Modular Control Plane Verification via Temporal Invariants

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Princeton University

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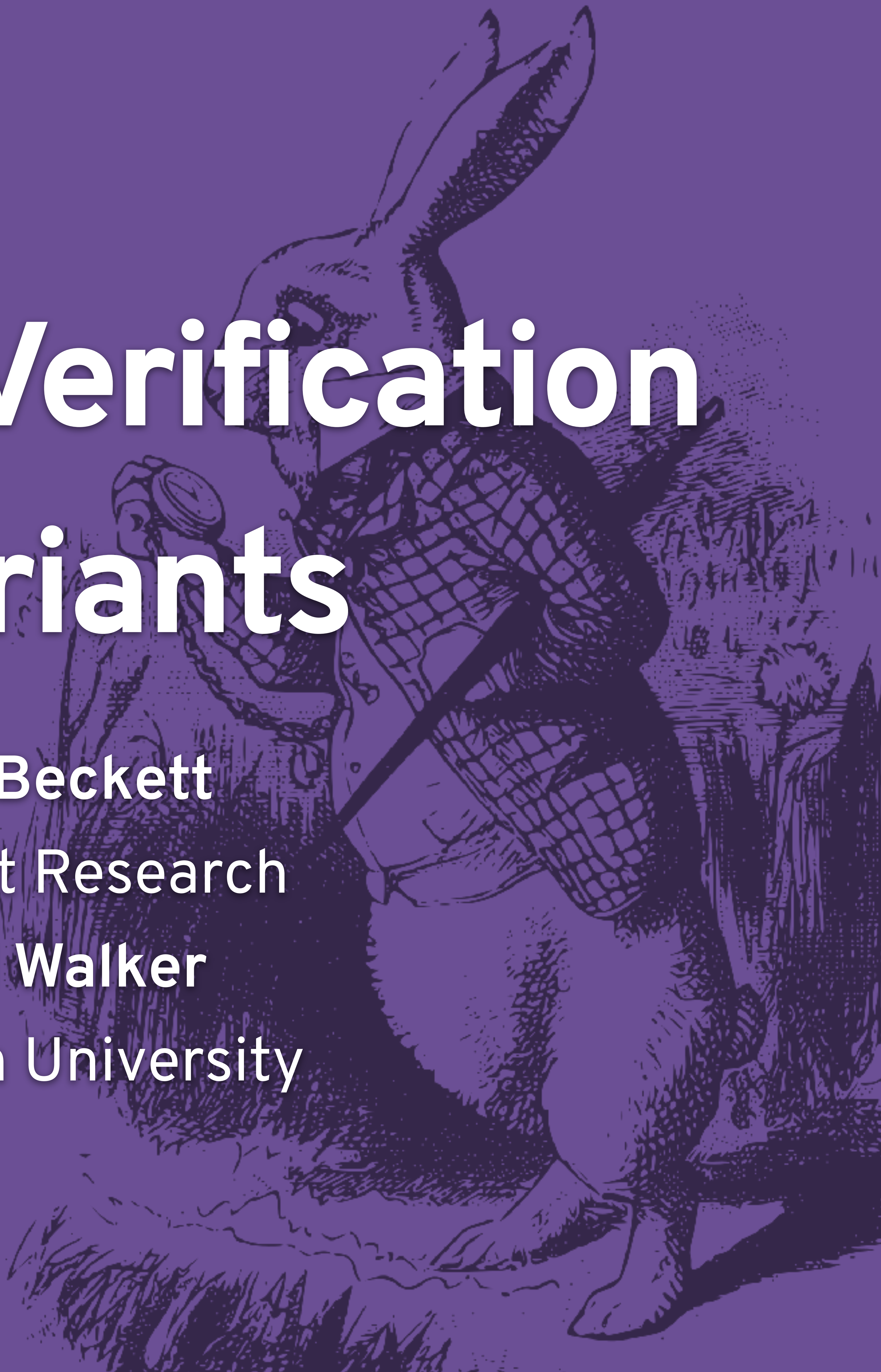
Princeton University

PLDI 2023



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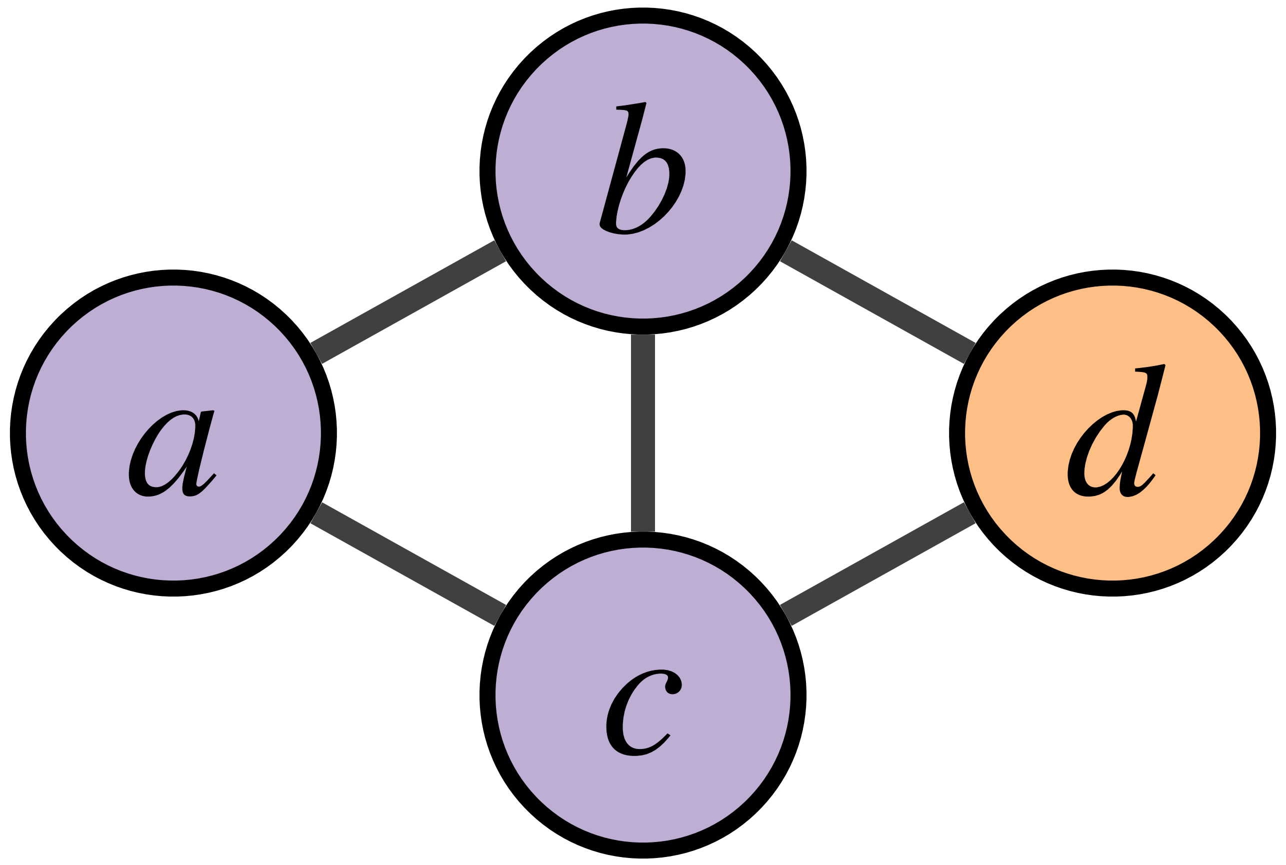

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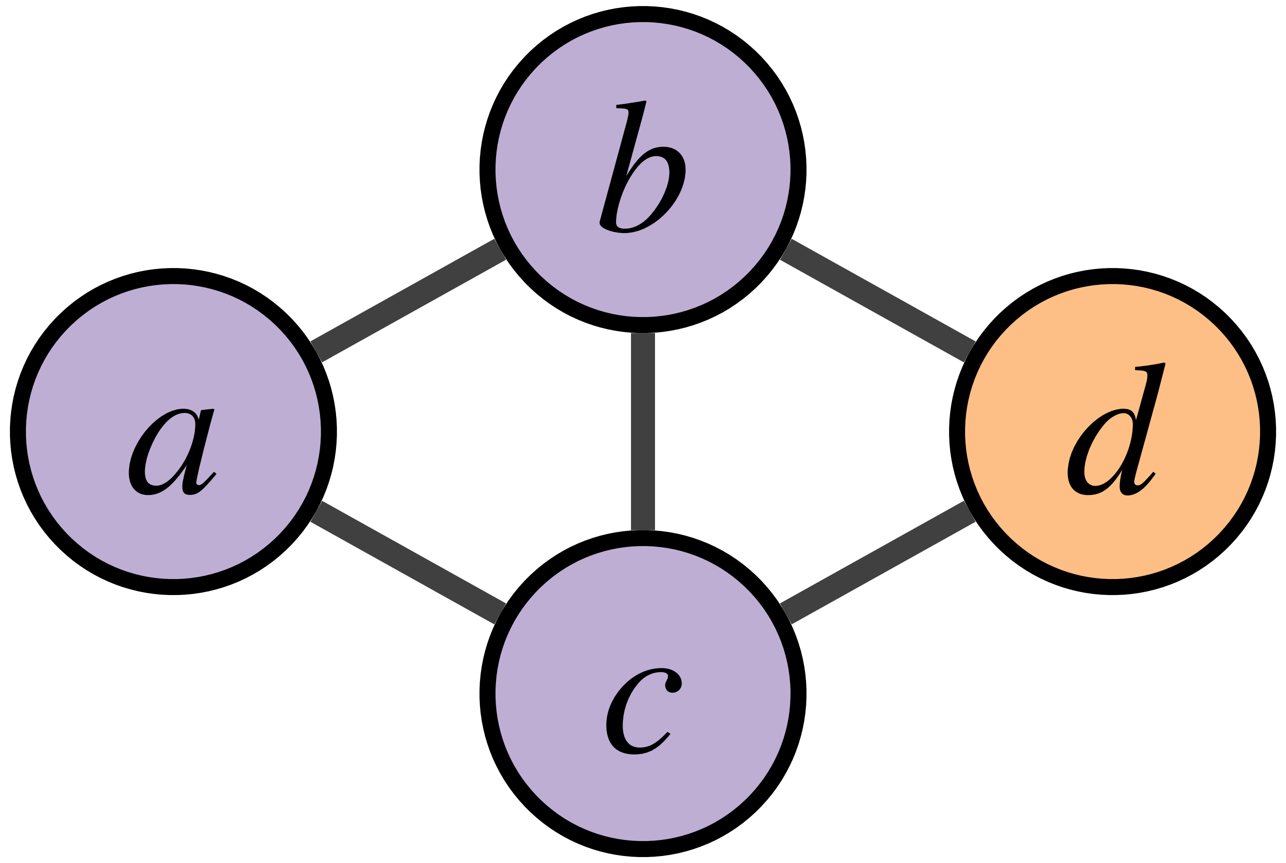
Goal: determine routes to use to forward traffic



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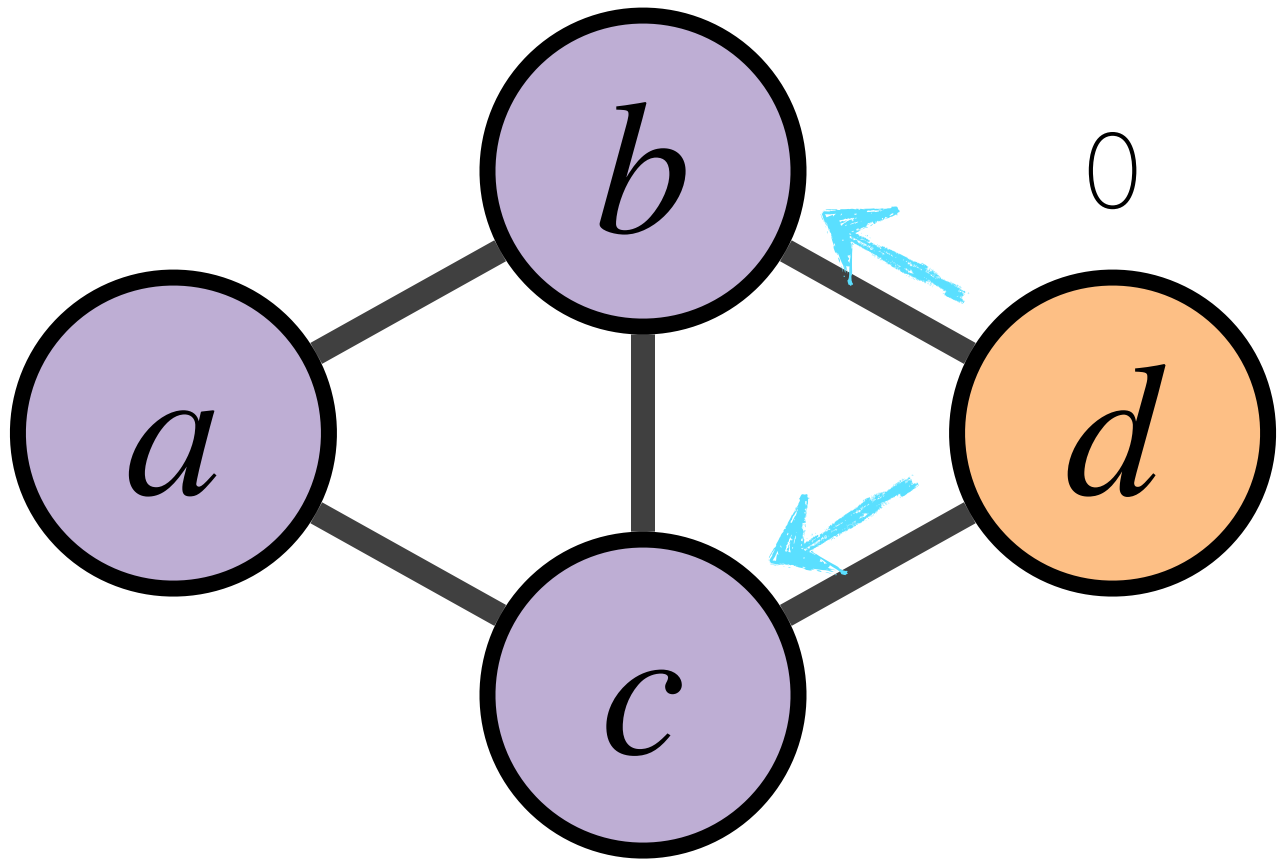

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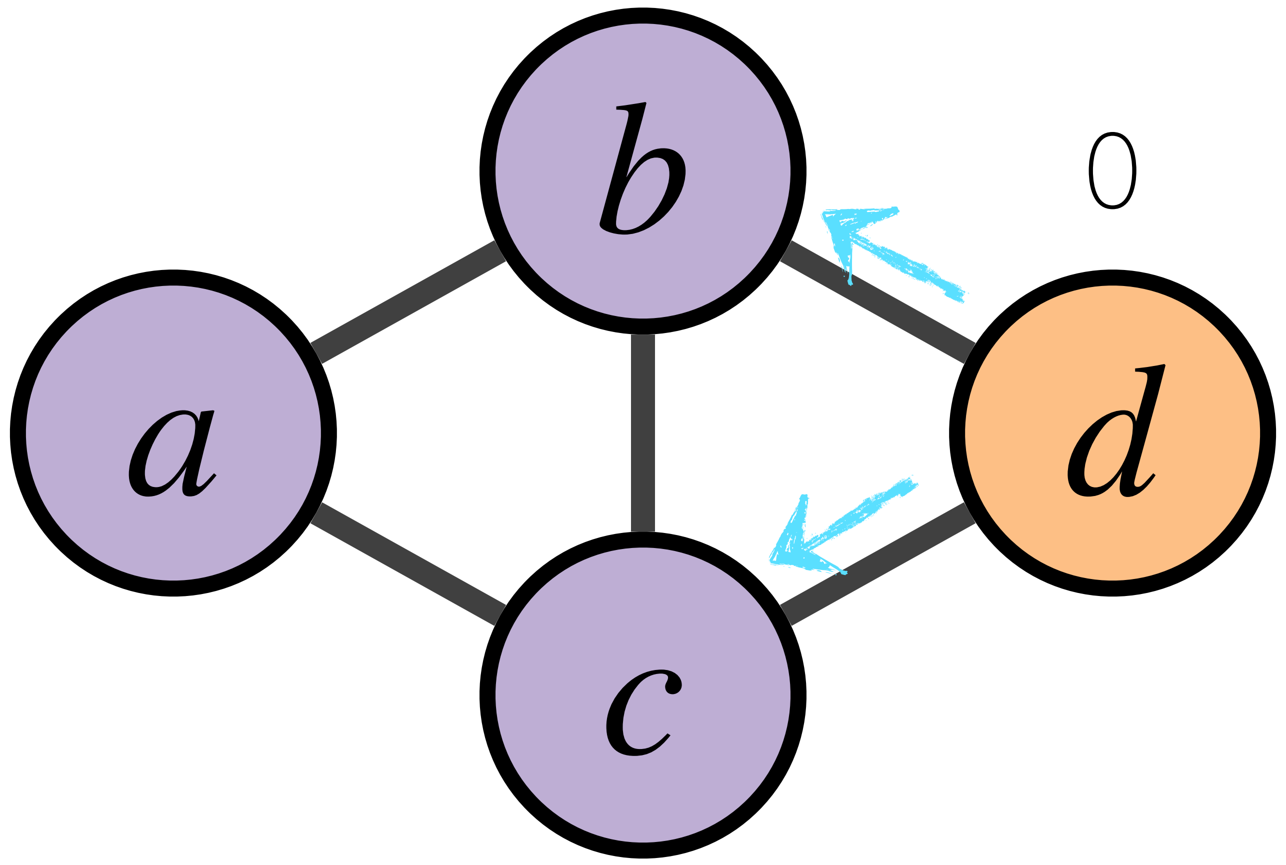
Receive announcements, process according to **configs**



