Content-Based Communication: The *Network* Underneath Event Processing

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Traditional Network Service

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  - “telephone service”
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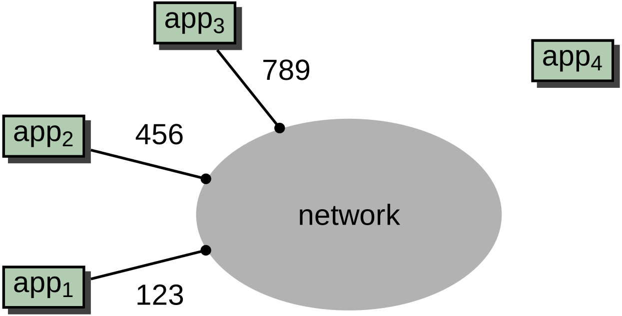

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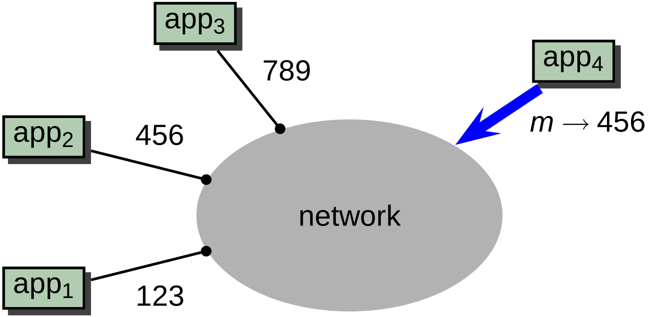

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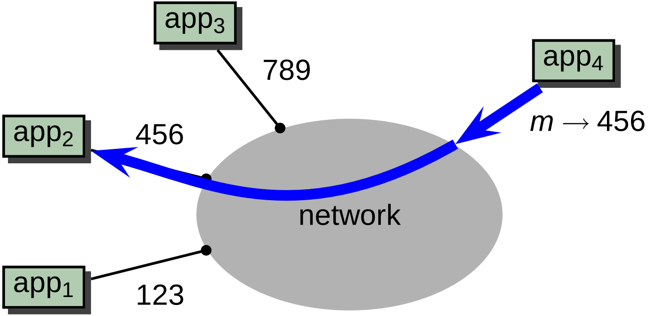

Multicast Service

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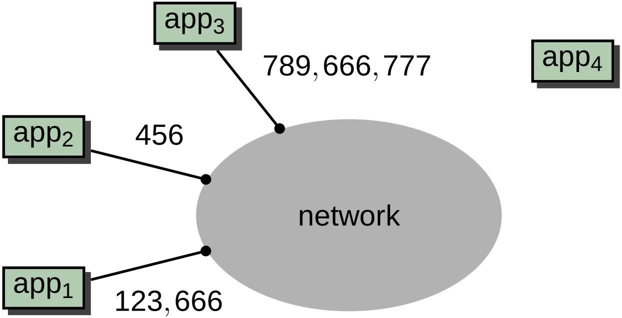

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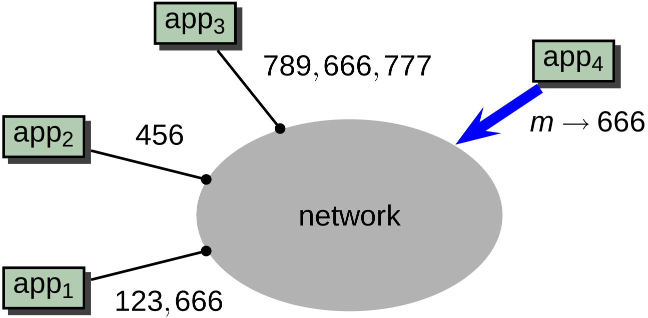

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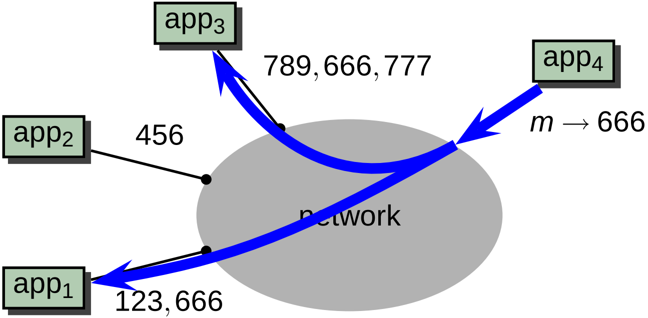

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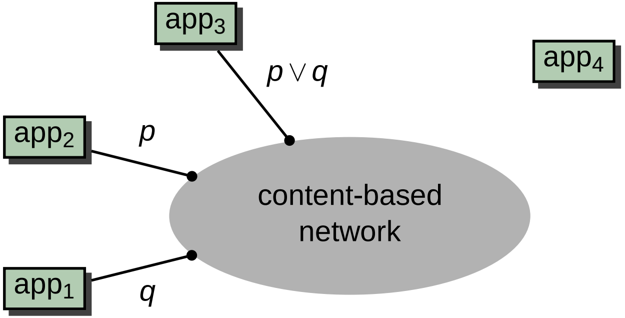
Publish/subscribe differs from IP multicast
only insofar as it is content-based

Content-Based Communication



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  - Boolean function $P : \mathit{Message} \rightarrow \{0,1\}$
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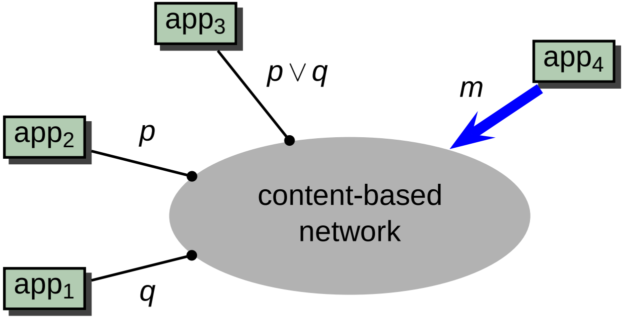

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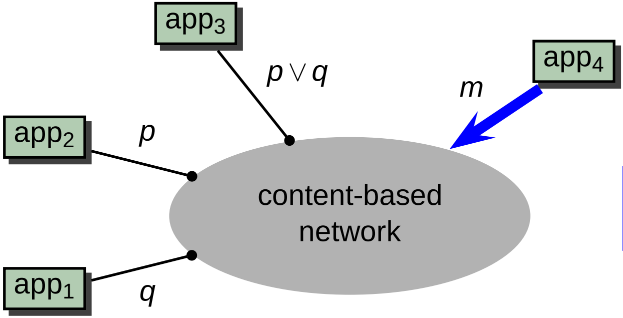

m matches p
but not q

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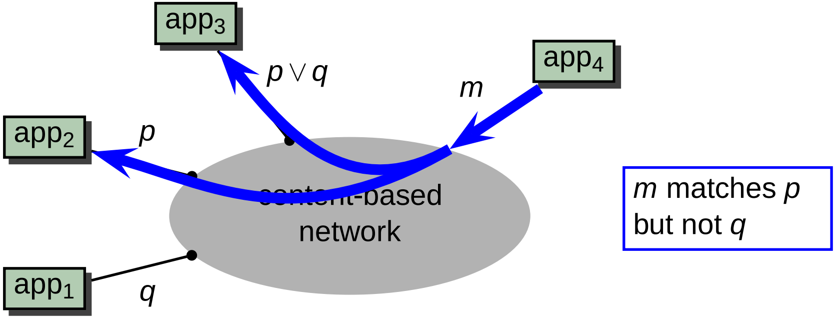

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- Senders send *messages* (without specifying a destination)
- Message m goes to all interested receivers

Application Domains

- *Publish/subscribe communication*

- News distribution
- System/network monitoring and management
- Intrusion detection
- Service discovery and brokering
- Peer-to-peer data sharing
- Distributed electronic auctions
- Multi-player games
- Caching systems
- . . .

Messages

- Example: *a set of attributes*

```
alert-system = “IT-ANAS”
alert = “conjestion”
cause = “accident”
date = [20/Aug/2006:06:14:40 +0200]
location-road = “A1”
location-km = 231
location-dir = “North”
delay-min = 35
detour-info = “sms:3141592653/5897”
report-to = “sms:2718281828/4590”
```

Predicates

- Example: *an expression of attribute constraints*

$$
\begin{array}{ll}
 & \text{alert} = \text{“conjestion”} \\
 & \wedge\ \text{location-road} = \text{“A1”} \\
 & \wedge\ \text{location-dir} = \text{“South”} \\
\vee & \text{alert} = \textit{any} \\
 & \wedge\ \text{cause} = \text{“accident”} \\
\vee & \text{alert} = \text{“weather”} \\
 & \wedge\ \text{severity} > 4 \\
\vee & \text{news-topic} =^{\text{regex}} \text{“sport/soccer/.}{*}\text{”} \\
 & \wedge\ \text{team} = \text{“Milan”}
\end{array}
$$

Content-Based Networking

- Content-based communication (a.k.a., “pub/sub”) *designed and implemented as a network service*
  - architecture
  - routing
  - forwarding
  - . . .

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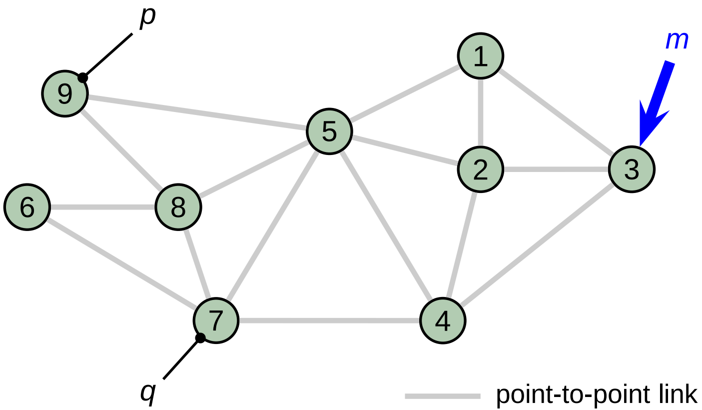
- Host interface
  - *send(m)*
  - *set_predicate(p)*

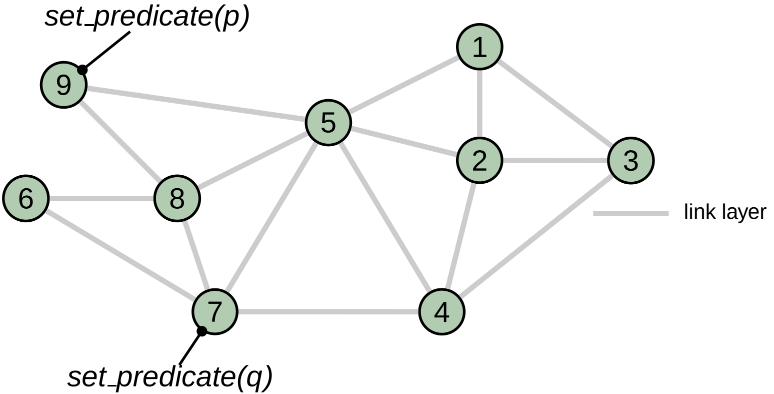
- Type of service
  - *datagram service (i.e., “best effort”)*

Content-Based Routing



- Where and how to forward *m*?
- Based on which kind of routing information?

