Automated Verification of Safety Properties of Declarative Networking Programs

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July 15, 2015

Networks are complex and error-prone

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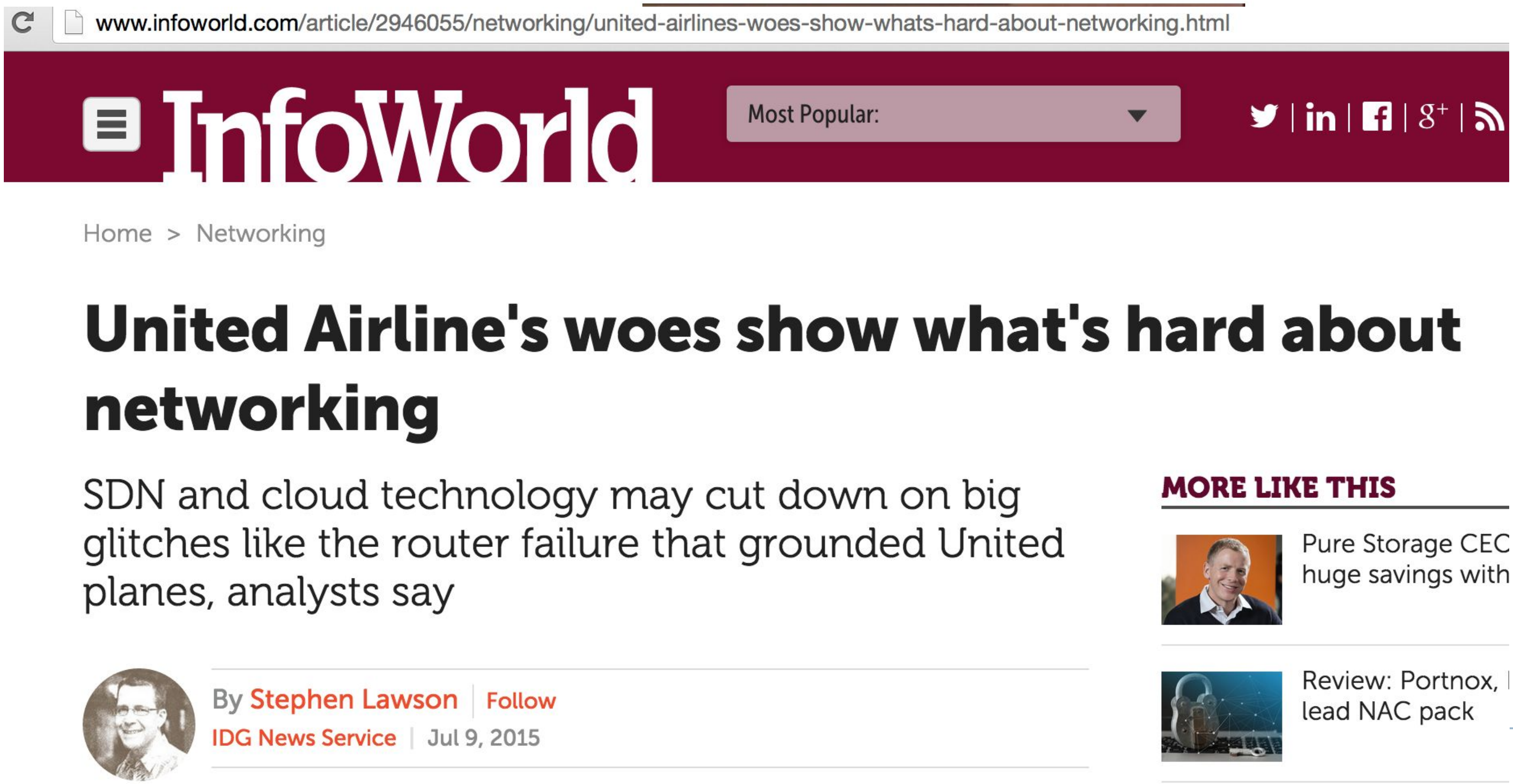

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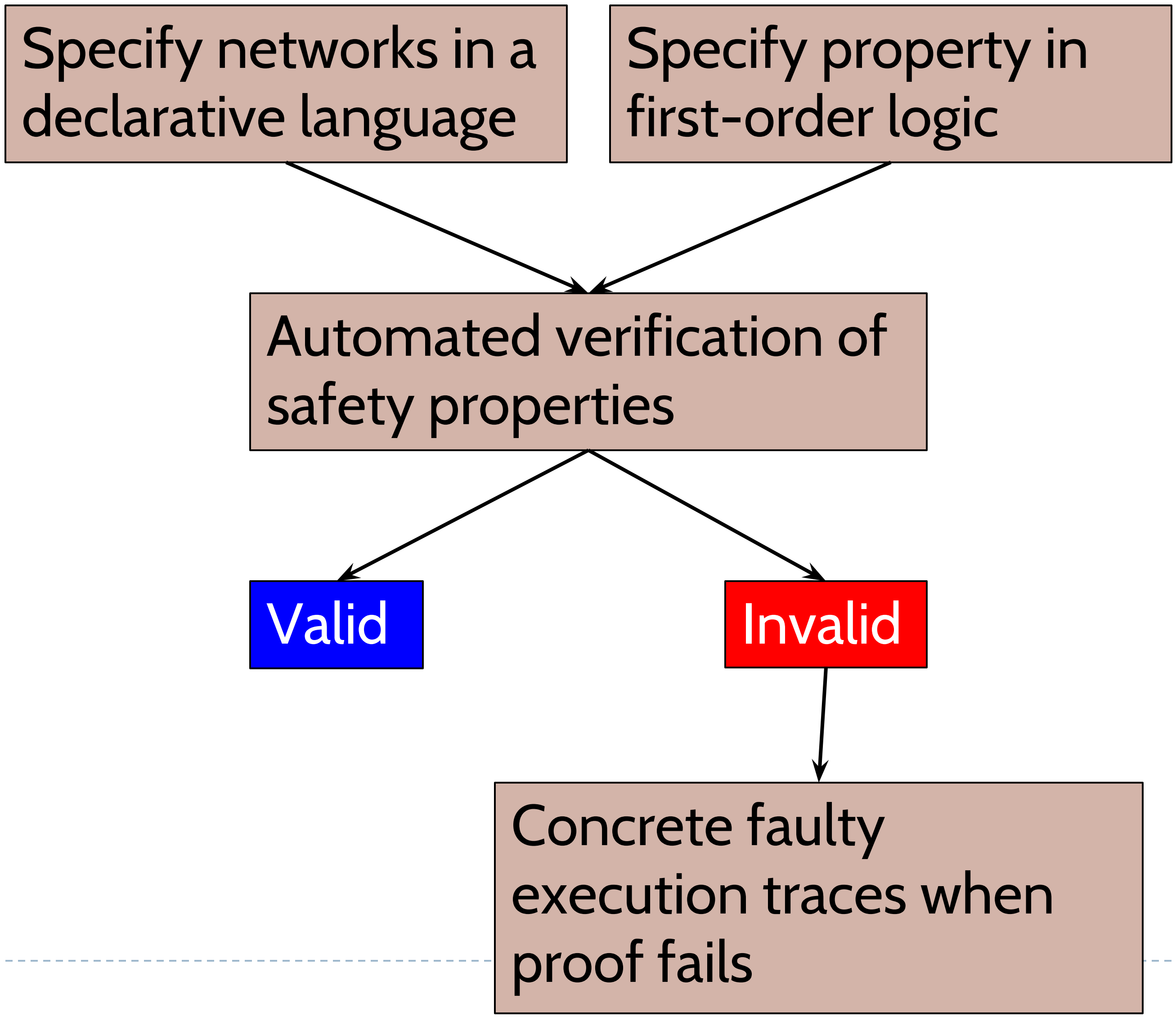
Our solution

