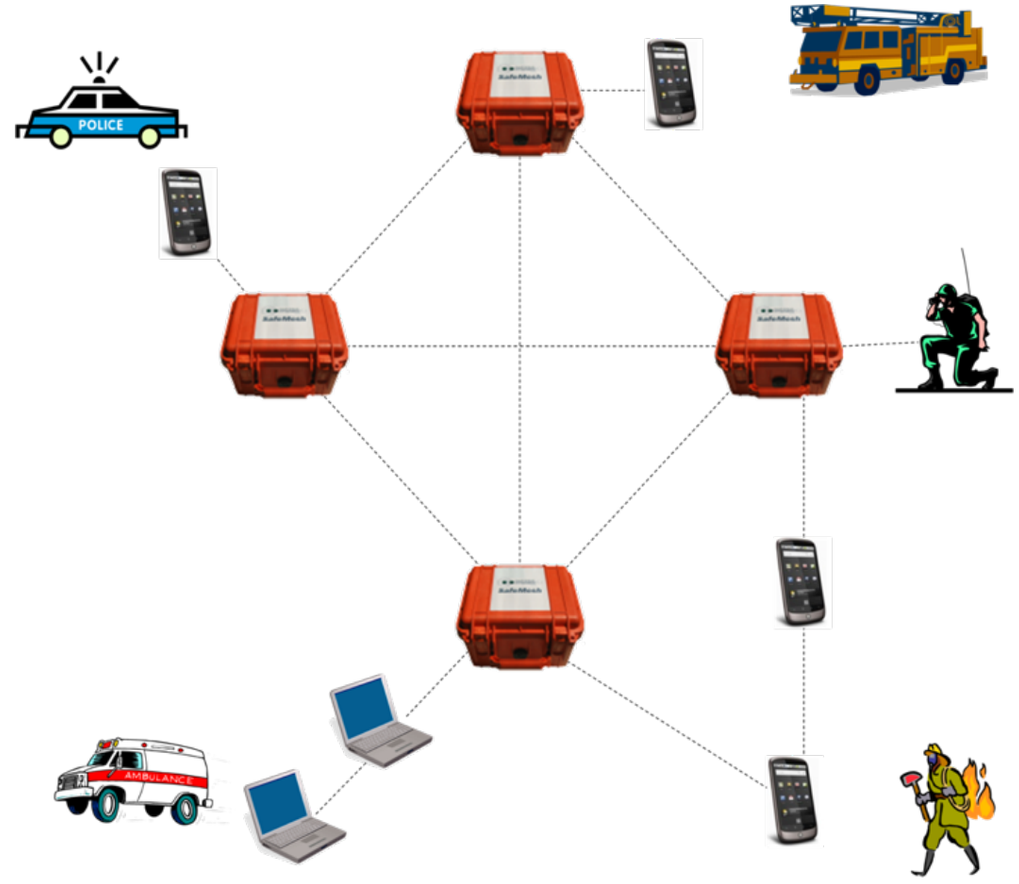
What is the Problem?

- WMNs promise to be fully
  - self-configuring
  - self-healing
  - self-optimising



What is the Problem?

- WMNs promise to be fully
  - self-configuring
  - self-healing
  - self-optimising
- **DOES NOT WORK** (in reality)
- Limitations in reliability and performance
- Limitations confirmed by
  - end users (e.g. police)
  - own experiments
    - Cisco, Motorola, Firetide, ...
  - industry



What is the Problem?

"Our requirement was for a system breadcrumb type deployment over at least 4 nodes and maintain a throughput of around 5Mbps-10Mbps to enable 'good' quality video to be passed. The commercial devices failed to meet our requirements [...]"

Rick Loebler, Applied Technology Manager,
NSW Police Force

Formal Methods for Mesh Networks

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- Goal
  - model, analyse, verify and increase the performance of wireless mesh protocols
  - develop suitable formal methods techniques
- Benefits
  - more reliable protocols
  - finding and fixing bugs
  - better performance
  - proving correctness
  - reduce “time-to-market”
- Team (Formal Methods)
  - Ansgar Fehnker, Rob van Glabbeek, Peter Höfner, Annabelle McIver, Marius Portmann, Wee Lum Tan

Formal Methods for Mesh Networks

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- Main Methods used so far
  - process algebra
  - model checking
  - routing algebra

Current Protocols

Network

(textual) Specification

... The route is only updated if the new sequence number is either

(i) higher than the destination sequence number in the route table, or
(ii) the sequence numbers are equal, but the hop count (of the new information) plus one, is smaller than the existing hop count in the routing table, or
(iii) the sequence number is unknown.

This route MAY now be used to send any queued data packets and fulfills any outstanding route requests. ...

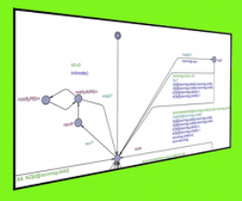
(RFC 3561)

Formal Methods

Process Calculus

/* update the sqn of ip by setting it to max(sqn(rt, ip), dsn) */
⟦rt := update(rt, (ip, dsn, valid, 0, ip, 0))⟧
/* unicast a RREP towards oip of the RREQ; next hop is sip */
unicast(sip, rrep(0, dip, sqn(rt, ip), oip, ip)) . aodv(ip, rt, rreqs, queues)
► /* If the packet transmission is unsuccessful, a RERR message is generated */
⟦dests := {(rip, rsn) | (rip, rsn, valid, ∗, sip, ∗) ∈ rt}⟧
⟦pre := ⋃{precs(rt, rip) | (rip, ∗) ∈ dests}⟧
⟦for all (rip, ∗) ∈ dests : invalidate(rt, rip)⟧
groupcast(pre, rerr(dests, ip)) . aodv(ip, rt, rreqs, queues)

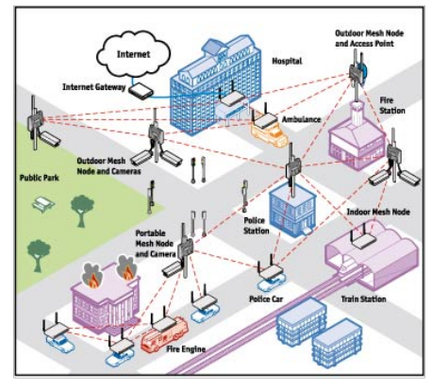
Model Checking



Algebra of Routing Tables

$$\begin{array}{c} \\ A \\ B \\ C \\ D \\ E \end{array} \begin{array}{c} \begin{array}{ccccc} A & B & C & D & E \end{array} \\ \begin{pmatrix} (\varepsilon,0) & (B,1) & (B,2) & (\varepsilon,\infty) & (\varepsilon,\infty) \\ (A,1) & (\varepsilon,0) & (C,1) & (\varepsilon,\infty) & (\varepsilon,\infty) \\ (\varepsilon,\infty) & (B,1) & (\varepsilon,0) & (\varepsilon,\infty) & (E,1) \\ (\varepsilon,\infty) & (\varepsilon,\infty) & (\varepsilon,\infty) & (\varepsilon,0) & (E,1) \\ (\varepsilon,\infty) & (\varepsilon,\infty) & (C,1) & (D,1) & (\varepsilon,0) \end{pmatrix} \end{array}$$

Better Protocols



Ad Hoc On-Demand Distance Vector Protocol

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- Routing protocol for WMNs

- Ad hoc (network is not static)
- On-Demand (routes are established when needed)
- Distance (metric is hop count)
- Vector (routing table has the form of a vector)

- Developed 1997-2001 by Perkins, Beldig-Royer and Das (University of Cincinnati)

Ad Hoc On-Demand Distance Vector Protocol

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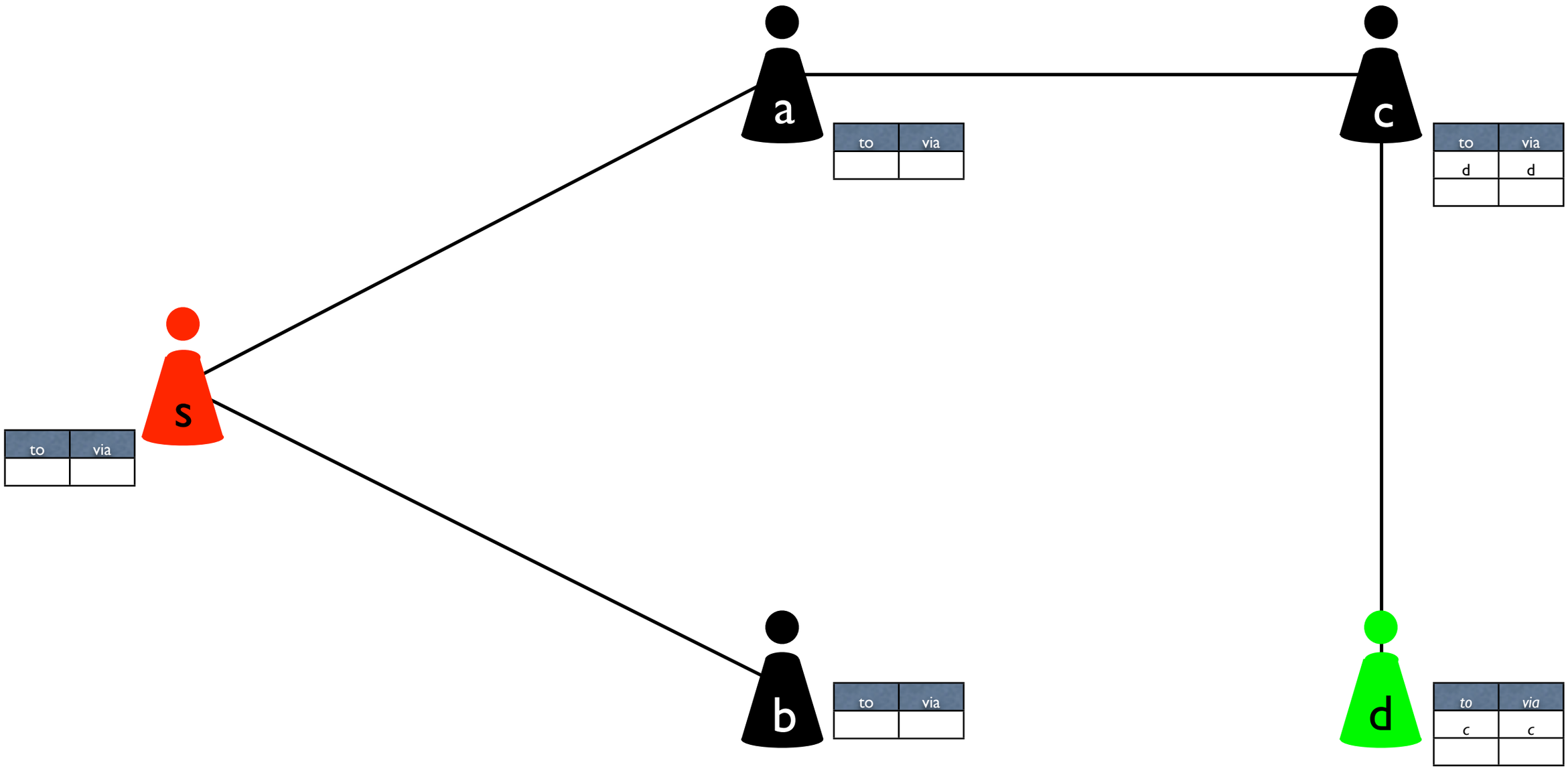
- AODV control messages
  - route request (RREQ)
  - route reply (RREP)
  - route error message (RERR)