Content-Based Routing Example



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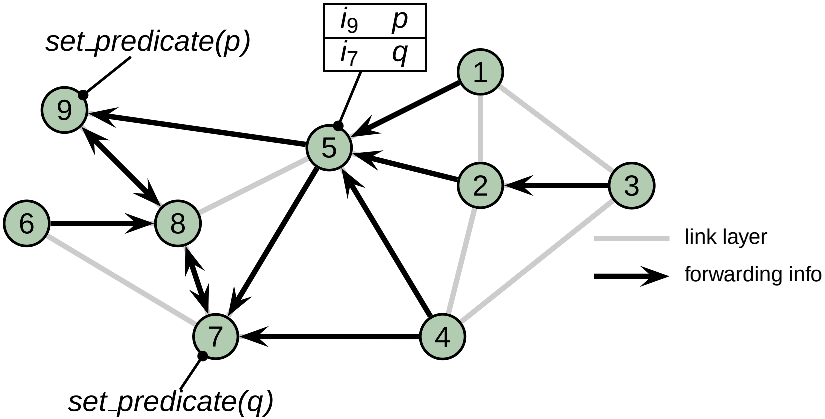

- Routing protocol propagates predicates
- Forwarding state “attracts” messages towards matching predicates

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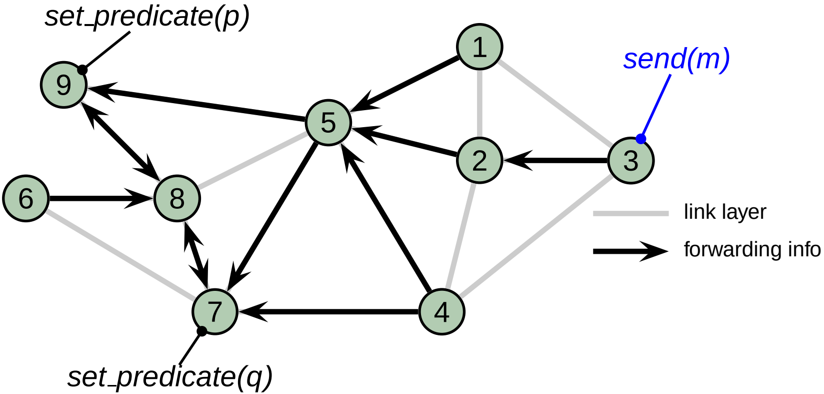

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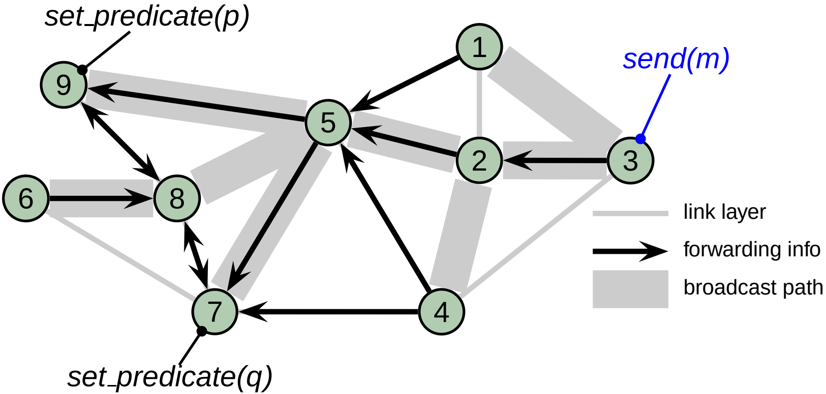

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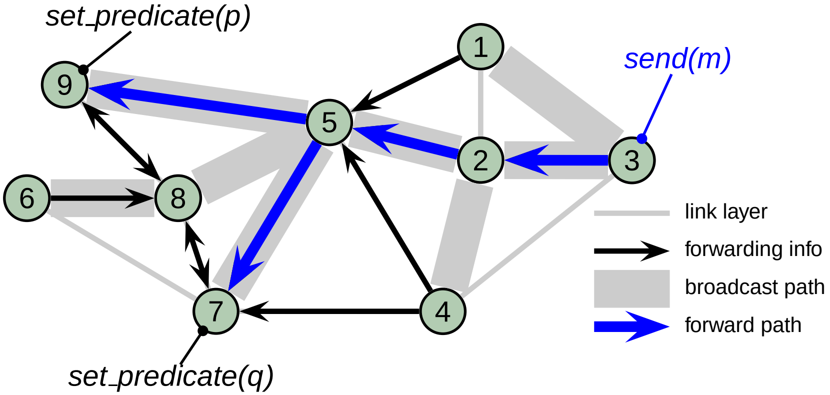

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  - routing policies

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- How do we design a routing protocols that allows autonomous systems to control input, output, and transit traffic?
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  - routing policies
- What is the *complexity* of content-based routing?
  - theoretical basis for content-based networking
  - correctness and complexity (memory requirements)
  - lower bounds

Some Research Questions (2)

- Routing: any good idea?
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- How do we preserve the *privacy* of receivers?
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- Is there a *content-based middleware?*
  - traditional subscriptions, content directories, etc.
  - synthesis of predicates, integration with applications, etc.

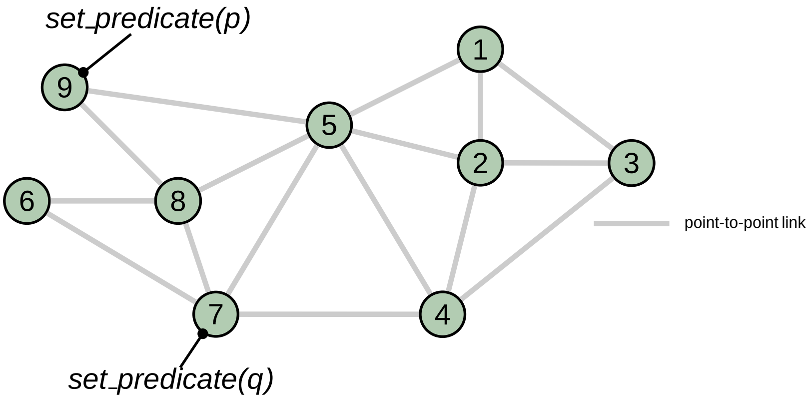
Menu

- A concrete routing protocol
- A concrete forwarding algorithm
- Theory of content-based routing
- Security in content-based networking
- Conclusions

Part I

A Concrete Routing Protocol

Content-Based Routing



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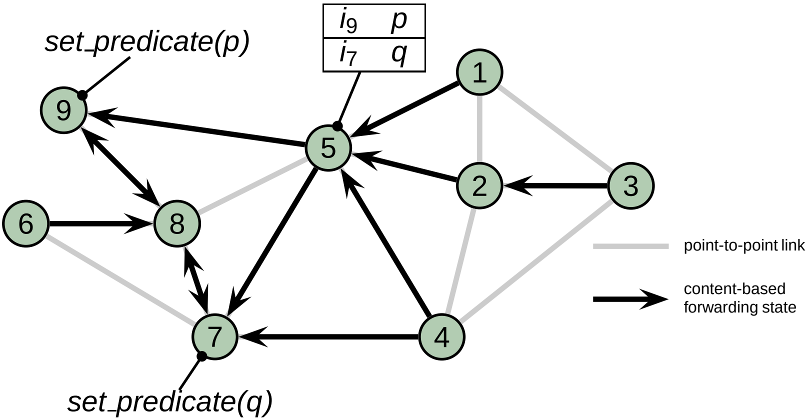

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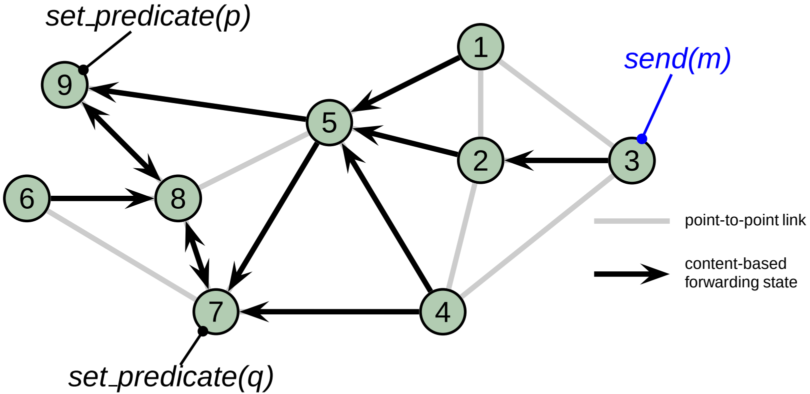

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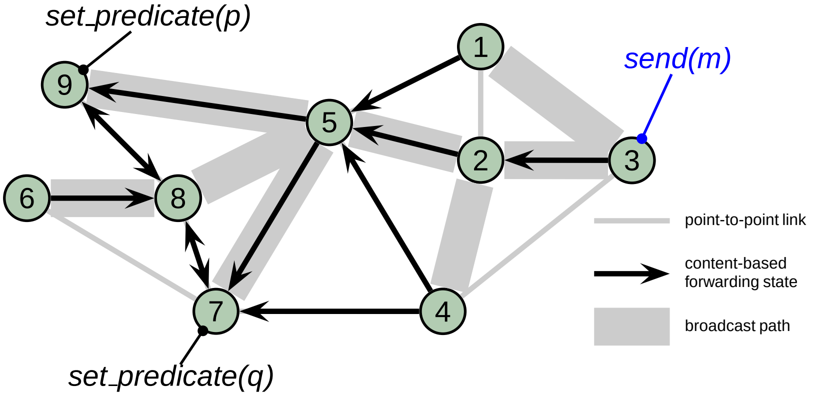

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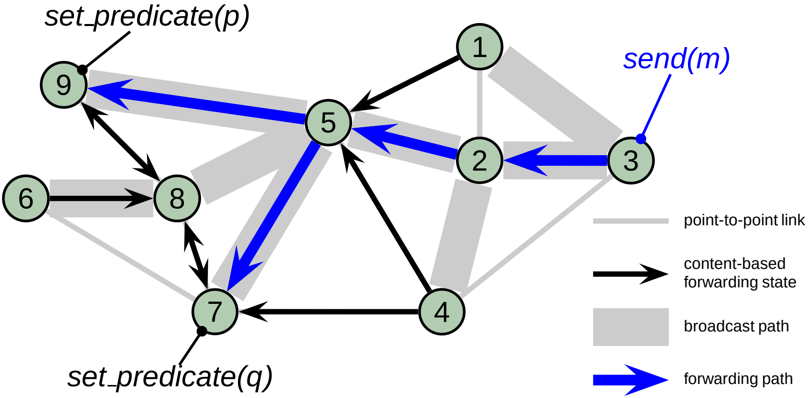

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CBCB Routing Scheme

Combined Broadcast and Content-Based Routing

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Broadcast Layer

- Well-known techniques
- A few additional requirements

Content-Based Routing

- "Push" propagation of predicates (RA protocol)
- "Pull" propagation of predicates (SR/UR protocol)

Receiver Advertisements (RA)

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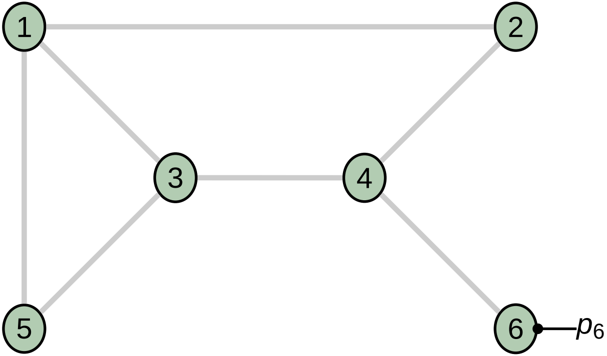

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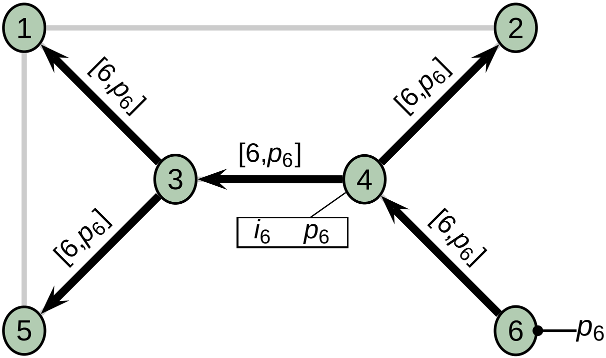
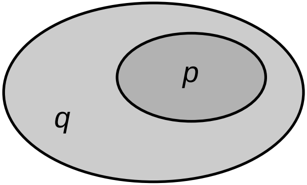


- *Forwarding/routing table* associates a predicate with each interface

Covering Relation

- Covering relation $p \prec q$: q *covers* p when every message matching p also matches q

$$p \prec q \stackrel{\mathrm{def}}{=} \forall m : p(m) \Rightarrow q(m)$$



- Represents the *content-based* *<u>subnet</u>* *address* relation

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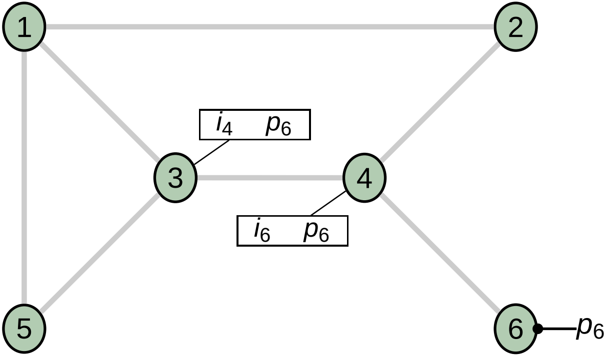

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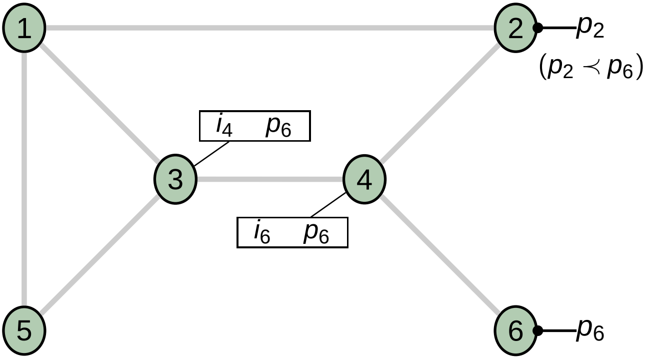

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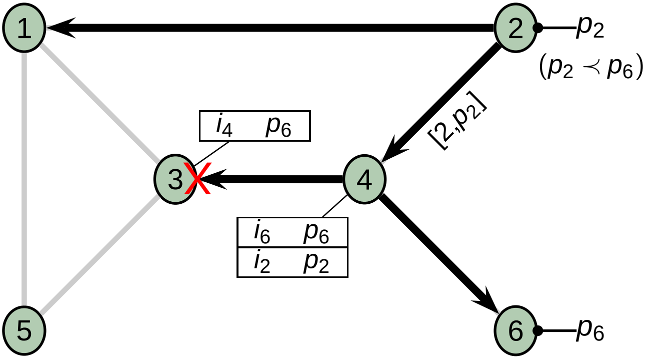