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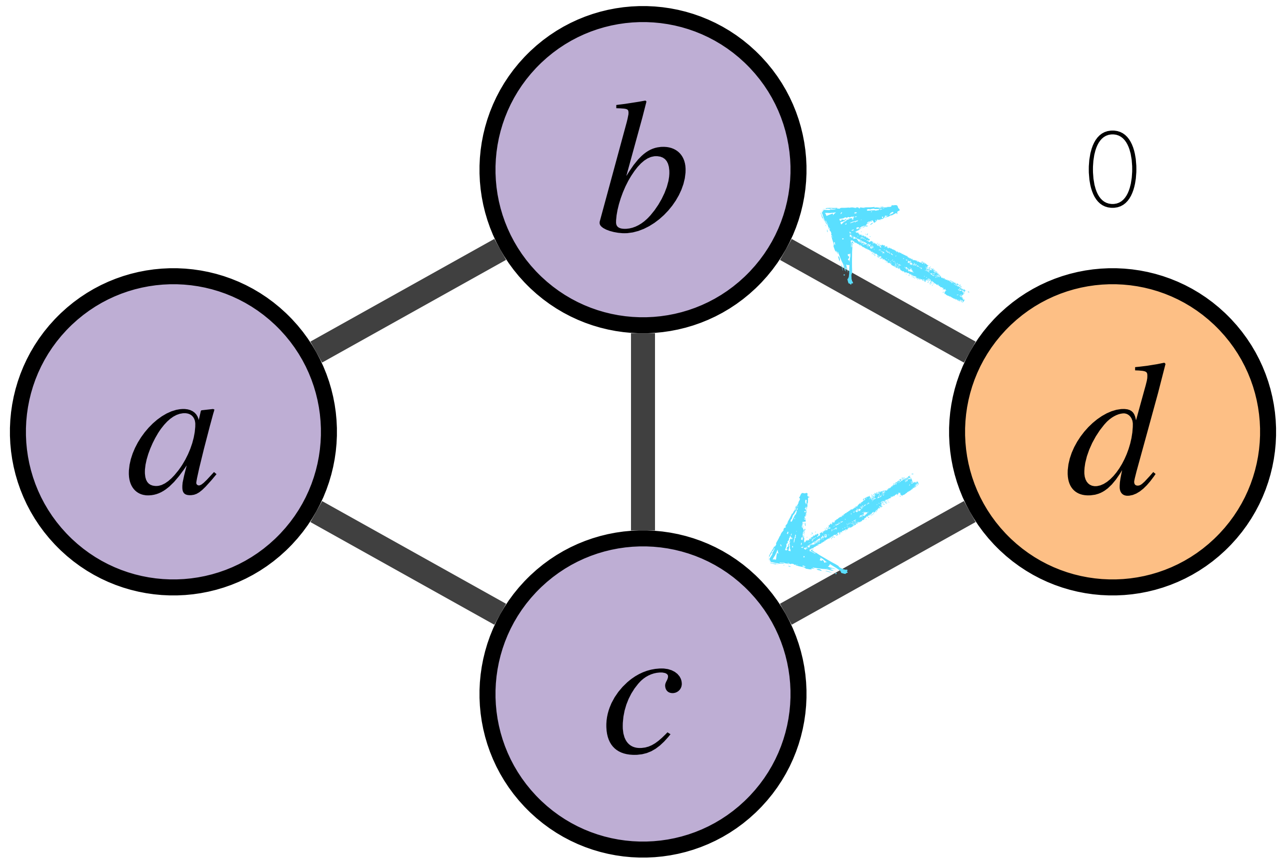

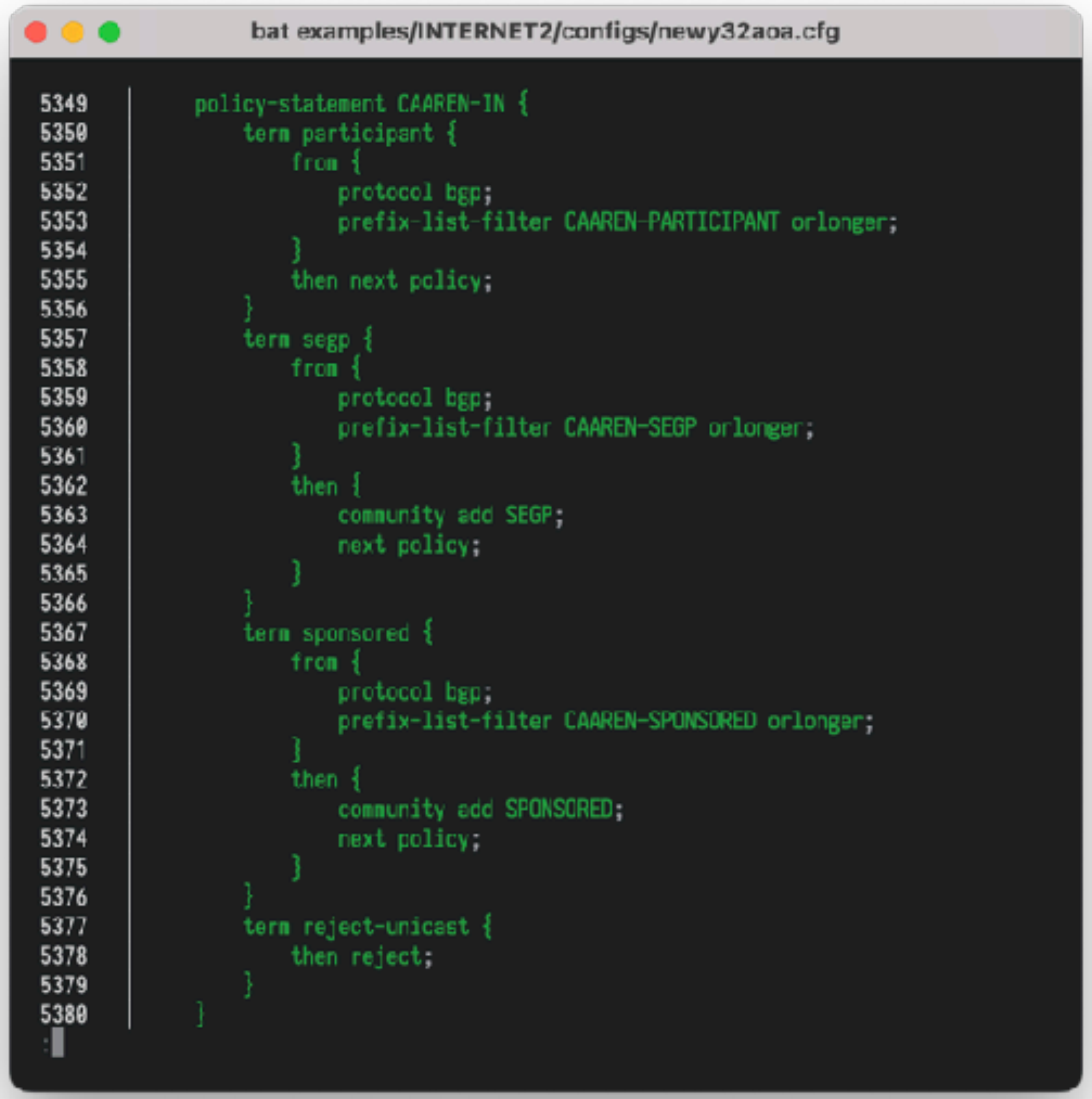

Distributed, written in vendor-specific, low-level language

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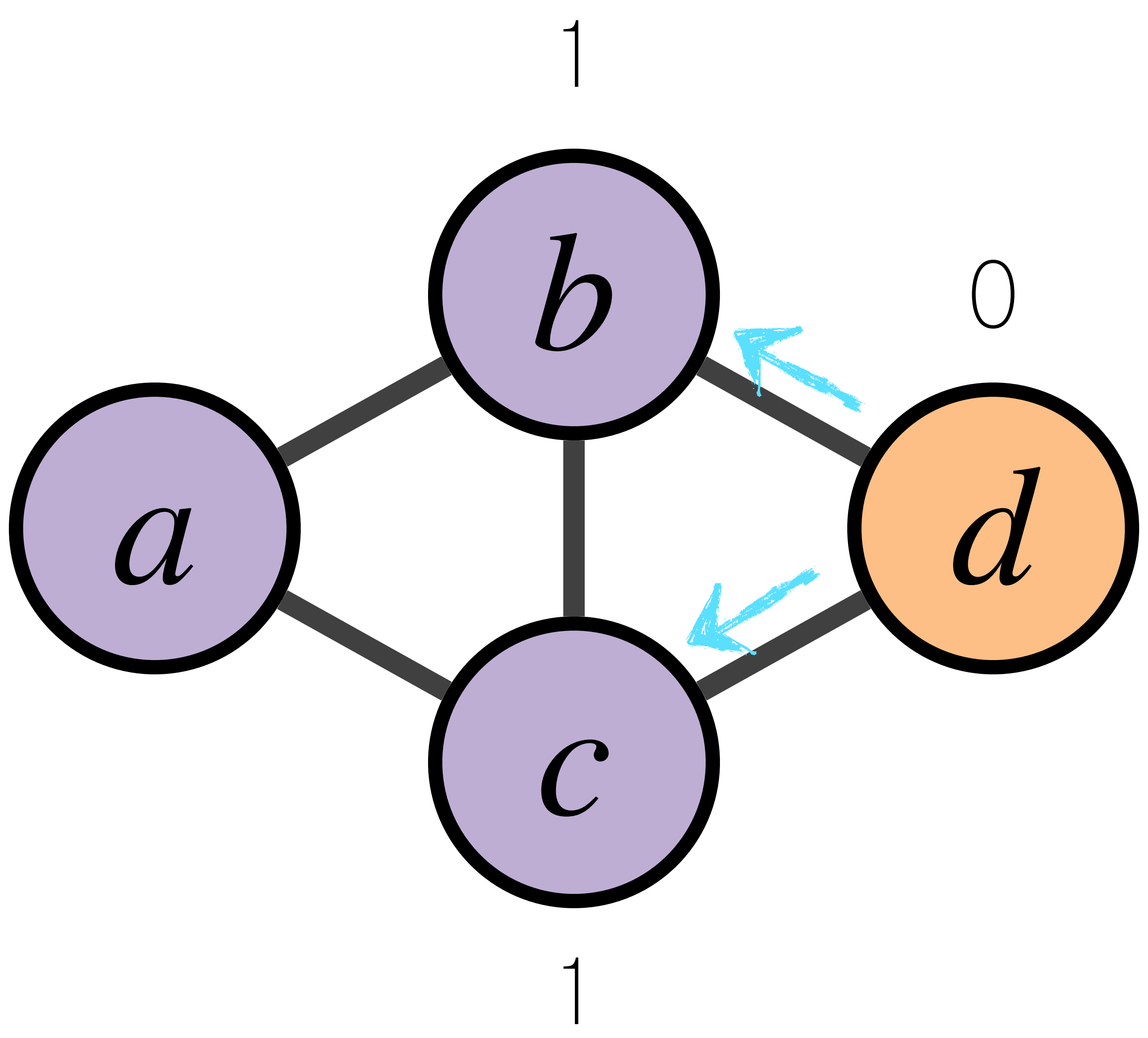
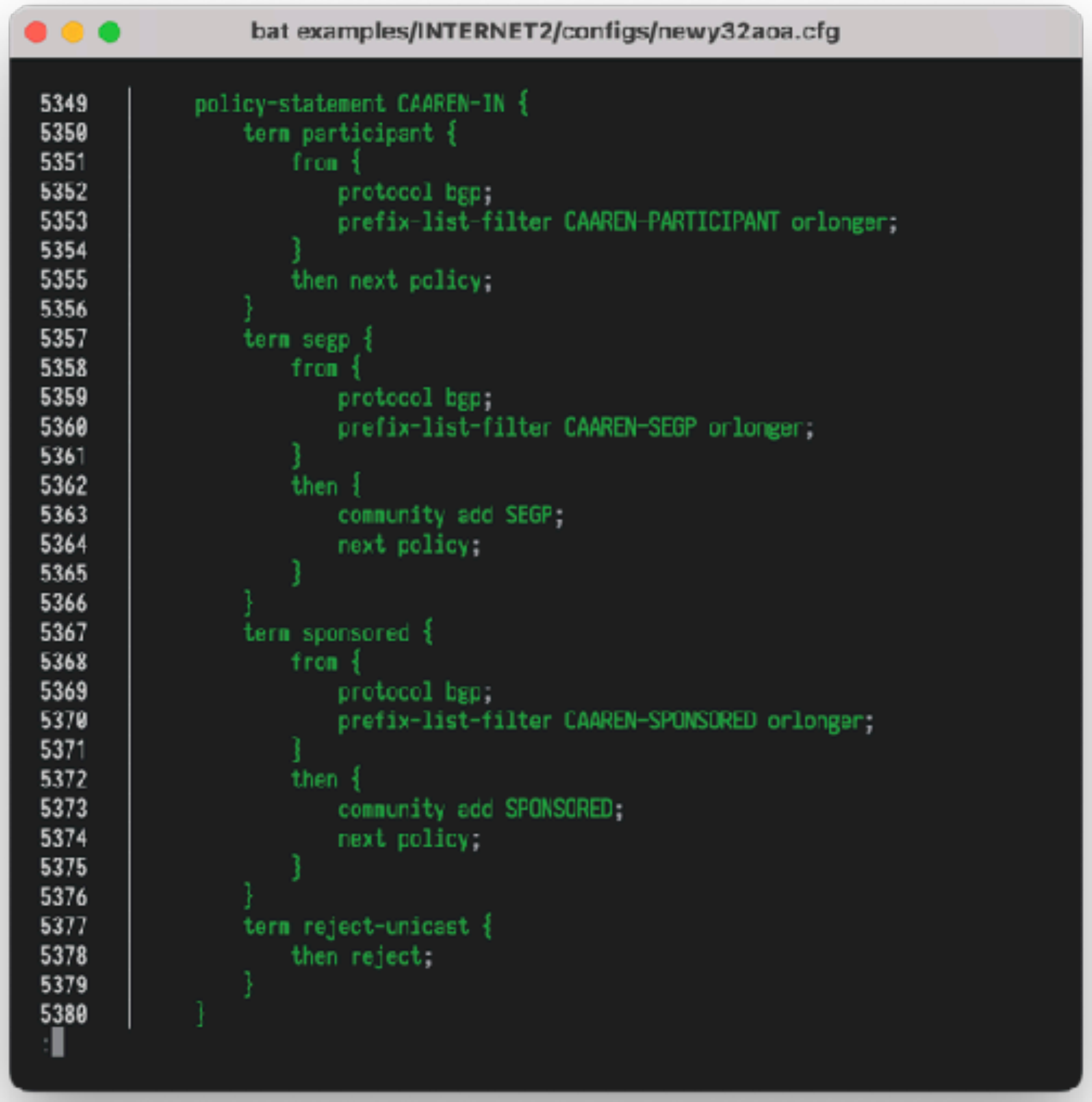
Select best announcement






```
policy-statement CAAREN-IN {
    term participant {
        from {
            protocol bgp;
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        }
        then next policy;
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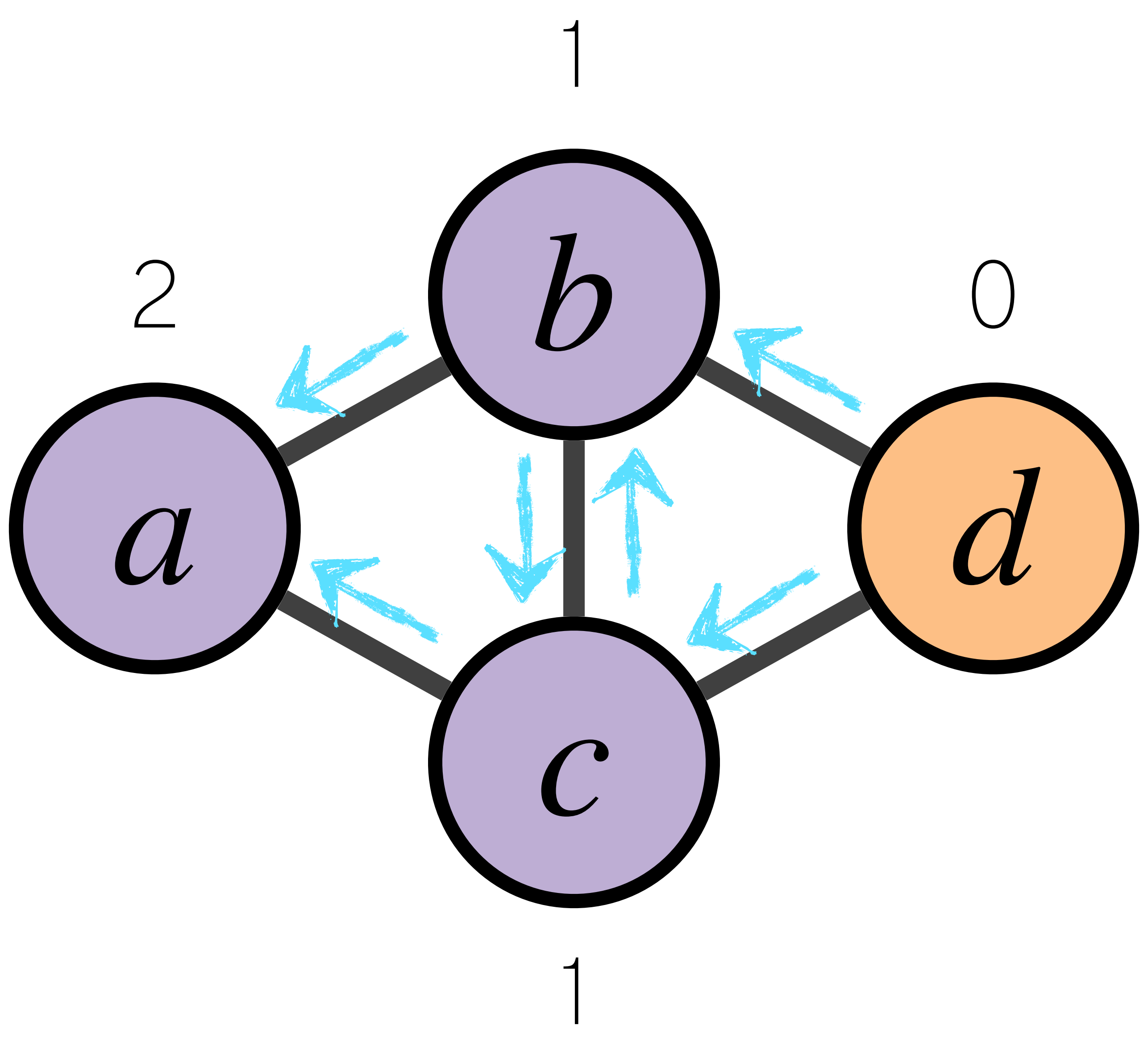
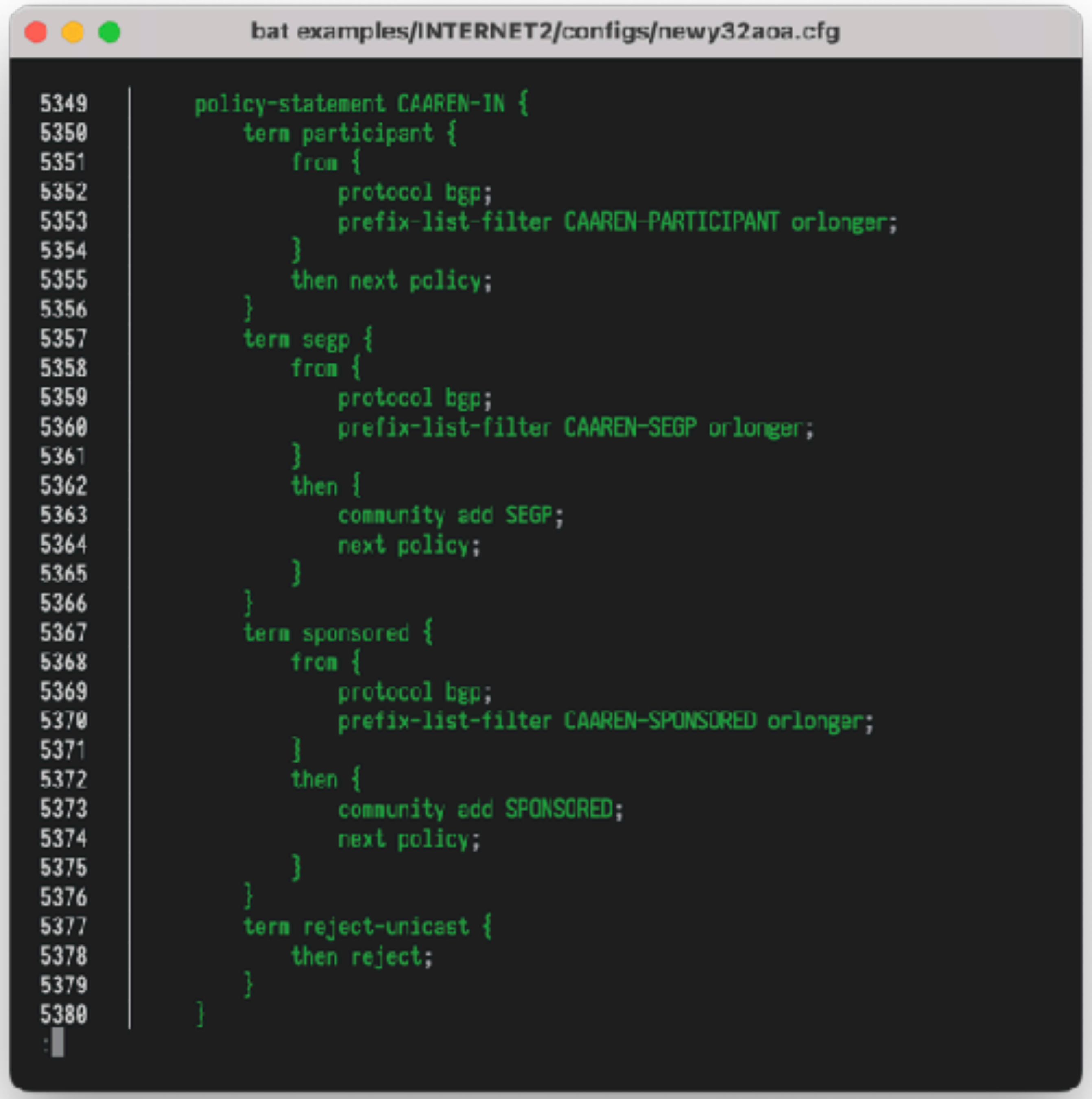