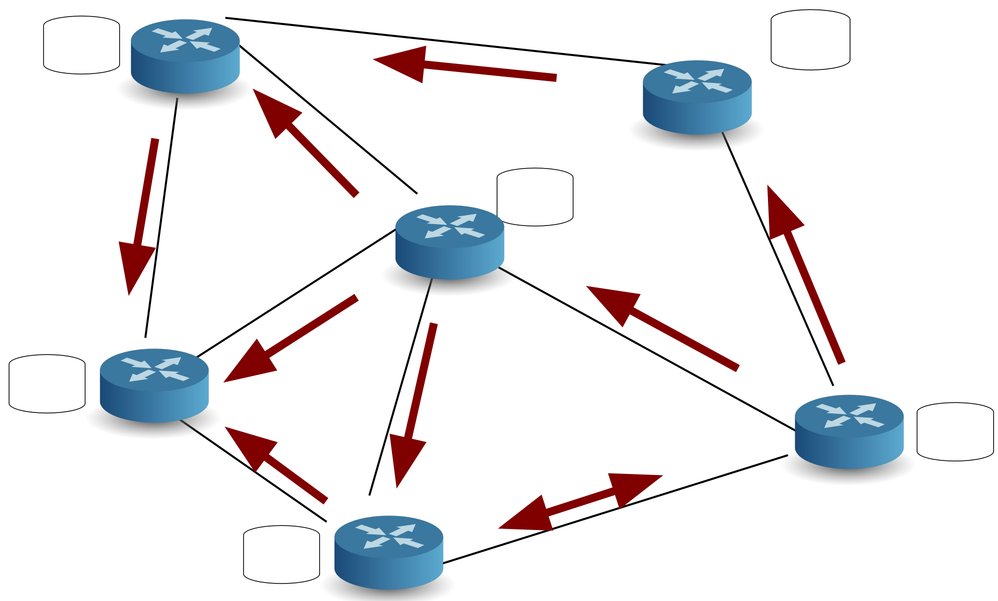


Roadmap

- Introduction of NDLog (Network Datalog)
- Algorithm analysis
  - Derivation pool construction
  - Property query
  - Network constraints
  - Recursive programs
- Case study
- Conclusion

Network Datalog (NDLog) [CACM'09]

- A distributed variant of Datalog
- Recursive query language over network states



Traditional Networks
- Network state
- Network Protocol

Declarative Networks
- Distributed Database
- Datalog Program

Rule format of NDLog

- Rule Head :- $Body_1$, $Body_2$, …, $Body_n$, Constraint
- @: Location specifier

<u>Twohops</u>

R1 onehop(@z,x,c2) :- link(@z,x,c2)

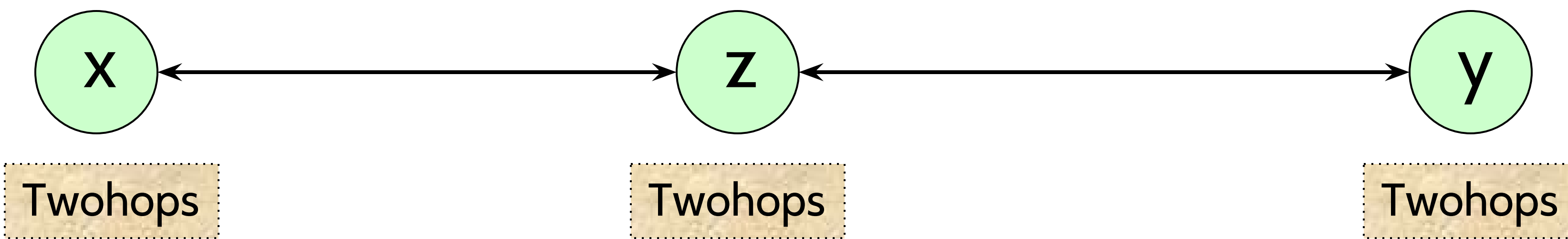
R2 twohops(@x,y,c) :- link(@z,y,c1), onehop(@z,x,c2), c=c1+c2

Running an example NDLog program

Twohops
R1 onehop(@z,x,c2) :- link(@z,x,c2)
R2 twohops(@x,y,c) :- link(@z,y,c1), onehop(@z,x,c2), c=c1+c2

link

@Src	Dst	Cost
@z	y	c1
@z	x	c2



Running an example NDLog program

<u>Twohops</u>

R1 onehop(@z,x,c2) :- link(@z,x,c2)

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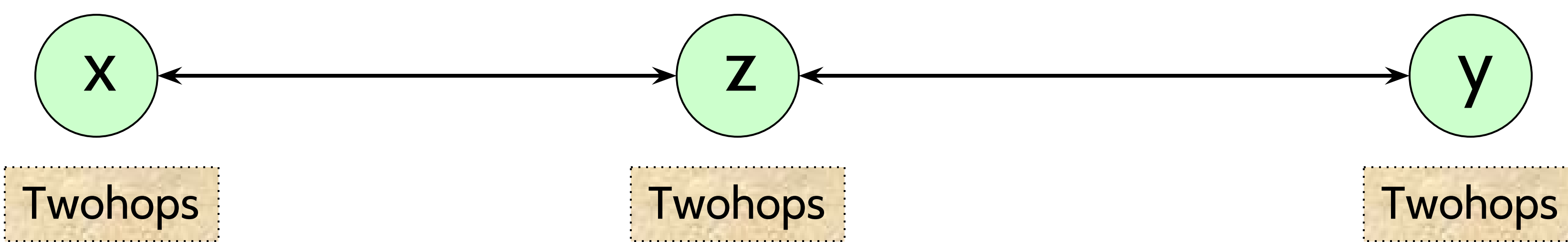
link

@Src	Dst	Cost
@z	y	c1
@z	x	c2

onehop

@Src	Dst	Cost
@z	x	c2



Running an example NDLog program

<u>Twohops</u>

R1 onehop(@z,x,c2) :- link(@z,x,c2)

