Declarative Networking

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Agenda

- Datalog and Recursive Query Processing
- Motivation to Declarative Networking
- NDLog : Extensions to Datalog
- Execution Plan generation
- Incremental Maintenance
- Use cases
- Conclusion and References

Declarative Networking

- A declarative framework for networks:
  - Network protocols are declaratively specified using a database query language
  - Distributed query engine executes specifications to implement network protocols
- Success of database research:
  - 70's – today: Database research has revolutionized data management
  - Today: Similar opportunity to revolutionize the Internet architecture

Declarative Networking: Motivation

- Internet faces many challenges today:
  - Unwanted, harmful traffic
  - Complexity/fragility in Internet routing
  - Proliferation of new applications and services
- Efforts at improving the Internet:
  - Evolutionary: App-level "*Overlay*" networks
  - Revolutionary: Clean-slate designs
    - NSF GENI initiative, FIND program

Motivation

- Routing?
  - Gathering local network state : Base Data
  - Deriving forwarding tables : Derived Data
  - Enforcing constraints : Constraints

- Recursive Query processing
  - Using derived data again in query processing

Datalog

Introduction to datalog and recursive query processing

Datalog

- Declarative Paradigm
  - Give only what, and not how
  - Used extensively in SQL, functional programming
  - Easy and more natural to state

- Datalog
  - Non procedural query language
  - Based on Prolog

  - V1(A,B) :- account (A, “Mumbai”, B), B> 700
  - This gives account numbers and balances for accounts in Mumbai with balance greater than 700

Datalog

- A simple Datalog rule

p :- q1, q2, …, qn

  - “q1 and q2 and … and qn implies p.”

p : head
q1..qn : body(list of literals), literals are either predicates or functions,
Commas are Logical Conjunction (AND)

Datalog

- Program consists of rules
- Many rules can be used to define a relation
- Order of defining rules does not matter
- Predicates(relations) and matched (joined) to produce head

  - *interest_rate(A,10) :- account(A,N,B), B >= 10000*
  - *interest_rate(A,5) :-account(A,N,B) , B < 10000*
  - *interest(A,I) :- account(A, ”Mumbai”, B), interest_rate(A,R),I = B*I/100*

- This is an example of non-recursive datalog program

Datalog

- Recursive datalog program
- Consider a program to give all paths between nodes of a graph

  - *path(src,Dest,Path,Cost) :- link(src,Dest,Cost), path=f_init(src,Dest).*
  - *path(src,Dest,Path,Cost) :- link(src,nxt,Cost1), path(nxt,Dest,path2,Cost2), Cost=Cost1+Cost2, Path=f_concatpath(src,path2)*

- Recursive programs use fixpoint evaluation
  - Tuples produced in each iteration are added to the relation
  - Duplicate tuples are removed
  - Repeated until no new tuples are produces, i.e. *“fixpoint”* is reached

Semi Naïve Evaluation

- New tuples that are generated for the first time in the current iteration are then used in the next iteration.
- This is repeated until a fixpoint is achieved (i.e., no new tuples are produced).

$$\Delta \mathrm{p}_j^{new} :- p_1^{old}, \ldots, p_{k-1}^{old}, \Delta \mathrm{p}_k^{old}, p_{k+1}, \ldots, p_n, b_1, b_2, \ldots, b_m.$$

p1,...,pn are recursive predicates and b1,..are base predicates

Language

NDLog, Datalog extended for networking

Language

- Simple example to find path between two nodes
- Paths in fully connected network:

sp1 path(src,Dest,path,Cost) :-
link(src,Dest,Cost), path=f_init(src,Dest).

- To get paths in a general network, we need to add one more rule
- **sp2** path(src,Dest,path,Cost) :-
  link(src,nxt,Cost1),
  path(nxt,Dest,path2,Cost2),
  Cost=Cost1+Cost2,
  path=f_concatpath(src,path2),
  f_inPath(src,path2)=false

Language

- Aggregation
  - To get the cost of the shortest path we can use aggregation
  - min, max, avg all can be obtained in the same way

- **sp3** spCost(src,Dest,min<Cost>) :- path(src,Dest,path,Cost).