Goal: determine routes to use to forward traffic

- Send initial route announcements
- Receive announcements, process according to **configs**
- Select best announcement
- Broadcast selected route to neighbors





bat examples/INTERNET2/configs/newy32aoa.cfg

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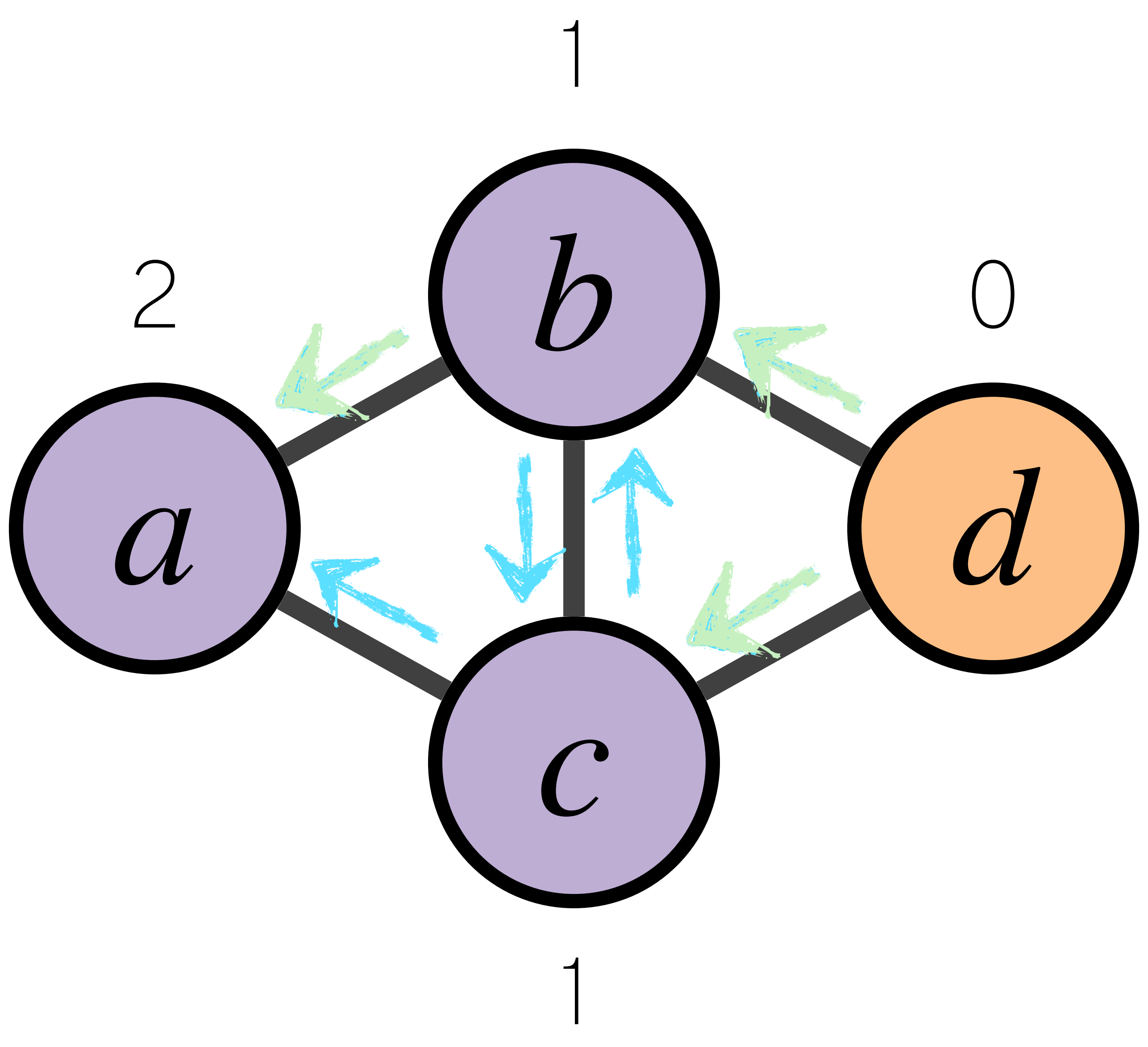

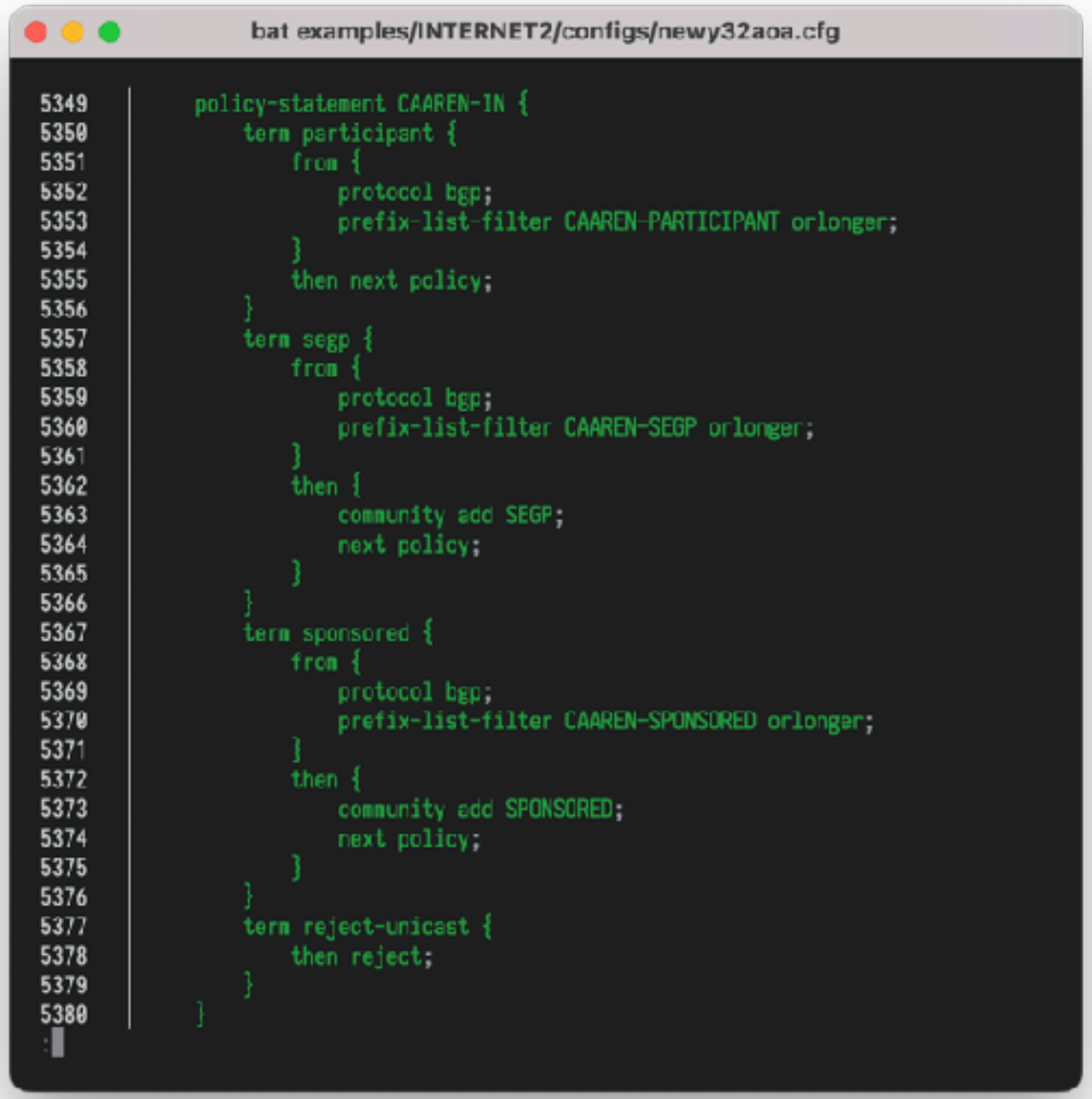
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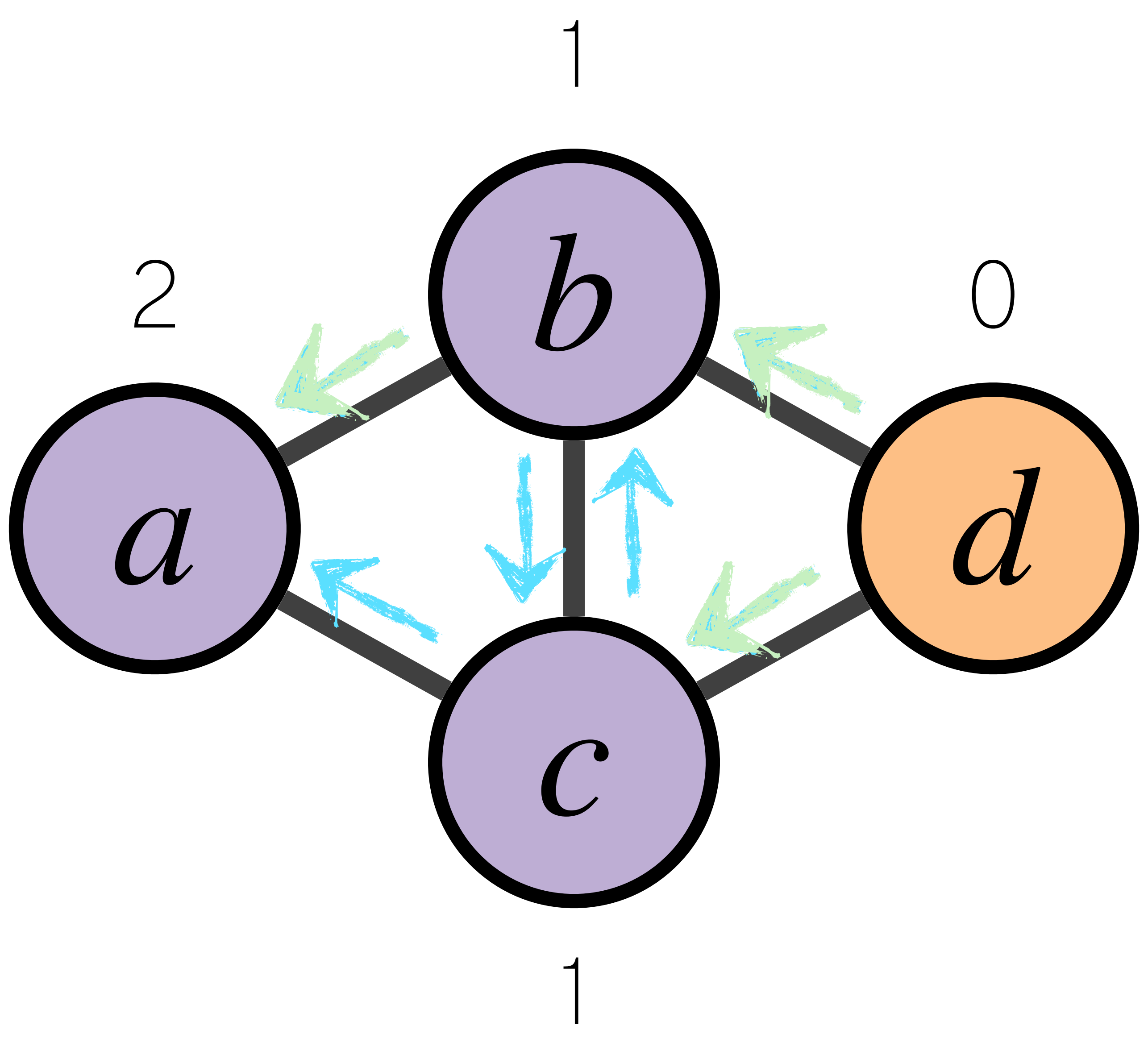
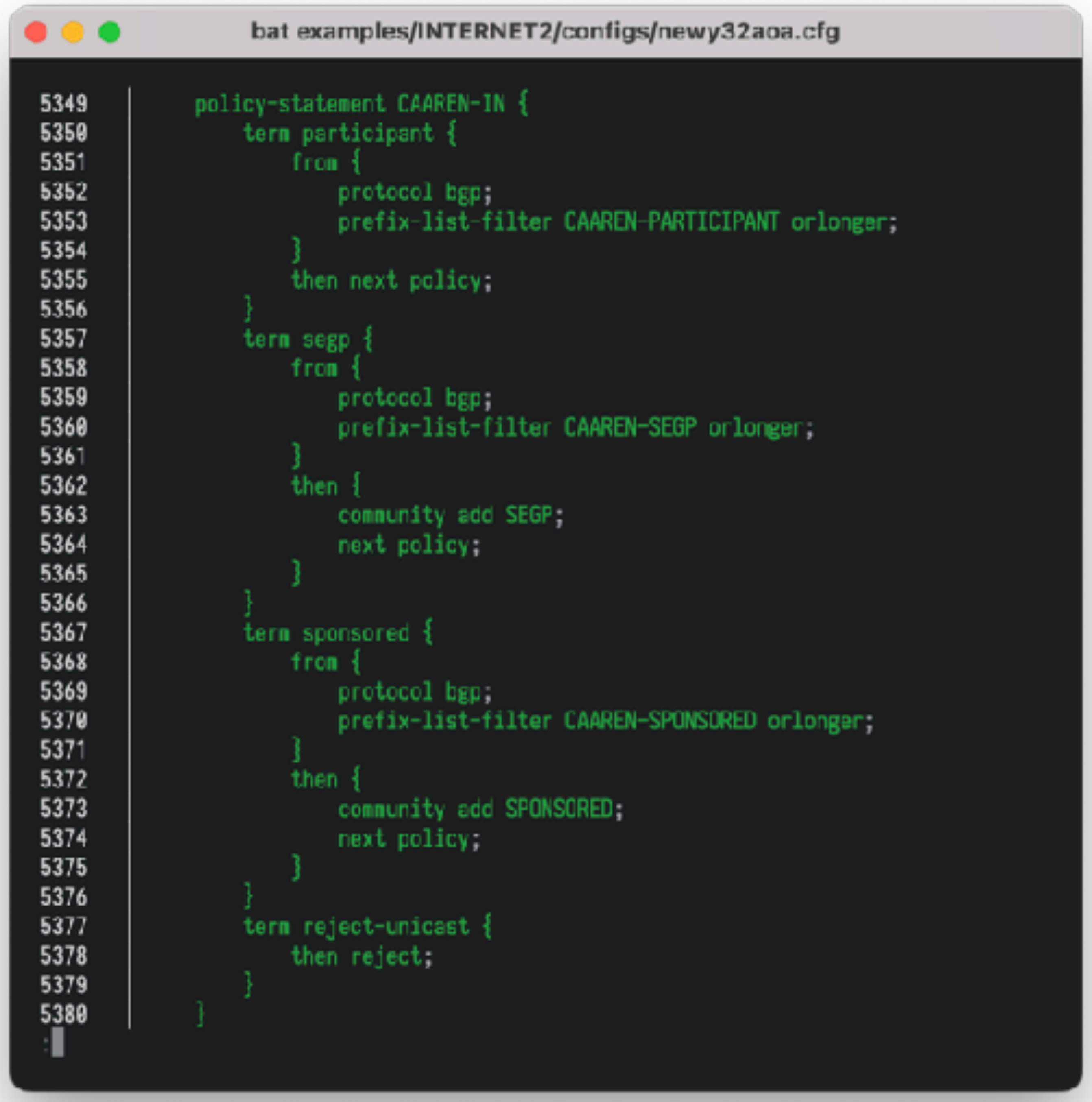


Policies for security, traffic engineering, fault tolerance, cost, *etc.*



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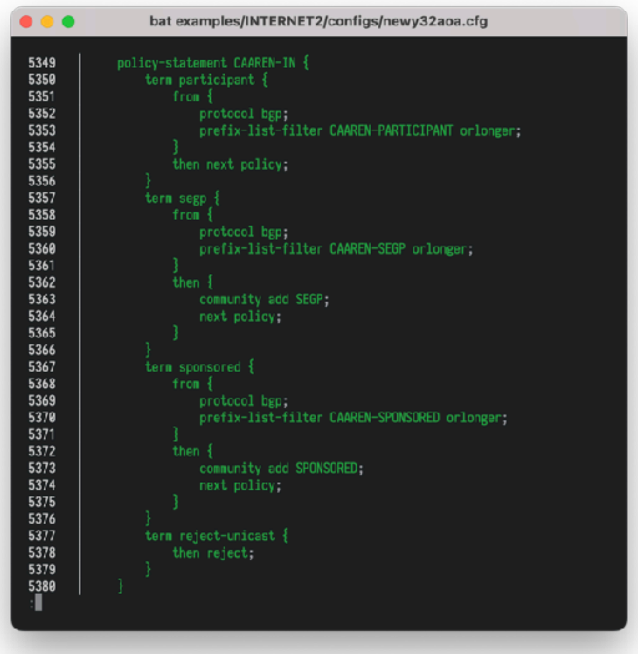
How Do We Verify Control Planes?