- Information at nodes
  - own IP address
  - a local sequence number (freshness/timer)
  - a routing table
    - local knowledge
    - entries: $(\texttt{dip}, \texttt{dsn}, \texttt{val}, \texttt{hops}, \texttt{nhip}, \texttt{pre})$

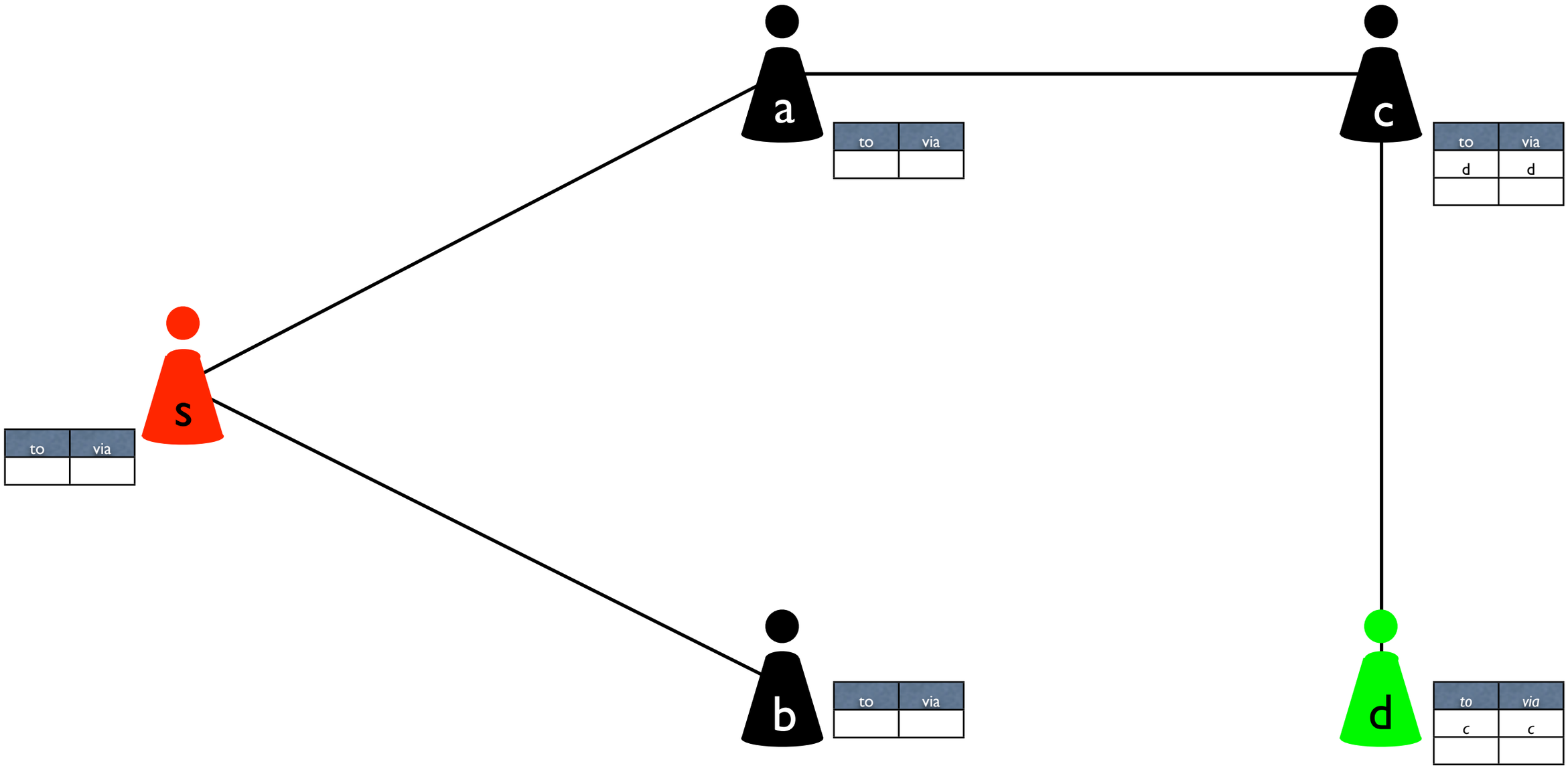
AODV – An Example



s is looking for a route to d

AODV – An Example

NICTA



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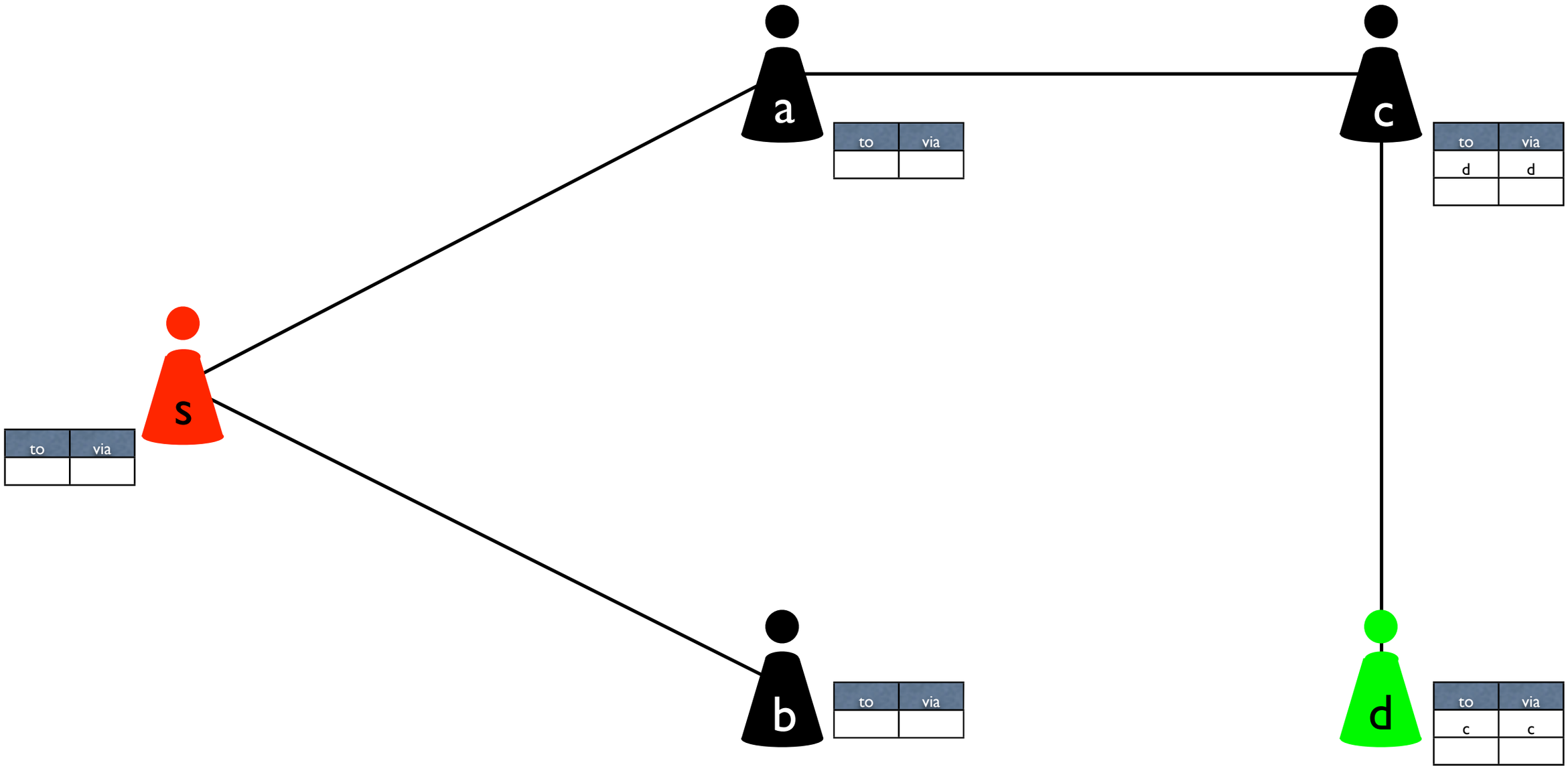