R2 twohops(@x,y,c) :- link(@z,y,c1), onehop(@z,x,c2), c=c1+c2

@Src	Dst	Cost
@x	y	c

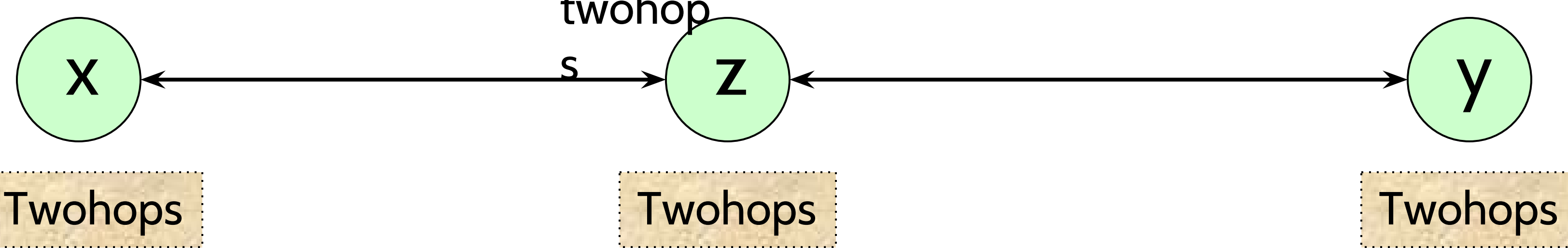
link

@Src	Dst	Cost
@z	y	c1
@z	x	c2

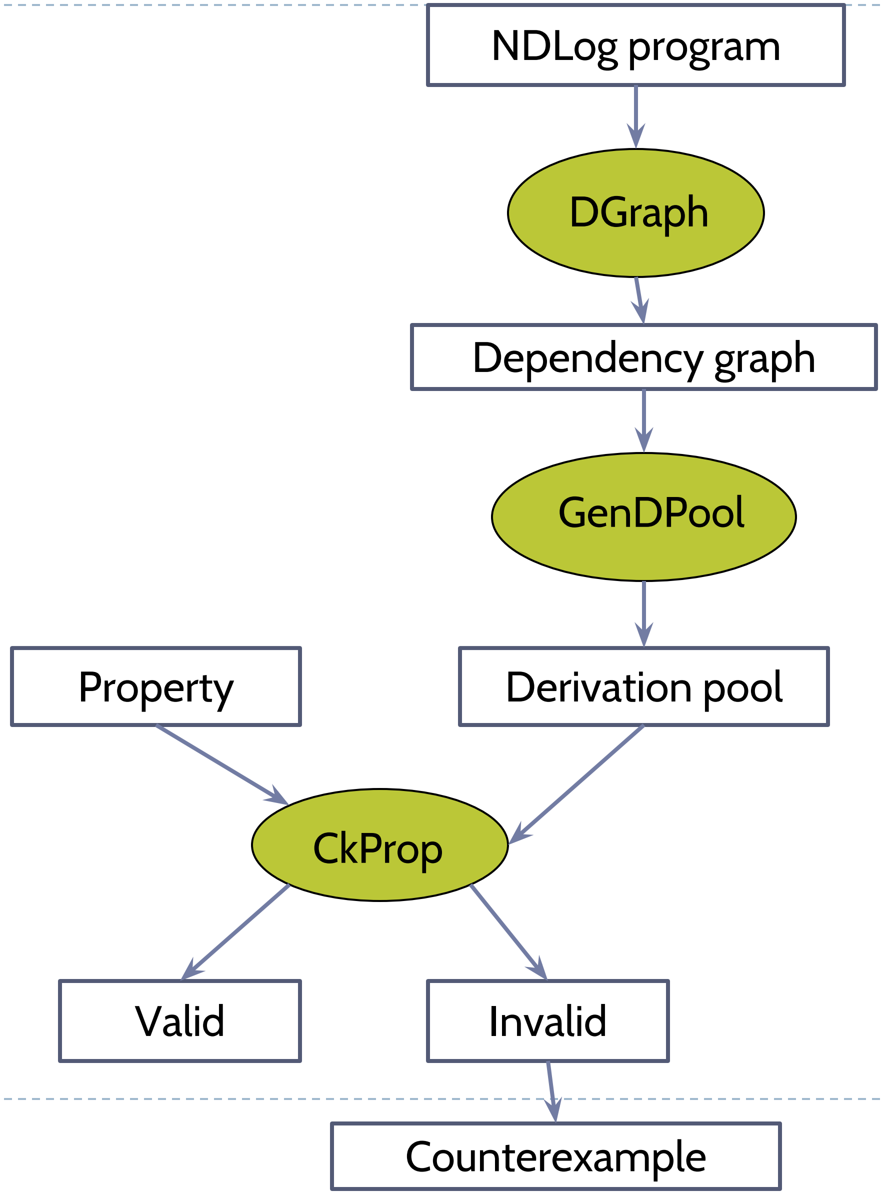
onehop

@Src	Dst	Cost
@z	x	c2

twohops



Overview of framework



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NDLog program ⇒ Dependency graph

- Dependency Graph G:

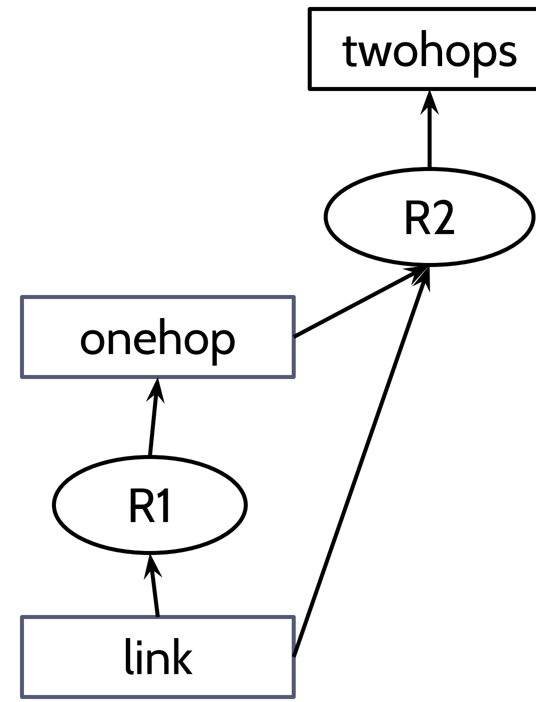
Vertex:

- V1: Tuple nodes
- V2: Rule nodes

Edge:

- (rule node → head node)
- (body node → rule node)

<u>Twohops</u>
R1 onehop(@z,x,c2) :- link(@z,x,c2)
R2 twohops(@x,y,c) :- link(@z,y,c1), onehop(@z,x,c2),
c=c1+c2