Language

- Location Specifiers (@)
  - Extension to datalog for networking
  - Specifies the location of data
  - Captures data partitioning
  - Enables distributed computations necessary for network protocols
  - Hides low level dataflow details

sp1 path(@src,Dest,path,Cost) :-
link(@src,Dest,Cost),
path=f_init(src,Dest).
sp2 path(@src,Dest,path,Cost) :-
link(@src,nxt,Cost1),
path(@nxt,Dest,path2,Cost2),
Cost=Cost1+Cost2,
path=f_concatpath(src,path2),
f_inPath(src,path2)=false

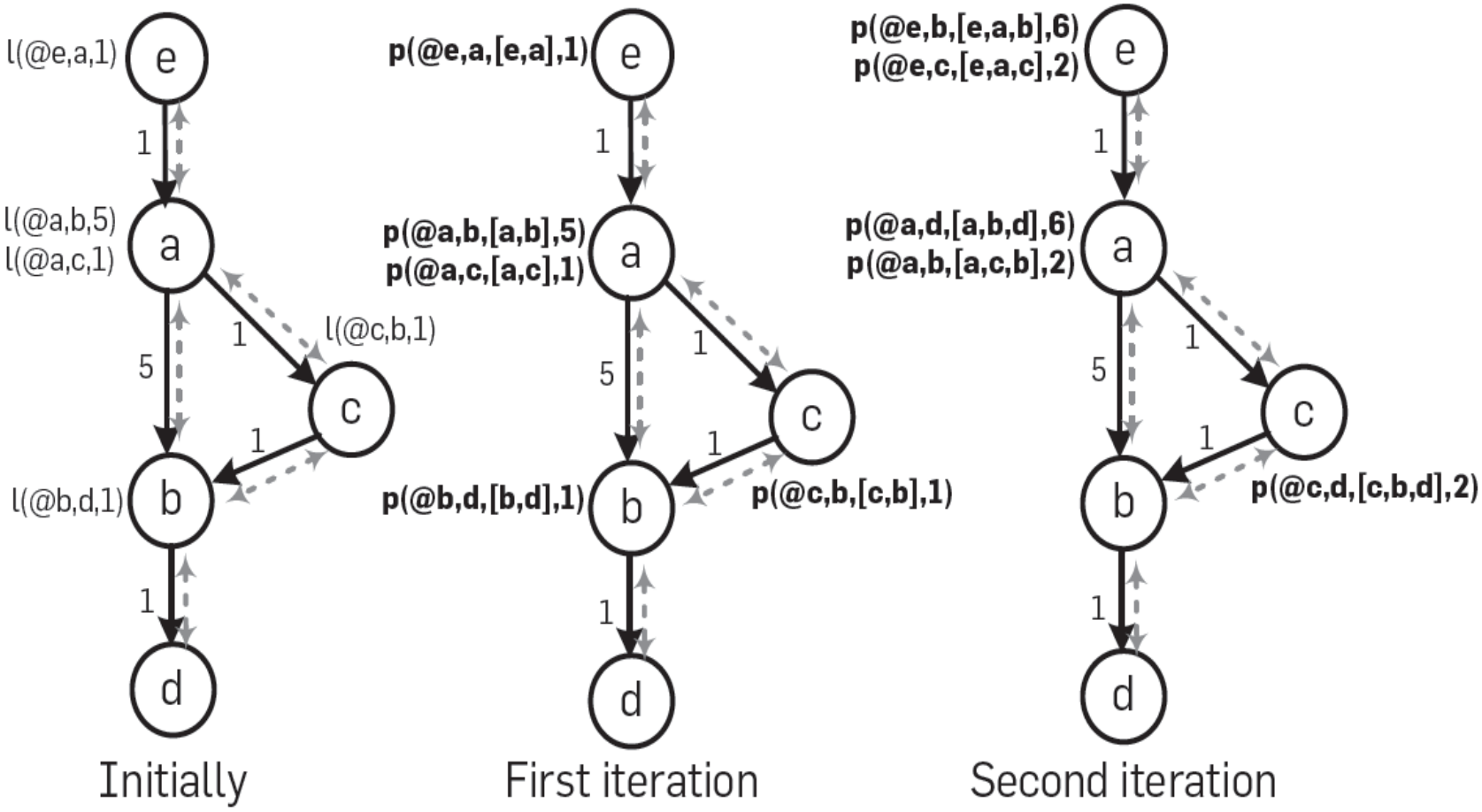
Language

- Link Restricted Rules
  - Models physical network where full connectivity is not available
  - One link predicate in each rule
  - There is exactly one link predicate in the body and rule is either..
    - Local rule or
    - All other predicates (including the head predicate)have their location specifier set to either the first (source) or second (destination) field of the link predicate.
  - p(@Dest,...):- link(@Src,Dest...),p1(@Src,...), …,pn(@Src,...).