- Table update in RA protocol: $p \leftarrow p \vee p_{RA}$
  notice that $(p \vee p_{RA} = p) \Leftrightarrow (p_{RA} \prec p)$

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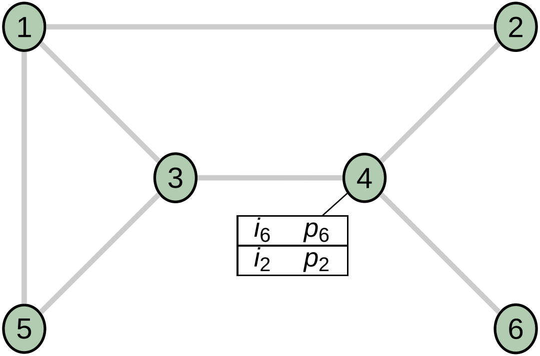

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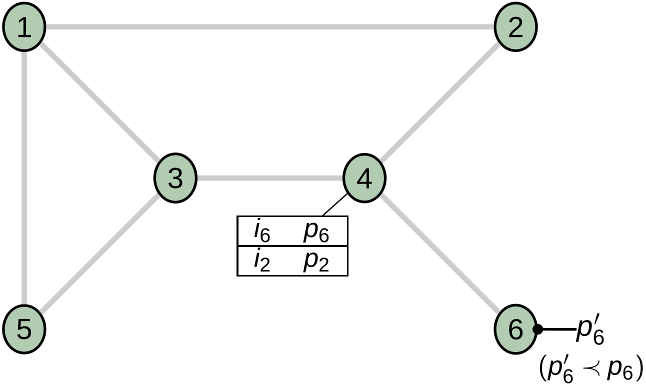

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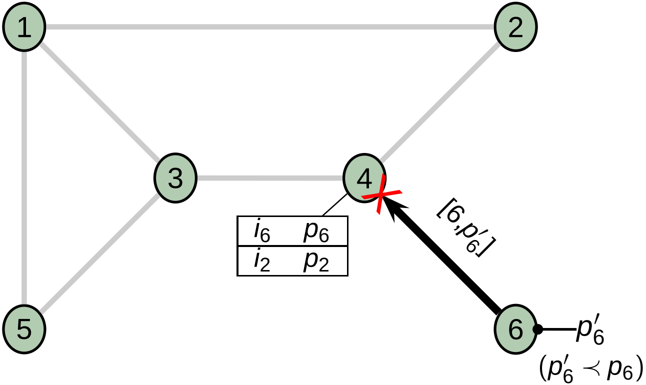

- Node 6 could now receive (from node 4) unwanted messages, i.e., messages that match p_6, but not p'_6

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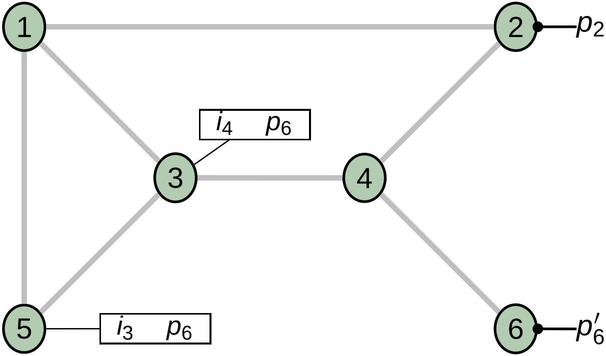

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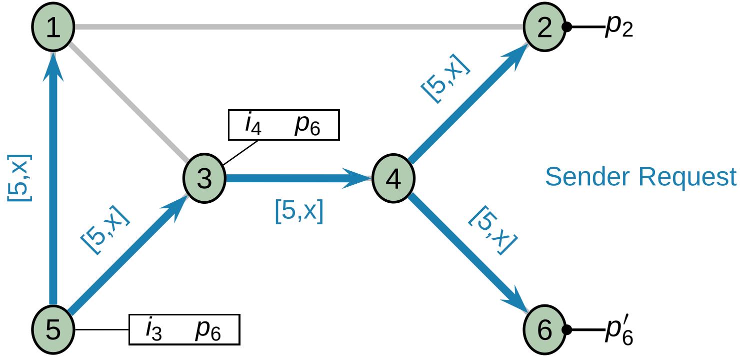

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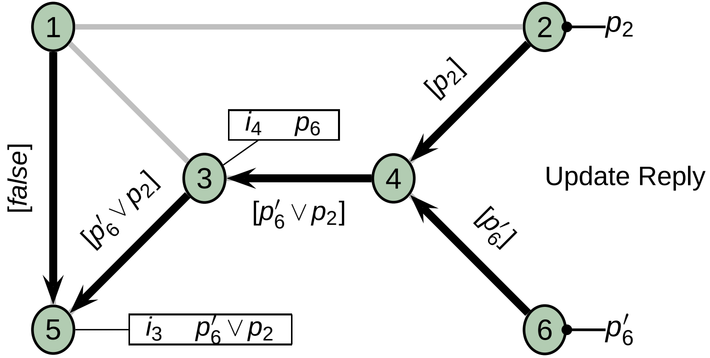

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Options and Optimizations

- The SR/UR protocol can be expensive
  - URs can be cached and reused, depending on the network topology
  - the SR/UR protocol can be triggered by the amount of *false positives*

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  - URs can be cached and reused, depending on the network topology
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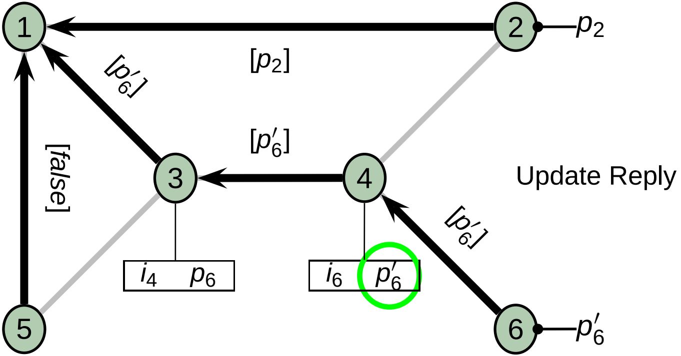
- Both RA and SR/UR manage complex predicates
  - updates in RAs ($p \leftarrow p \vee p_{RA}$) and URs ($p_{UR} \leftarrow p_1 \vee p_2 \vee \ldots \vee p_k$) can be "simplified"

Caching and Reusing URs



- Node 4 may reuse the update reply received from node 6
  - because the 4–6 link is a *bridge*

CBCB Evaluation

- We implemented and tested CBCB within a simulator

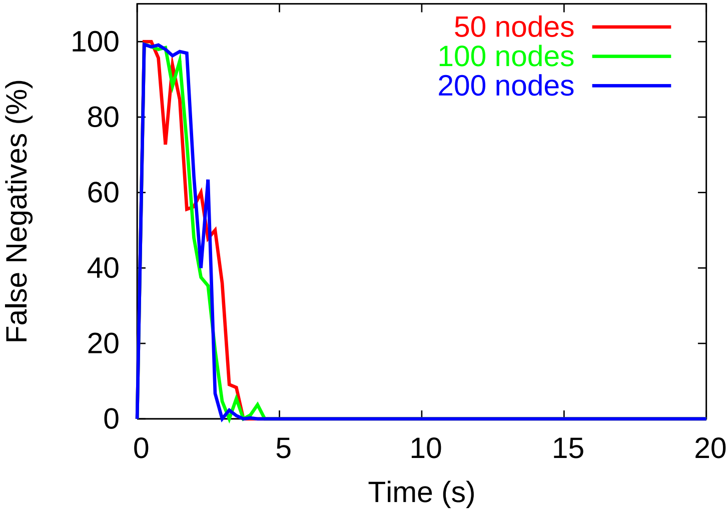
- Evaluation goals

  - *main functionality:* does the protocol deliver messages to nodes that are interested in them?

  - *traffic filtering:* does the protocol prevent unnecessary message traffic?

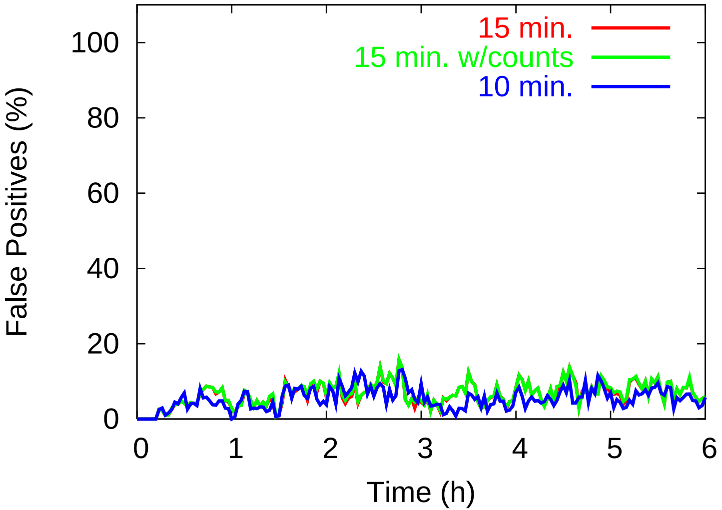
  - *protocol scalability:* does the protocol produce a reasonable and stable amount of control traffic?

Main Functionality



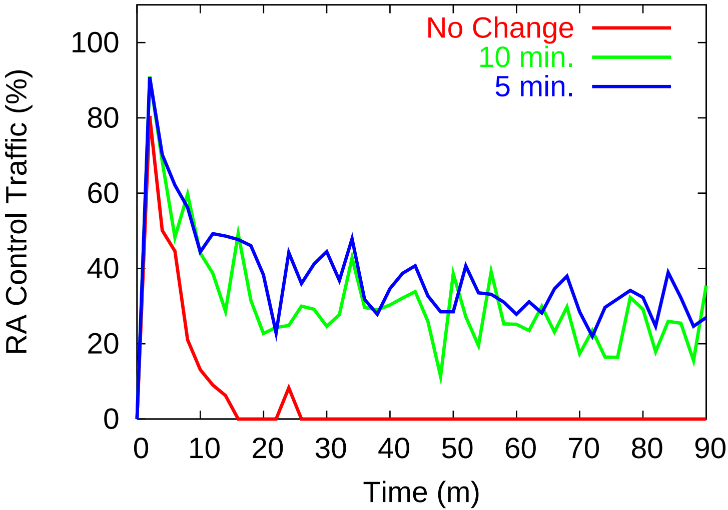
- RAs propagate predicates very quickly

Traffic Filtering



- The amount of false positives remains under 10%

Control Traffic Stability



total msg traffic 40 msg/min

- The amount of RA traffic is stable and contained

Summary of CBCB Routing

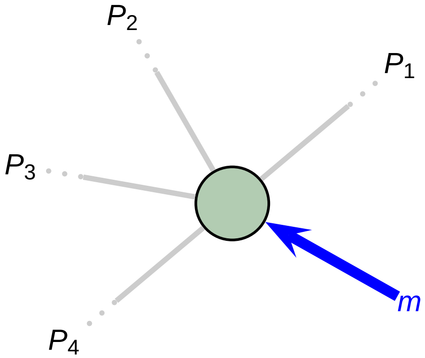
- Content-based routing protocol
- Generic networks (i.e., unrestricted topology)
- Idea 1: use a broadcast layer
- Idea 2: use a “push/pull” routing protocol
- Good behavior for both functionality and stability
- Software and documentation available at
  http://www.cs.colorado.edu/serl/cbn/

Part II

A Concrete Forwarding Algorithm

Content-Based Forwarding

- Forwarding table: *interface* ↔ *predicate*



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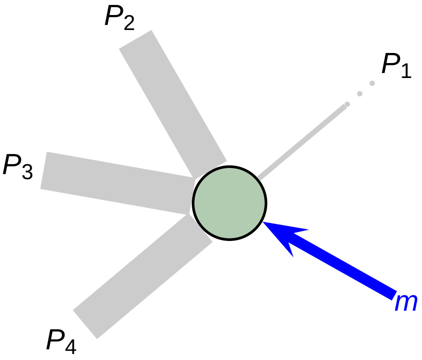

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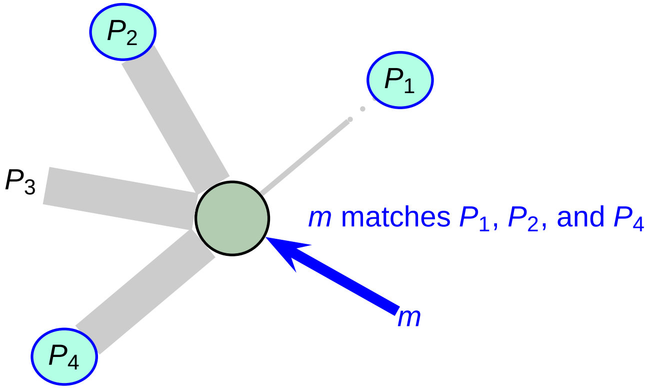
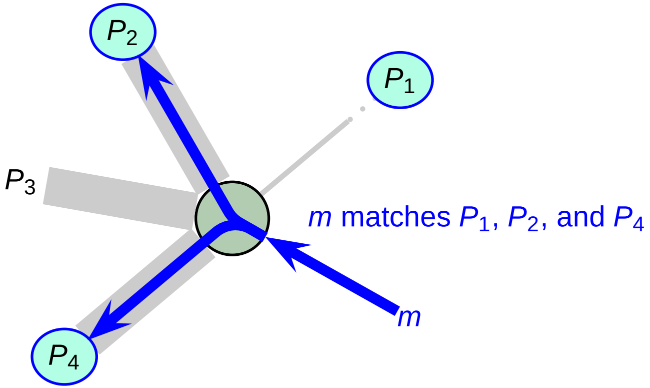