Dependency graph ⇒ Derivation pool

R1 onehop(@z,x,c2) :- link(@z,x,c2)
R2 twohops(@x,y,c) :- link(@z,y,c1), onehop(@z,x,c2), c=c1+c2

R1 onehop($@x_1,x_2,x_3$) :- link($@x_4,x_5,x_6$), $x_1=x_4 \wedge x_2=x_5 \wedge x_3=x_6$
R2 twohops($@x_7,x_8,x_9$) :- link($@x_{10},x_{11},x_{12}$), onehop($@x_{13},x_{14},x_{15}$), $x_7=x_{14} \wedge x_8=x_{11} \wedge x_{10}=x_{13} \wedge x_9=x_{12}+x_{15}$

	Link	Onehop
Derivations	(BaseTuple, link $(z_{\lambda1},z_{\lambda2},z_{\lambda3})$)	(R1, onehop(z_{o1},z_{o2},z_{o3}), (BaseTuple, link(z_{o4},z_{o5},z_{o6}))::nil)
Constraints	True	$z_{o1}=z_{o4} \wedge z_{o2}=z_{o5} \wedge z_{o3}=z_{o6}$

Twohops
(R2, twohops(z_{t7},z_{t8},z_{t9}), (BaseTuple,link$(z_{t10},z_{t11},z_{t12})$) ::(R1,onehop$(z_{t13},z_{t14},z_{t15})$, (BT,link$(z_{t3},z_{t4},z_{t5})$):: nil) ::nil)
$(z_{t3}=z_{t13} \wedge z_{t4}=z_{t14} \wedge z_{t5}=z_{t15}) \wedge (x_{t7}=x_{t14} \wedge x_{t8}=x_{t11} \wedge x_{t10}=x_{t13} \wedge x_{t9}=x_{t12}+x_{t15})$

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Property specification

- Safety property
  - Something bad never happens
- Restricted property format:
  - ◆ Indicates the temporal operation “past”

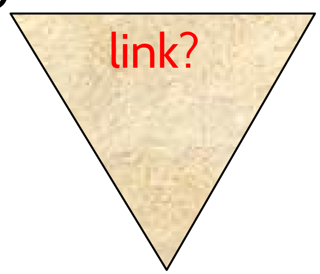
$$\forall \mathbf{x_1}.p_1(\mathbf{x_1}) \wedge \forall \mathbf{x_2}.p_2(\mathbf{x_2}) \wedge \ldots \wedge \forall \mathbf{x_n}.p_n(\mathbf{x_n}) \wedge c_q(\mathbf{x_1}, \ldots, \mathbf{x_n}) \supset \exists \mathbf{y_1}.\blacklozenge q_1(\mathbf{y_1}) \wedge \exists \mathbf{y_2}.\blacklozenge q_2(\mathbf{y_2}) \wedge \ldots \wedge \exists \mathbf{y_m}.\blacklozenge q_m(\mathbf{y_m}) \wedge c_q(\mathbf{x_1}, \ldots, \mathbf{x_n}, \mathbf{y_1}, \ldots, \mathbf{y_m})$$

- Example:
  - $\forall x_1,x_2,x_3.\mathrm{onehop}(x_1,x_2,x_3) \wedge x_3>0 \supset$
    $\exists y_1,y_2,y_3.\blacklozenge \mathrm{link}(y_1,y_2,y_3) \wedge y_3<0$

Property verification algorithm

- Verify the property holds for all possible derivations
  - Enumerate all derivations for the tuples in the antecedent

$$\varphi = \forall x_1, x_2, x_3.\ onehop(x_1,x_2,x_3) \wedge x_3>0 \supset \exists y_1,y_2,y_3.\ \blacklozenge link(y_1,y_2,y_3) \wedge y_3<0$$



onehop

Derivation of onehop *in derivation pool*

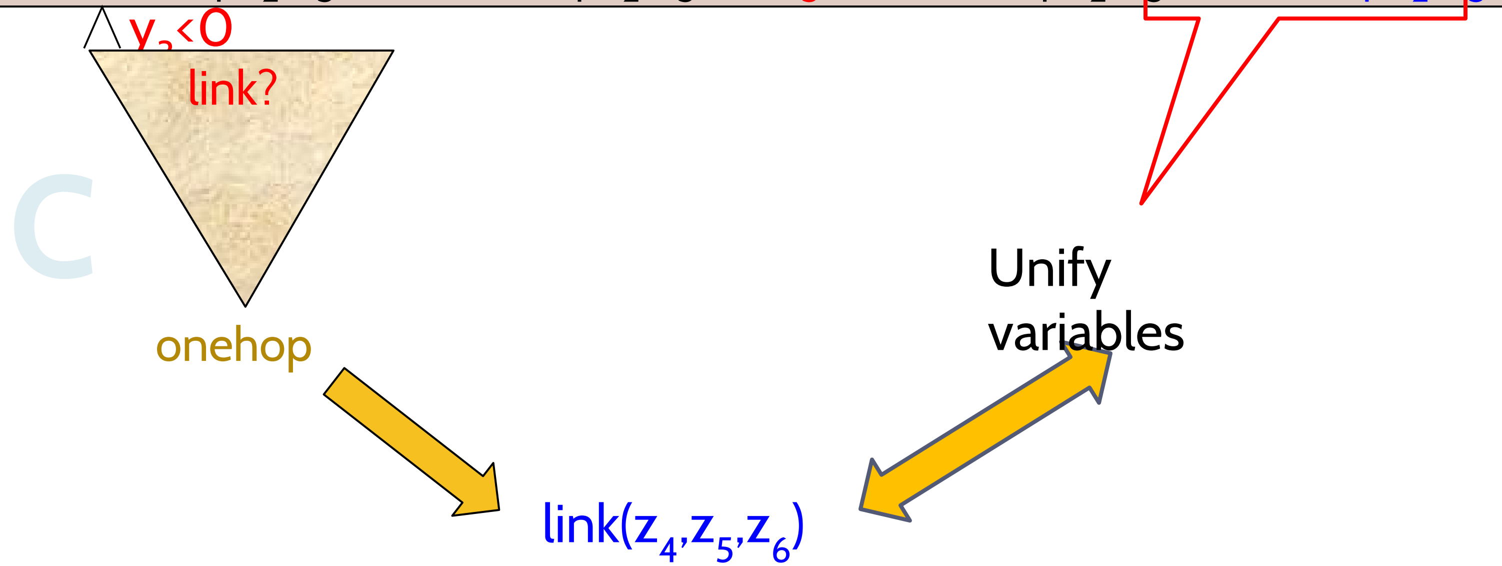
C

Constraint in derivation pool for the derivation on onehop

Property verification algorithm

- Verify existence of tuples in the conclusion
  - Look for instances of tuples in the given derivation