Network configuration files

Policies for security, traffic engineering, fault tolerance, cost, *etc.*

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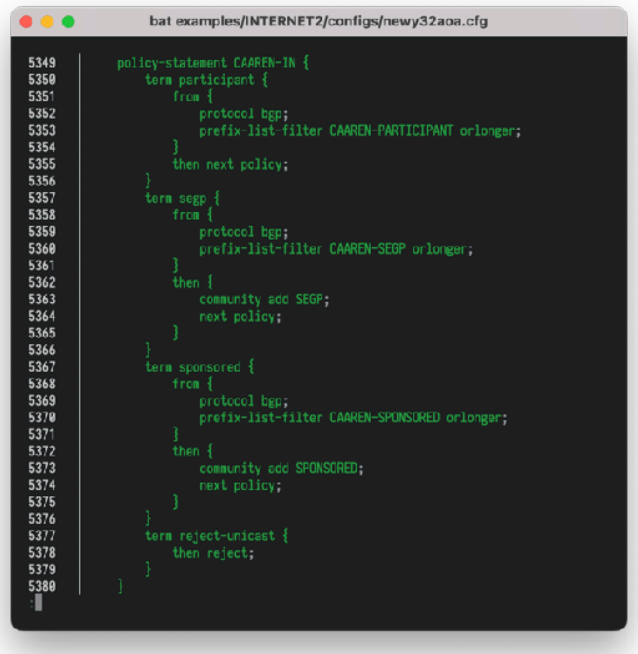


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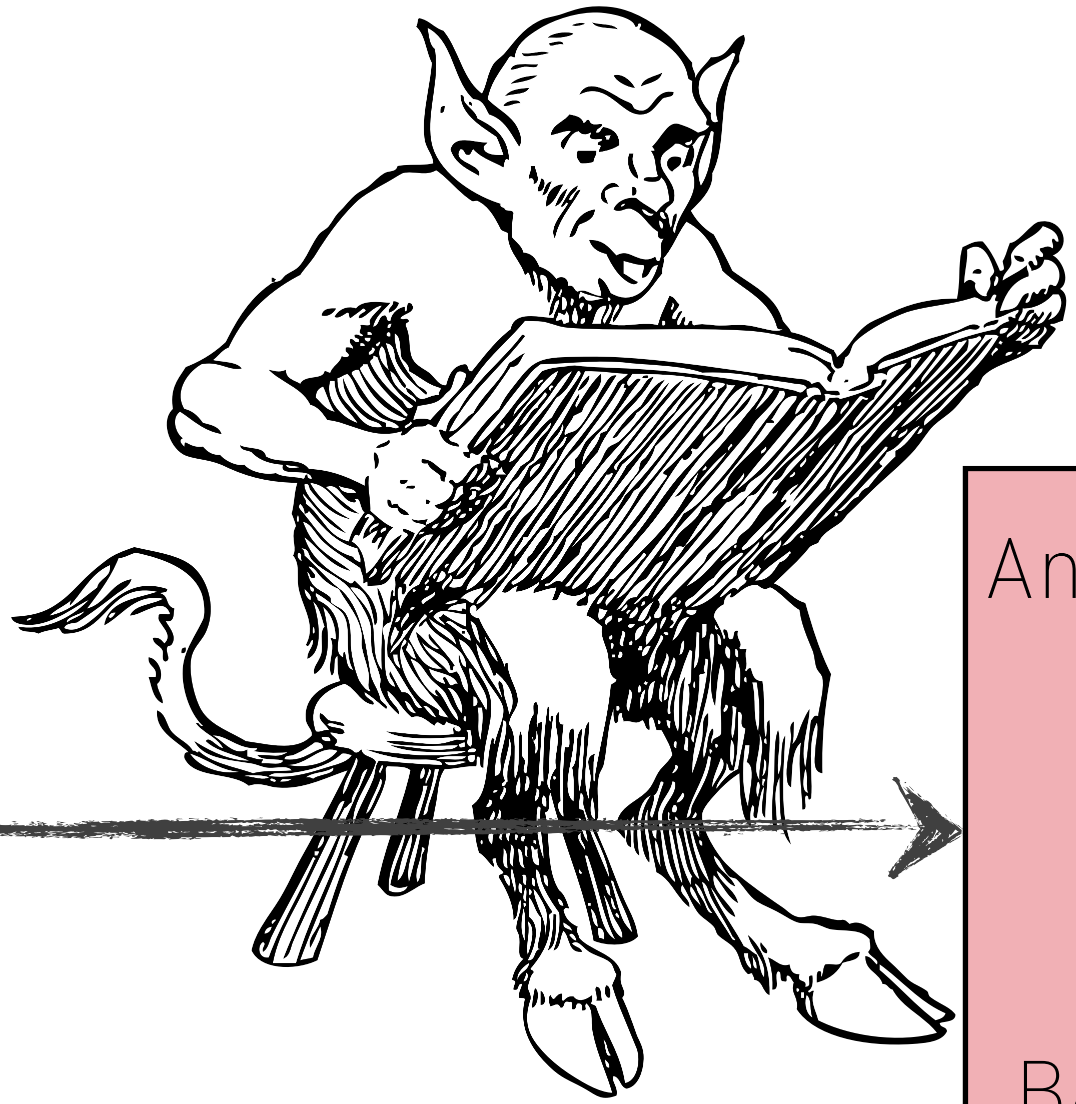

Analyze <u>all configurations together</u> to find property violations using a control plane verifier (e.g., Batfish, ARC, Minesweeper, Bagpipe, Tiramisu, Plankton, Hoyan)

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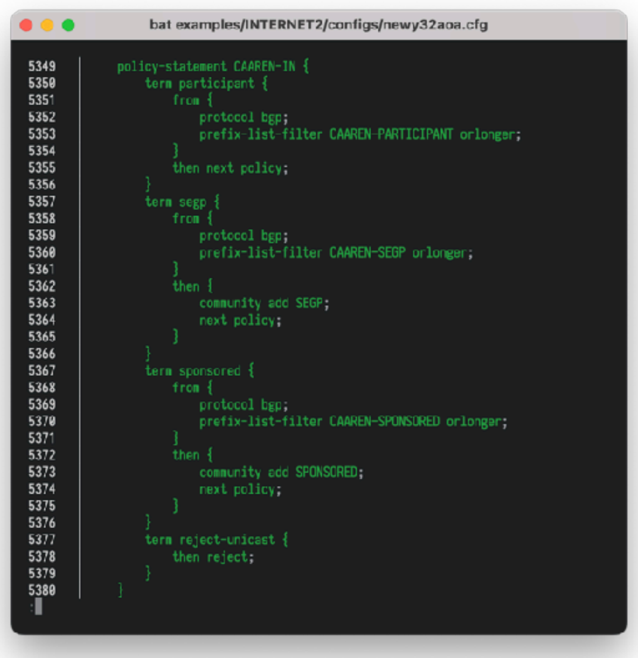

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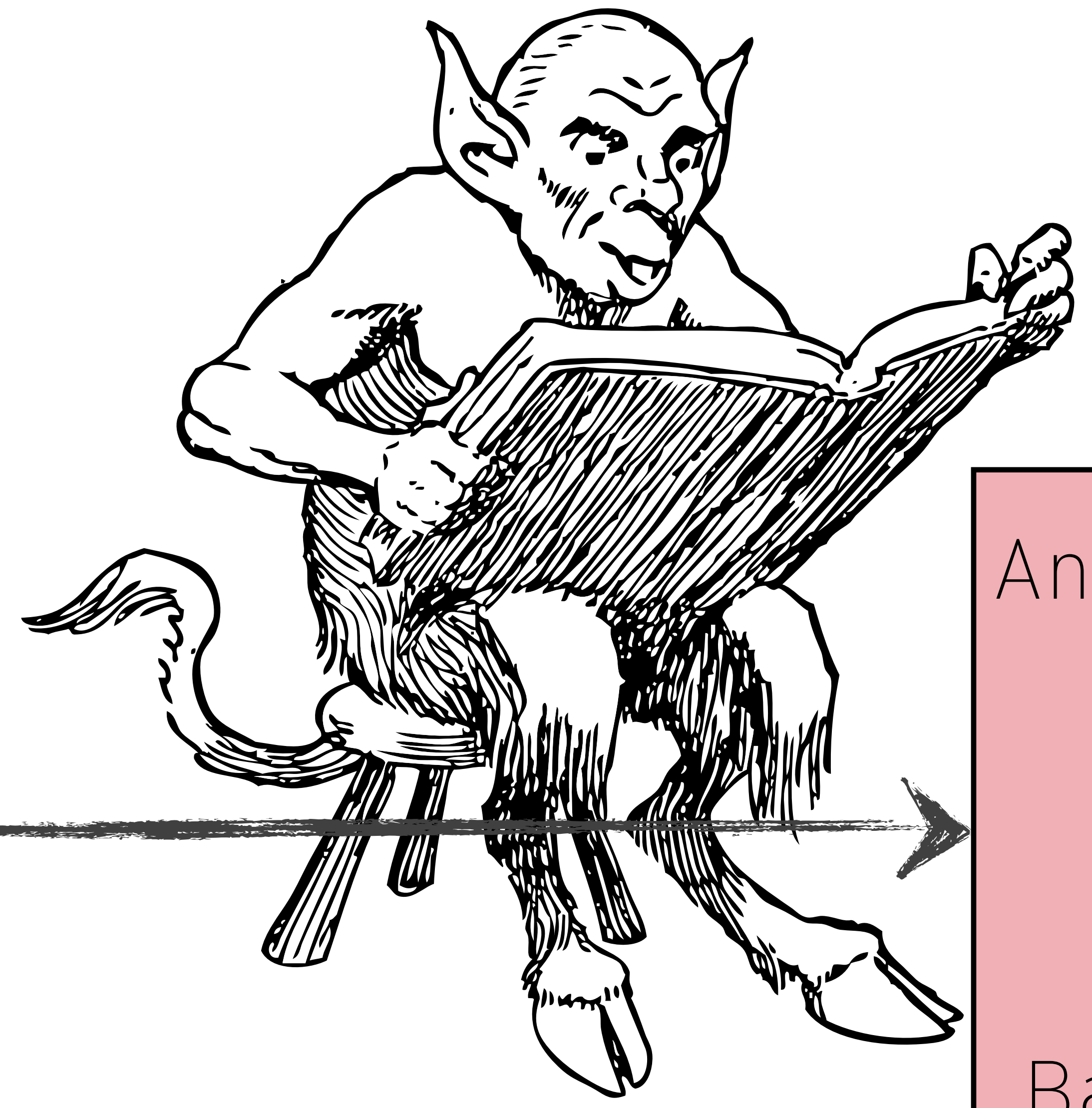


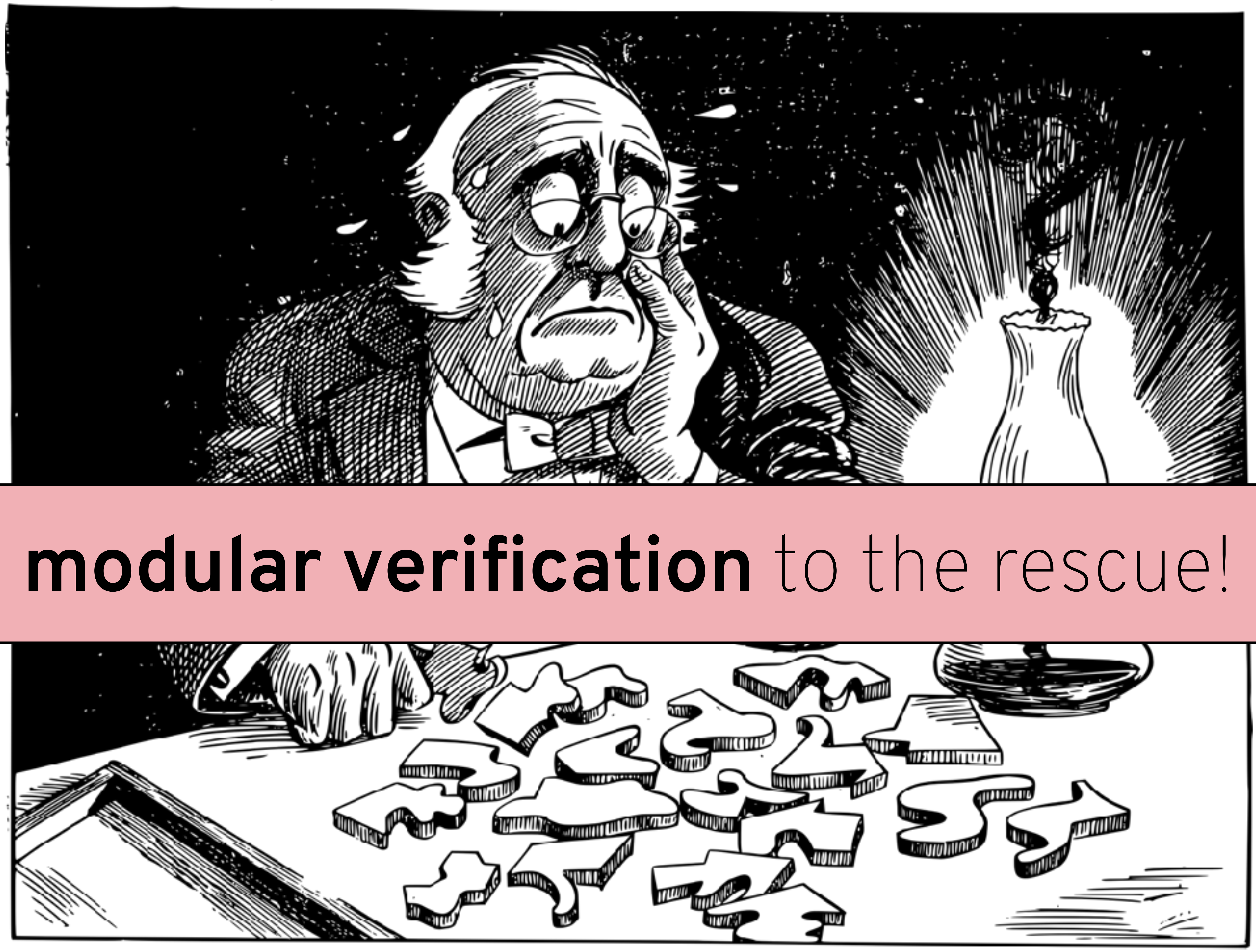
Analyze all configurations together to find property violations using a control plane verifier (e.g., Batfish, ARC, Minesweeper, Bagpipe, Tiramisu, Plankton, Hoyan)

Repeat when configurations change

Scaling Control Plane Verification

Many networks are **too big and too complex** to verify monolithically!

Scaling Control Plane Verification

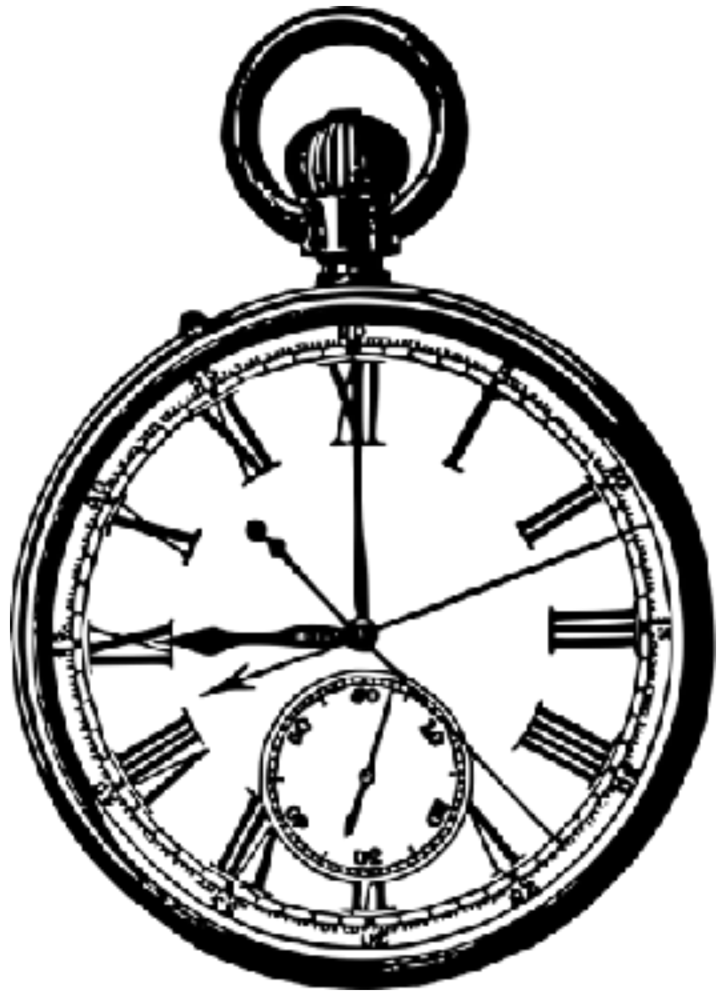


modular verification to the rescue!

Many networks are **too big and too complex** to verify monolithically!