Content-Based Forwarding

- Forwarding table: *interface* $\leftrightarrow$ *predicate*
- Broadcast forwarding (or other constraints)
- Content-based forwarding

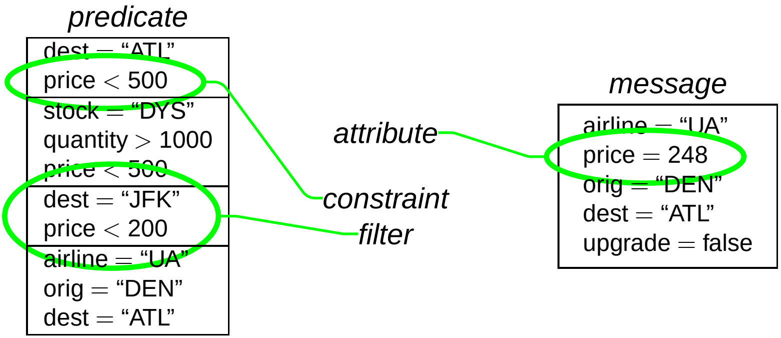


Predicates and Messages

predicate
dest $=$ "ATL" price $<$ 500
stock $=$ "DYS" quantity $>$ 1000 price $<$ 500
dest $=$ "JFK" price $<$ 200
airline $=$ "UA" orig $=$ "DEN" dest $=$ "ATL"

message
airline $=$ "UA" price $=$ 248 orig $=$ "DEN" dest $=$ "ATL" upgrade $=$ false

Predicates and Messages



- *Predicate:* a disjunction of *filters*
- *Filter:* a conjunction of *constraints*
- *Constraint:* a condition on the value of an *attribute*

Matching Problem

forwarding table

I_1	dest $=$ "ATL" price $<$ 500
	stock $=$ "DYS" quantity $>$ 1000 price $<$ 500
I_2	airline $=$ "UA" orig $=$ "DEN" dest $=$ "ATL"
	dest $=$ "JFK" price $<$ 200
	orig $=$ "DEN"
	airline $=$ "UA" upgrade $=$ true
I_3	stock $=$ "MSFT" price $<$ 200

message

airline $=$ "UA" fare $=$ "T" price $=$ 248 orig $=$ "DEN" dest $=$ "ATL" upgrade $=$ false

Matching Problem

forwarding table

I_1	dest = "ATL" price < 500
	stock = "DYS" quantity > 1000 price < 500
I_2	airline = "UA" orig = "DEN" dest = "ATL"
	dest = "JFK" price < 200
	orig = "DEN"
	airline = "UA" upgrade = true
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message

airline = "UA" fare = "T" price = 248 orig = "DEN" dest = "ATL" upgrade = false

Matching Problem

forwarding table

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message

airline $=$ "UA" fare $=$ "T" price $=$ 248 orig $=$ "DEN" dest $=$ "ATL" upgrade $=$ false

Target: forwarding table containing millions of constraints

Matching Strategies

- Naïve
  - evaluate constraints one by one

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- Index-based
  - build an index structure for the forwarding table
  - define a look-up algorithm

Matching Strategies

- Naïve
  - evaluate constraints one by one
- Index-based
  - build an index structure for the forwarding table
  - define a look-up algorithm
    - walk through the index as in a decision diagram [Gough+:ACSC95, Aguilera+:PODC99, Campailla+:ICSE01]
    - walk through the message [Yan+:TODS99, Fabret+:SIGMOD01, Carzaniga&Wolf:SIGCOMM03]

Predicate Index

I_1	$f_{1.1}$	dest = "ATL" price < 500
	$f_{1.2}$	stock = "DYS" quantity > 1000 price < 500
I_2	$f_{2.1}$	airline = "UA" orig = "DEN" dest = "ATL"
	$f_{2.2}$	dest = "JFK" price < 200
	$f_{2.3}$	orig = "DEN"
	$f_{2.4}$	airline = "UA" upgrade = true
I_3	$f_{3.1}$	stock = "MSFT" price < 200

Predicate Index

I_1	$f_{1.1}$	dest $=$ "ATL" price $<$ 500
	$f_{1.2}$	stock $=$ "DYS" quantity $>$ 1000 price $<$ 500
I_2	$f_{2.1}$	airline $=$ "UA" orig $=$ "DEN" dest $=$ "ATL"
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	$f_{2.4}$	airline $=$ "UA" upgrade $=$ true
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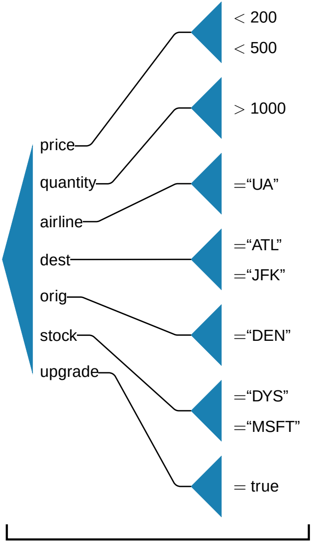

constraint index

Predicate Index

I_1	$f_{1.1}$	dest = "ATL" price < 500
	$f_{1.2}$	stock = "DYS" quantity > 1000 price < 500
I_2	$f_{2.1}$	airline = "UA" orig = "DEN" dest = "ATL"
	$f_{2.2}$	dest = "JFK" price < 200
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	$f_{2.4}$	airline = "UA" upgrade = true
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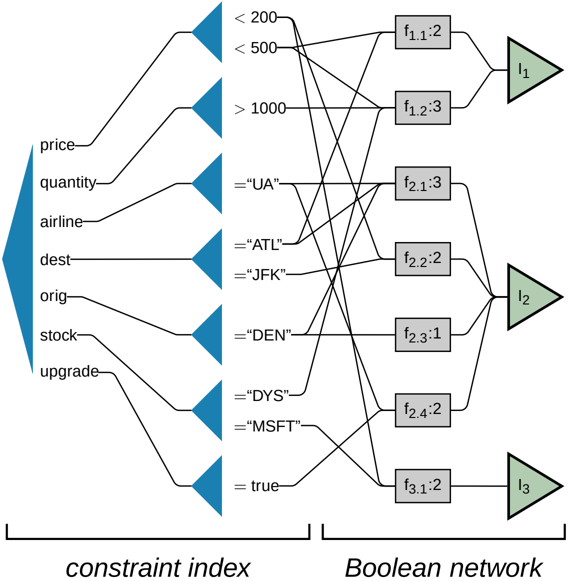

Matching Algorithm

```
proc counting_CBF(Message msg) {
  map<Filter,int> counters ← ∅
  set<Interface> exclude ← broadcast_exclude(msg)
  foreach attribute in msg {
    set<Constraint> C ← find_matching_constraints(attribute)
    foreach constraint in C {
      foreach filter in constraint.filters {
        if filter.interface ∉ exclude {
          if filter ∉ counters {
            counters ← counters ∪ ⟨filter,0⟩ }
          counters[filter] ← counters[filter] + 1
          if counters[filter] = filter.size {
            output(msg, filter.interface)
            exclude ← exclude ∪ {filter.interface}
            if |exclude| = total_interface_count {
              return } } } } } } }
```