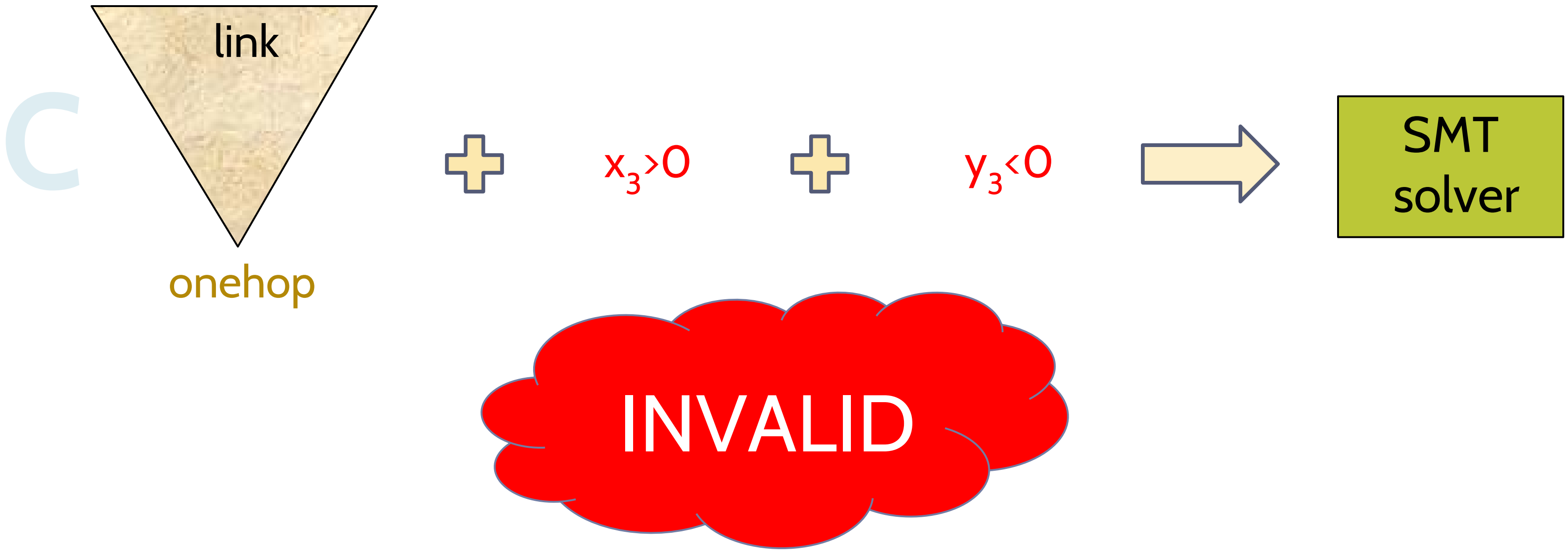
$$\varphi = \forall x_1,x_2,x_3.\ \text{onehop}(x_1,x_2,x_3) \wedge x_3>0 \supset \exists y_1,y_2,y_3.\ \blacklozenge \text{link}(y_1,y_2,y_3)$$



Property verification algorithm

- Verify validity of constraints
  - SMT solver

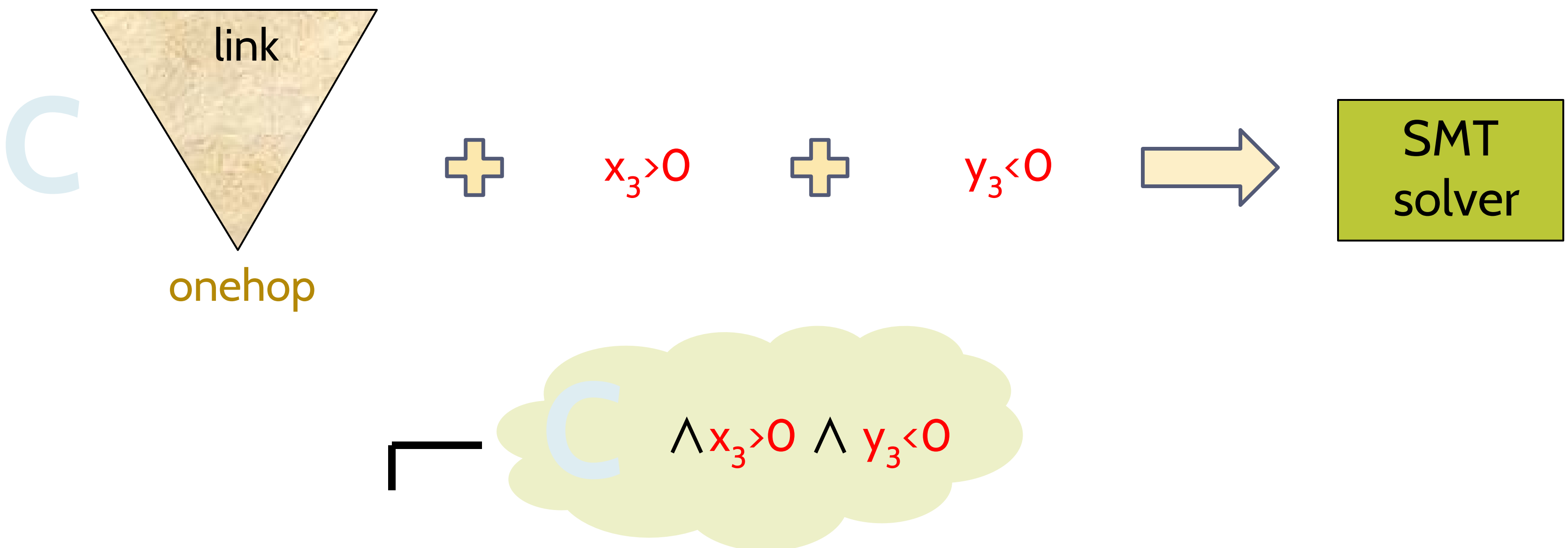
$\varphi = \forall x_1,x_2,x_3.\ \mathrm{onehop}(x_1,x_2,x_3) \wedge x_3>0 \supset \exists y_1,y_2,y_3.\ \blacklozenge \mathrm{link}(y_1,y_2,y_3)$
$\wedge\, y_3<0$



Property verification algorithm

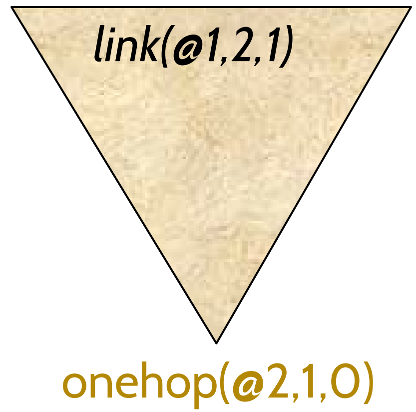
- Find a satisfying substitution for the negation of the constraints to generate a concrete counterexample

$$\varphi = \forall x_1,x_2,x_3.\ \mathrm{onehop}(x_1,x_2,x_3) \wedge x_3>0 \supset \exists y_1,y_2,y_3.\ \blacklozenge \mathrm{link}(y_1,y_2,y_3) \wedge y_3<0$$