Language

- **sp1** path(@src,Dest,path,Cost) :- link(@src,Dest,Cost), path=f_init(src,Dest).
- **sp2** path(@src,Dest,path,Cost) :- link(@src,nxt,Cost1), path(@nxt,Dest,path2,Cost2), Cost=Cost1+Cost2, path=f_concatpath(src,path2), f_inPath(src,path2)=false
- **sp3** spCost(@src,Dest,min<Cost>) :- path(@src,Dest,path,Cost).
- **sp4** shortestpath(@src,Dest,path,Cost) :- spCost(@src,Dest,Cost),path(@src,Dest,path,Cost).
- **Query** shortestpath(@src,Dest,path,Cost).

Language


l(@e,a,1)
e
1
l(@a,b,5)
l(@a,c,1)
a
5
1
l(@c,b,1)
c
1
l(@b,d,1)
b
1
d
Initially
p(@e,a,[e,a],1)
e
1
p(@a,b,[a,b],5)
p(@a,c,[a,c],1)
a
5
1
c
1
p(@b,d,[b,d],1)
b
p(@c,b,[c,b],1)
1
d
First iteration
p(@e,b,[e,a,b],6)
p(@e,c,[e,a,c],2)
e
1
p(@a,d,[a,b,d],6)
p(@a,b,[a,c,b],2)
a
5
1
c
1
b
p(@c,d,[c,b,d],2)
1
d
Second iteration

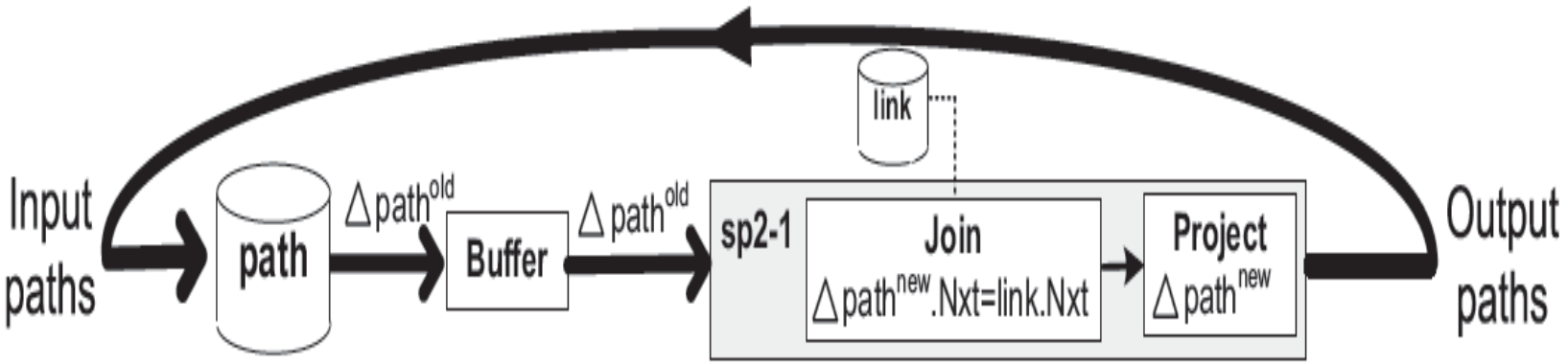
Execution Plan generation

Execution Plan Generation

- Network Protocols : State machines
- NDlog : Developed as Distributed dataflow execution engines (runtime similar to Parallel Database Systems)
- Recursive flows and the asynchronous communication difficult to handle
- Two types : Centralized / Distributed

Centralized Evaluation

sp2-1 $\Delta path^{new}$ (@Src, Dest,Path,Cost) :-
link(@Src,Nxt,Cost1),
$\Delta path^{old}$(@Nxt,Dest,Path2,Cost2),
Cost=Cost1+Cost2,
Path=*f_concatPath*(Src,Path2).