Matching Algorithm

```
proc counting_CBF(Message msg) {
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            counters ← counters ∪ ⟨filter,0⟩ }
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            exclude ← exclude ∪ {filter.interface}
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```
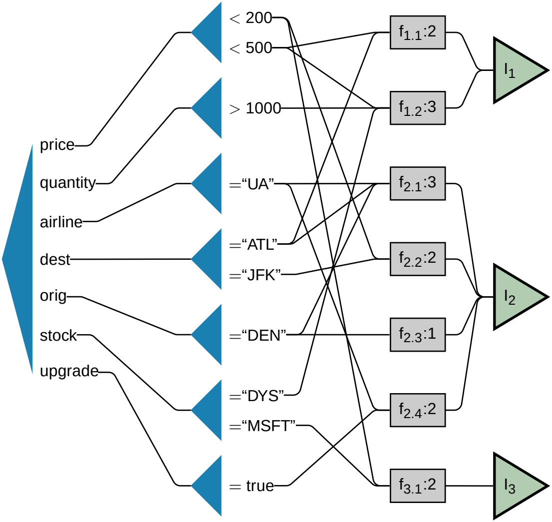

Counting Algorithm

message

airline = "UA"
fare = "T"
price = 248
orig = "DEN"
dest = "ATL"
upgrade = false

// local variables
excluded = $\{I_3\}$
output = $\emptyset$



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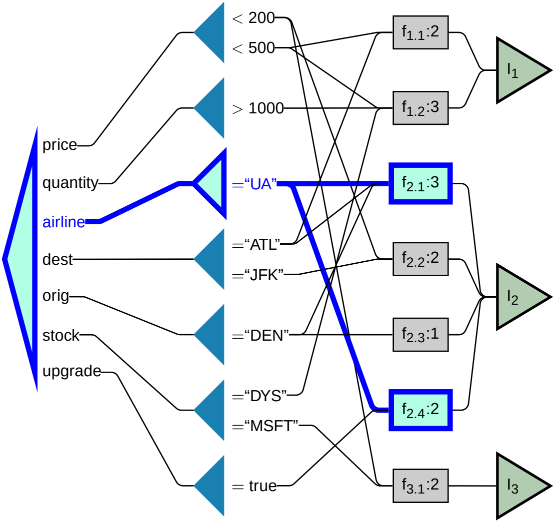

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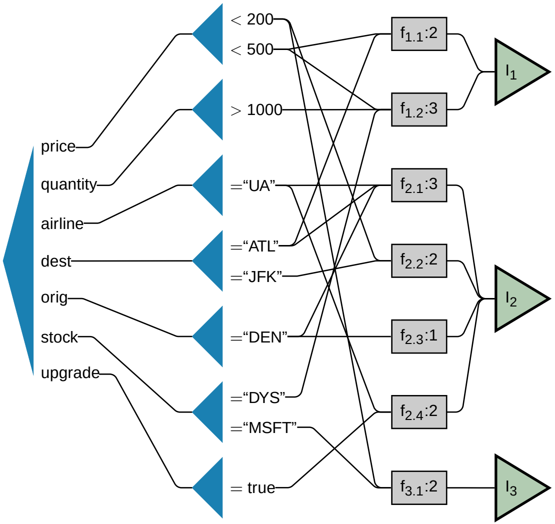

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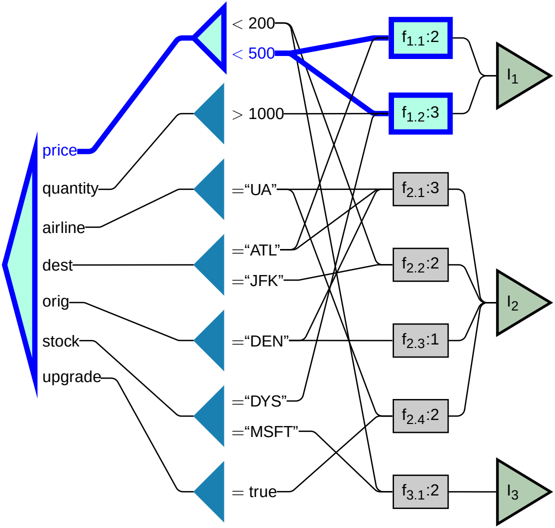

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Counting Algorithm

message

airline = "UA"
fare = "T"
price = 248
orig = "DEN"
dest = "ATL"
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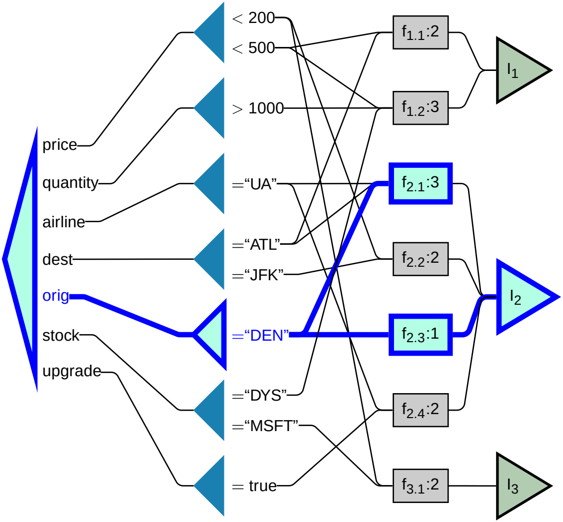
// local variables
excluded = $\{I_3, I_2\}$
output = $\{I_2\}$
counter[$f_{2.1}$] = 2/3
counter[$f_{2.4}$] = 1/2
counter[$f_{1.1}$] = 1/2
counter[$f_{1.2}$] = 1/3
counter[$f_{2.3}$] = 1/1



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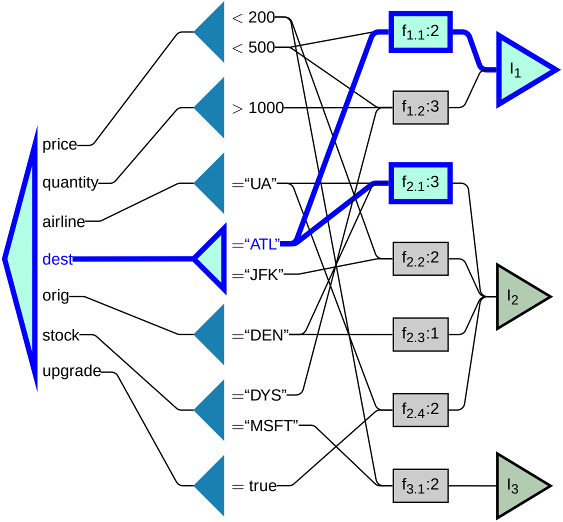

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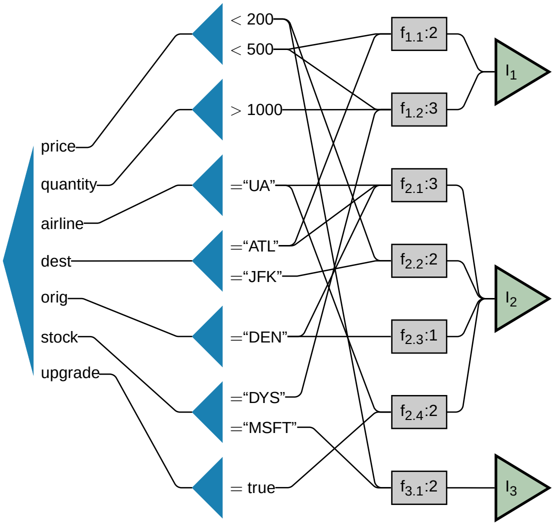


Evaluation

- C++ implementation
- Synthetic workloads
- Experiments on a 950Mhz computer with 512Mb

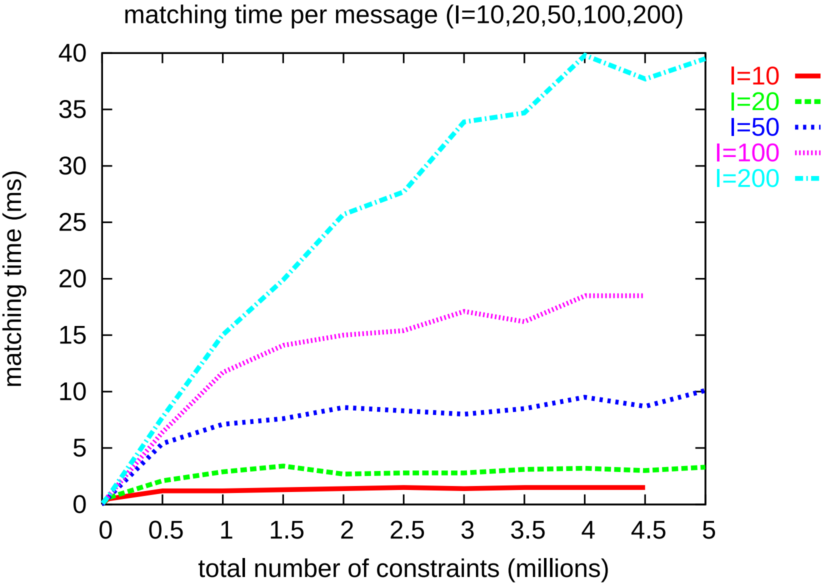
Evaluation

- C++ implementation
- Synthetic workloads
- Experiments on a 950Mhz computer with 512Mb
  - okay, remember that this was done in 2002
  - much better results today thanks to progress in CPU speeds

Workload Parameters

- Messages: 5–10 attributes
- Filters: 1–6 constraints
- Attributes and values: dictionary of 1000 words with Zipf distribution
- Operators
  - *integers*: 60% equality, 20% less-than, and 20% greater-than
  - *strings*: 35% equality, 15% prefix, 15% suffix, 15% substring, 10% less-than, and 10% greater-than
- Forwarding table: up to 5M constraints, from 2 interfaces to 1M interfaces

Main Results



An Improvement

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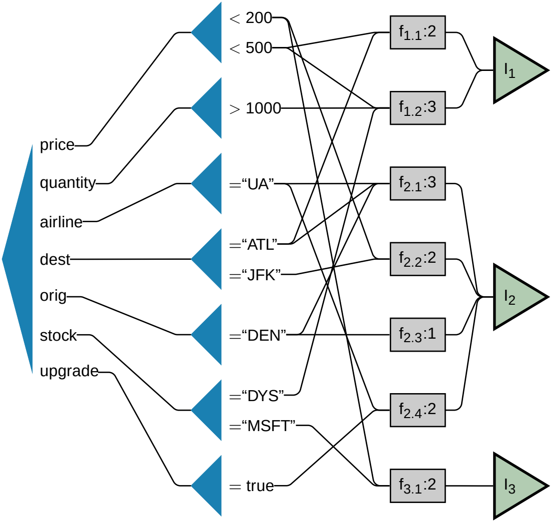

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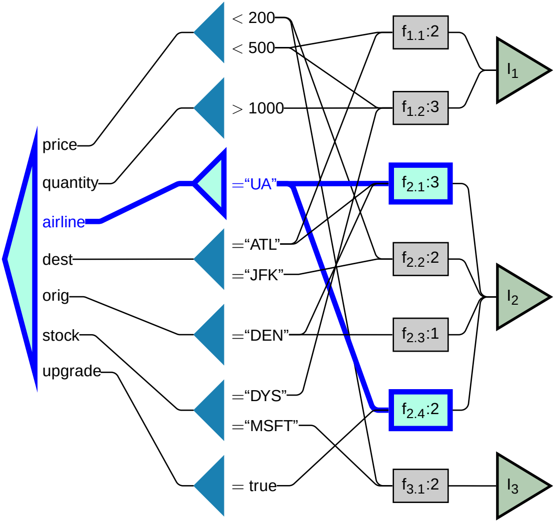

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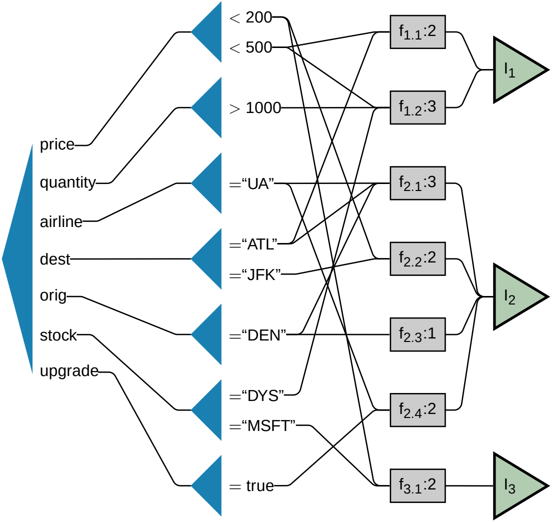

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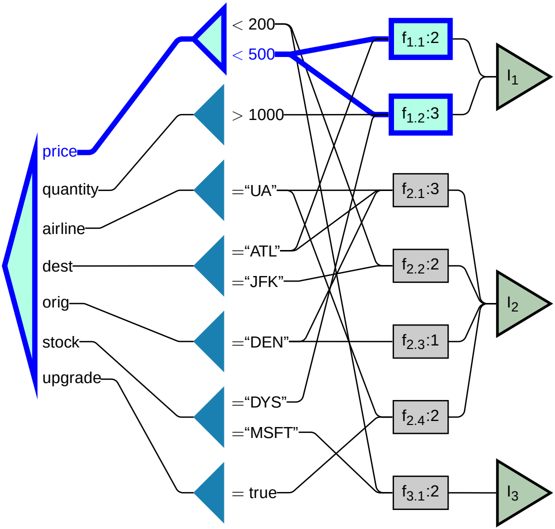
counter[$f_{1.1}$] = 1/2
counter[$f_{1.2}$] = 1/3



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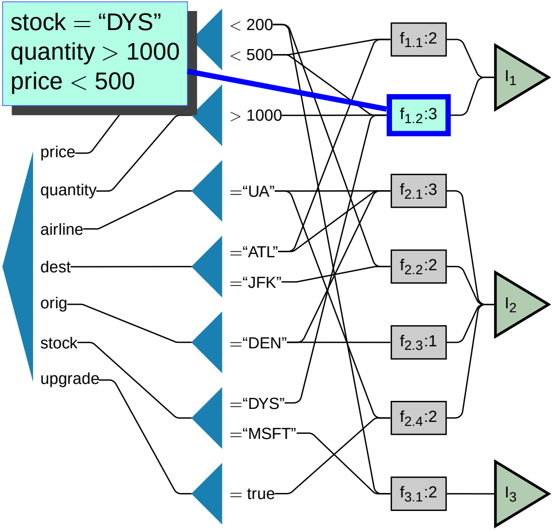

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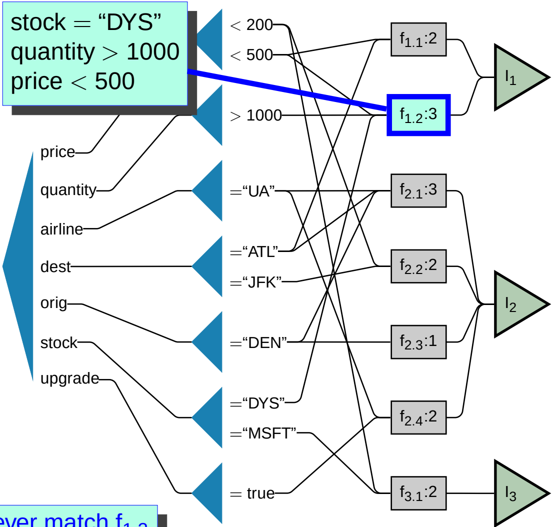
stock = “DYS”
quantity > 1000
price < 500



Useless—the message will never match $f_{1.2}$

Idea: Bloom Filters

We can use *Bloom filters* to represent set of names in a filter f and in a message m

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We can use *Bloom filters* to represent set of names in a filter *f* and in a message *m*

message m	*filter f*
airline = "UA" fare = "T" price = 248 orig = "DEN" dest = "ATL" upgrade = false	stock = "DYS" quantity $>$ 1000 price $<$ 500
$B_m = [0110100011]$	$B_f = [0010010010]$

Idea: Bloom Filters

We can use *Bloom filters* to represent set of names in a filter f and in a message m

message m	*filter f*
airline = "UA" fare = "T" price = 248 orig = "DEN" dest = "ATL" upgrade = false	stock = "DYS" quantity > 1000 price < 500
$B_m = [0110100011]$	$B_f = [0010010010]$

If $B_m \not\supseteq B_f$ then we can immediately skip f (i.e., we don't bother maintaining a counter for f, and we don't look up f's interface, etc.)

Observations on Bloom Filters

- Bloom filters for filters (B_f) are computed statically with the forwarding table

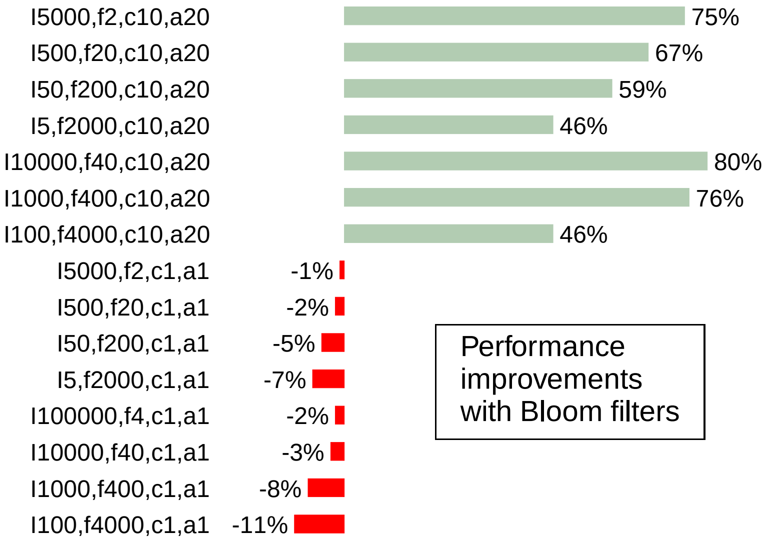
- B_m is computed dynamically, but we can use very simple hash functions

- The complexity of checking $B_f \subseteq B_m$ is $O(1)$
  - in C: `(Bf & Bm) == Bf`

- False positives do not affect correctness

- The idea works with messages with sets of attributes that do not always “cover” filters

Experimental Results



A Further Improvement

Observation:

- By excluding interfaces, we can short-circuit the evaluation of a message and speed up forwarding

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Idea:

- Compute a table of “selective” attributes
  - an attribute a is *selective* for an interface i if a must exist in a message m in order for m to match P_i
  - i.e., a must appear in every conjunct of the disjunct P_i
- Use the *selectivity table* to *exclude* interfaces from processing (*selectivity preprocessing*)

Selectivity Table Example

forwarding table

I_1	dest = "ATL" price < 500
	stock = "DYS" quantity > 1000 price < 500
I_2	airline = "UA" orig = "DEN" dest = "ATL"
	dest = "JFK" price < 200
	orig = "DEN"
	airline = "UA" upgrade = true
I_3	stock = "MSFT" price < 200

Selectivity Table Example

forwarding table

I_1	dest $=$ “ATL” price $<$ 500
	stock $=$ “DYS” quantity $>$ 1000 price $<$ 500
I_2	airline $=$ “UA” orig $=$ “DEN” dest $=$ “ATL”
	dest $=$ “JFK” price $<$ 200
	orig $=$ “DEN”
	airline $=$ “UA” upgrade $=$ true
I_3	stock $=$ “MSFT” price $<$ 200

selectivity table

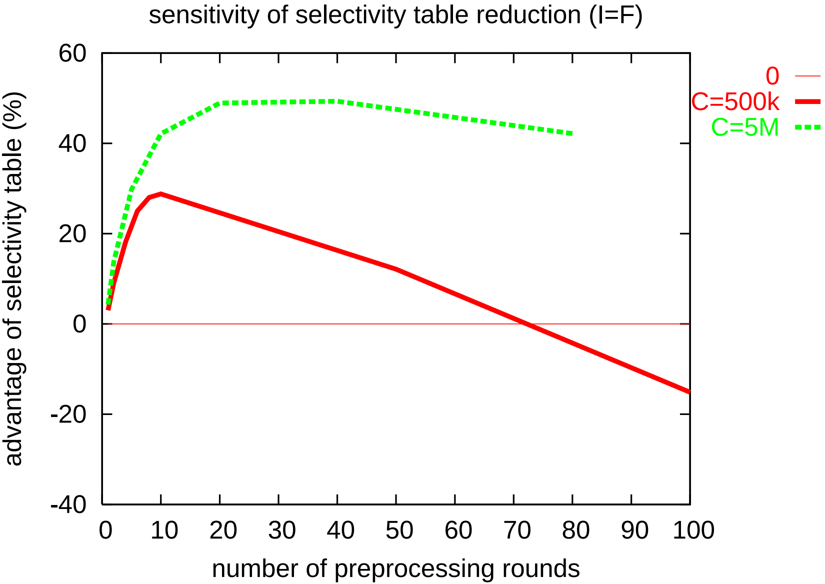
price	I_1, I_3
stock	I_3

Selectivity Preprocessing