Property verification algorithm

$$\varphi = \forall x_1,x_2,x_3.\ onehop(x_1,x_2,x_3) \wedge x_3>0 \supset \exists y_1,y_2,y_3.\ \blacklozenge link(y_1,y_2,y_3) \wedge y_3<0$$

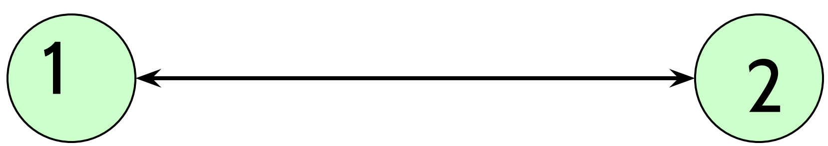


link

@Src	Dst	Cost
@1	2	1

onehop

@Src	Dst	Cost
@2	1	0



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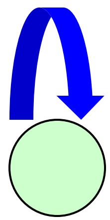
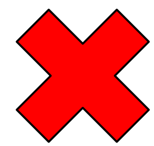
Network constraint examples

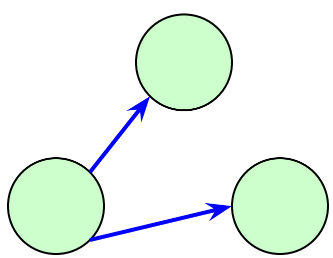
$$\varphi_{net} = \forall u_1,u_2,u_3.\ \mathrm{link}(u_1,u_2,u_3) \supset u_1 \neq u_2$$



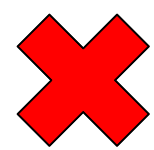
No self-loops



$$\varphi_{net} = \forall u_1,u_2,u_3.\ \mathrm{link}(u_1,u_2,u_3) \land \forall u_4,u_5,u_6.\ \mathrm{link}(u_4,u_5,u_6) \supset (u_1 = u_4 \rightarrow u_2 \neq u_5)$$



Every node in the network has only one outgoing link



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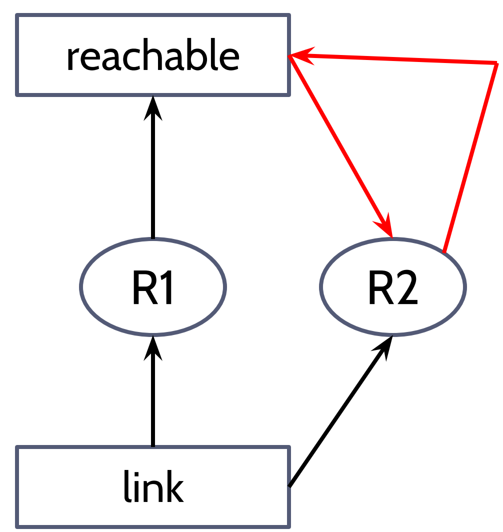
Recursive programs

- Dependency graph has cycles
- Break the cycle using user-provided annotations on tuples on the cycle
  - Equivalent to disjunction of constraints over the list of possible derivations for tuples on the cycle

Reachability
R1 reachable(@x,y) :- link(@x,y)
R2 reachable(@x,y) :- link(@x,z), reachable(@z,y)



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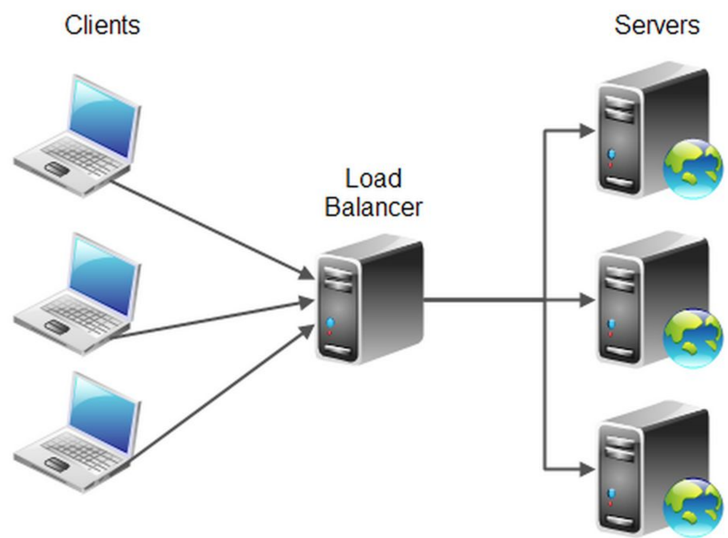
Introduction to load balancers

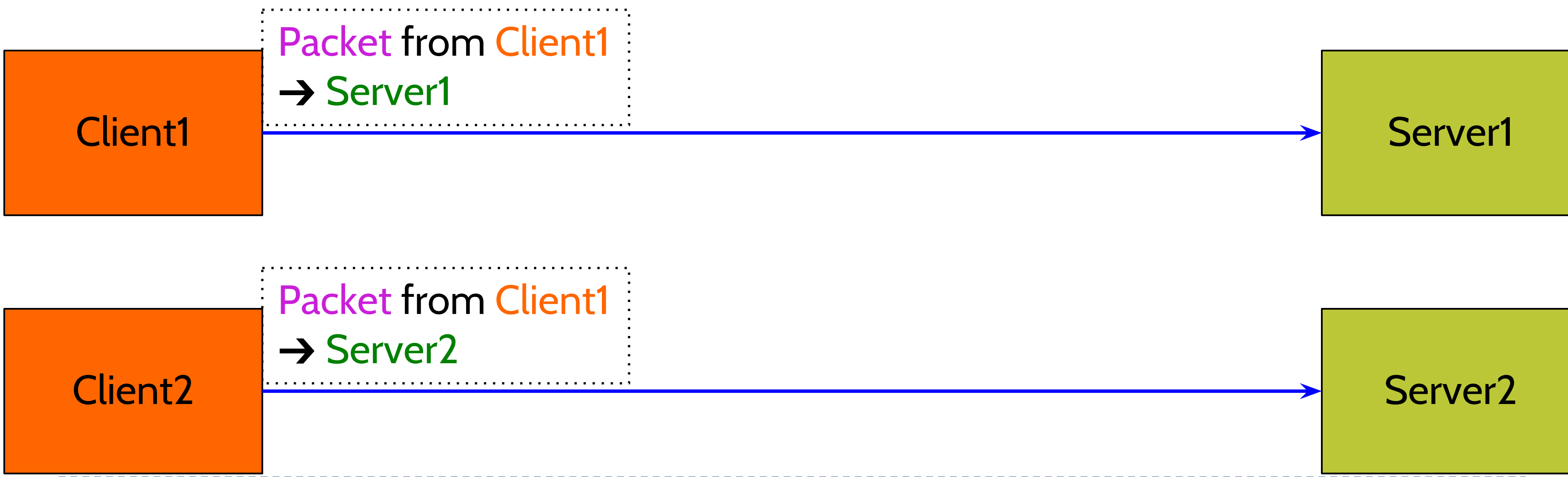
- A way to distribute client requests to an application onto multiple servers
  - Allows application to process a higher work load
  - Provides redundancy in an application
- Flow affinity
  - Packets received on different servers cannot share the same source address