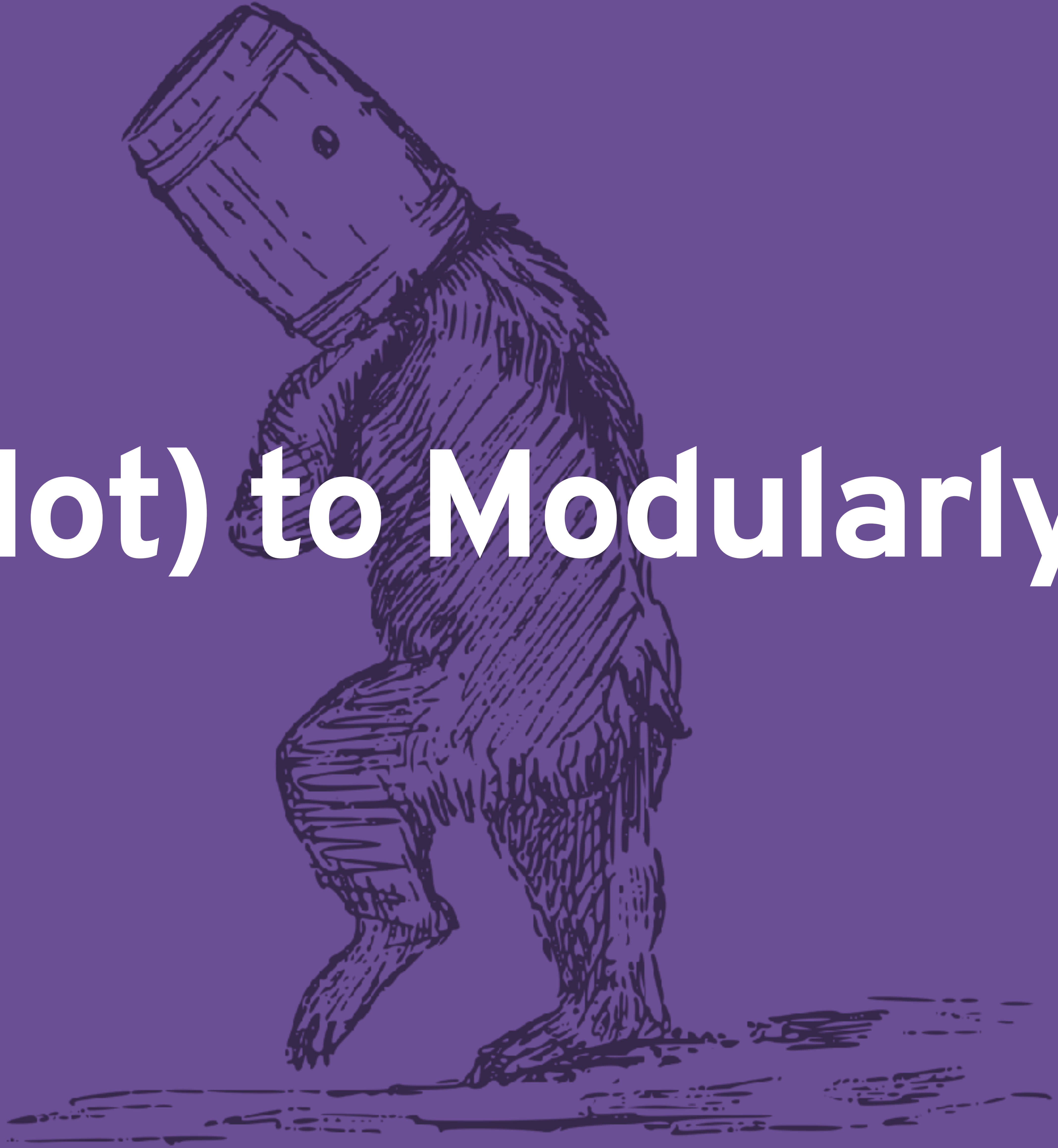
Our Contributions

demonstrate why naive stable states analysis is unsuitable for modular verification



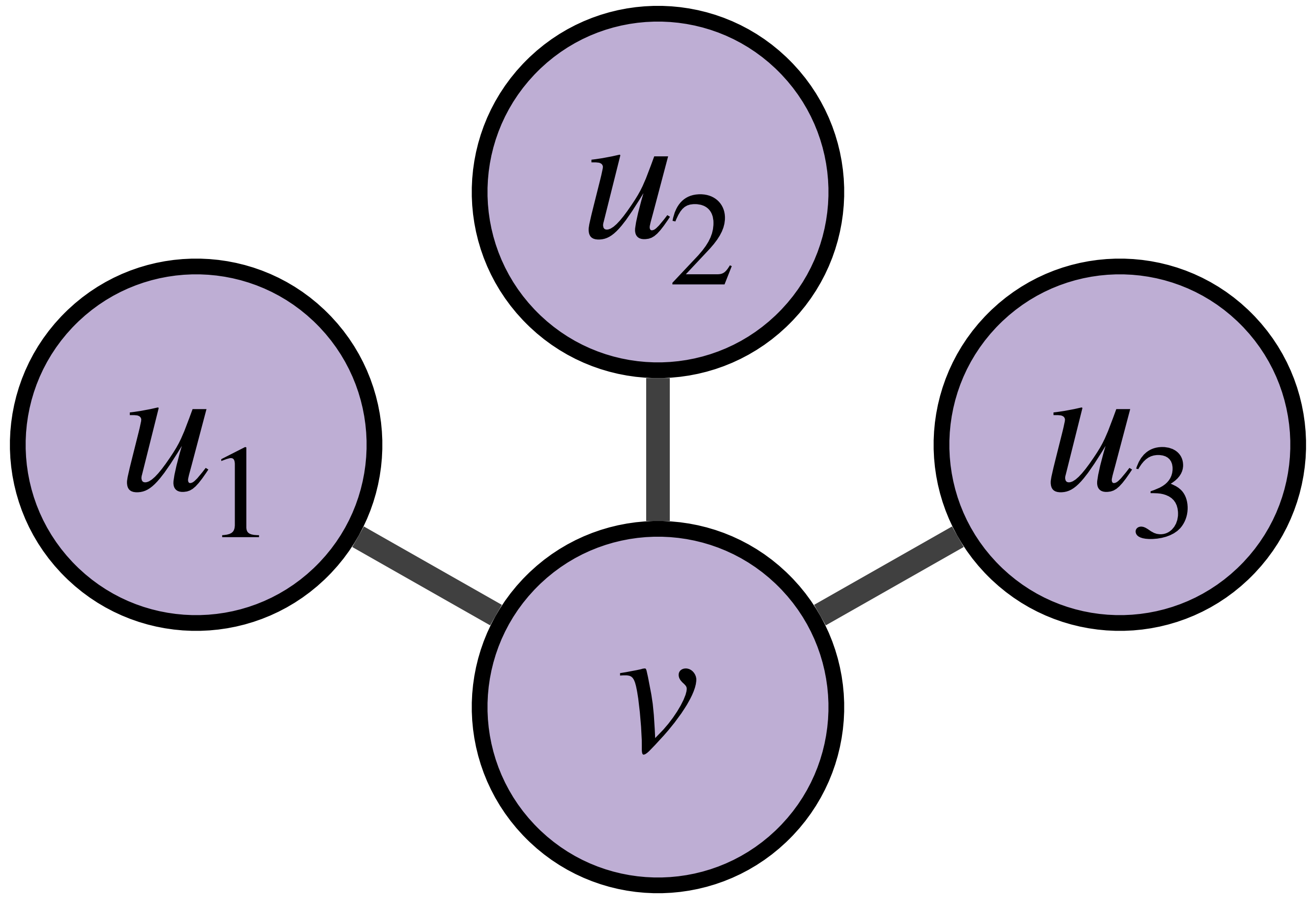
present time-based theory for modular control plane analysis, with SMT-based verification procedure

verify properties of 2000-node data centers and complex wide-area networks in seconds!



How (Not) to Modularly Verify

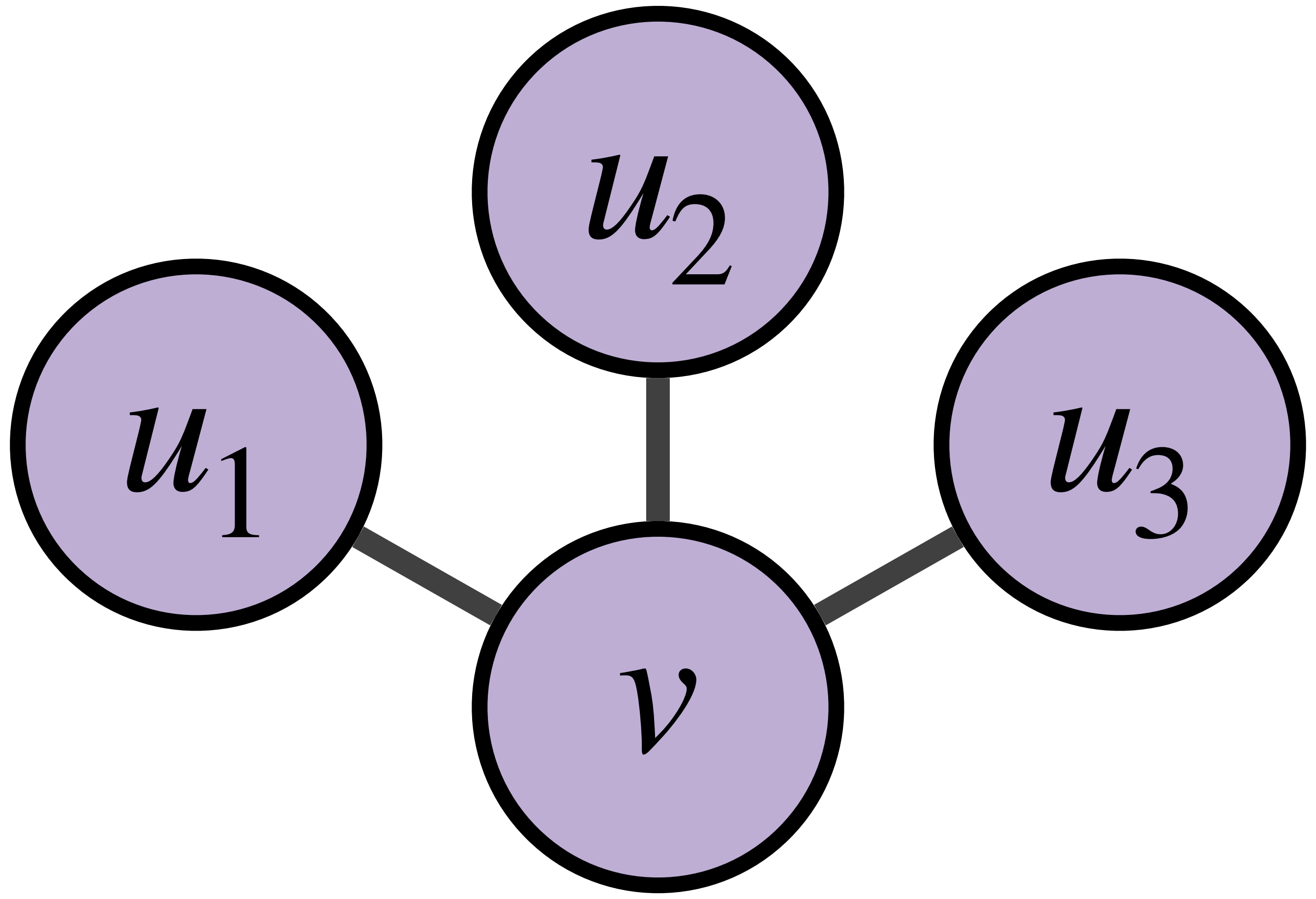
Modular Network Verification



Modular Network Verification

sound modular analysis:

captures all monolithic routing behavior



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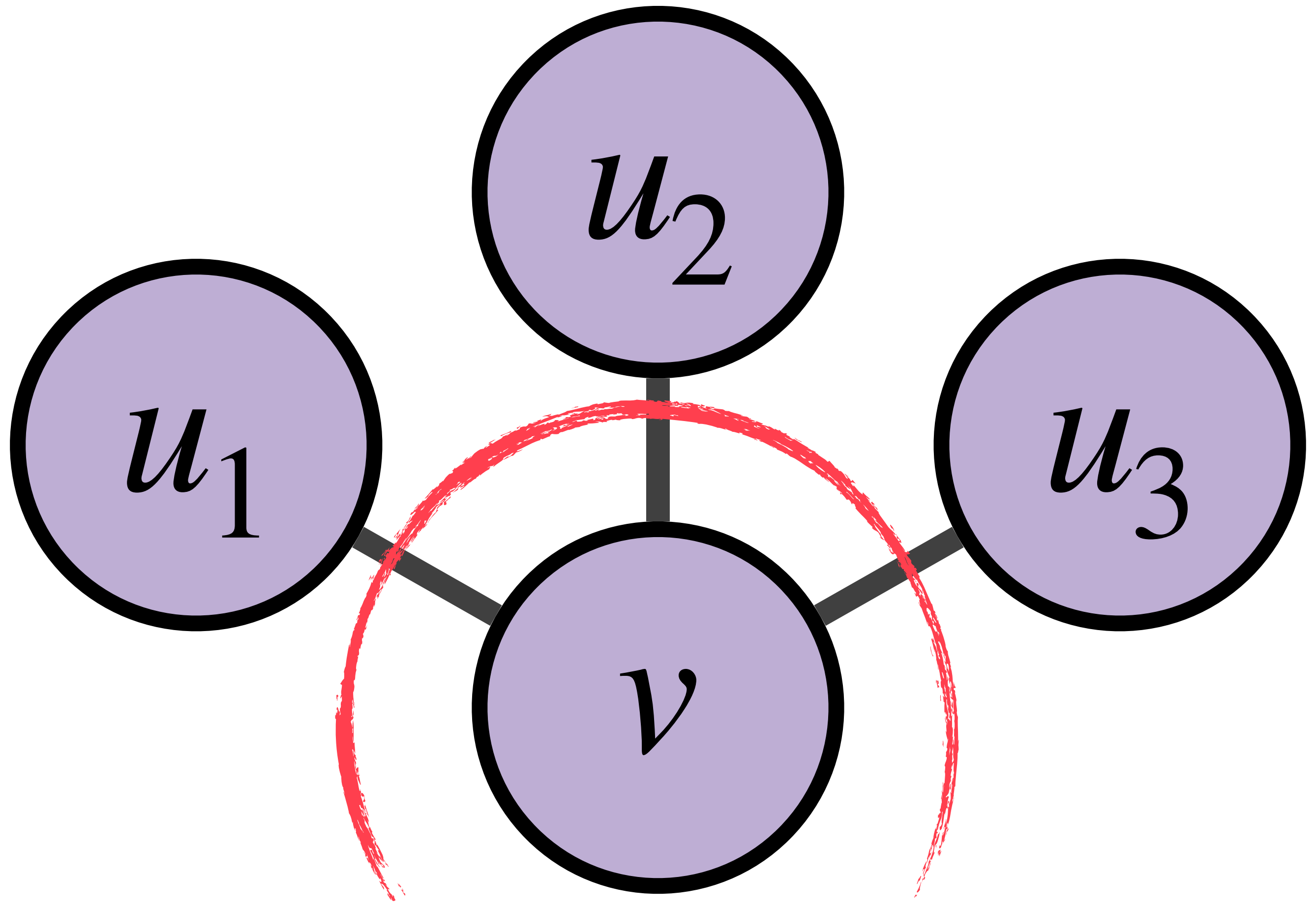
split the network up into **node-local components** to verify independently



Modular Network Verification

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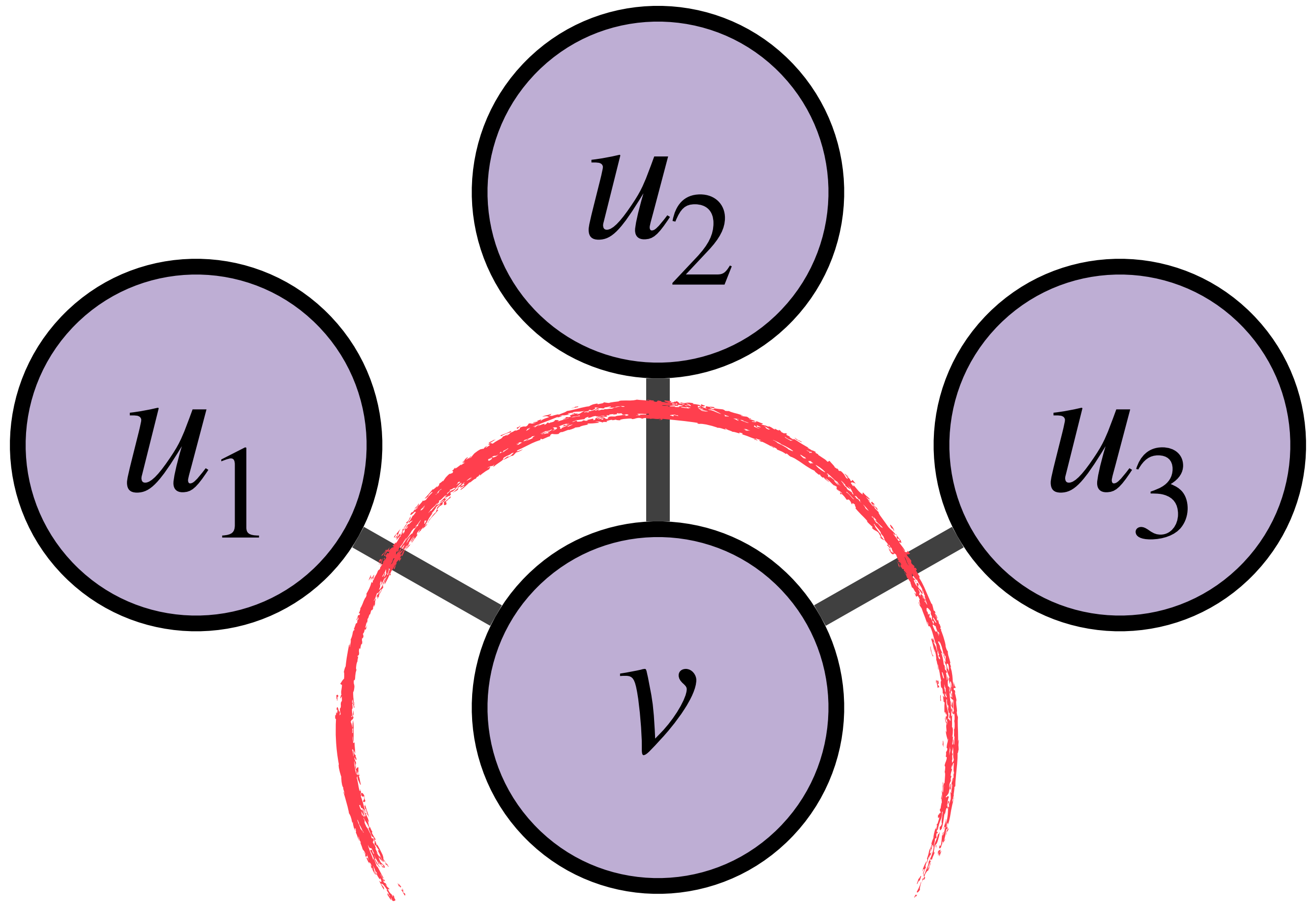