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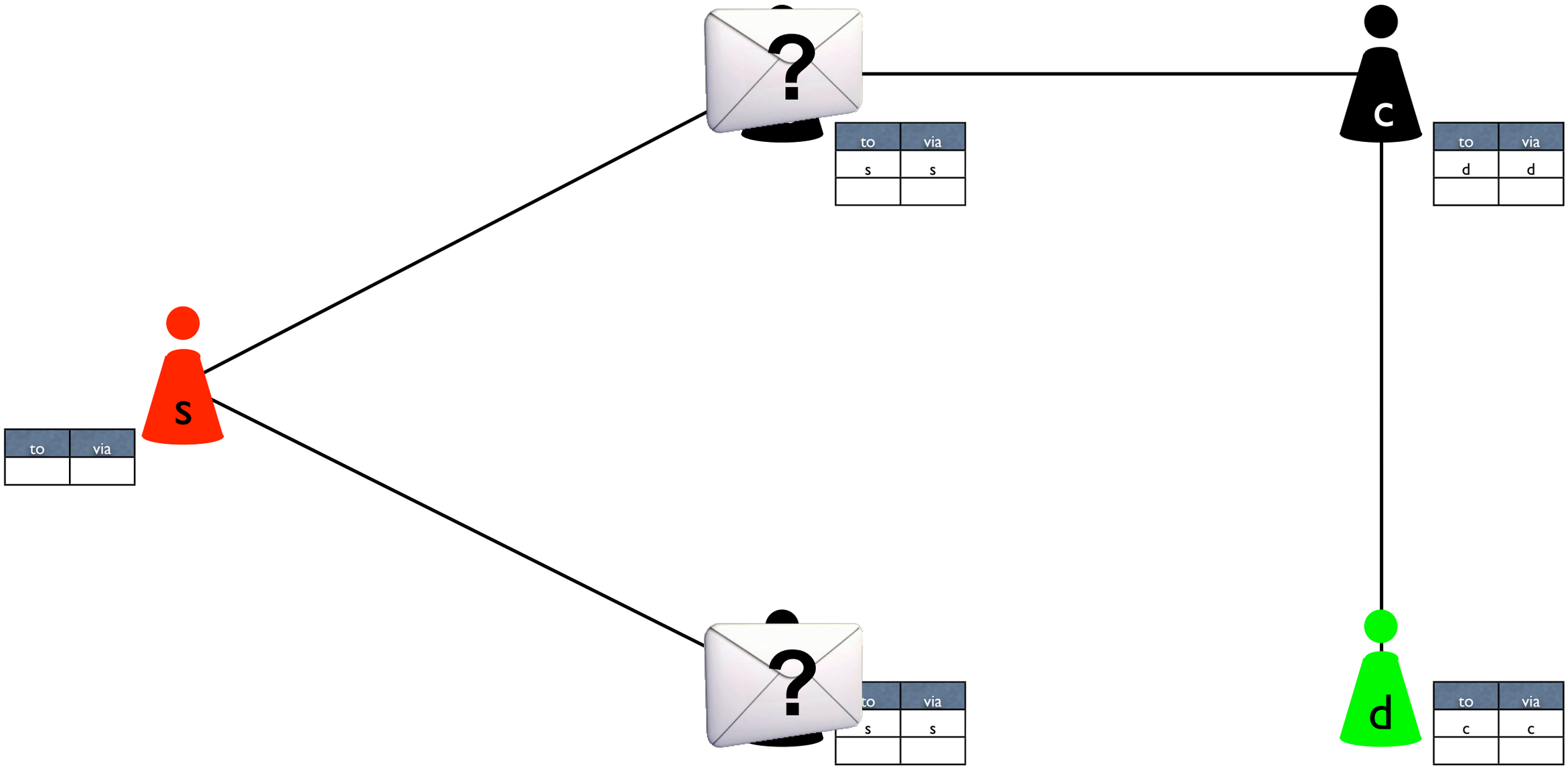

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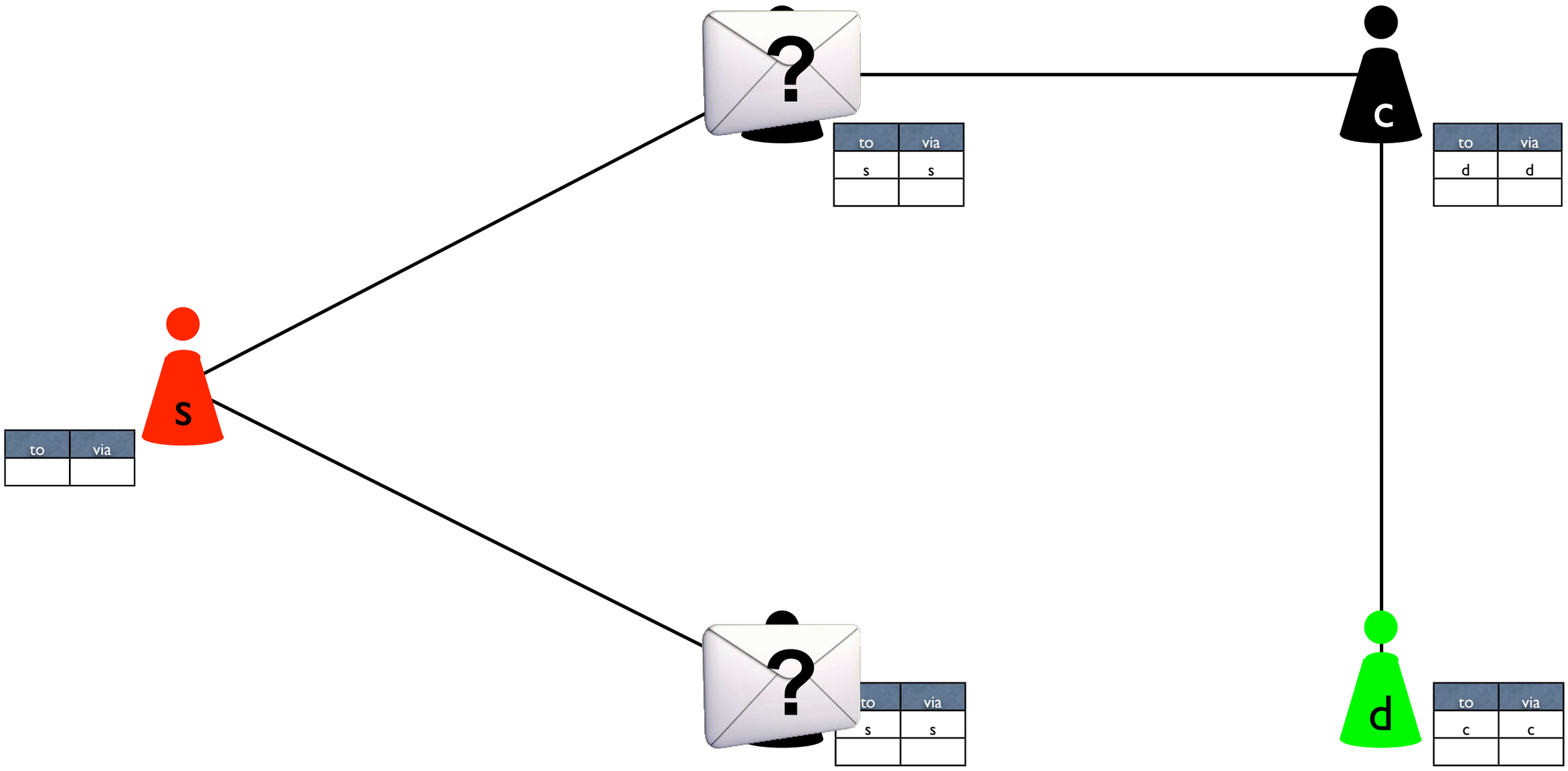

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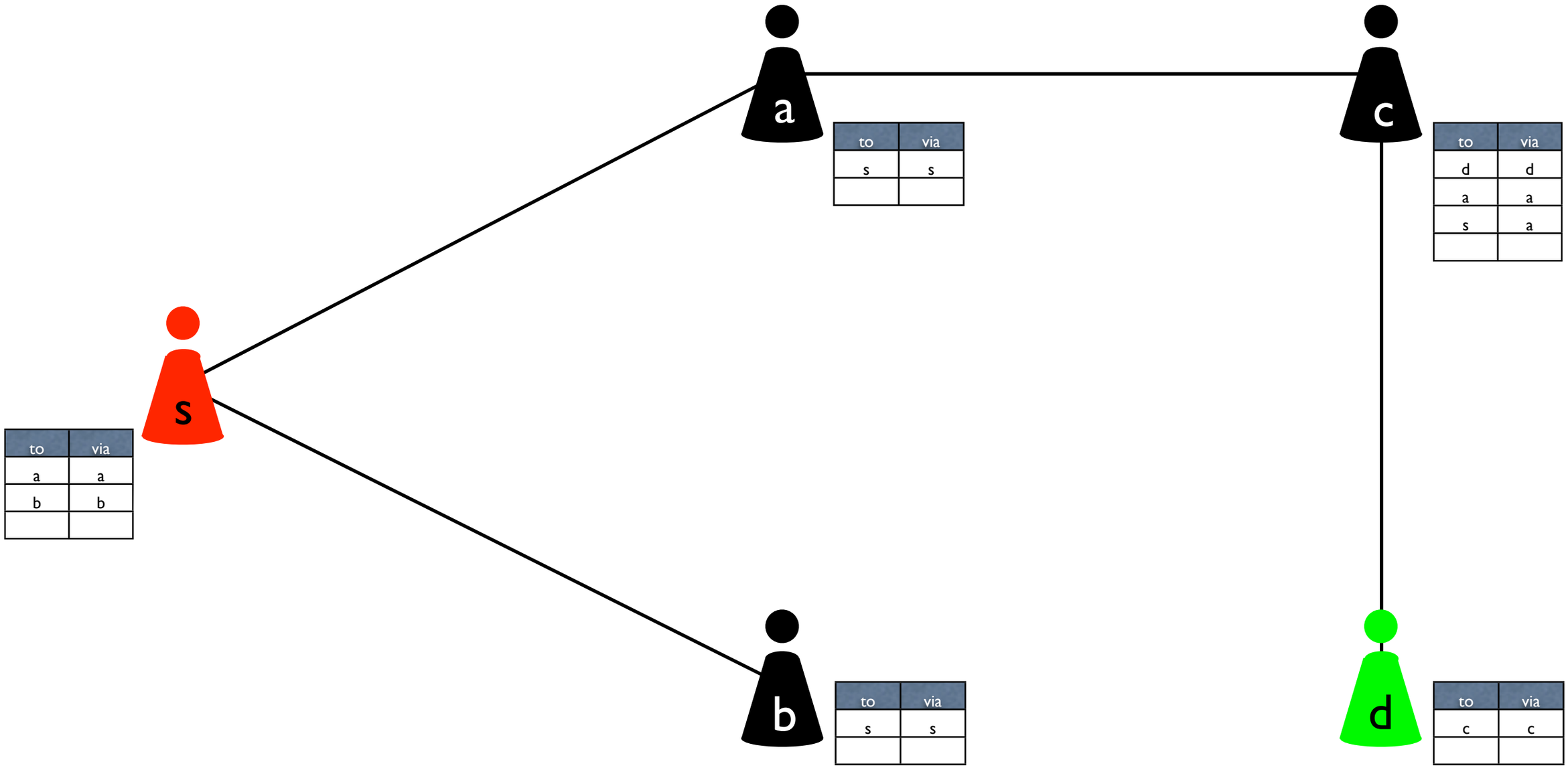