Flow affinity

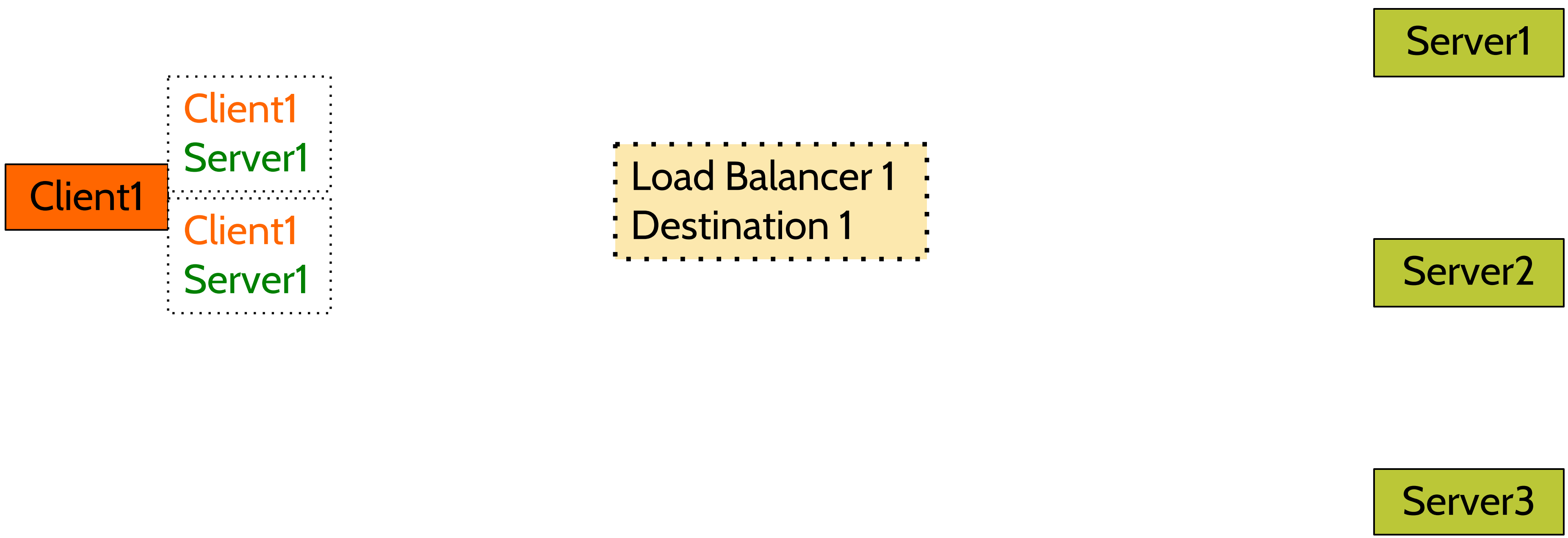
- Packets received on different servers cannot share the same cli

$\forall$ Server1, Client1, LoadBalancer1. $\forall$ Server2, Client2, LoadBalancer2.
recvPacket(Server1, Client1, LoadBalancer1)
$\wedge$ recvPacket(Server2, Client2, LoadBalancer2)
$\wedge$ Server1 $\neq$ Server2 $\supset$
Client1 $\neq$ Client2

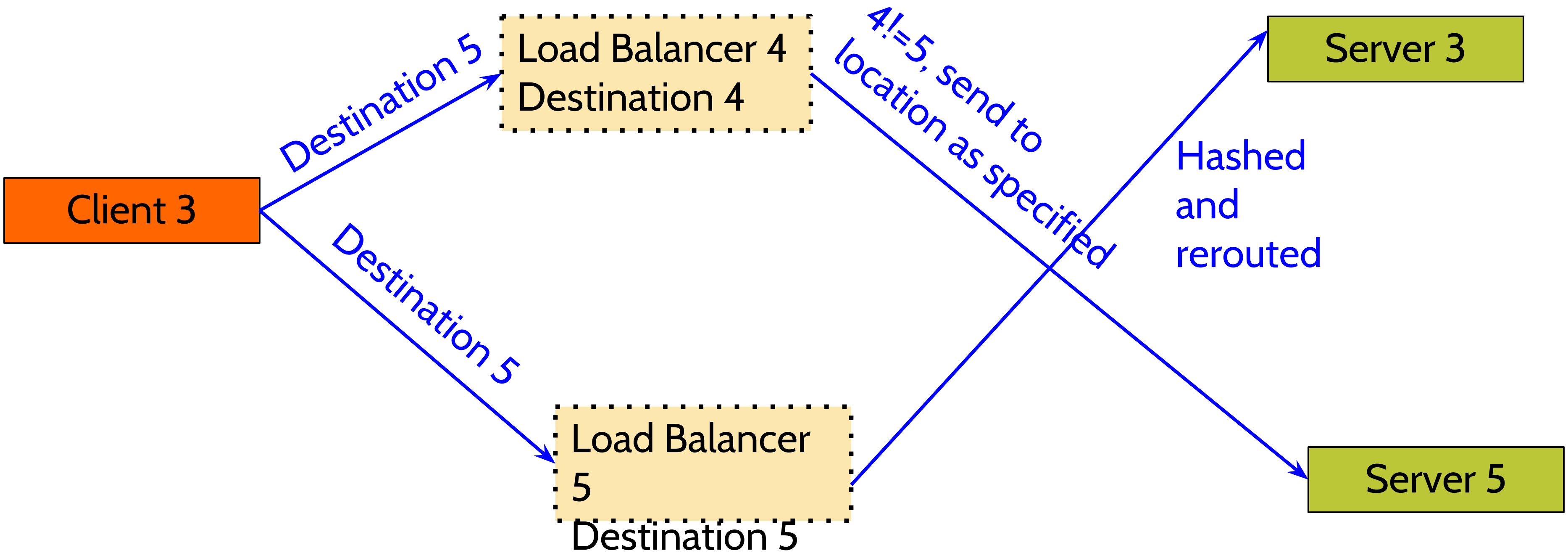


A naïve load balancer

- Our load balancer balances traffic towards a specific destination address
  - Determines the path of a packet based on the hash value of its source address



Counterexample produced by our tool



$\forall$ Server1, Client1, LoadBalancer1. $\forall$ Server2, Client2, LoadBalancer2.