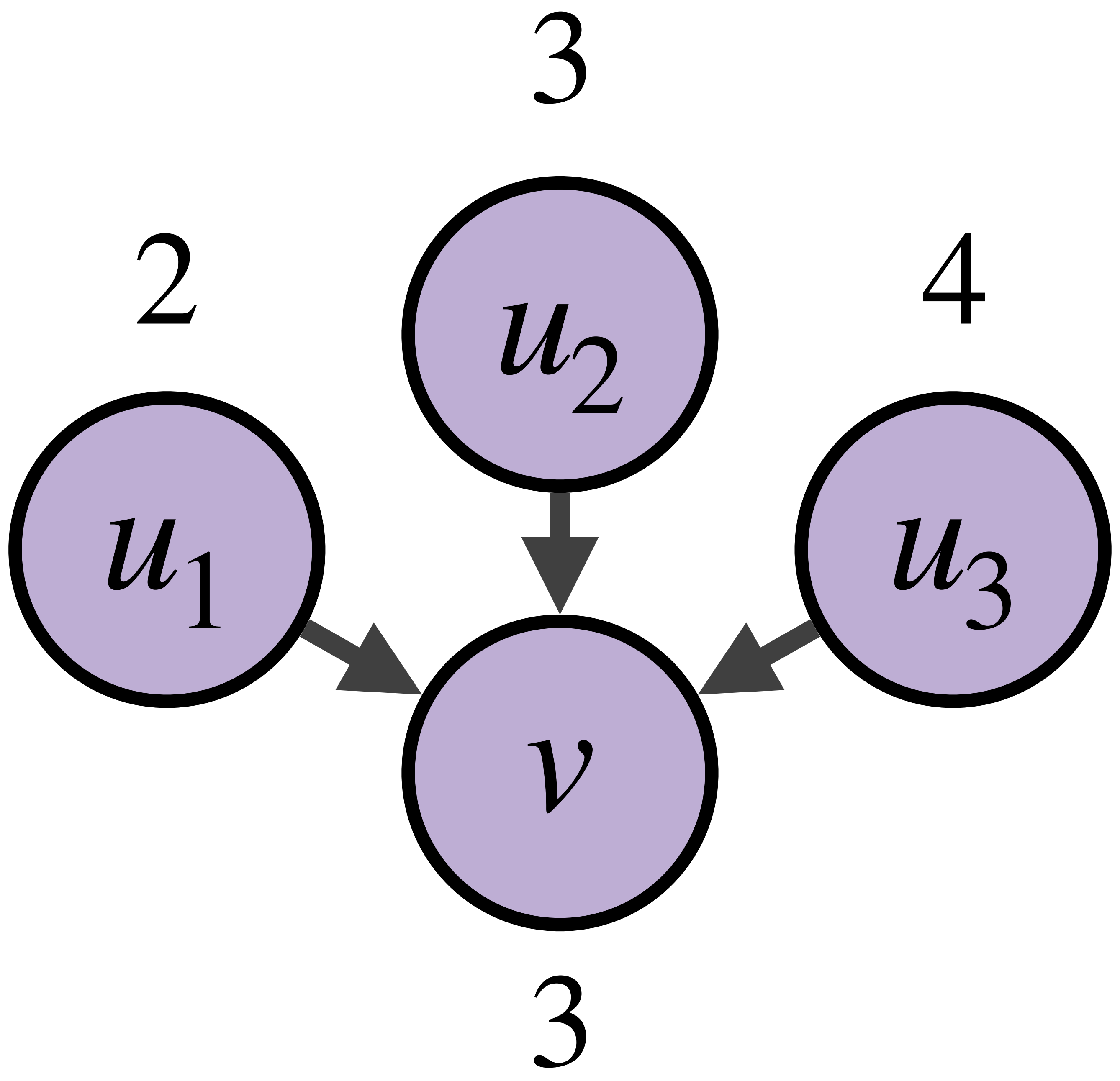
split the network up into **node-local components** to verify independently

represent cross-component dependencies using **interfaces**



Interfaces

User



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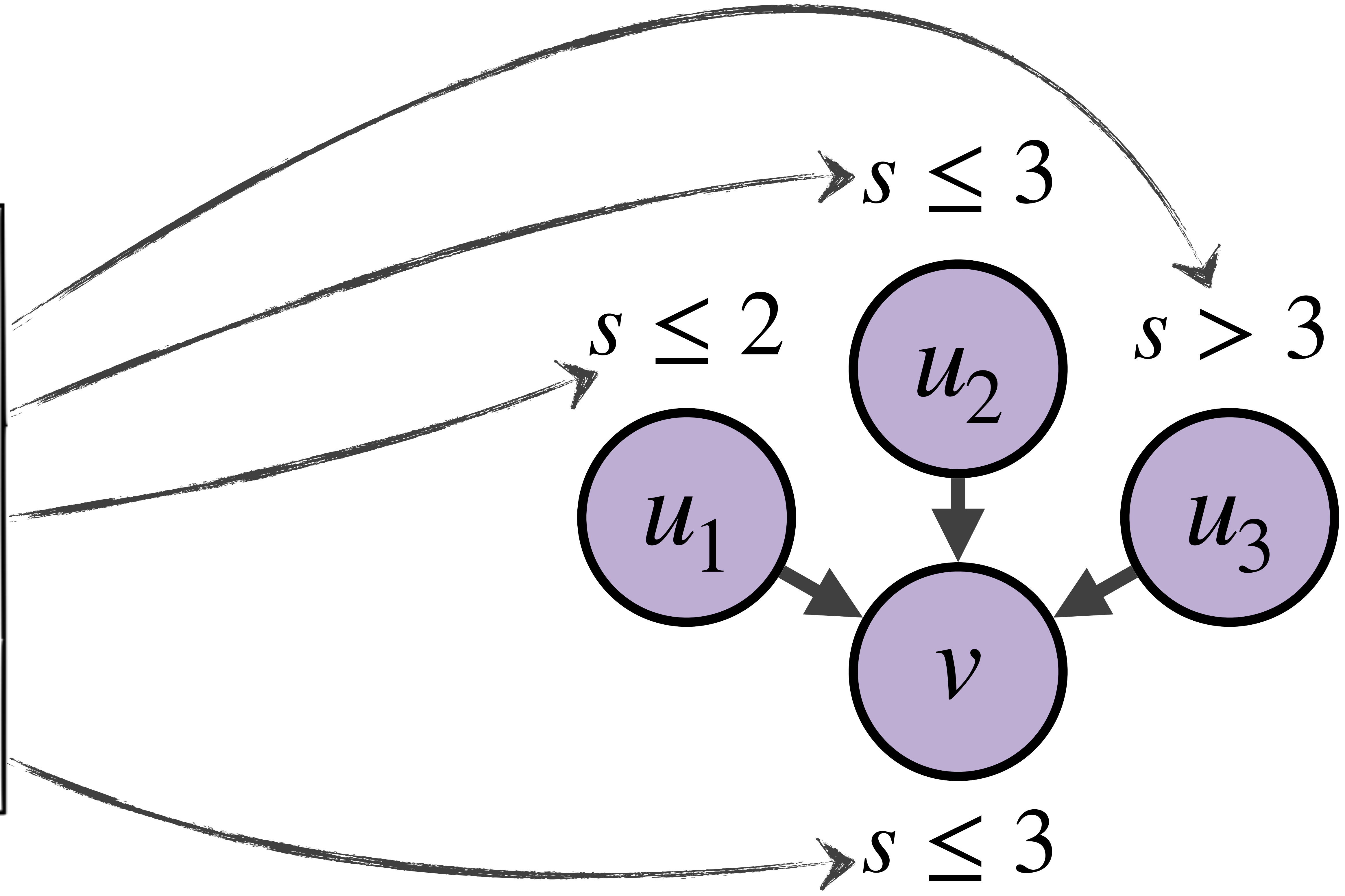
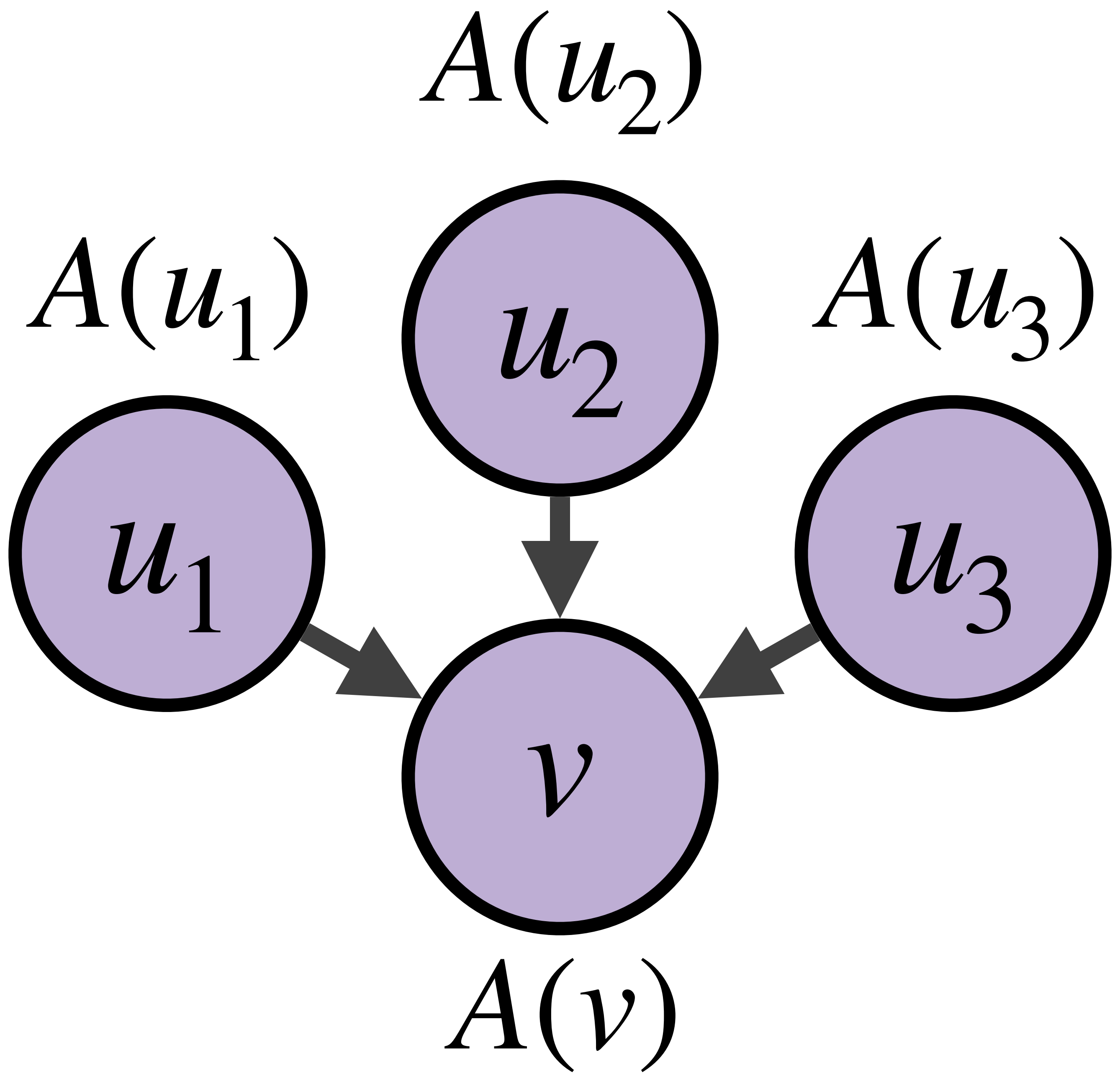
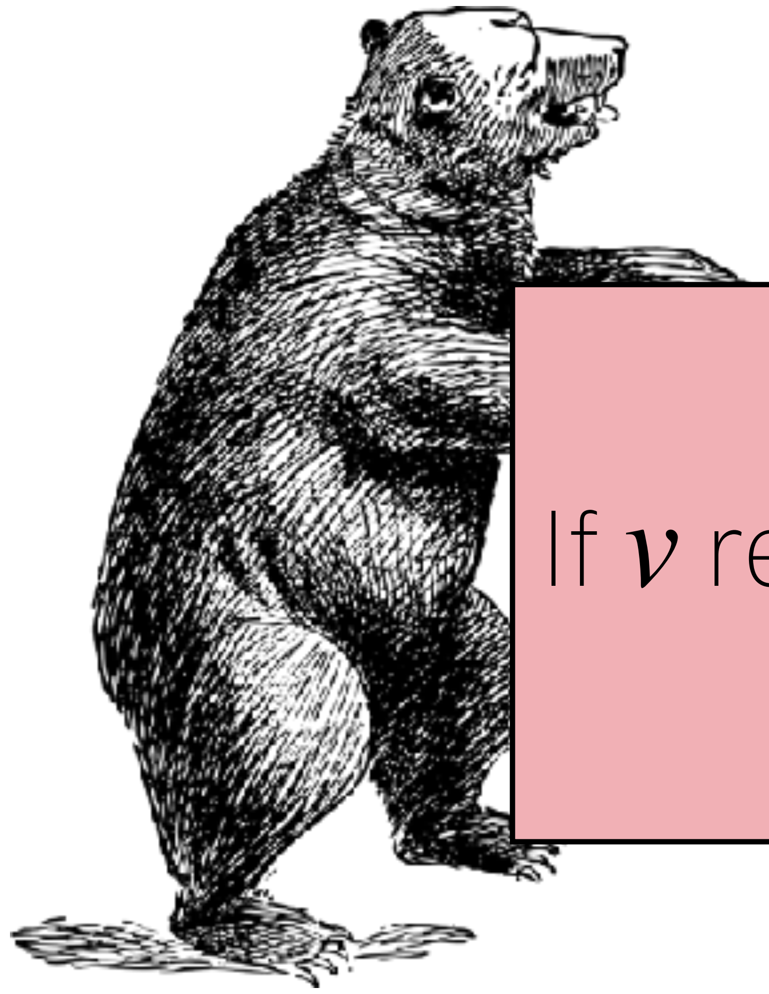


interface A over-approximates the converged states of the node v with a set of states $A(v)$

Bear's Modular Verification Procedure



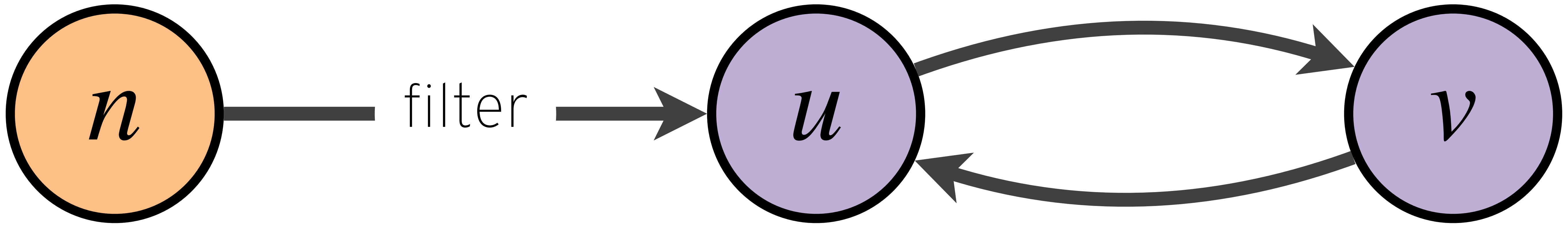


Verification condition:

If v receives any routes satisfying $A(u_1), A(u_2), \ldots, A(u_m)$,

does its selected route satisfy $A(v)$?

An Example Network



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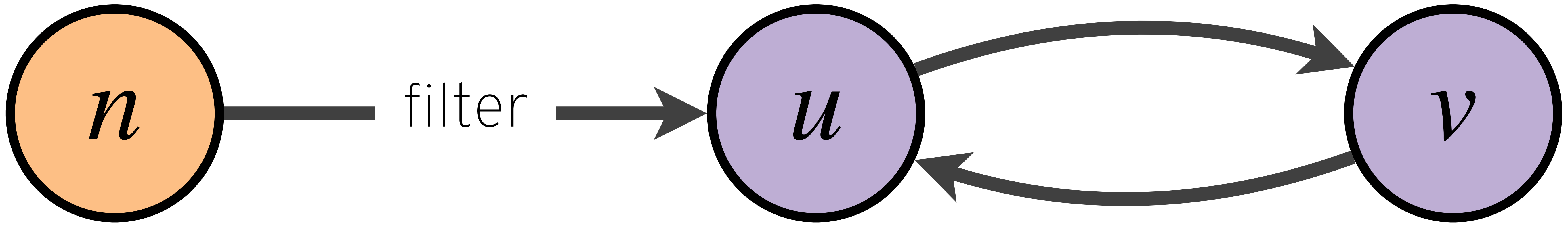
routes: ⟨**lp** : $\mathbb{N}$, **len** : $\mathbb{N}$⟩ or ∞