```
map<Name, set<Interface>> selectivity_table
int preprocessing_rounds

proc preprocess(Message msg, set<Interface> exclude) {
  int rounds ← preprocessing_rounds
  foreach ⟨attribute,selectivity⟩ in selectivity_table {
    if rounds = 0
      return exclude
    rounds ← rounds − 1
    if attribute ∉ msg {
      exclude ← exclude ∪ selectivity
      if |exclude| = total_interface_count
        return exclude
    }
  }
  return exclude
}
```

Sensitivity to Preprocessing



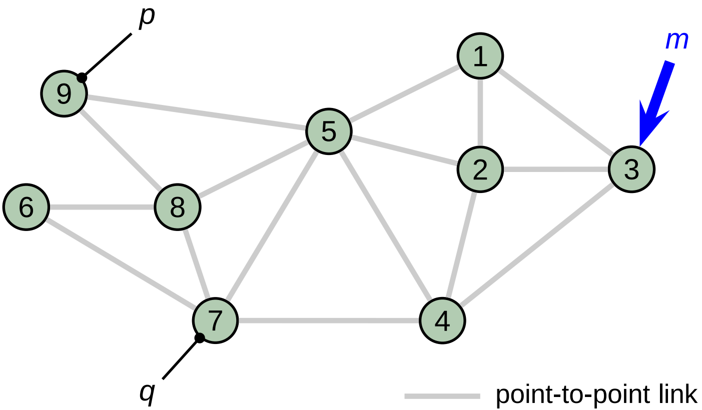
Summary of C-B Forwarding

- Focus on performance and scalability
- Predicate index with lookup based on iteration over the input message
- Novel ideas
  - short-circuit evaluation of disjunctions
  - use *Bloom filters* to exclude conjunctions
  - use (absence of) *selective attributes* to exclude entire disjunctions
- Experiments show good absolute performance and a synergistic behavior of our optimizations
- Software and documentation available at http://www.inf.unisi.ch/carzaniga/cbn/

Part III

Theory of Content-Based Routing

Content-Based Routing



- Where and how to forward *m*?
- Based on which kind of routing information?

Theory of Content-Based Routing

- State of the art
  - a number of concrete routing protocols (including ours)
  - validation through simulation
  - focus on the exchange of routing information

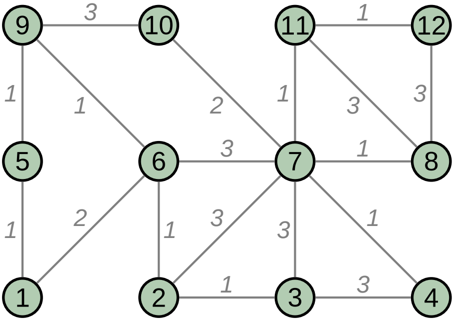
Theory of Content-Based Routing

- State of the art
  - a number of concrete routing protocols (including ours)
  - validation through simulation
  - focus on the exchange of routing information
- New research: *theoretical foundations of content-based routing*
  - provable properties of a protocol
  - properties of content-based routing
    - i.e., properties of *any* protocol
  - focus on routing *state* (i.e., memory complexity)

Research Plan

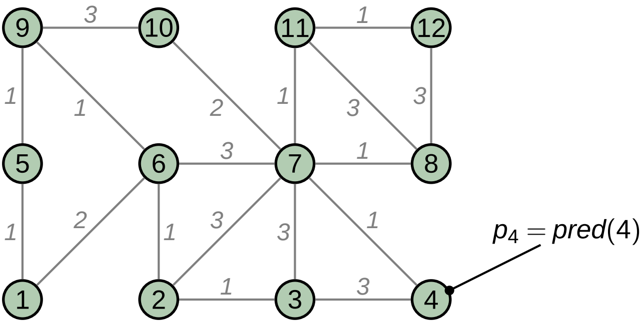
- Models
  - network model
  - general model of content-based routing (forwarding)
  - model of routing information and its space complexity
- Analysis of specific routing protocols
  - upper bounds for the space complexity of content-based routing
- New improved routing protocols
  - design of light-weight content-based routing protocols
- General analysis
  - lower bounds

Content-Based Network Model



- $CBN = (V, E, weight, \mathscr{M}, \mathscr{P}, pred)$
  - $v \in V$ is a processor (host or router)
  - $e \in E$ is a reliable bidirectional communication link
  - $weight : E \to \mathbb{R}$ is a link-weight function

Content-Based Network Model



- $CBN = (V, E, weight, \mathscr{M}, \mathscr{P}, pred)$
  - $v \in V$ is a processor (host or router)
  - $e \in E$ is a reliable bidirectional communication link
  - $weight : E \to \mathbb{R}$ is a link-weight function
  - $\mathscr{M}$ is a set of *messages*
  - $\mathscr{P}$ is a set of *predicates*; $p \in \mathscr{P}$ is a function $p : \mathscr{M} \to \{0,1\}$
  - $pred : V \to \mathscr{P}$ associates a processor $v \in V$ to a predicate $p \in \mathscr{P}$

Content-Based Routing Scheme

Extension of a standard model by Peleg and Upfal [JACM'89]

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- Messages travel in *packets*

$$c = \langle m, h \rangle$$

  - $m = msg(c)$ is a message; $m \in \mathscr{M}$
  - $h = hdr(c)$ is a *header*; $h \in \mathscr{H}$
  - a scheme defines $\mathscr{H}$, the set of allowable message headers

- Packets are forwarded hop-by-hop from source to destinations

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  - a scheme defines $\mathscr{H}$, the set of allowable message headers

- Packets are forwarded hop-by-hop from source to destinations

- A routing scheme is a *distributed algorithm* consisting of *per-processor, processor-local routing functions*
  - (re)writing packet headers
  - deciding where to forward a packet

Per-Process Routing Functions

For each processor v

Per-Process Routing Functions

For each processor v

- *Initial header function*

$$\mathbf{Init}_v : \mathscr{M} \rightarrow \mathscr{H}$$

given a message m originating at v, $\mathbf{Init}_v(m)$ is m's initial header, so v proceeds by forwarding a packet $c = \langle \mathbf{Init}_v(m), m \rangle$

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- *Forwarding function*

$$\mathbf{Fwd}_v : \mathscr{H} \times \mathscr{M} \rightarrow \mathbb{P}(\mathit{neighbors}(v))$$

v forwards $c = \langle h, m \rangle$ to the subset of its neighbors $\mathbf{Fwd}_v(h, m)$

Per-Source Forwarding (PSF) Scheme

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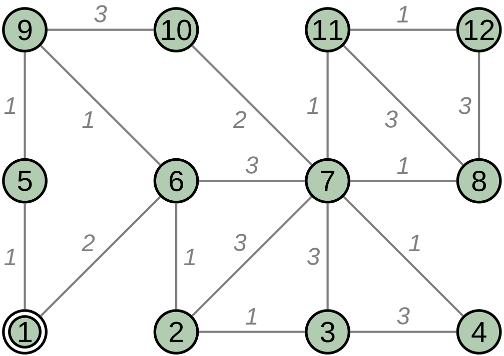
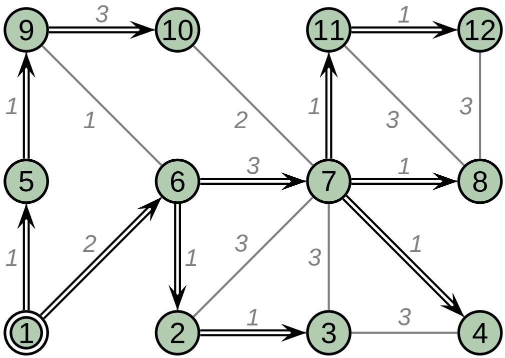
- Idea



Per-Source Forwarding (PSF) Scheme

- Idea
  - per-source spanning trees T_v



Per-Source Forwarding (PSF) Scheme

- Idea
  - per-source spanning trees T_v
  - annotate edges $e = (u, w)$ in T_v with the disjunction of the predicates of processor w and all its descendents in T_v
  - processor-local functions F store edge annotations

F_6: annotations for processor 6

source,next-hop $\rightarrow$ *predicate*

$\ldots$
$1, 1 \mapsto \emptyset$
$1, 2 \mapsto p_2 \vee p_3$
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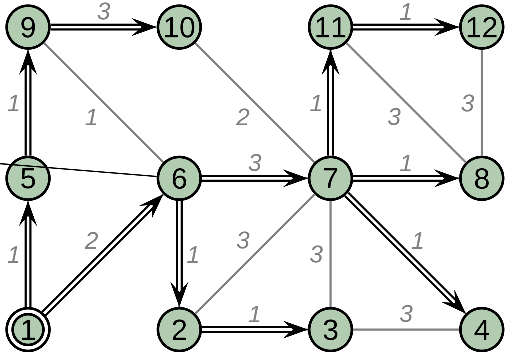

- Headers are used to store the source of a message

$$\mathscr{H} = V$$

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$$\mathbf{Hdr}_u(v) = v$$

PSF Scheme

- Headers are used to store the source of a message

$$\mathscr{H} = V$$

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- Processor u forwards $c = \langle v, m \rangle$ using F_u

$$\mathbf{Fwd}_u(v, m) = \{w | m \in F_u(v, w)\}$$

notation extension: if p is a predicate, $m \in p$ means $p(m) = 1$

Analysis of PSF

- It is easy to prove that *PSF is correct*
  - correctness not yet defined, but quite straightforward

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- How "expensive" is PSF?

- How much memory does it require?
  - focus on the *total memory requirement*

- Preliminary additional definitions
  - $M(X)$ denotes the memory requirements of a function or set X
    - e.g., processor v uses $M(\mathbf{Hdr}_v)$ bits to represent its **Hdr** function