recvPacket(Server1, Client1, LoadBalancer1)

$\wedge$ recvPacket(Server2, Client2, LoadBalancer2)

$\wedge$ Server1 $\neq$ Server2 $\supset$

Client1 $\neq$ Client2

Case studies

Test Case	# rules	# properties	# counterexamples	Max eval time (ms)
Ethernet source learning	11	5	2	60
Firewall	5	3	0	40
Load balancer	4	1	1	80
Address resolution	9	2	0	210

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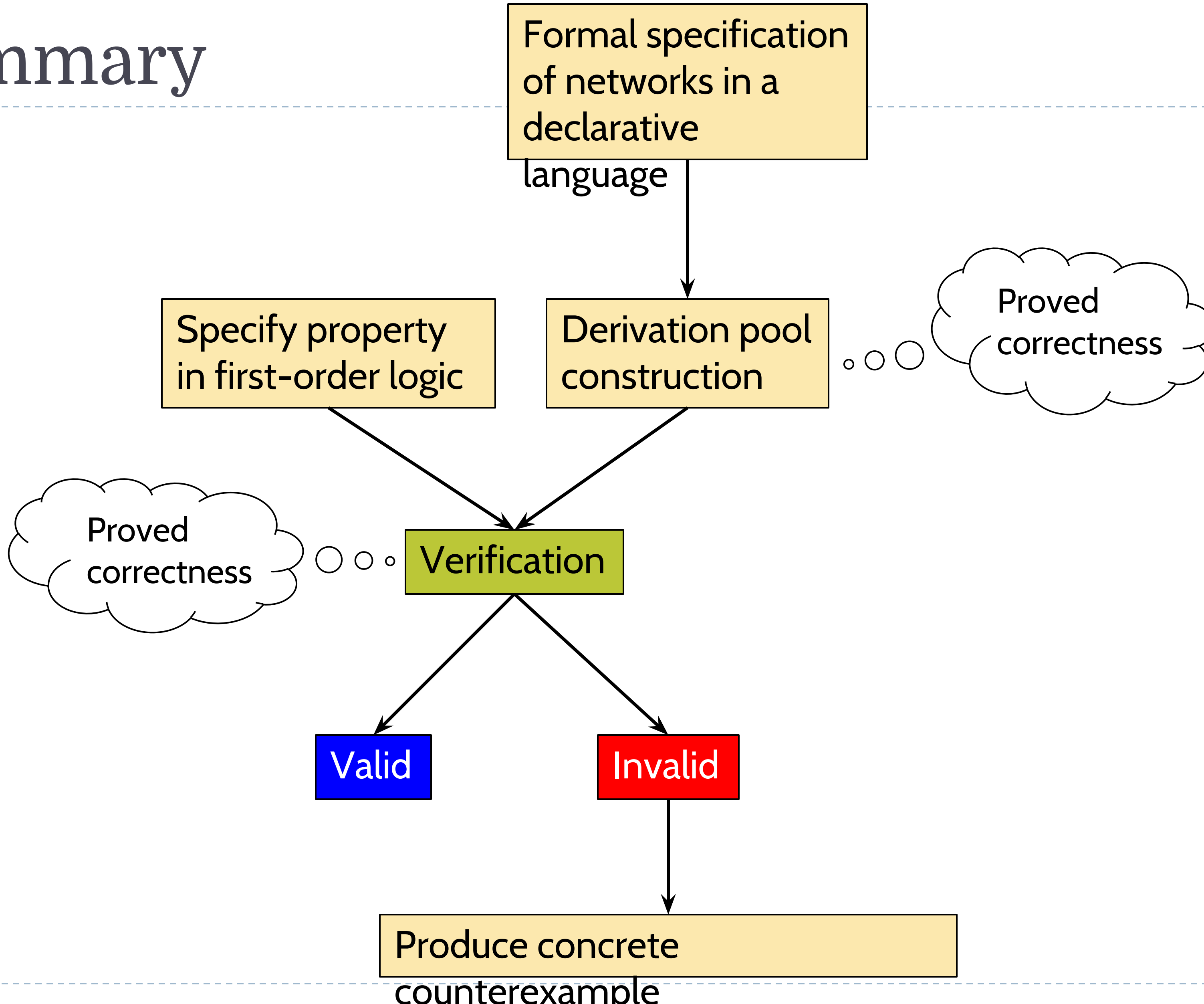
Summary



Formal specification of networks in a declarative language
Specify property in first-order logic
Derivation pool construction
Proved correctness
Proved correctness
Verification
Valid
Invalid
Produce concrete counterexample

Related work

- Network verification
  - Model network behavior using trace semantics. Relies on manual proofs
  - Examples: FORTE'14, TPHOLs'09
  - *Our solution: Enables automated static analysis of safety properties, generates counterexamples for debugging purposes*
- Software defined networking (SDN) verification
  - Specific to analyzing SDN controllers and data places
  - Examples: PLDI'14, SIGCOMM'11
  - *Our solution: Does the above, can also analyze other distributed systems expressible in NDLog*
- Verification of declarative programs
  - Proves correctness properties of networking protocols using theorem provers. User experience with theorem provers required.
  - Example: PADL'09
  - *Our solution: Validate protocol correctness using an SMT solver. User experience with SMT solvers unnecessary.*

Future work

- Analyze liveness properties
  - Something good eventually happens
- Provenance related topics

Questions?

Time complexity (non-recursive)

- Notation
  - $P = p_1,\ldots,p_n$
    - $|P|=n$
  - $Q = q_1,\ldots,q_m$
    - $|Q|=m$
  - Given an NDLog program with R rules
    - Each rule has at most W body tuples

$$\forall \mathbf{x}_1.p_1(\mathbf{x}_1) \wedge \forall \mathbf{x}_2.p_2(\mathbf{x}_2) \wedge \ldots \wedge \forall \mathbf{x}_n.p_n(\mathbf{x}_n) \wedge c_q(\mathbf{x}_1, \ldots, \mathbf{x}_n) \supset \exists \mathbf{y}_1.\blacklozenge q_1(\mathbf{y}_1) \wedge \exists \mathbf{y}_2.\blacklozenge q_2(\mathbf{y}_2) \wedge \ldots \wedge \exists \mathbf{y}_m.\blacklozenge q_m(\mathbf{y}_m) \wedge c_q(\mathbf{x}_1, \ldots, \mathbf{x}_n, \mathbf{y}_1, \ldots, \mathbf{y}_m)$$

- Time complexity: $O((R^{nW^{\wedge}R})n^m W^{Rn})$

- In practice, R and W are small
  - Can be treated as constants

Possible ways to fix the network counterexample

- Add network assumptions
  - Servers are connected to at most one load balancer
- Change property specification
  - Load balanced packets that are forwarded out of different load balancers were not sent out by the same client