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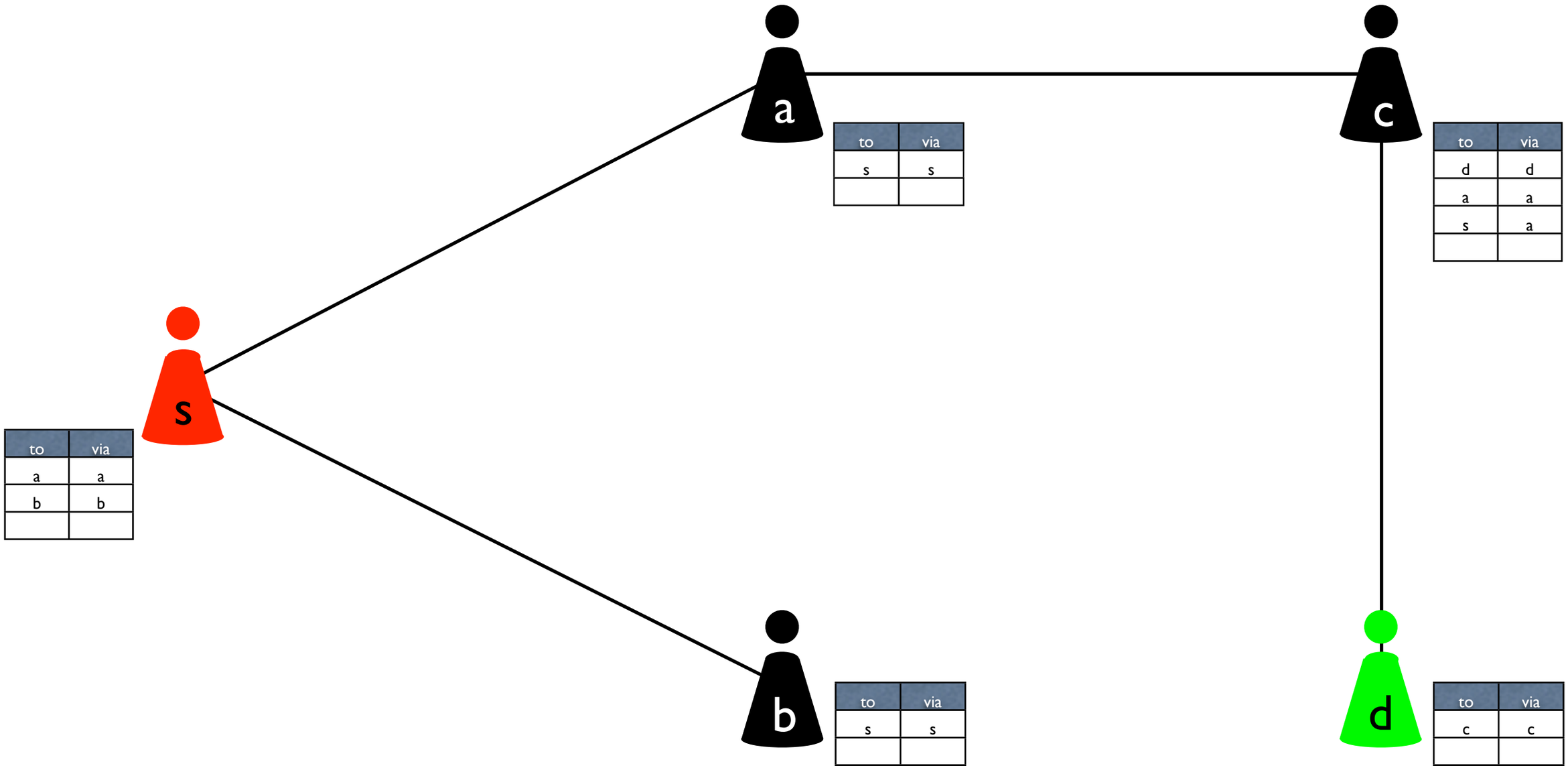

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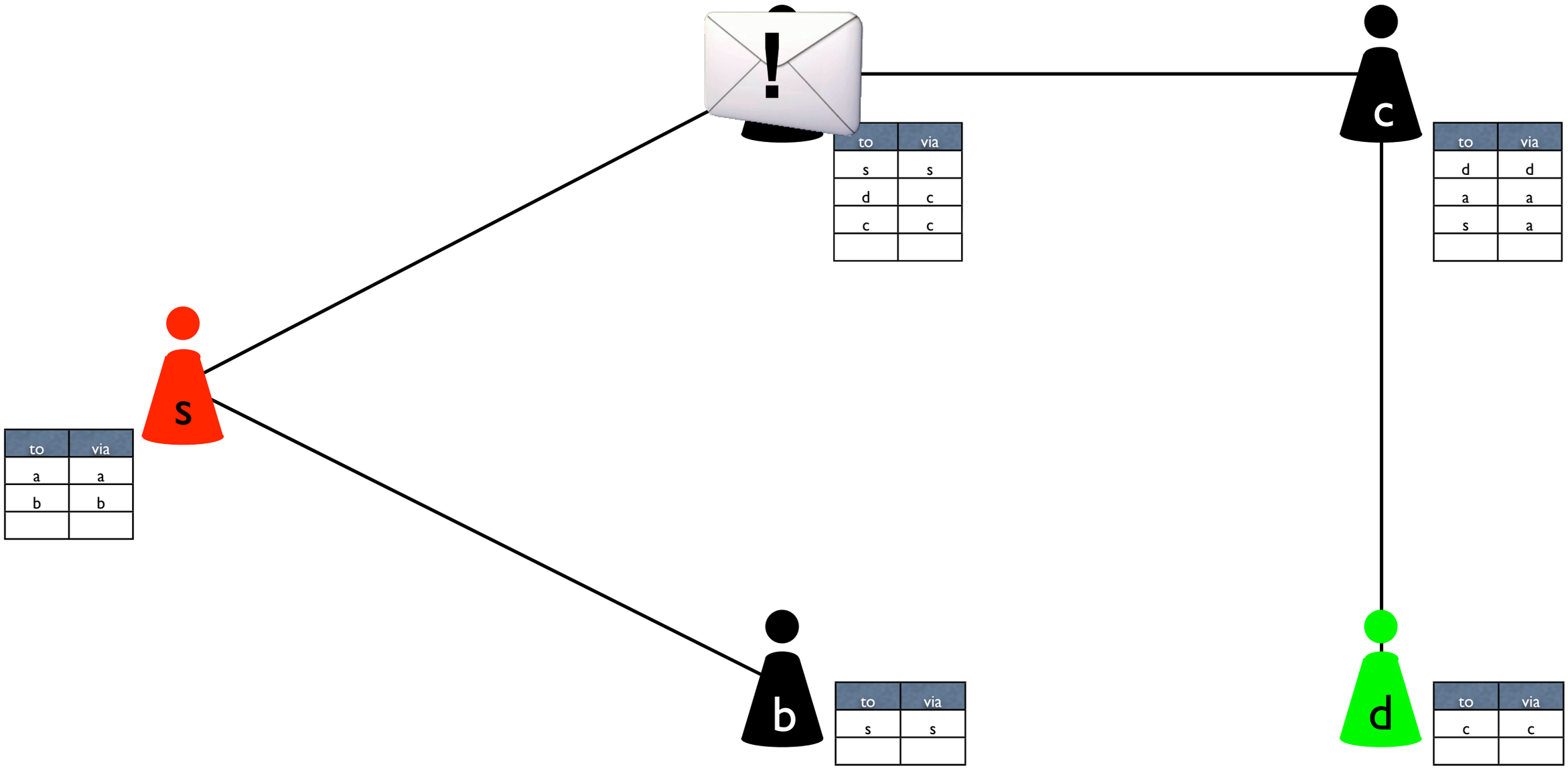