Centralized Evaluation

while $\exists B_k.size > 0$

$\forall B_k \; where \; B_k.size > 0, \Delta p_k^{old} \leftarrow B_k.flush()$

$execute \; all \; rule \; strands$

foreach $recursive \; predicate \; p_j$

$p_j^{old} \leftarrow p_j^{old} \cup \Delta p_j^{old}$

$B_j \leftarrow \Delta p_j^{new} - p_j^{old}$

$p_j \leftarrow p_j^{old} \cup B_j$

$\Delta p_j^{new} \leftarrow \phi$

Distributed Plan Generation

For Distributed implementation:

Nonlocal rules whose body predicates have different location Can not be executed as a single node

Tuples to be joined are situated at diff nodes

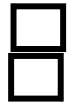
Rule localization rewrite ensures all tuples to be joined at same node

Localization Rewrite

- Rules may have body predicates at different locations:

  R2: path(@S,D,P) ← link(@S,Z), path(@Z,D,P2), P=S•P2.

Matching variable Z = “Join”



Rewritten rules:

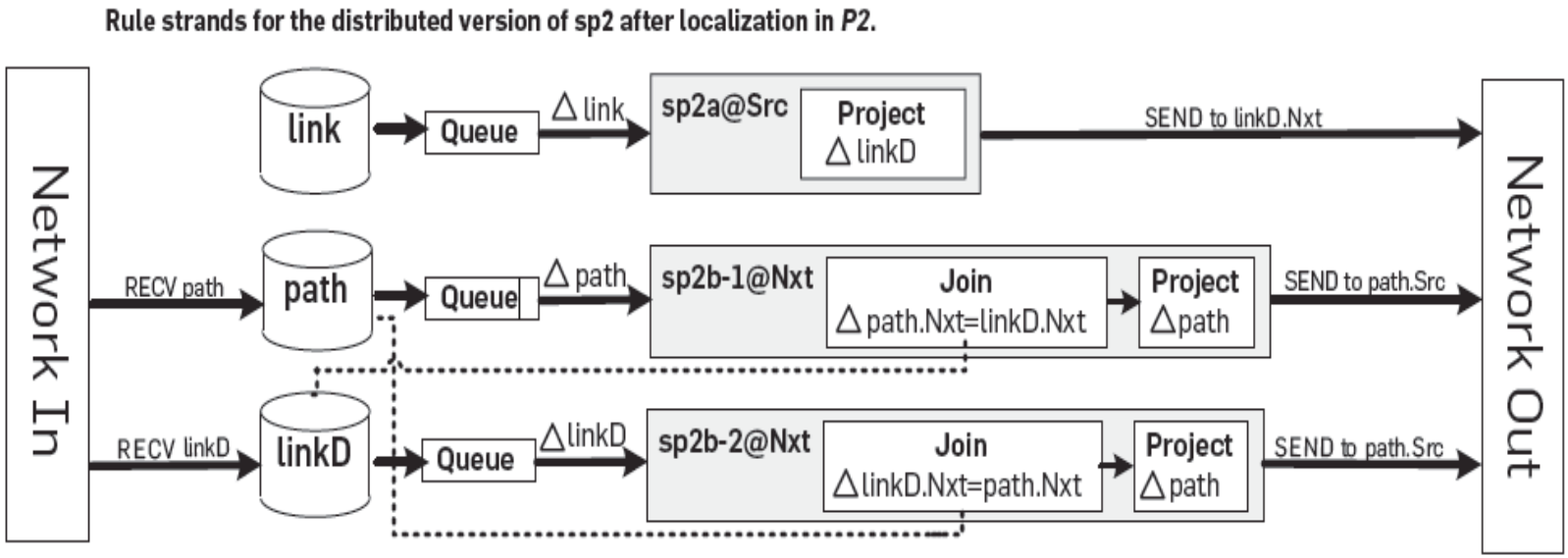
sp2a: linkD(S,@D) ← link(@S,D)

sp2b: path(@S,D,P) ← linkD(S,@Z), path(@Z,D,P2), P=S•P2.