select by highest **lp**, lowest **len**



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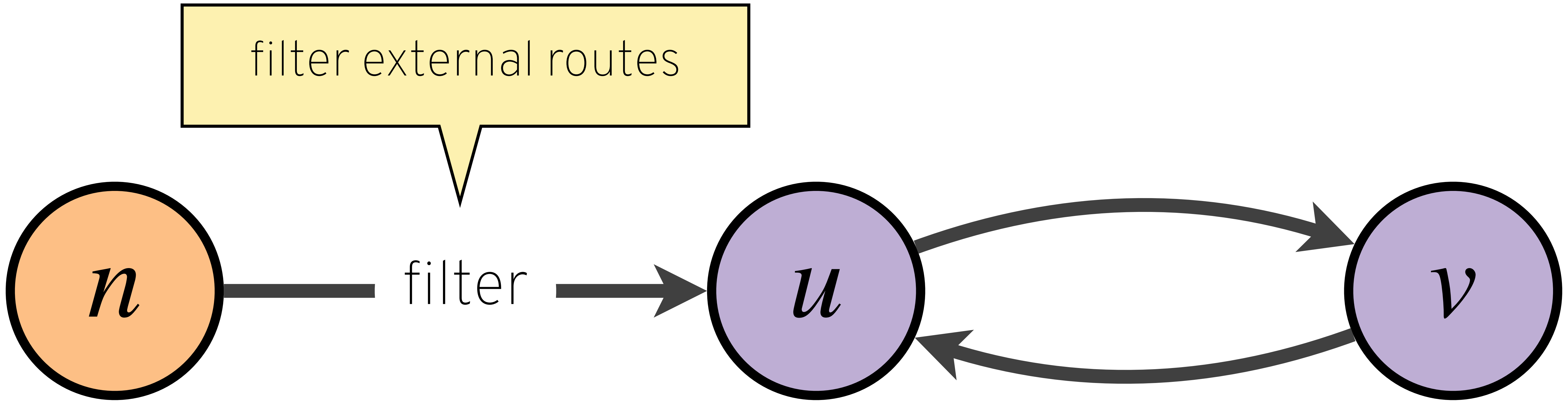

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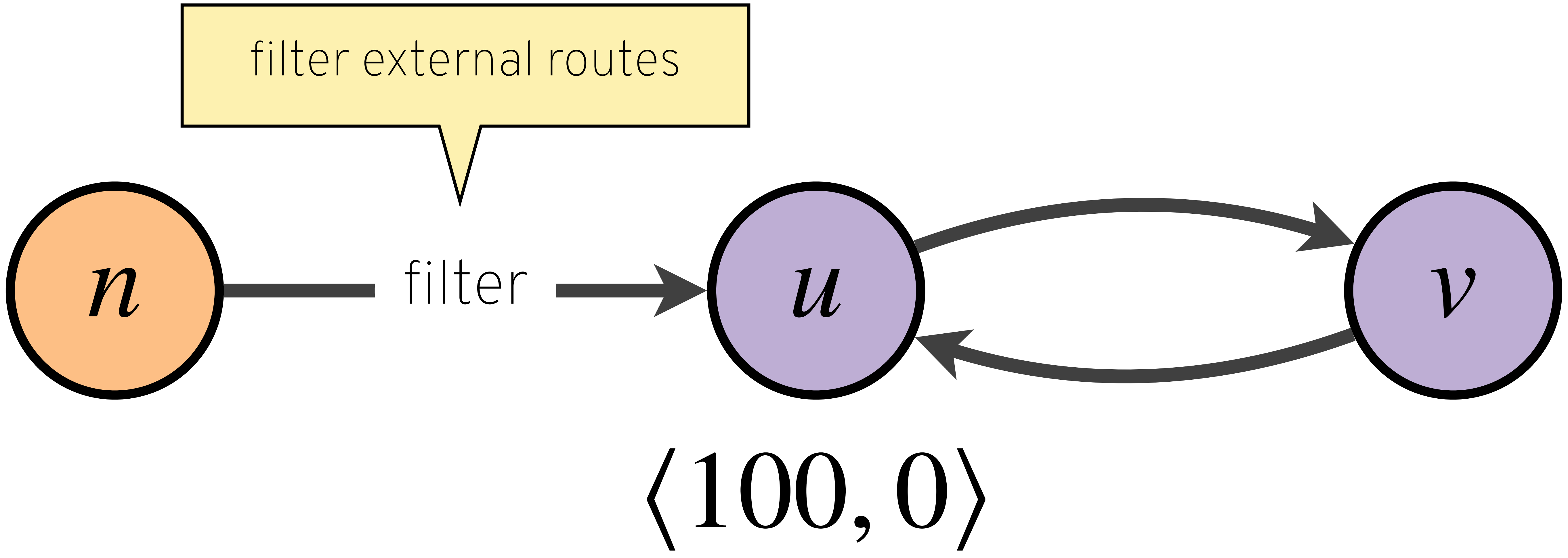

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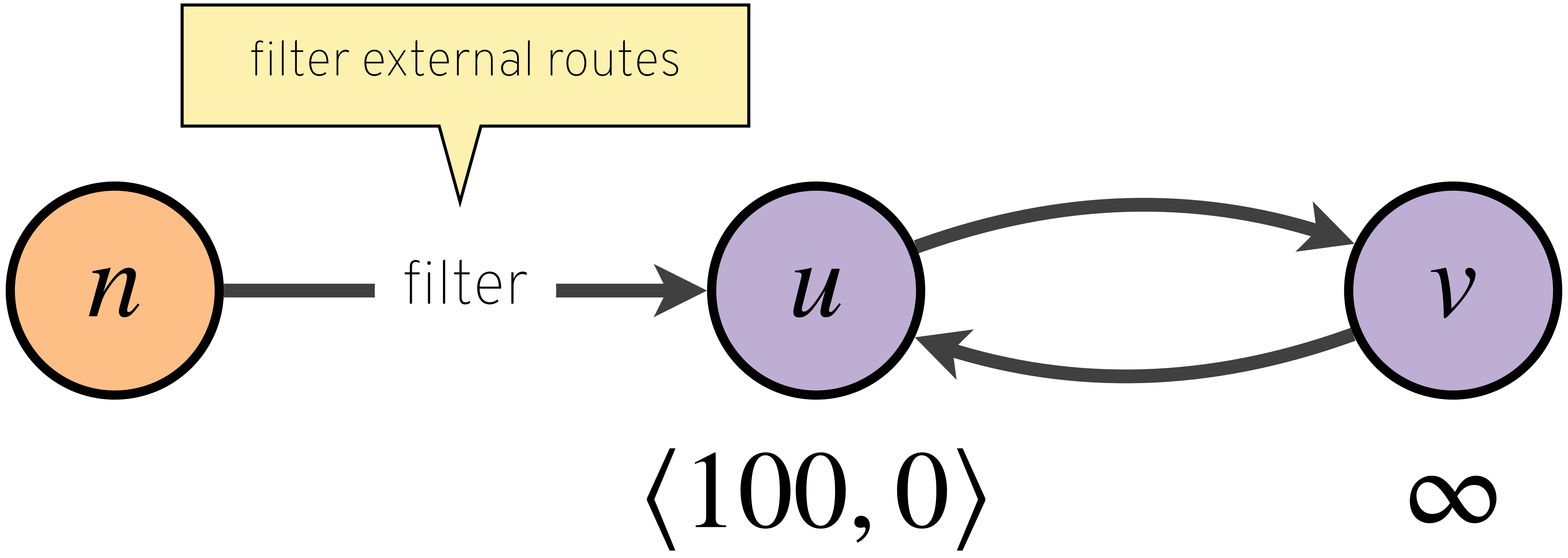

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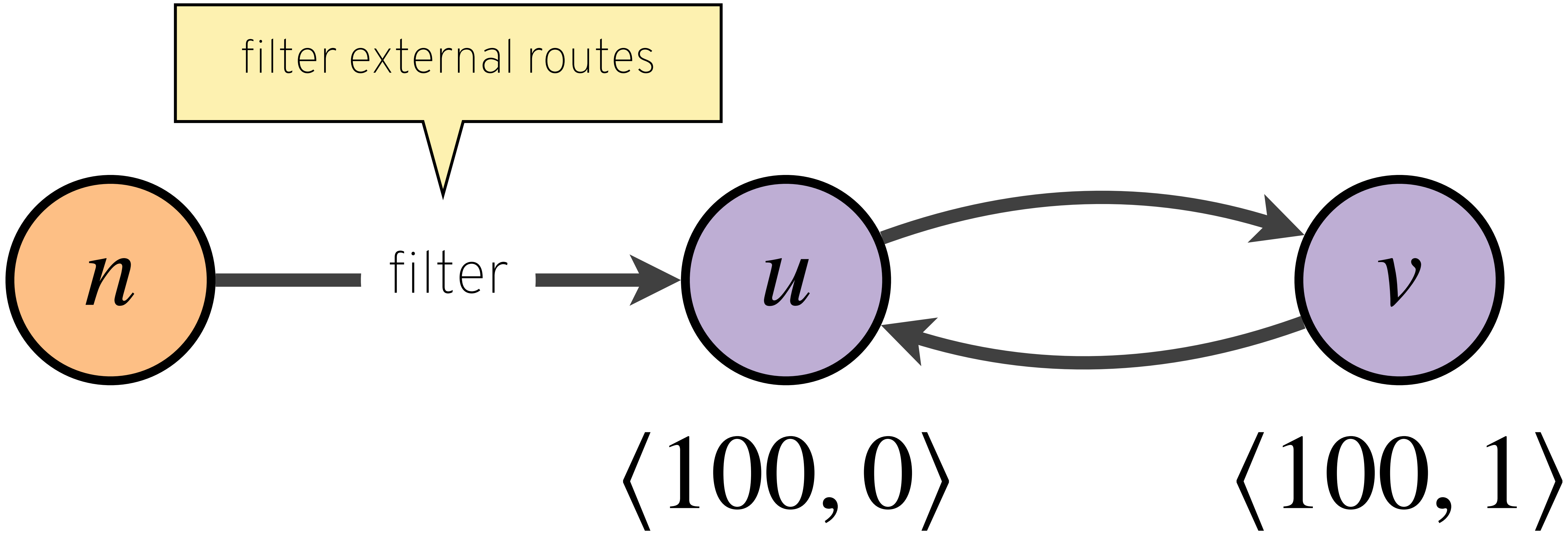
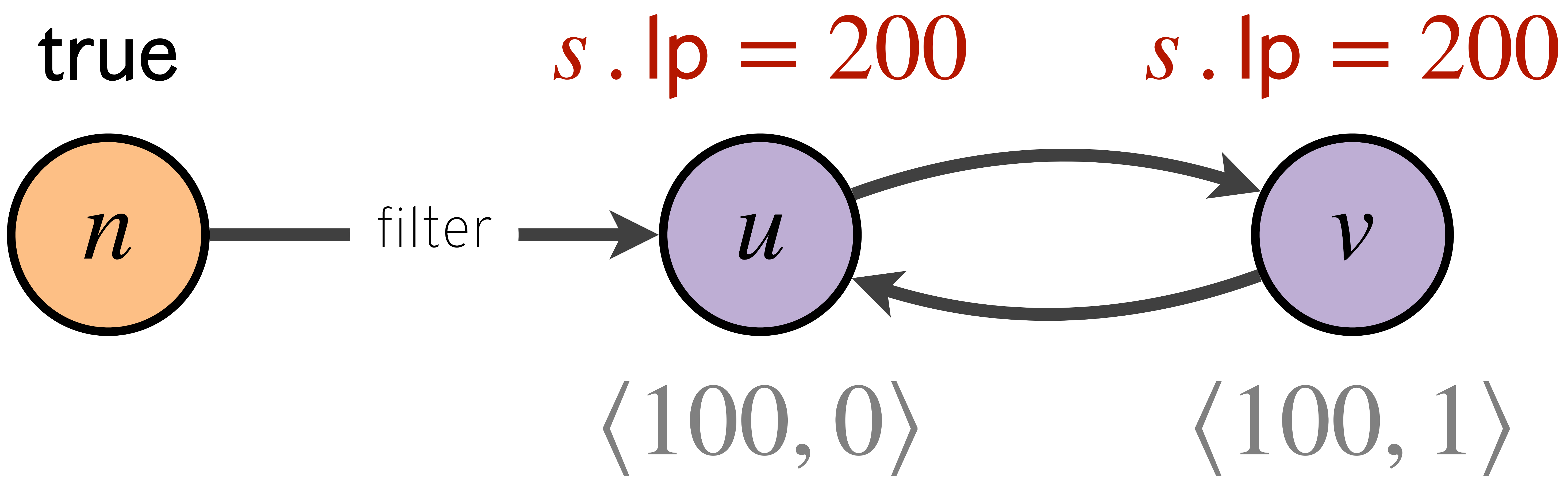


Execution Interference



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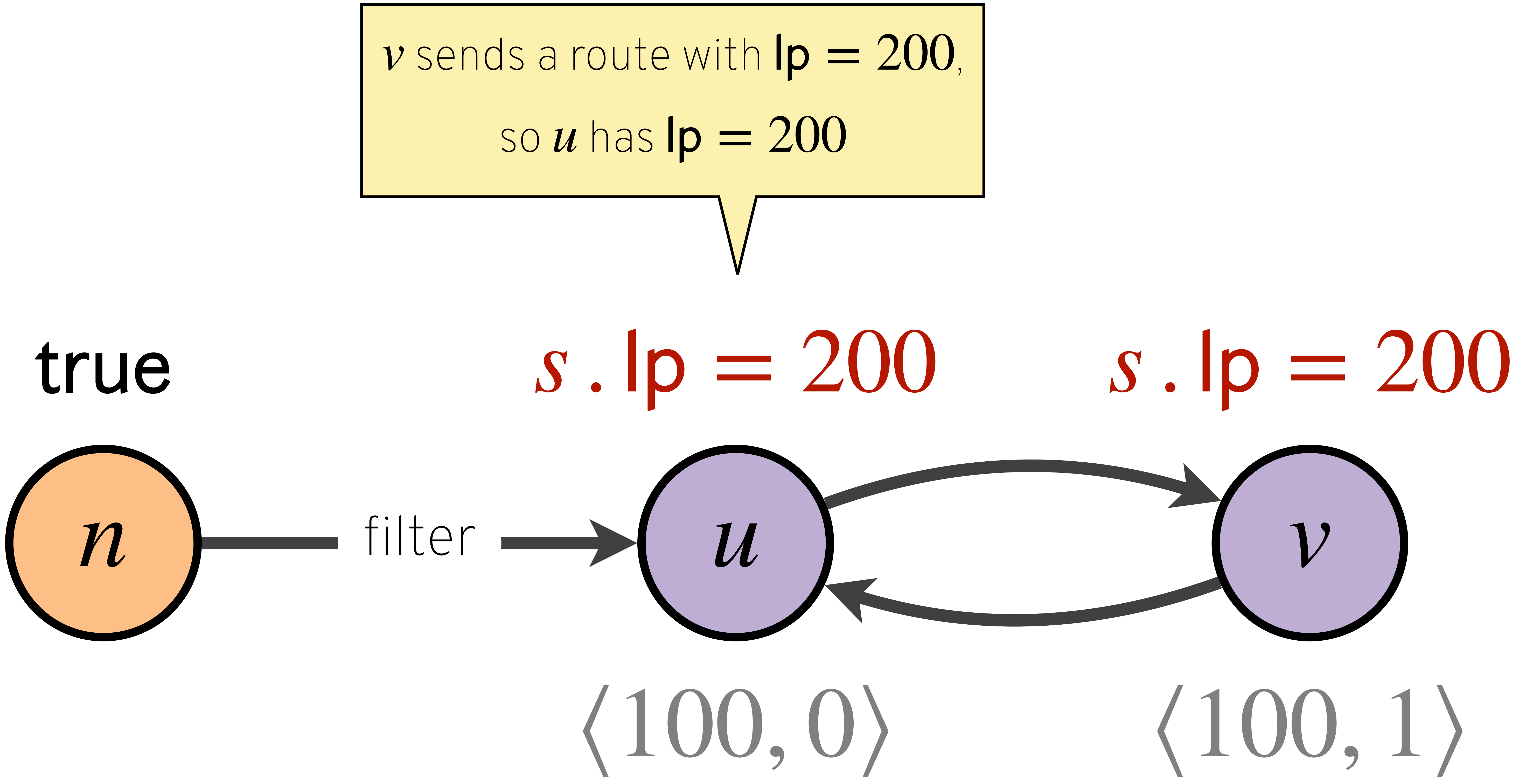

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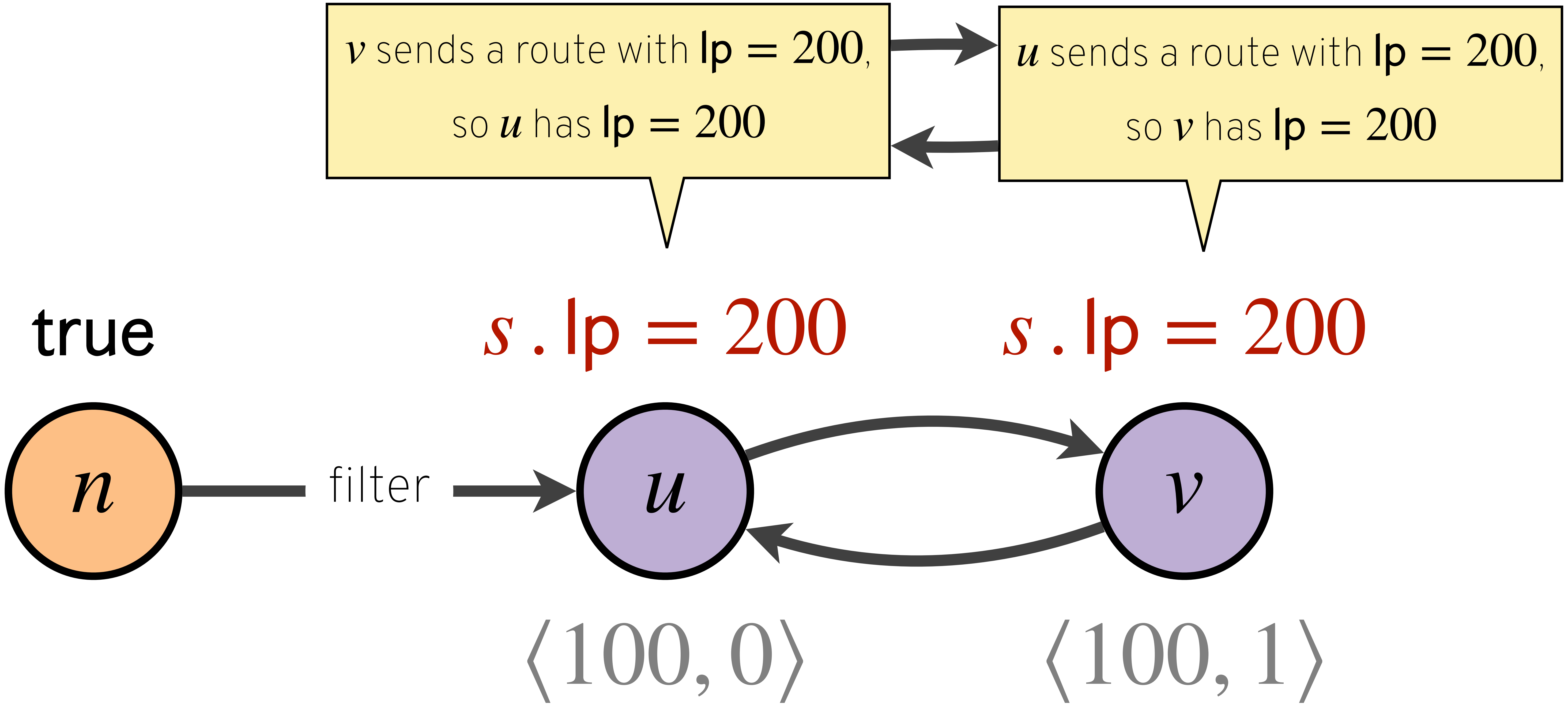

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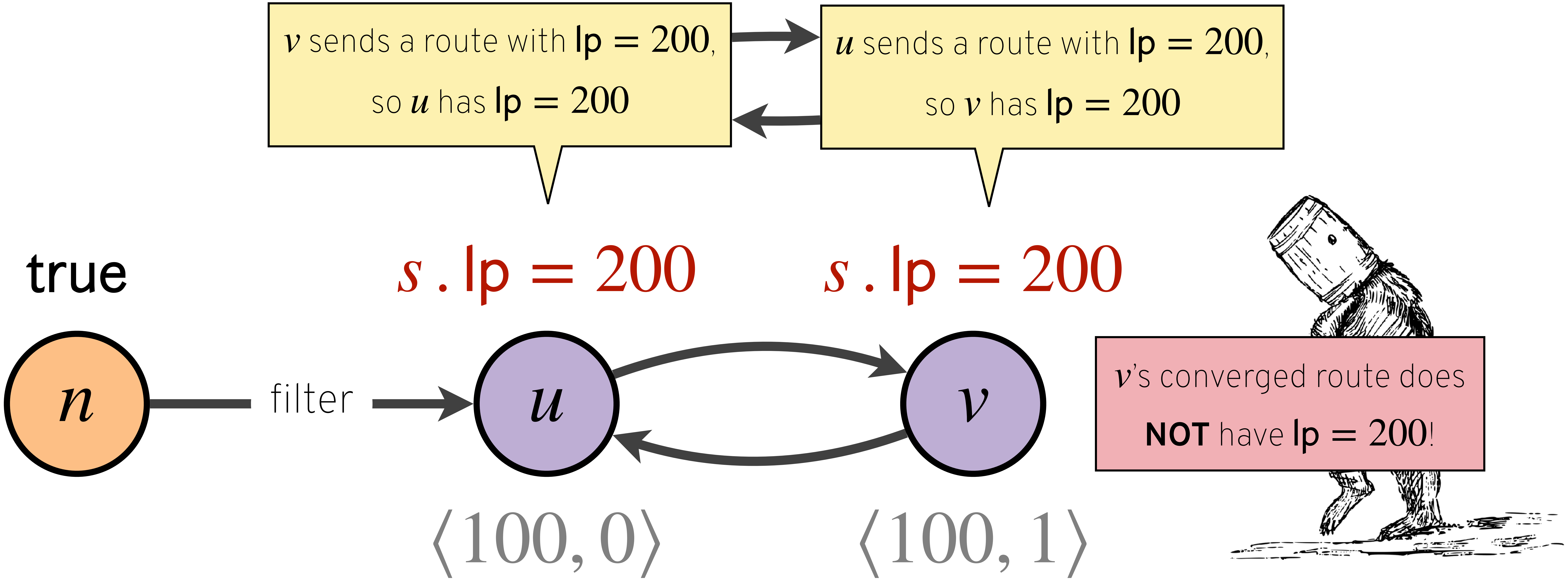
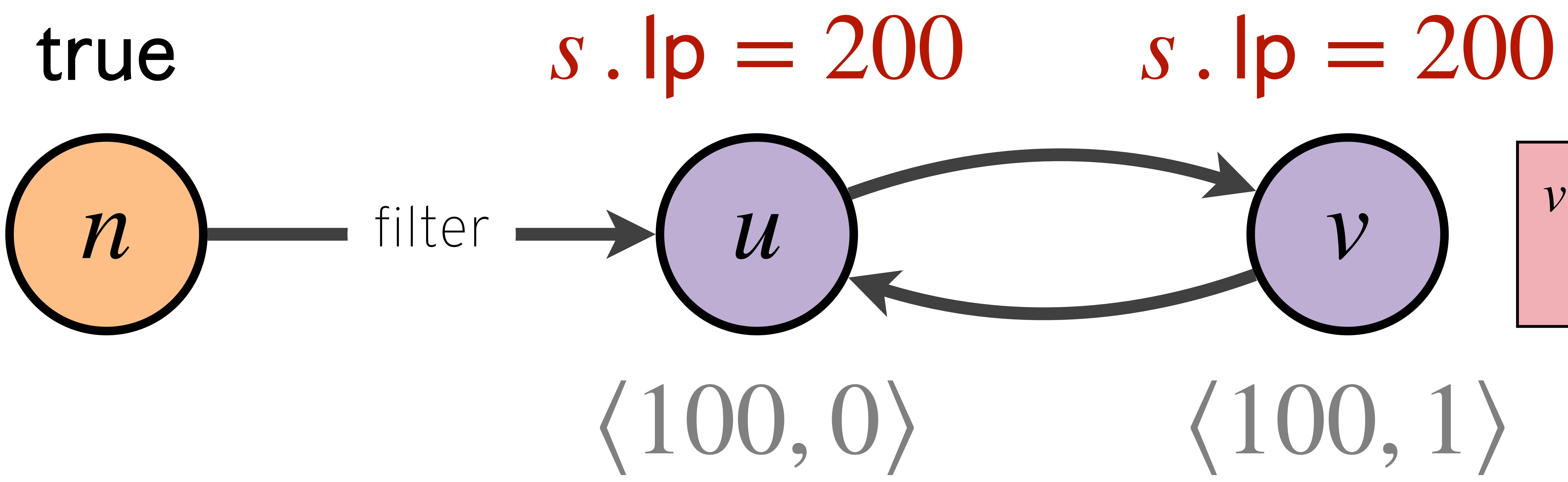