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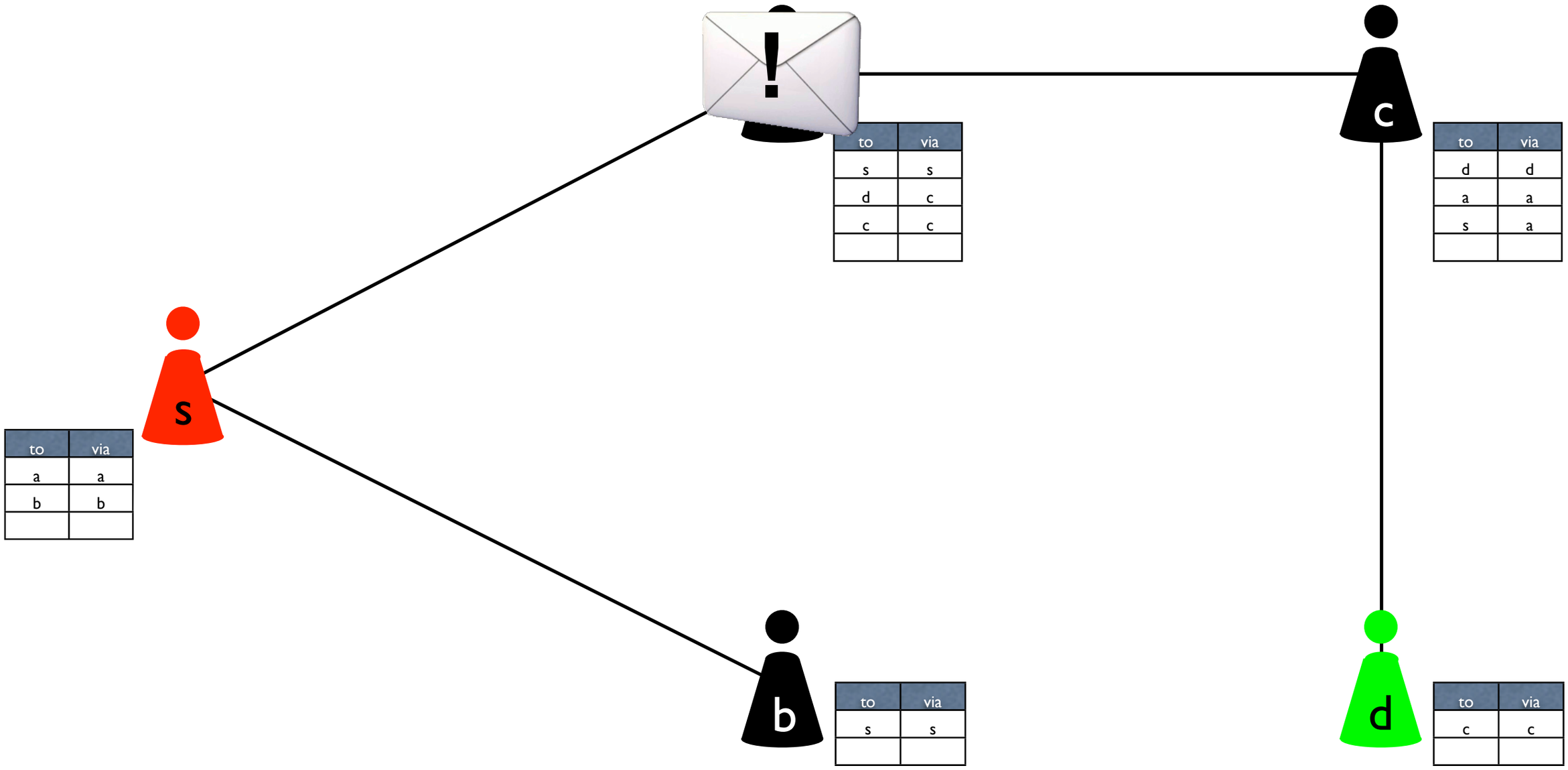

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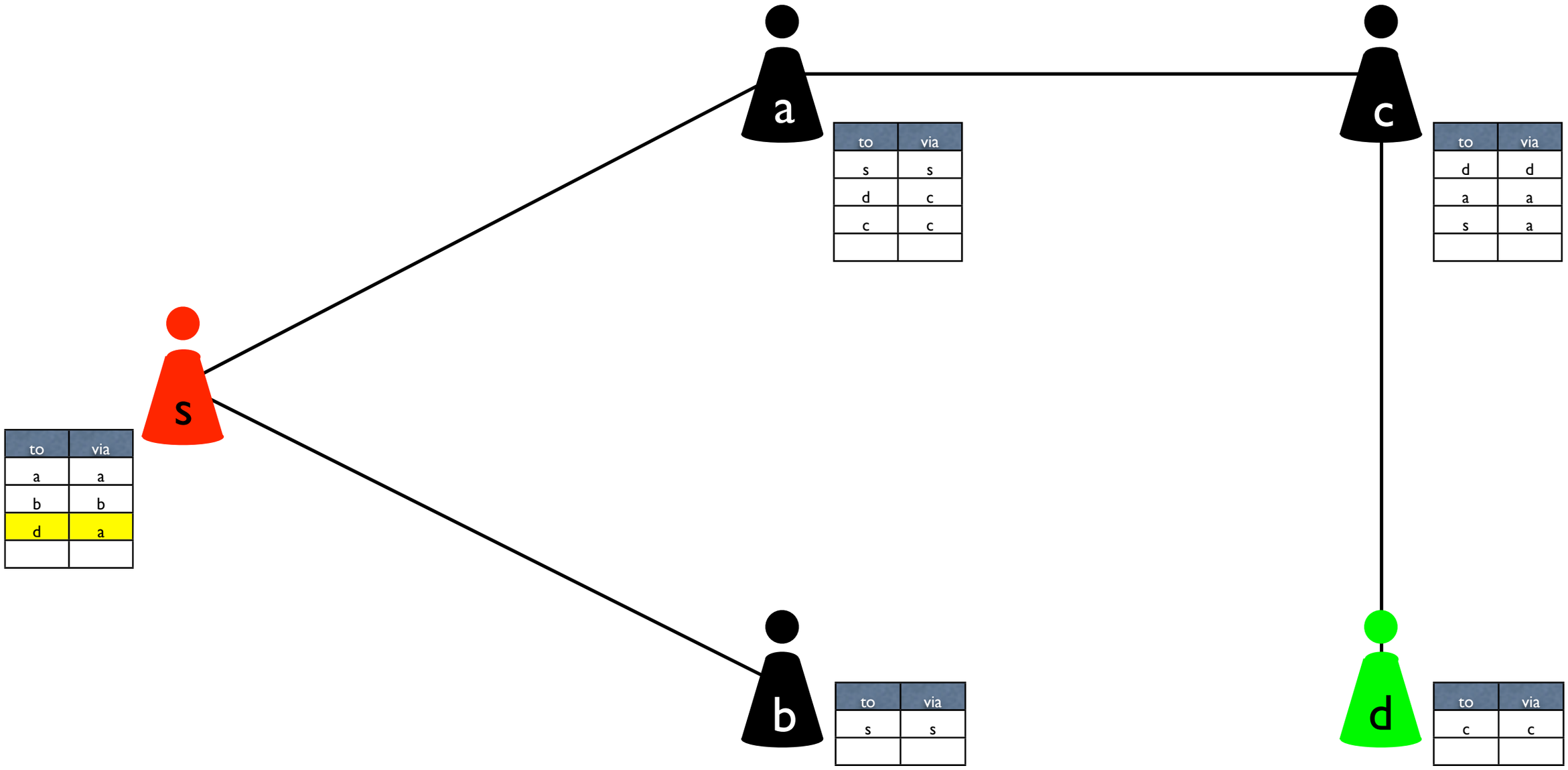

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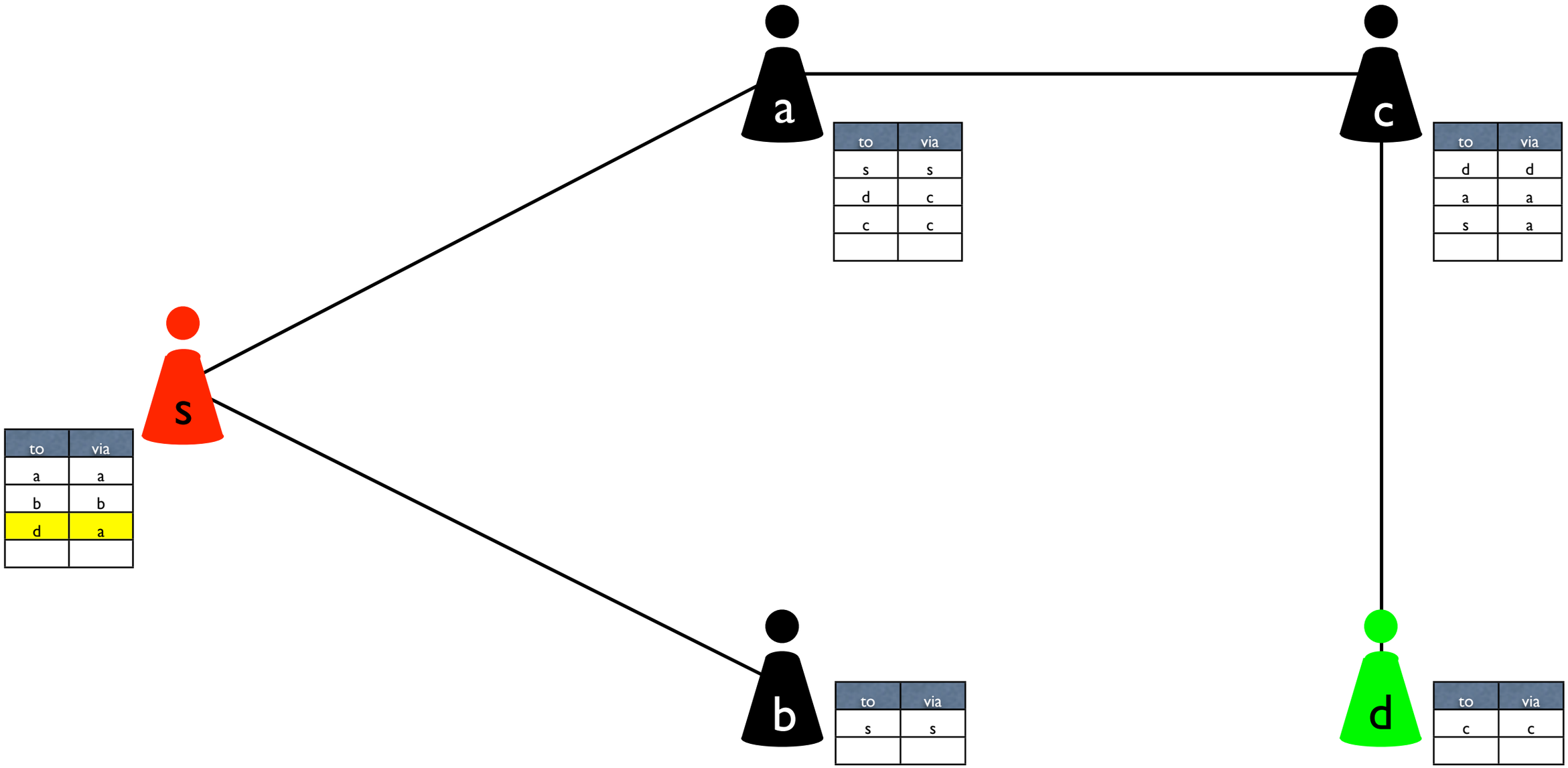