Matching variable Z = “Join”

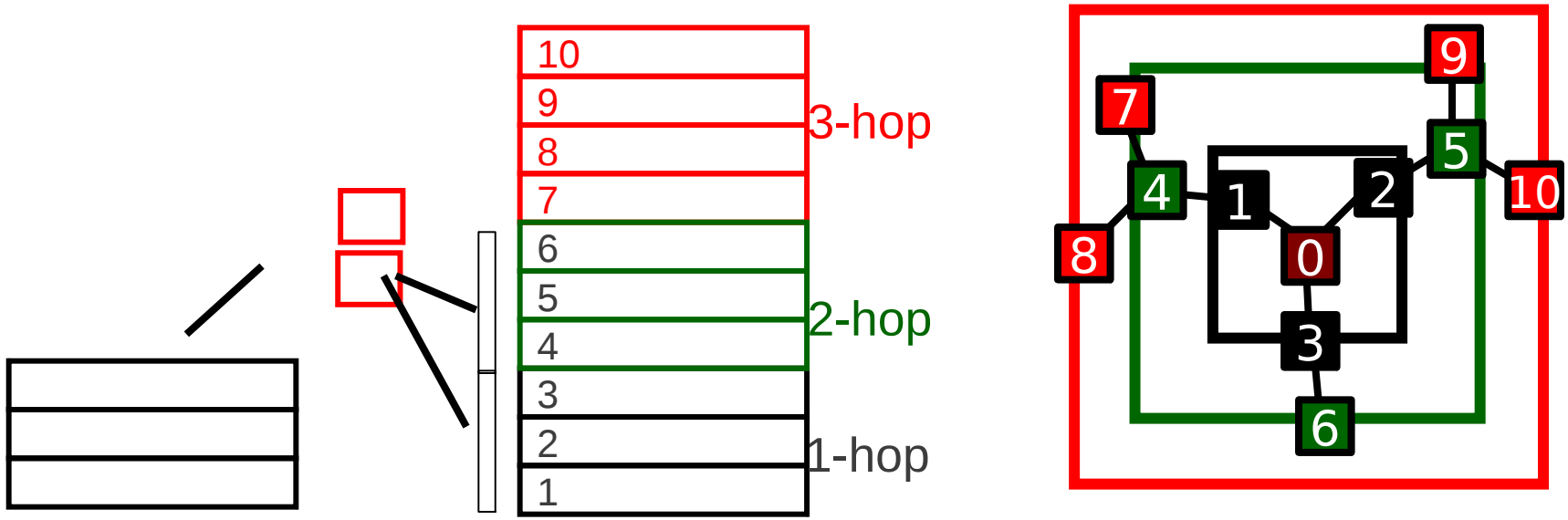
Distributed Plan Generation

- Rule sp2a@Src sends links to dest. add with as linkD tuples.
- Rule sp2b-2@Nxt takes linkD and performs join with path tuple.



Recursive Query Evaluation

- Semi-naïve evaluation:
  - Iterations (rounds) of synchronous computation
  - Results from iteration ith used in (i+1)th