  - $n = |V|$, therefore $M(v) = O(\log n)$
  - $S \subseteq V$ is a given set of senders, with $s = |S|$
  - $R \subseteq V, R = \{u \in V | pred(u) \neq \emptyset\}$, is the set of receivers, $r = |R|$

Memory Requirements of PSF

$$M(PSF) = \sum_{u \in V} \big(M(\mathbf{Init}_u) + M(\mathbf{Hdr}_u) + M(\mathbf{Fwd}_u)\big)$$

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- The memory requirement of **Fwd** boils down to that of F

$$M(\mathbf{Fwd}_u) = M(F_u)$$

- The total memory requirement of **Fwd** is the sum of the memory requirements of each per-source tree

$$\sum_{u \in V} M(F_u) = \sum_{v \in S} M(T_v)$$

Memory Requirements of PSF (2)

- Memory requirement of a source-rooted tree T_v

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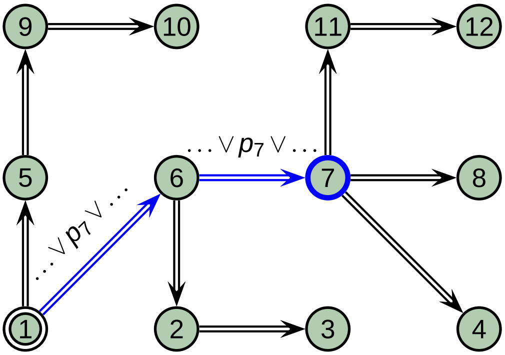

notation:
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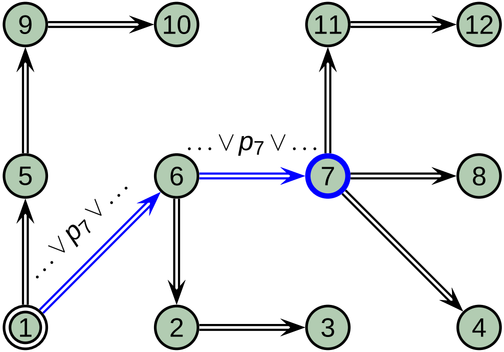

notation:
$p_7 = pred(7)$

$$M(T_v) = \sum_{x \in R} M(pred(x))distance(v,x)$$

Memory Requirements of PSF (3)

- Total memory requirement for PSF

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$$M(PSF) = O(n^2 \log \log n)$$

Assumptions on $M(F_u)$

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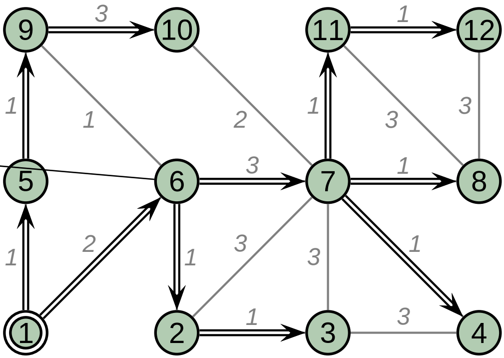

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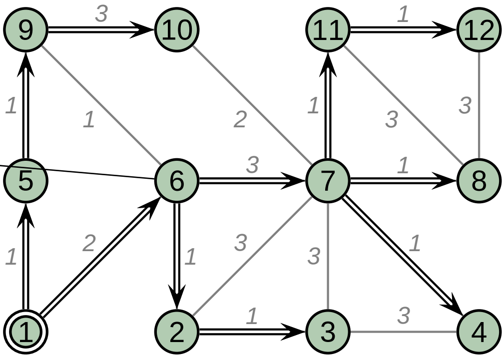

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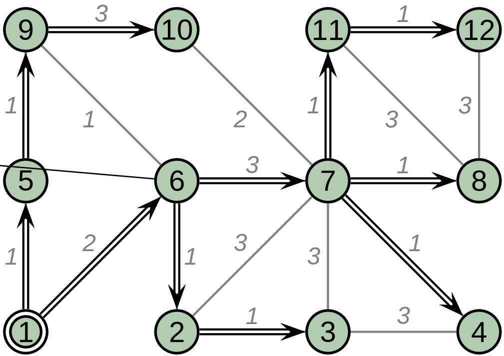

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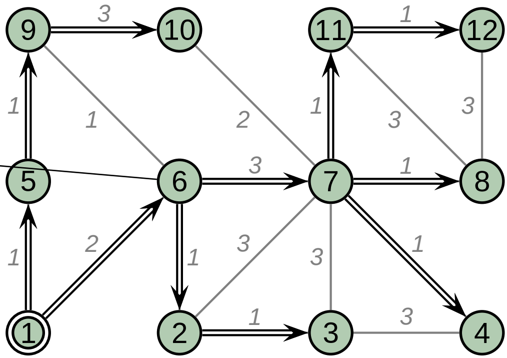

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  - e.g., $p_2 = (\text{port} > 1000) \wedge (\text{port} < 3000)$ and $p_3 = (\text{port} > 2000) \wedge (\text{port} < 4000)$ can be combined in the disjunction $p_2 \vee p_3 = (\text{port} > 1000) \wedge (\text{port} < 4000)$

Disjunction Advantage

- Given a set of predicates $P = \{p_1, p_2, \ldots, p_n\}$, we define the *disjunction advantage*

$$\alpha(P) = \frac{M(p_1 \vee p_2 \vee \ldots \vee p_n)}{M(p_1) + M(p_2) \cdots + M(p_n)}$$

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- How does α affect the space complexity of a given scheme?

- Can we quantify α?

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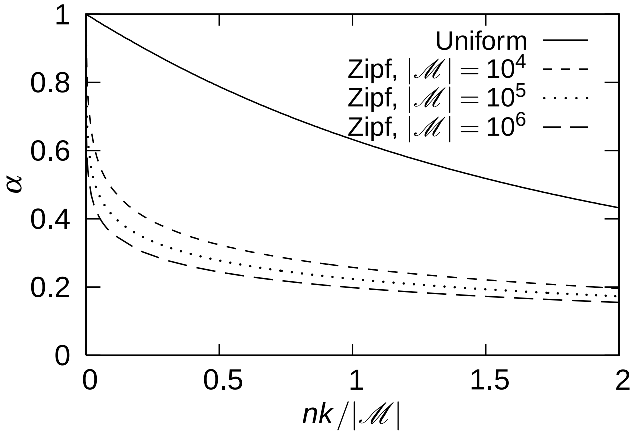
expected size of P and then the expected disjunction advantage

$$\mathrm{E}(\alpha) = \frac{|\mathscr{M}|}{nh}\left(1 - \left(1 - \frac{h}{|\mathscr{M}|}\right)^n\right) \approx \frac{|\mathscr{M}|}{nh}\left(1 - e^{-\frac{nh}{|\mathscr{M}|}}\right)$$

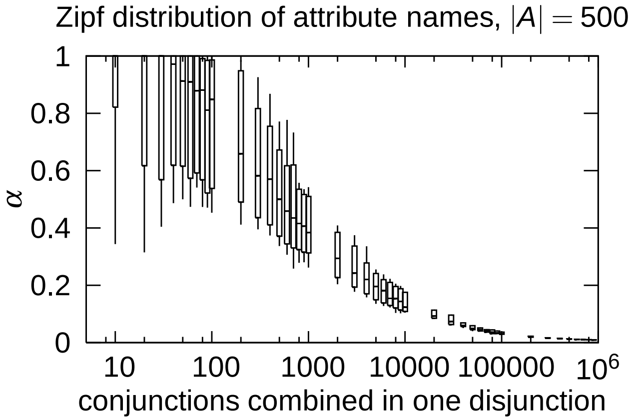
α in a Generic Predicate Model (2)

- Monte Carlo simulation
- Uniform vs. Zipf distribution for messages



α in a Specific Predicate Model (1)

- Monte Carlo simulation
- Disjunctive normal form of attribute constraints



α in a Specific Predicate Model (2)

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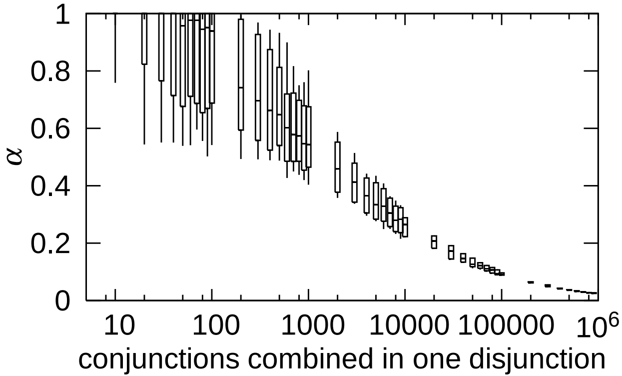
Zipf distribution of attribute names, $|A| = 5000$



α in a Specific Predicate Model (3)

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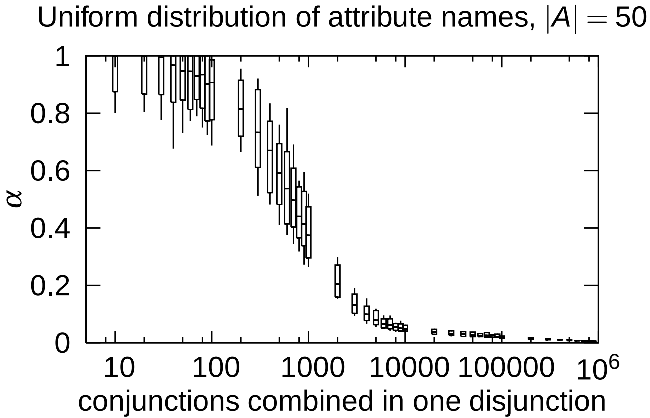

α in a Specific Predicate Model (4)

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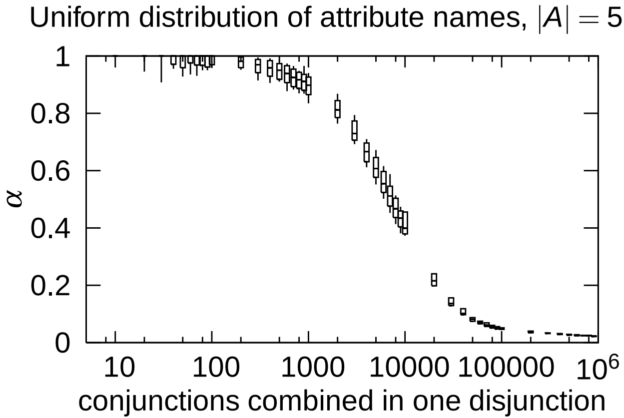

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- Definition and characterization of the α *reduction factor*
  - general model (analytical characterization)
  - common concrete model (Monte Carlo simulations)
- Future work
  - more protocols and perhaps lower bounds

Part IV

Security in Content-Based Networking

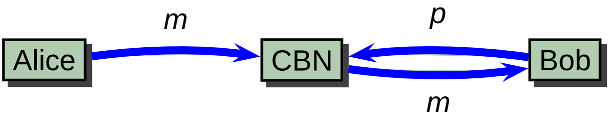
Security

Security

- Easy part
  - authentication
  - privacy with a trusted network
  - *e.g., traditional e-mail or web security*
- Difficult part
  - privacy in the presence of an untrusted network
  - *we want the network to route information on the basis of message content and receiver interests. But we do not want the network to learn anything about message content and receiver interests.*

Security Model

- Simplified content-based communication scenario



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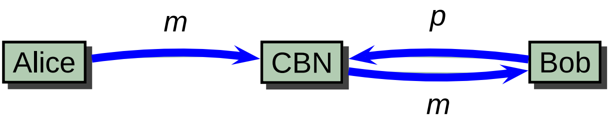

- Objectives

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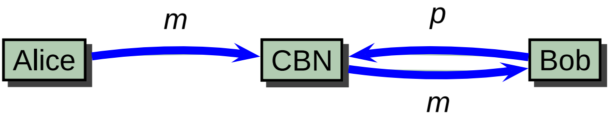

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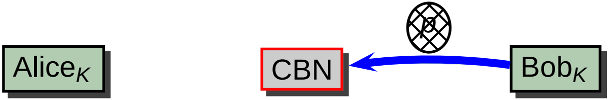

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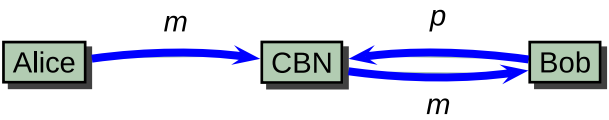

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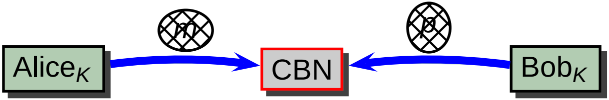

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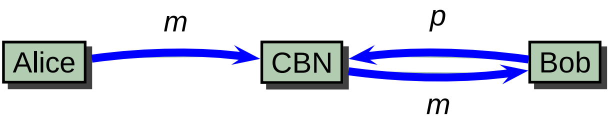

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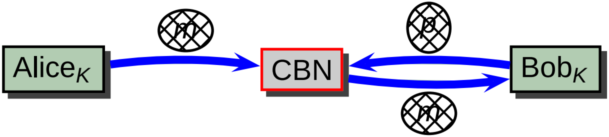

Approximate Solutions

- *Goup anonymity*
  - receivers “hide” behind a trusted *proxy*
  - limited security

- *Overly generic predicates*
  - Bob declares a p' covering p
  - limited security (similar to group anonymity)

- *Obfuscation*
  - p is given as an “obfuscated” executable
  - incompatible with efficient routing protocols
  - limited security (dubious security for p, no security for m)

- *Computing over encrypted data*
  - either very inefficient or very limited

Approach

- Encode p and m with some K-dependent function(s)

$$
\begin{array}{ccc}
m & & p \\
\downarrow X_K & & \downarrow Y_K \\
m' & & p'
\end{array}
$$

Approach

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$$\begin{tikzcd} m \arrow[r, leftrightarrow] \arrow[d, "X_K"] & p \arrow[d, "Y_K"] \\ m' \arrow[r, leftrightarrow] & p' \end{tikzcd}$$

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- Method: encoding using *Bloom filters*

Bloom Filters

- Compact data structure
- Efficient set membership test
- Probabilistic result
  - false positives are possible
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- *One-way information compression through hash functions*

Definitions

- $U = \{x_1, x_2, \ldots\}$ is the universe of values we intend to represent

- A Bloom set over U is defined by
  - a bit vector B of size m