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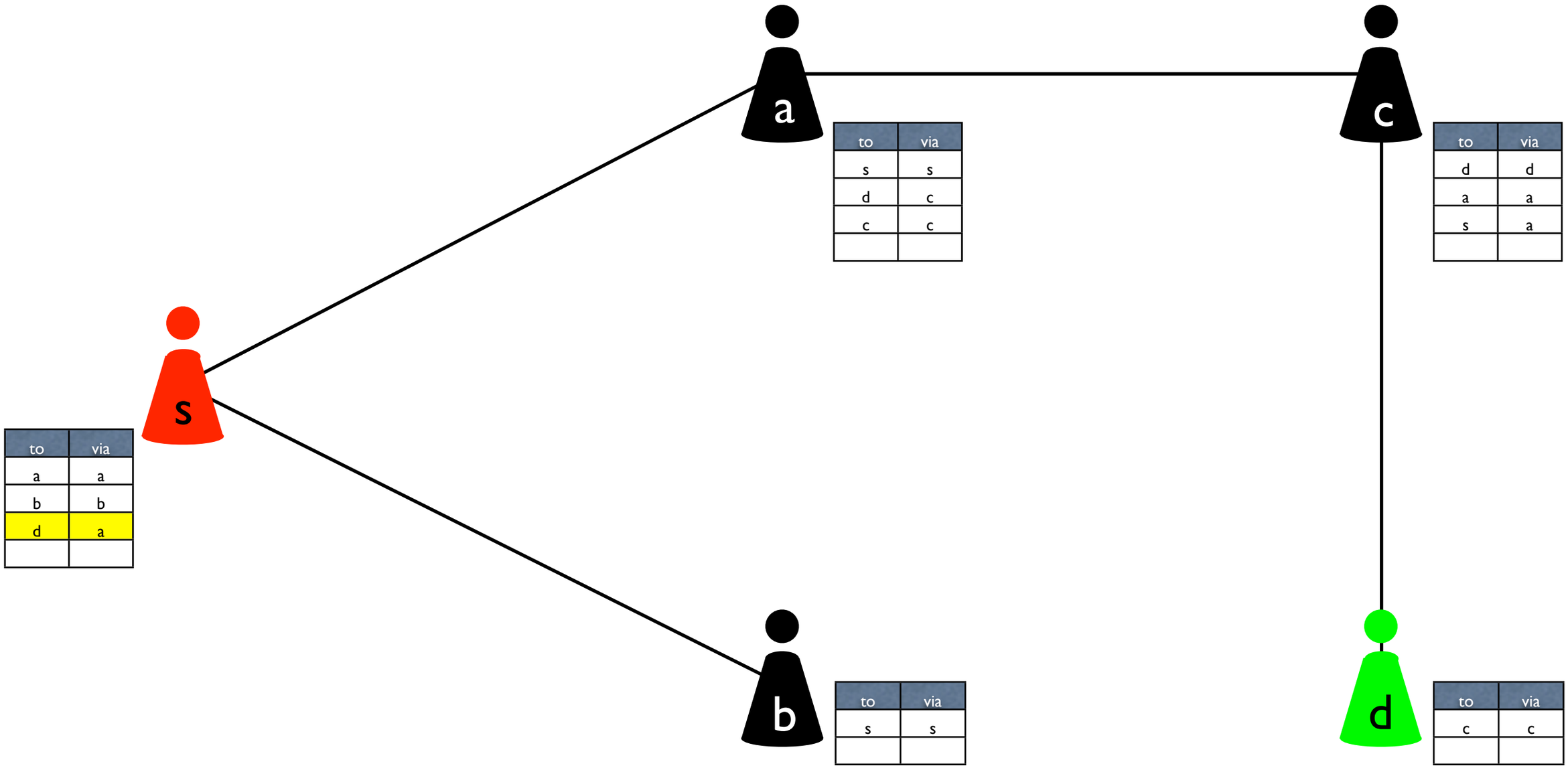

s has found a route to d

Ad Hoc On-Demand Distance Vector Protocol

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- *Properties of AODV*
  - *route correctness*
  - *loop freedom*
  - *route found*
  - *packet delivery*

Ad Hoc On-Demand Distance Vector Protocol

NICTA

- *Properties of AODV*
  - *route correctness* ✓
  - *loop freedom* ✓ (at least for some interpretations)
  - *route found* ✗
  - *packet delivery* ✗

Ad Hoc On-Demand Distance Vector Protocol

NICTA

- Properties of AODV
  - route correctness 
  - loop freedom 
  - route found 
  - packet delivery 
- so far only simulation and test-bed evaluations
  - important, valid methods
  - limitations
    - resource intensive, time-consuming, no generality