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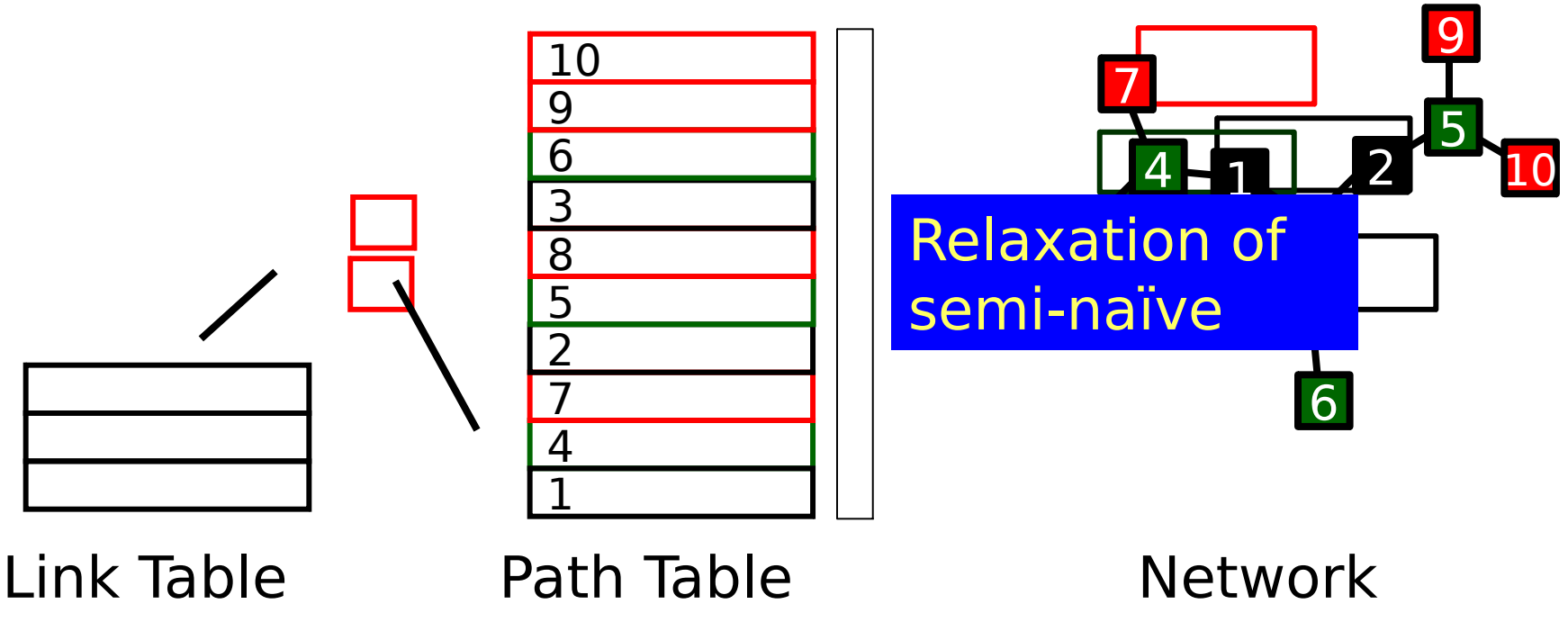
Problem: Unpredictable delays and failures

Pipelined Semi-naïve (PSN)

- Fully-asynchronous evaluation:
  - Computed tuples in *any* iteration pipelined to next iteration
  - Natural for distributed dataflows



Pipelined Semi-naïve (PSN)

- Node receiving new tuple can immediately process the tuple without waiting for local iteration to complete.

Algorithm Pipelined Semi-naïve (PSN) Evaluation

while $\exists\, Q_k.size > 0$

$t_k^{old,i} \leftarrow Q_k.dequeueTuple()$

foreach *rule strand execution*

$\Delta p_j^{new,i+1}$:—

$p_1,\ldots,p_{k-1}, t_k^{old,i}, p_{k+1},\ldots, p_n, b_1, b_2,\ldots, b_m$

foreach $t_j^{new,i+1} \in \Delta p_j^{new,i+1}$

if $t_j^{new,i+1} \notin p_j$

then $p_j \leftarrow p_j \cup t_j^{new,i+1}$

$Q_j.enqueueTuple(t_j^{new,i+1})$

Incremental Maintenance

Semantics in Dynamic Network

- Underlying Network Changes.
- Use Bursty update model for re-computations

- Three types of changes:
  - Insertion : Tuple can be inserted at any stage , handled by pipelined Evaluation.
  - Deletion : Deletion of base tuple leads to deletion of tuples derived from base tuple.
  - Update : Treated as deletion followed by insertion. Updating base tuple leads to more updates propagated further.