  - k distinct hash functions $h_1, h_2, \ldots, h_k$ with signature $H : U \rightarrow \{0, 1, \ldots, m-1\}$

- $B(x)$ is computed as follows $B \leftarrow \emptyset$

  for $i \leftarrow 1 \ldots k$

  $\quad B[h_i(x)] \leftarrow 1$

Using Bloom Filters

- Given a set of n elements $S = \{x_1, x_2, \ldots x_n\}$

  $B(S) \leftarrow B(x_1) \cup B(x_2) \cup \ldots B(x_n)$

  i.e.,
  $B \leftarrow \emptyset$
  foreach $x \in S$
      for $i \leftarrow 1 \ldots k$
          $B[h_i(x)] \leftarrow 1$

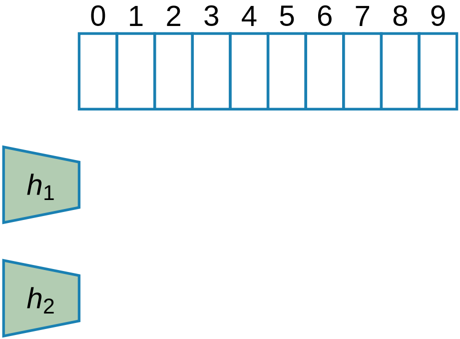
- Testing $x \in S$ amounts to testing $B(x) \subseteq B(S)$

  i.e., (assuming B is implemented as an integer)

  $x \in S \Leftrightarrow$ `(Bx & BS) == Bx`

Example

U is the universe of character strings; $k = 2$; $m = 10$



$S = \{$"ciao", "foo", "bar"$\}$

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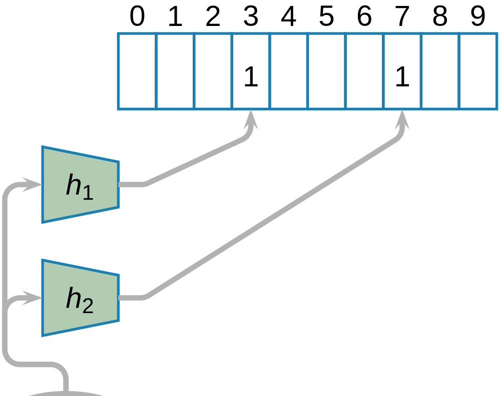

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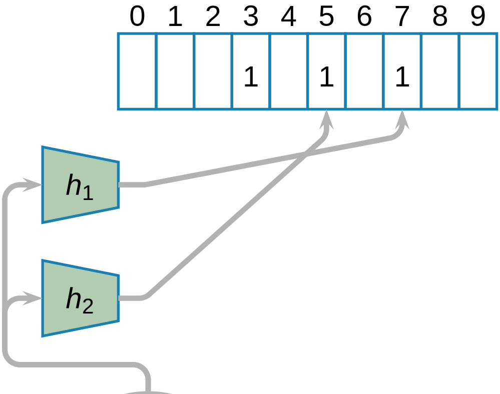

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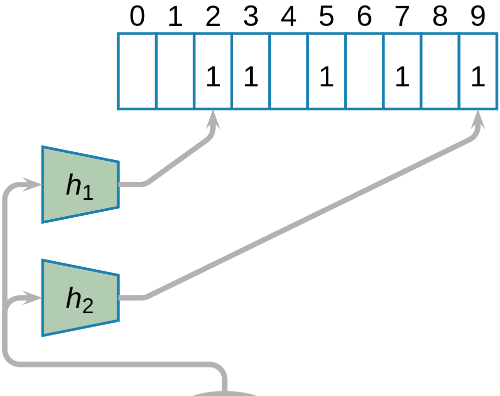

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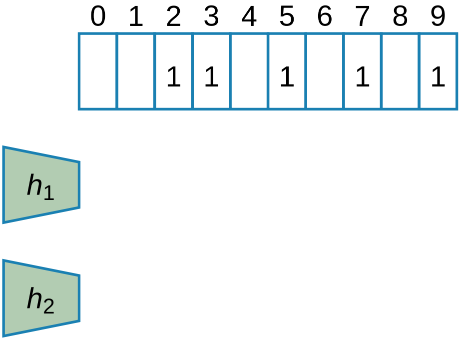

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Test:

Example

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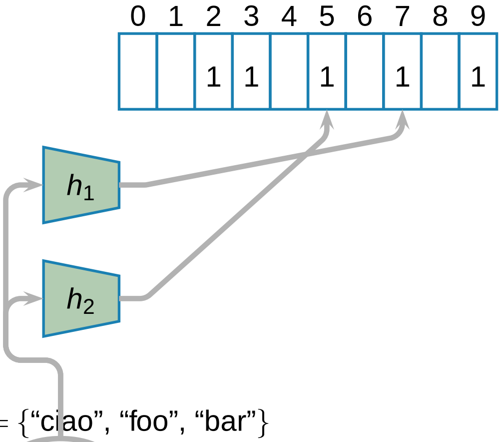

$S = \{$“ciao”, “foo”, “bar”$\}$

Test: “foo”

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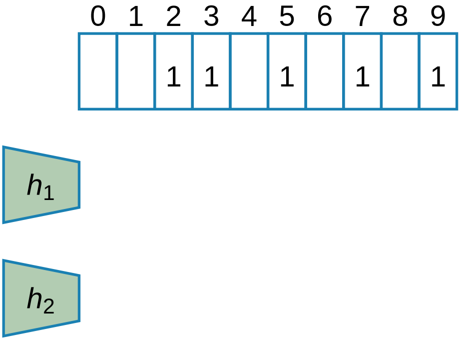

$S = \{$“ciao”, “foo”, “bar”$\}$

Test: “foo”: *yes*

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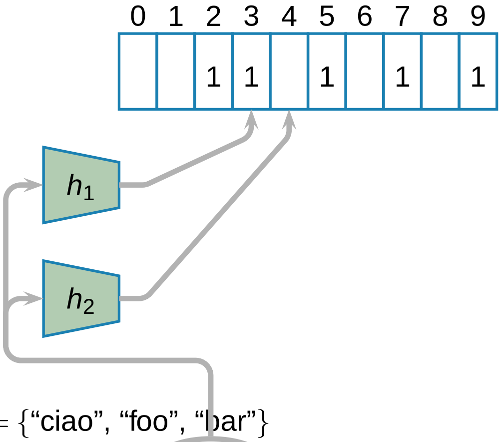

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Test: "foo": *yes*, "abc"

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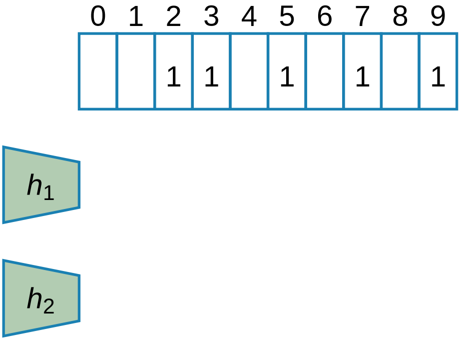

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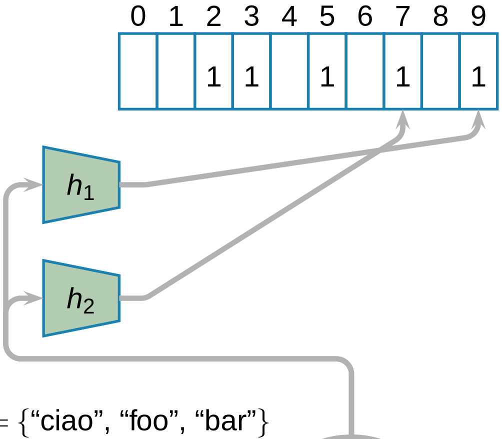

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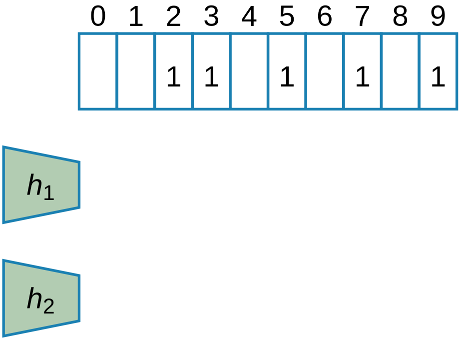

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Test: “foo”: *yes*, “abc”: *no*, “xyz”: *yes* (false positive)

Idea

$$m \xleftrightarrow{\;p(m)\;} p$$

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$$\begin{tikzcd}
m \arrow[rr, leftrightarrow, "p(m)"] \arrow[d, "X_S"'] & & p \arrow[d, "X_P"] \\
S_m \arrow[rr, leftrightarrow, "S_m \supseteq S_p"] & & S_p
\end{tikzcd}$$

1. Reduce p and m into sets of strings, S_p and S_m, such that $p(m) \Rightarrow S_p \subseteq S_m$

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\end{tikzcd}$$

1. Reduce p and m into sets of strings, S_p and S_m, such that $p(m) \Rightarrow S_p \subseteq S_m$
2. Represent S_p and S_m with Bloom filters, B_p^K and B_m^K (the K superscript means that the Bloom filters use keyed cryptographic hash functions, with key K)

Predicate Encoding

1. Constraint encoding

   name$=$*value* (*equality* constraint)

   name$=$ *any* (*existence* constraint)

   e.g., idmef_version$>$2 $\rightarrow$ "$\exists$idmef_version", idmef_version$=$2 $\rightarrow$ "idmef_version$=$2"

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3. A predicate $P = f_1 \vee f_2 \vee \ldots \vee f_F$ P is encoded with a list of sets $S_P = \{S_1, S_2, \ldots, S_F\}$

Message Encoding

1. Every attribute *name*=*value* is encoded with two strings $s^{=}$ =“*name*=*value*” and $s^{\exists}$ =“*name*”

$$\text{idmef\_version}=2 \rightarrow \begin{cases} s^{=} = \text{“idmef\_version=2”} \\ s^{\exists} = \text{“}\exists\text{idmef\_version”} \end{cases}$$

Message Encoding

1. Every attribute *name*$=$*value* is encoded with two strings $s^{=} =$"*name*$=$*value*" and $s^{\exists} =$"*name*"

   $$\text{idmef\_version}{=}2 \rightarrow \begin{cases} s^{=} = \text{"idmef\_version=2"} \\ s^{\exists} = \text{"}\exists\text{idmef\_version"} \end{cases}$$

2. A message $m = \{a_1, a_2, \ldots, a_n\}$ is therefore encoded with a set $S_m = S_m^{=} \cup S_m^{\exists}$

“Encoded” Matching

Given P’s encoding $B_P = \{B_{f_1}, B_{f_2}, \ldots\}$, and m’s encoding B_m, we define the *Bloom-encoded matching* relation $m \prec_B P$ as follows:

$$m \prec_B P \Leftrightarrow \exists f \in P : B_f \subseteq B_m$$

Observations

- Matching an encoded message m with an encoded filter f amounts to testing inclusion of two Bloom filters
  - in C, this may be done with `(Bm & Bf) == Bf`
- The covering relation $f \prec g$ works exactly the same way
  - `(Bf & Bg) == Bg`

Summary

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  - traditional methods

- Privacy in the presence of an untrusted network
  - approach: encoding messages and filters
  - method: Bloom filters

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  - efficient representation and processing of large sets of Bloom filters
    - *ideas: BDDs*

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- http://www.inf.unisi.ch/carzaniga/cbn/

Part V

Conclusions

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- Several disciplines
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  - algorithms
  - systems
  - software

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April 2008

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References

- A. Carzaniga and A. L. Wolf. **"Content-Based Networking: A New Communication Infrastructure."** In *NSF Workshop on an Infrastructure for Mobile and Wireless Systems*, LNCS 2538, Scottsdale, Arizona, Oct. 2001. Springer-Verlag.
- A. Carzaniga and A. L. Wolf. **"Forwarding in a Content-Based Network."** In *Proceedings of ACM SIGCOMM 2003*, Karlsruhe, Germany, Aug. 2003.
- A. Carzaniga, M. J. Rutherford, and A. L. Wolf. **"A Routing Scheme for Content-Based Networking."** In *Proceedings of IEEE INFOCOM 2004*, Hong Kong, China, Mar. 2004.
- A. Carzaniga, A. J. Rembert, and A. L. Wolf. **"Understanding Content-Based Routing Schemes."** *Technical Report 2006-05*, Faculty of Informatics, University of Lugano, Sep., 2006.
- C. P. Hall, A. Carzaniga, and A. L. Wolf. **"DV/DRP: A Content-Based Networking Protocol For Sensor Networks."** *Technical Report 2006-04*, Faculty of Informatics, University of Lugano, Sep., 2006.