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- Request for Comments (de facto standard)

```
sequence number field is set to false.  The route is only updated if
the new sequence number is either

(i)       higher than the destination sequence number in the route
          table, or

(ii)      the sequence numbers are equal, but the hop count (of the
          new information) plus one, is smaller than the existing hop
          count in the routing table, or

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```

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NICTA

- Main Methods used so far
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  - model checking
  - routing algebra

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(RFC 3561)

Formal Methods

Process Calculus

/* update the sqn of ip by setting it to max(sqn(rt, ip), dsn) */
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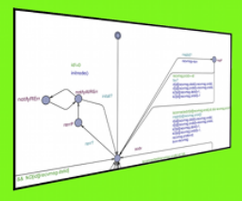
Model Checking



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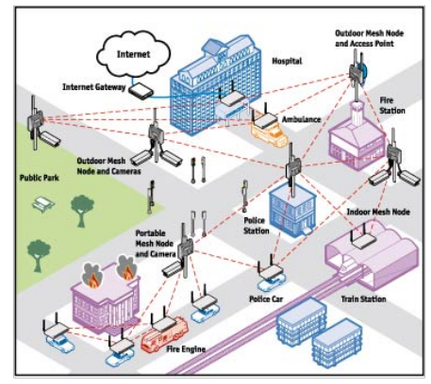
Better Protocols



Process Algebra

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$+$ [$(\mathtt{oip}, \mathtt{rreqid}) \notin \mathtt{rreqs}$] /* the RREQ is new to this node */
/* update the route to oip in rt */
⟦$\mathtt{rt} := \mathtt{update}(\mathtt{rt}, (\mathtt{oip}, \mathtt{osn}, \mathtt{valid}, \mathtt{hops}+1, \mathtt{sip}, \emptyset))$⟧
/* update rreqs by adding (oip, rreqid) */
⟦$\mathtt{rreqs} := \mathtt{rreqs} \cup \{(\mathtt{oip}, \mathtt{rreqid})\}$⟧
(
[$\mathtt{dip} = \mathtt{ip}$] /* this node is the destination node */
/* update the sqn of ip by setting it to max(sqn(rt, ip), dsn) */
⟦$\mathtt{rt} := \mathtt{update}(\mathtt{rt}, (\mathtt{ip}, \mathtt{dsn}, \mathtt{valid}, 0, \mathtt{ip}, \emptyset))$⟧
/* unicast a RREP towards oip of the RREQ; next hop is sip */
unicast$(\mathtt{sip}, \mathtt{rrep}(0, \mathtt{dip}, \mathtt{sqn}(\mathtt{rt}, \mathtt{ip}), \mathtt{oip}, \mathtt{ip}))$. $\mathtt{AODV}(\mathtt{ip}, \mathtt{rt}, \mathtt{rreqs}, \mathtt{queues})$
▶ /* If the packet transmission is unsuccessful, a RERR message is generated */
⟦$\mathtt{dests} := \{(\mathtt{rip}, \mathtt{rsn}) \mid (\mathtt{rip}, \mathtt{rsn}, \mathtt{valid}, *, \mathtt{sip}, *) \in \mathtt{rt}\}$⟧
⟦$\mathtt{pre} := \bigcup\{\mathtt{precs}(\mathtt{rt}, \mathtt{rip}) \mid (\mathtt{rip}, *) \in \mathtt{dests}\}$⟧
⟦for all $(\mathtt{rip}, *) \in \mathtt{dests}$: $\mathtt{invalidate}(\mathtt{rt}, \mathtt{rip})$⟧
groupcast$(\mathtt{pre}, \mathtt{rerr}(\mathtt{dests}, \mathtt{ip}))$. $\mathtt{AODV}(\mathtt{ip}, \mathtt{rt}, \mathtt{rreqs}, \mathtt{queues})$
$+$ [$\mathtt{dip} \neq \mathtt{ip}$] /* this node is not the destination node */
(
[$\mathtt{dip} \in \mathtt{aD}(\mathtt{rt}) \wedge \mathtt{dsn} \leq \mathtt{sqn}(\mathtt{rt}, \mathtt{dip}) \wedge \mathtt{sqn}(\mathtt{rt}, \mathtt{dip}) \neq 0$] /* valid route to dip that is fresh enough */
/* update rt by adding sip to precs(rt, dip) */
⟦$\mathtt{r} := \mathtt{addpre}(\sigma_{route}(\mathtt{rt}, \mathtt{dip}), \{\mathtt{sip}\})$; $\mathtt{rt} := \mathtt{update}(\mathtt{rt}, \mathtt{r})$⟧

Process Algebra

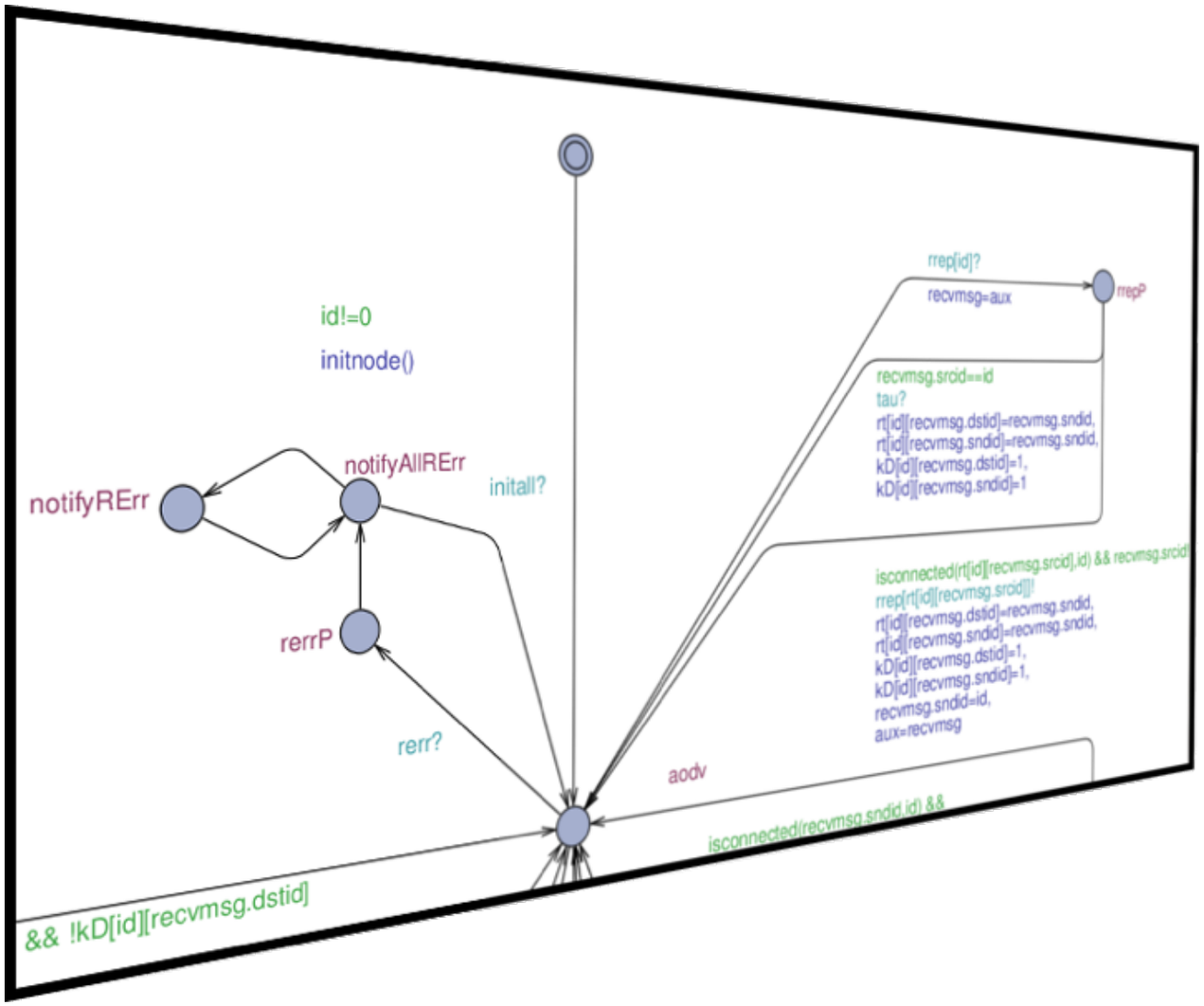
- New process algebra developed
- Language for formalising specs of network protocols
- Key features:
  - guarantee broadcast
  - prioritised unicast
  - data handling
- Achievements
  - full concise specification of AODV (RFC 3561) (no time)
  - formally verified loop-freedom (without timeouts)
    - invariant proof
  - found several ambiguities, mistakes, shortcomings
  - found solutions for some limitations

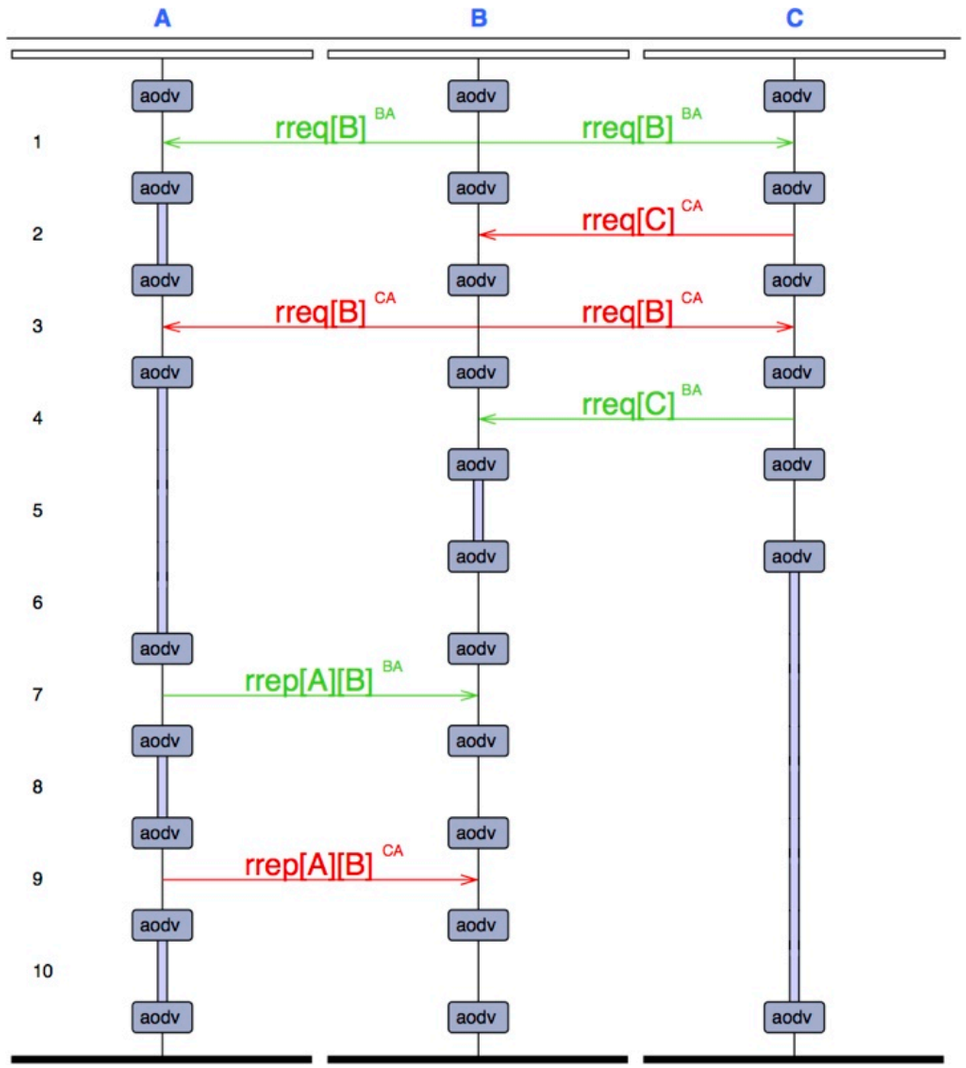
Structure of WMNs

- User
  - Network as a “cloud”
- Collection of nodes
  - connect / disconnect / send / receive
  - “parallel execution” of nodes

- Nodes
  - data management
    - data packets, messages, IP addresses ...
  - message management (avoid blocking)
  - core management
    - broadcast / unicast / groupcast ...
  - “parallel execution” of sequential processes

Model Checking





Model Checking

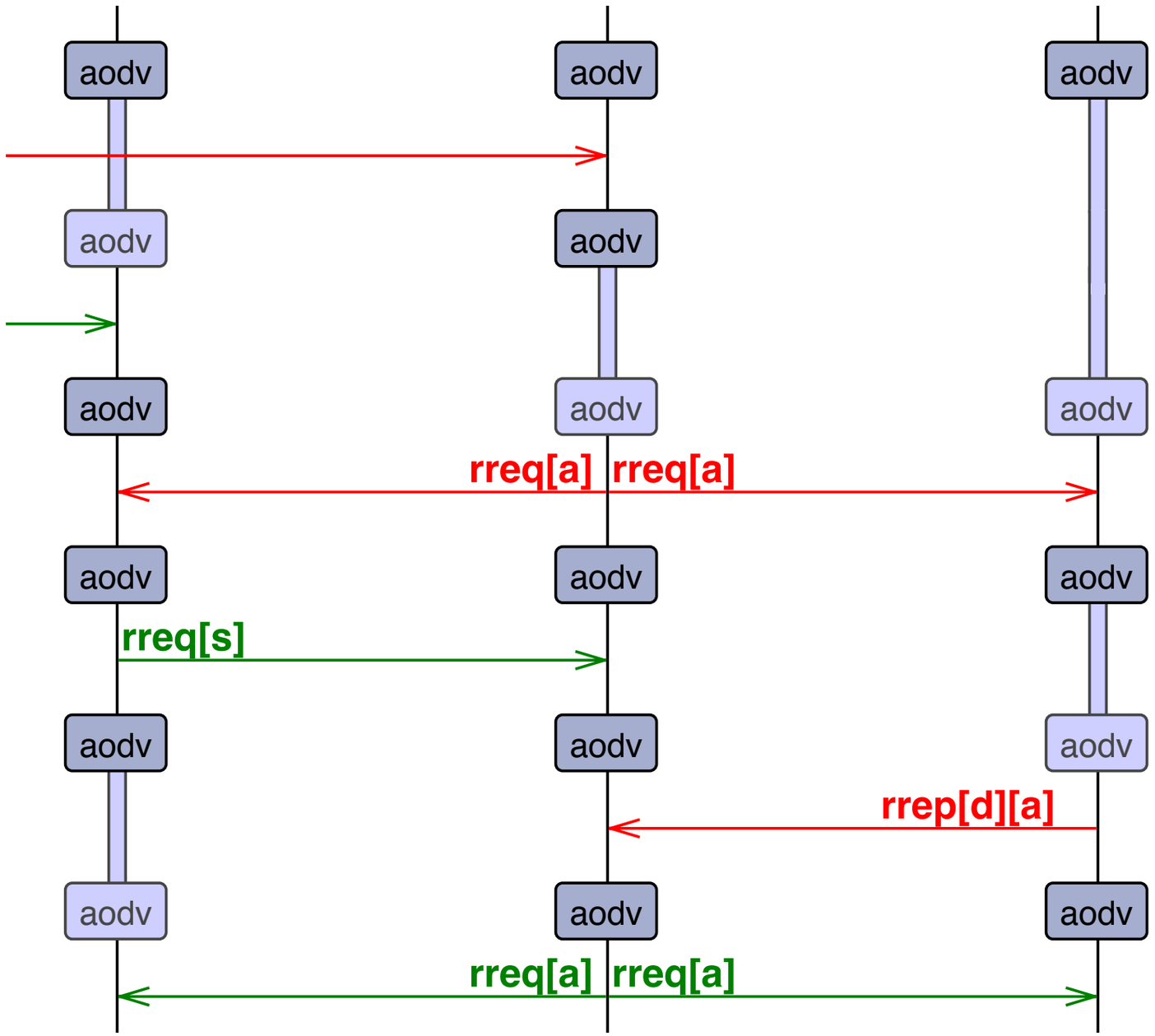
- Model checking routing algorithms
  - executable models
- Complementary to process algebra
  - find bugs and typos in model of process algebra
  - check properties of specification applied to particular topology
  - easy adaption in case of change
  - automatic verification
- Achievements
  - implemented process algebra specification of AODV
  - found/replayed shortcomings

Experiments Set-Up

- Exhaustive search
  - different properties
  - all topologies up to 5 nodes (one topology change)
  - 2 route discovery processes
  - 17400 scenarios
  - variants of AODV (4 models)