Semantics in Dynamic Network

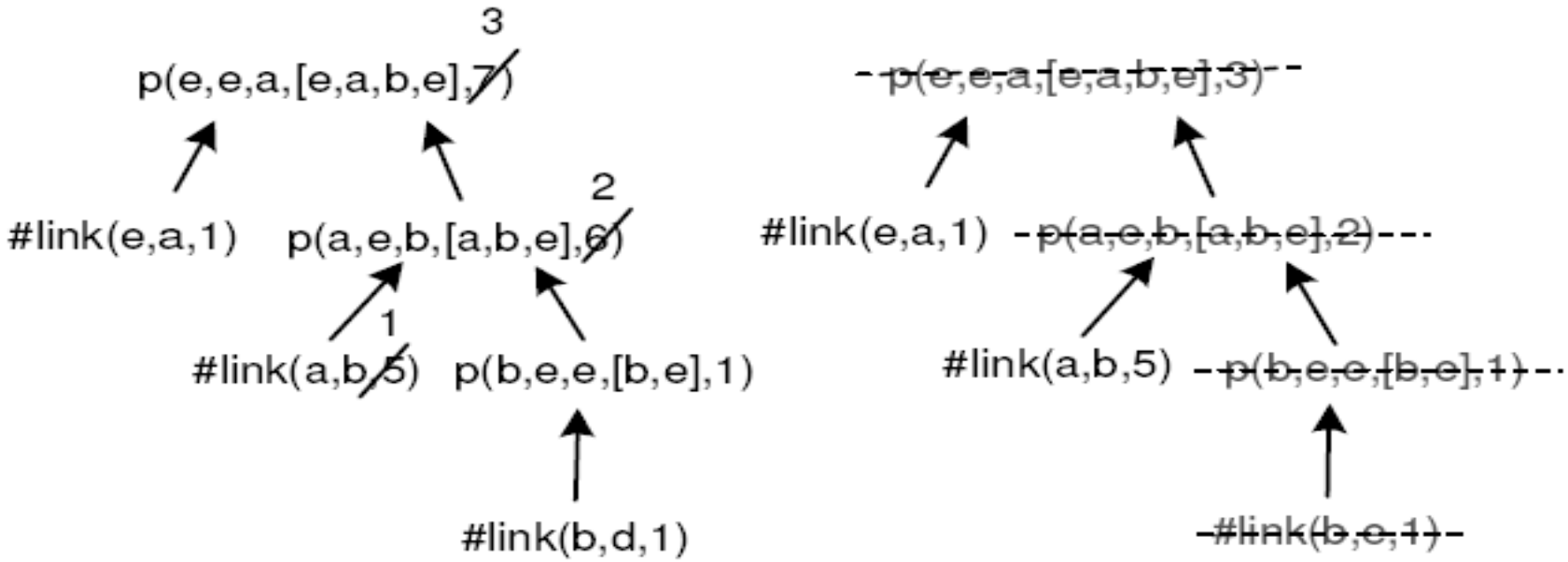


Figure : *Derivation tree for derived path tuple from a to e. The left diagram shows updating the tree due to a change in base tuple* $\#link(\mathbf{a}, b, 5)$*, and the right diagram shows the deletion of* $\#link(\mathbf{b}, e, 1)$.

Semantics in Dynamic network

- Use of Count Algorithm for multiple derivations
- Standard view maintenance technique for aggregates
- Ensures that tuples no longer derivable are deleted on deletes/updates.
- Example : Calculate 2 hop paths for given link set
  - Link={(a,b),(b,c),(b,e),(a,d),(d,c)}
  - Evaluates to {[(a,c)-2],[(a,e)-1]}
  - We keep count with both paths
  - If link (a,b) is deleted, algo uses stored count to reevaluate hop to {(a,c)}

Use Cases

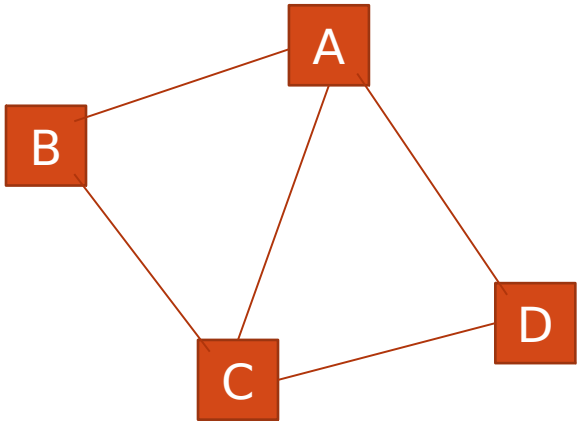
Use Cases of Declarative Networking

Declarative Routing

- Routing Protocol is implemented by writing query in NDlog
- Queries executed in distributed fashion on nodes
- Static analysis tests for termination of query in Ndlog (check for recursive defination and check for termination)
- NDlog can express variety of routing protocols such as distance vector, path vector ,dynamic source routing easily

Distance Vector Routing

- At each node, save next hop each destination with the cost
- Nodes exchange this information to get knowledge about complete network state



	A	C	D
1	1, A	1, C	--
2	1, A	1, C	2, A

	B	C	D
1	1, B	1, C	1, B

Distance Vector Routing

- DV1: path(@S,D,D,C) :- link(@S,D,C).
- DV2: path(@S,D,Z,C) :- link(@S,Z,C1),
- path(@Z,D,W,C2), C = C1 + C2
- DV3: shortestCost(@S,D,min<C>) :- path(@S,D,Z,C).
- DV4: nextHop(@S,D,Z,C) :- path(@S,D,Z,C), shortestCost(@S,D,C).
- Query: nextHop(S,D,Z,C).

Distance Vector Routing

- DV1: path(@S,D,D,C) :- link(@S,D,C).
- DV2: path(@S,D,Z,C) :- link(@S,Z,C1),
- path(@Z,D,W,C2), C = C1 + C2
- DV3: shortestCost(@S,D,min<C>) :- path(@S,D,Z,C).
- DV4: nextHop(@S,D,Z,C) :- path(@S,D,Z,C), shortestCost(@S,D,C).
- Query: nextHop(S,D,Z,C).

- Count to Infinity problem?
- DV2: path(@S,D,Z,C) :- link(@S,Z,C1),
- path(@Z,D,W,C2), C = C1 + C2, W != S
- DV5: path(@S,D,Z,∞) :- link(@S,Z,C1), path(@Z,D,S,C2)

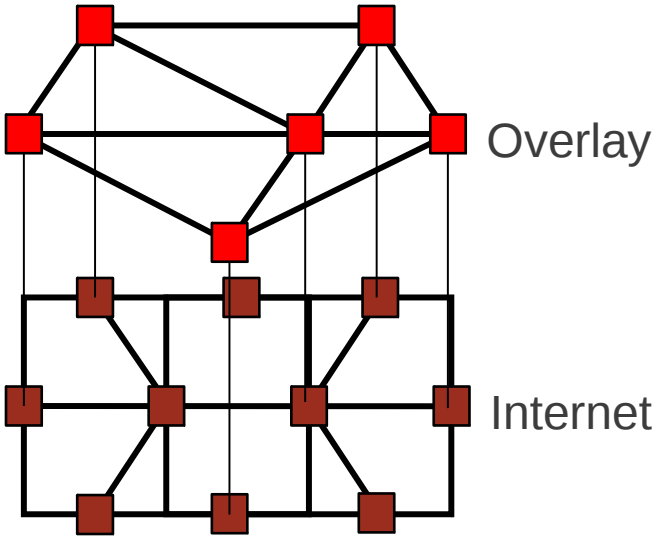
Policy Based Routing

- Some of the policies
  - Node Utilization
  - Link Utilization
  - Security issues
  - Transit- Peer relationships

- PBR1: invalidPath(@S,D,P,C) :- path(@S,D,P,C), excludeNode(@S,W), f_inPath(P,W) = true.
- PBR2: permitPath(@S,D,P,C) :- path(@S,D,P,C), not invalidPath(@S,D,P,C)
- Query: permitPath(@S,D,P,C).
- excludeNode(@S,W) : this says that node W can not carry any traffic for node S

Declarative Overlays

- **Overlay network** : Virtual nodes built on top of internet
- To provide services that are not available in existing network.



- Overlog declarative language an extension on NDlog.
- Soft-state is introduced on Overlog

Soft State

- Stored data has associated Time-to-live(TTL)
- Soft state dataum needs to be periodically refreshed
- If more time than TTL passes without datum being refreshed, that datum is deleted.
- Soft State is favored in networking implementations since it provides eventual consistency.
- Eventual values are obtained in case of transient errors such as reordered messages, node disconnection.
- In case of persistent failure no coordination is required, since any data provided by failed node would be forgotten.

Soft State

- In Overlog use materialized keyword
  - materialized(link, {1,2}, 10) , this specifies link tuple has a life time of ten seconds

- If TTL set to infinity : Hard State
- If predicate has no materialized keyword it is treated as event predicate (TTL =0)
- Event predicates are transient tables and use to trigger rules periodically or case of network events
- ping(@Y, X) :- periodic(@X, 10) , link(@X, Y)

Conclusion

- Ease of programming:
  - Compact and high-level representation of protocols
  - Orders of magnitude reduction in code size
  - Easy customization
- Safety:
  - Queries are “sandboxed” within query processor
  - Potential for static analysis techniques on safety
- What about efficiency?
  - No fundamental overhead when executing standard routing protocols
  - Application of well-studied query optimizations

References

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Thank you