Results: Route Discovery (2004)

- Route discovery fails in a linear 3-node topology



Results: Route Discovery

- exhaustive search
  (potential failure in route discovery)
  - static topology: 47.3%
  - dynamic topology (add link): 42.5%
  - dynamic topology (remove link): 73.7%
- AODV repeats route request
- Other solution: forward route reply

Routing Algebra

$$
\begin{array}{c}
 \\
A \\
B \\
C \\
D \\
E
\end{array}
\begin{array}{c}
\begin{array}{ccccc} A & B & C & D & E \end{array} \\
\begin{pmatrix}
(\epsilon,0) & (B,1) & (B,2) & (\epsilon,\infty) & (\epsilon,\infty) \\
(A,1) & (\epsilon,0) & (C,1) & (\epsilon,\infty) & (\epsilon,\infty) \\
(\epsilon,\infty) & (B,1) & (\epsilon,0) & (\epsilon,\infty) & (E,1) \\
(\epsilon,\infty) & (\epsilon,\infty) & (\epsilon,\infty) & (\epsilon,0) & (E,1) \\
(\epsilon,\infty) & (\epsilon,\infty) & (C,1) & (D,1) & (\epsilon,0)
\end{pmatrix}
\end{array}
$$

Routing Algebra – Elements, Operators

- Routing table entries (no sequence number so far)

$$(\texttt{nhip}, \texttt{hops})$$

- Choice: $(A, 5) + (B, 2) = (B, 2)$
- Multiplication: $(A, 5) \cdot (B, 2) = (A, 7)$
  - destination and source must coincide

- idea: back to Backhouse, Carré, Griffin, Sobrinho

Routing Algebra – Elements, Operators

- Matrices over routing table entries

$$\begin{array}{c} \\ A \\ B \\ C \\ D \\ \vdots \end{array} \begin{array}{c} \begin{array}{cccccc} A & B & C & D & \dots \end{array} \\ \left(\begin{array}{cccccc} (\_,0) & (B,1) & (B,2) & (\_,\infty) & \\ (A,1) & (\_,0) & (C,1) & (\_,\infty) & \dots \\ (\_,\infty) & (B,1) & (\_,0) & (\_,\infty) & \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,0) & \\ & \vdots & & & \ddots \end{array} \right) \end{array}$$

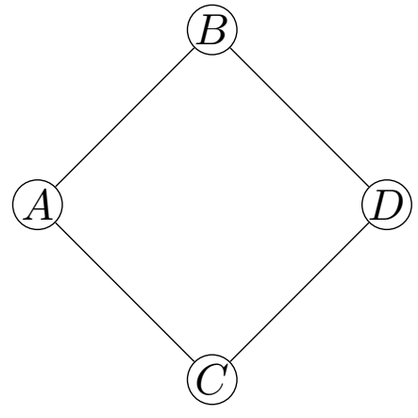
routing table of A

"routes" to B

- standard matrix operations
- further abstraction possible (semirings, test, domain, modules ...)

Example

- A route request is broadcast



$$\begin{pmatrix} (\_,0) & (B,1) & (C,1) & (\_,\infty) \\ (A,1) & (\_,0) & (\_,\infty) & (D,1) \\ (A,1) & (\_,\infty) & (\_,0) & (D,1) \\ (\_,\infty) & (B,1) & (C,1) & (\_,0) \end{pmatrix} \bullet \begin{pmatrix} (\_,0) & (\_,\infty) & (\_,\infty) & (\_,\infty) \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,\infty) \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,\infty) \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,\infty) \end{pmatrix} \bullet \begin{pmatrix} (\_,0) & (B,1) & (\_,\infty) & (\_,\infty) \\ (\mathbf{D},\mathbf{3}) & (\_,0) & (\_,\infty) & (\_,\infty) \\ (A,1) & (\_,\infty) & (\_,0) & (D,1) \\ (C,2) & (\_,\infty) & (C,1) & (\_,0) \end{pmatrix}$$

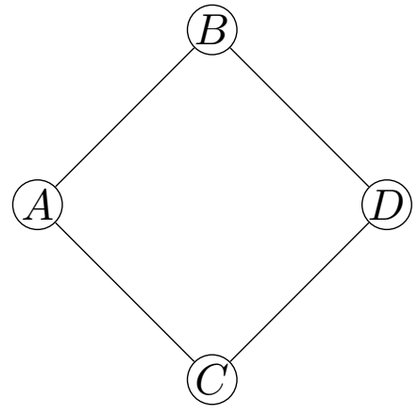
topology sender routing table

$$= \begin{pmatrix} (\_,0) & (B,1) & (\_,\infty) & (\_,\infty) \\ (\mathbf{A},\mathbf{1}) & (\_,0) & (\_,\infty) & (\_,\infty) \\ (A,1) & (\_,\infty) & (\_,0) & (D,1) \\ (C,2) & (\_,\infty) & (C,1) & (\_,0) \end{pmatrix}$$

updated routing table

Example

- A route request is broadcast



$$\begin{pmatrix} (\_,0) & (B,1) & (C,1) & (\_,\infty) \\ (A,1) & (\_,0) & (\_,\infty) & (D,1) \\ (A,1) & (\_,\infty) & (\_,0) & (D,1) \\ (\_,\infty) & (B,1) & (C,1) & (\_,0) \end{pmatrix} \bullet \begin{pmatrix} (\_,0) & (\_,\infty) & (\_,\infty) & (\_,\infty) \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,\infty) \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,\infty) \\ (\_,\infty) & (\_,\infty) & (\_,\infty) & (\_,\infty) \end{pmatrix} \bullet \begin{pmatrix} (\_,0) & (B,1) & (\_,\infty) & (\_,\infty) \\ (\mathbf{D},\mathbf{3}) & (\_,0) & (\_,\infty) & (\_,\infty) \\ (A,1) & (\_,\infty) & (\_,0) & (D,1) \\ (C,2) & (\_,\infty) & (C,1) & (\_,0) \end{pmatrix}$$

topology sender routing table

$$= \begin{pmatrix} (\_,0) & (B,1) & (\_,\infty) & (\_,\infty) \\ (\mathbf{A},\mathbf{1}) & (\_,0) & (\_,\infty) & (\_,\infty) \\ (A,1) & (\_,\infty) & (\_,0) & (D,1) \\ (C,2) & (\_,\infty) & (C,1) & (\_,0) \end{pmatrix}$$

updated routing table

Sent Messages

- sending messages

$$a + p \cdot b \cdot q \cdot (1 + c)$$

- by distributivity

$$a \; + \; p \cdot b \cdot q \; + \; p \cdot b \cdot q \cdot c$$

  snapshot, 1-hop connection learnt, content sent

- broadcast, unicast, groupcast are the same (modelled by different topologies)
- Kleene star models flooding the network (modal operators terminate flooding)

- QUESTION: Can unicast modelled purely algebraically?

Conclusion/Future Work

- So far concentrated on AODV
  - well known
  - IETF standard
- Extend formal methods to other protocols
  - OSLR, DYMO, ...
- Add further necessary concepts
  - time
  - probability (links, measurements)
  - define quality of protocols

NICTA

From **imagination** to **impact**

Different Network Layers