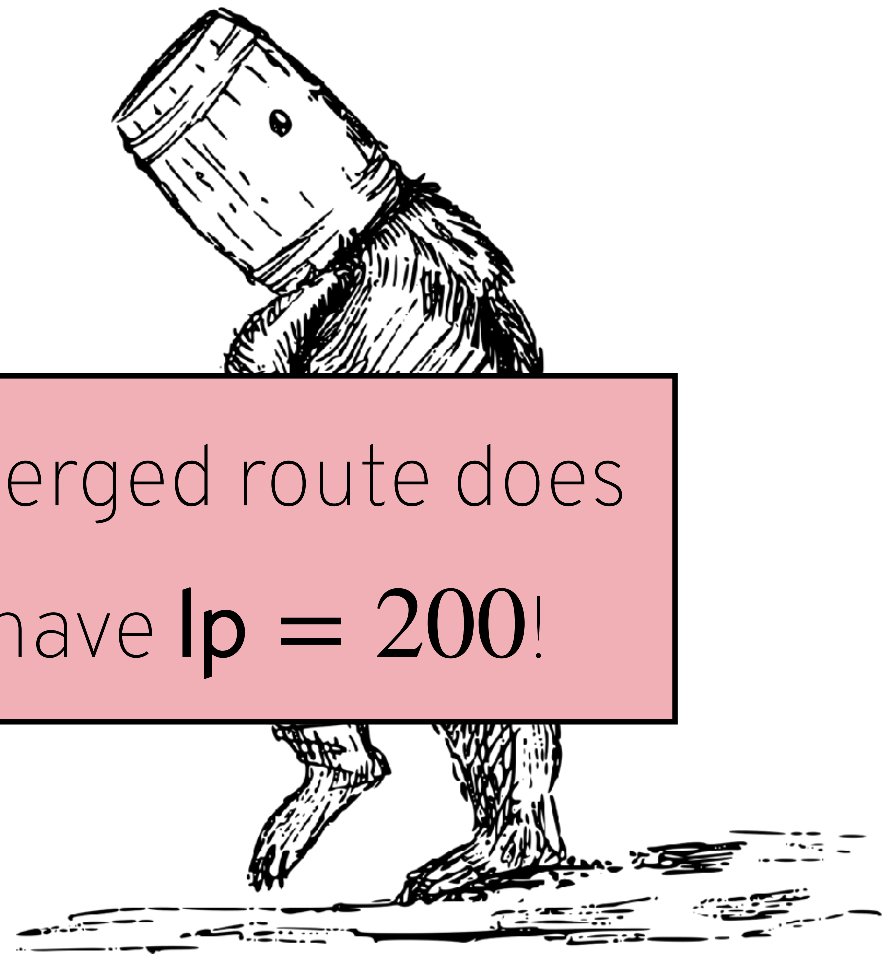
Execution Interference

v sends a route with $\mathsf{lp} = 200$, so u has $\mathsf{lp} = 200$

u sends a route with $\mathsf{lp} = 200$, so v has $\mathsf{lp} = 200$

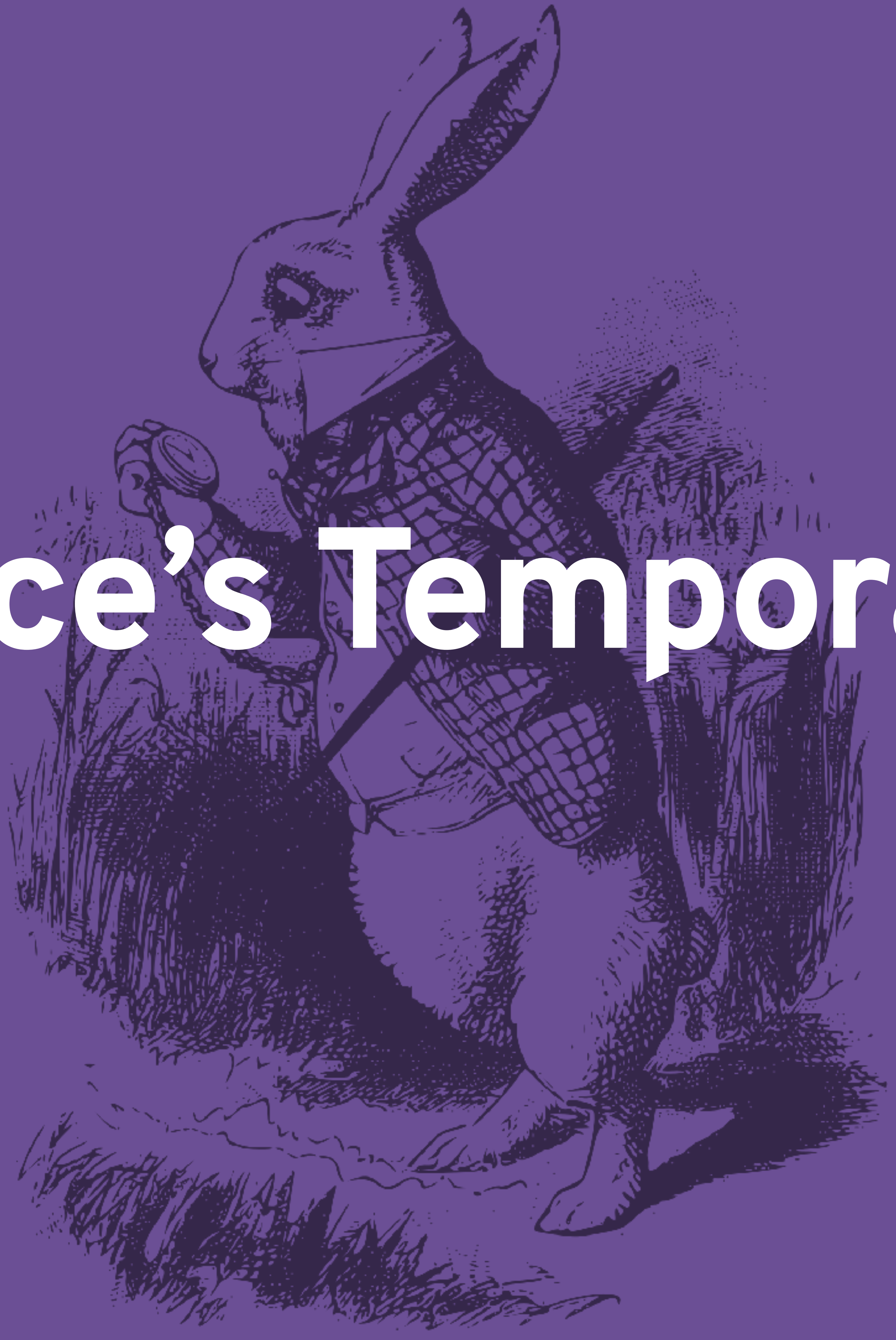


v's converged route does **NOT** have $\mathsf{lp} = 200$!

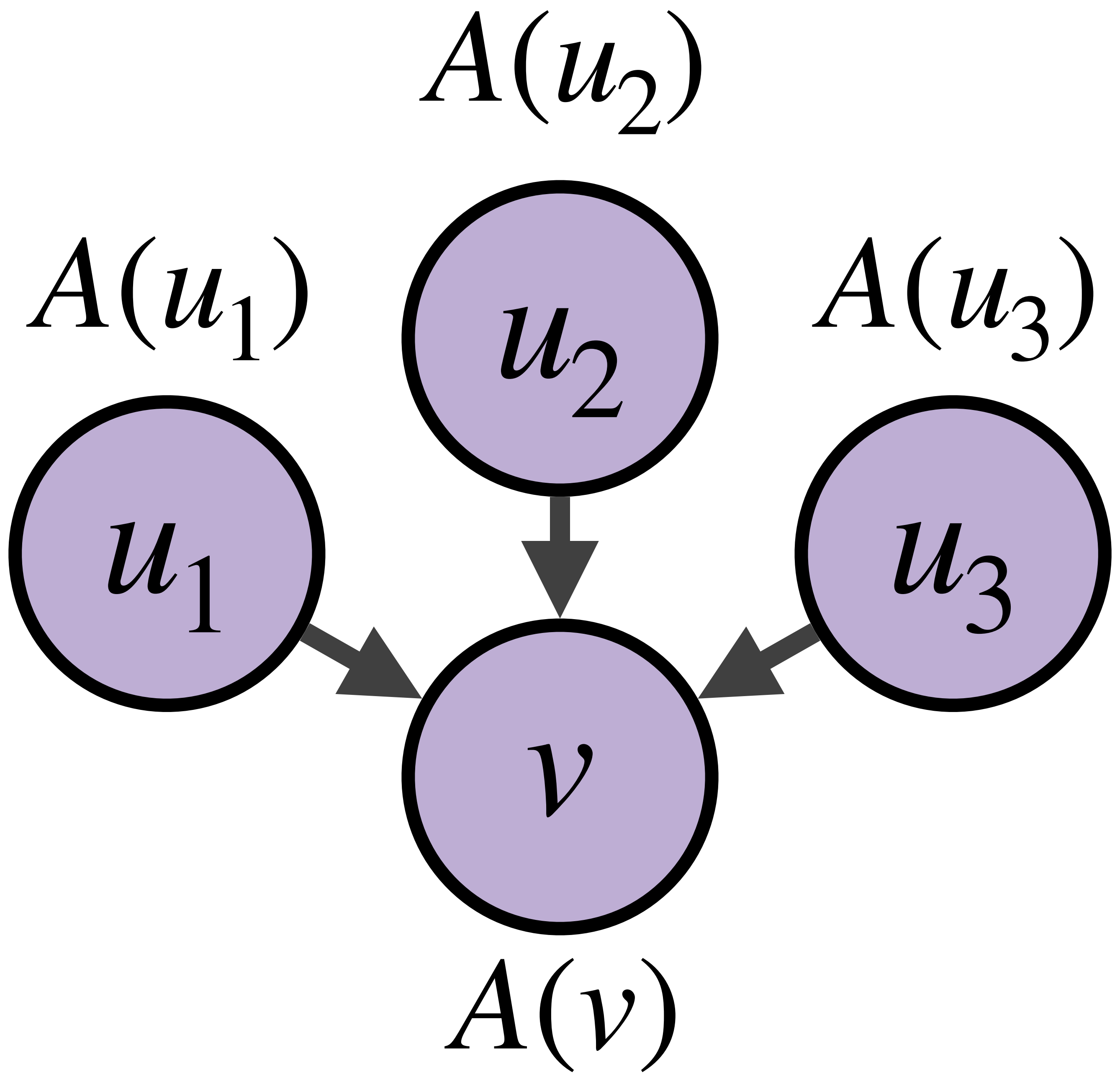


interfaces are **unsound**: exclude the legitimate converged routes, but the checks pass!

Timepiece’s Temporal Model



Temporal Interfaces



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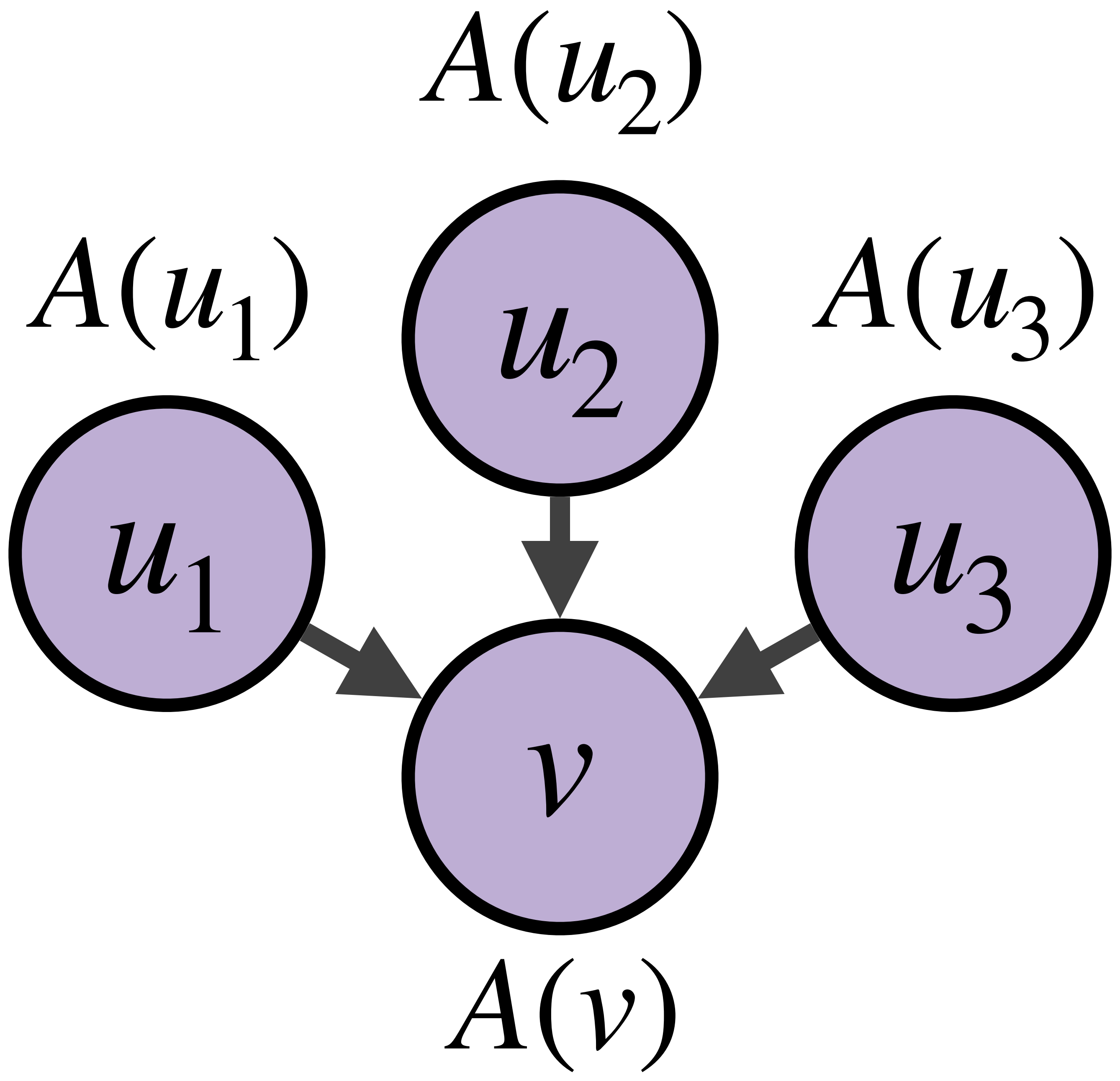
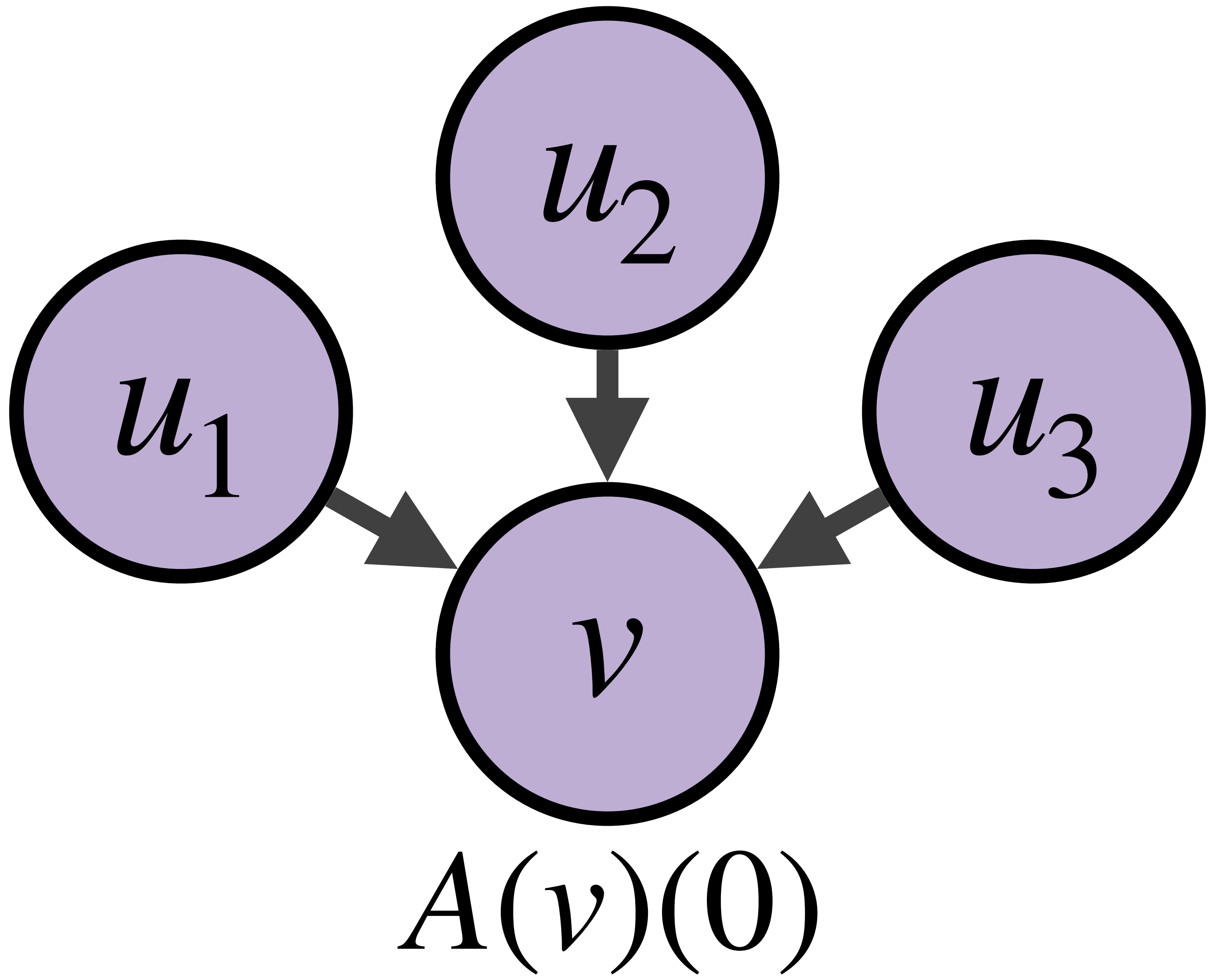


temporal interface A over-approximates the states of the node v **at time** t with a set of states $A(v)(t)$

Temporal Interfaces

base check: interfaces at time 0 holds on initial routes



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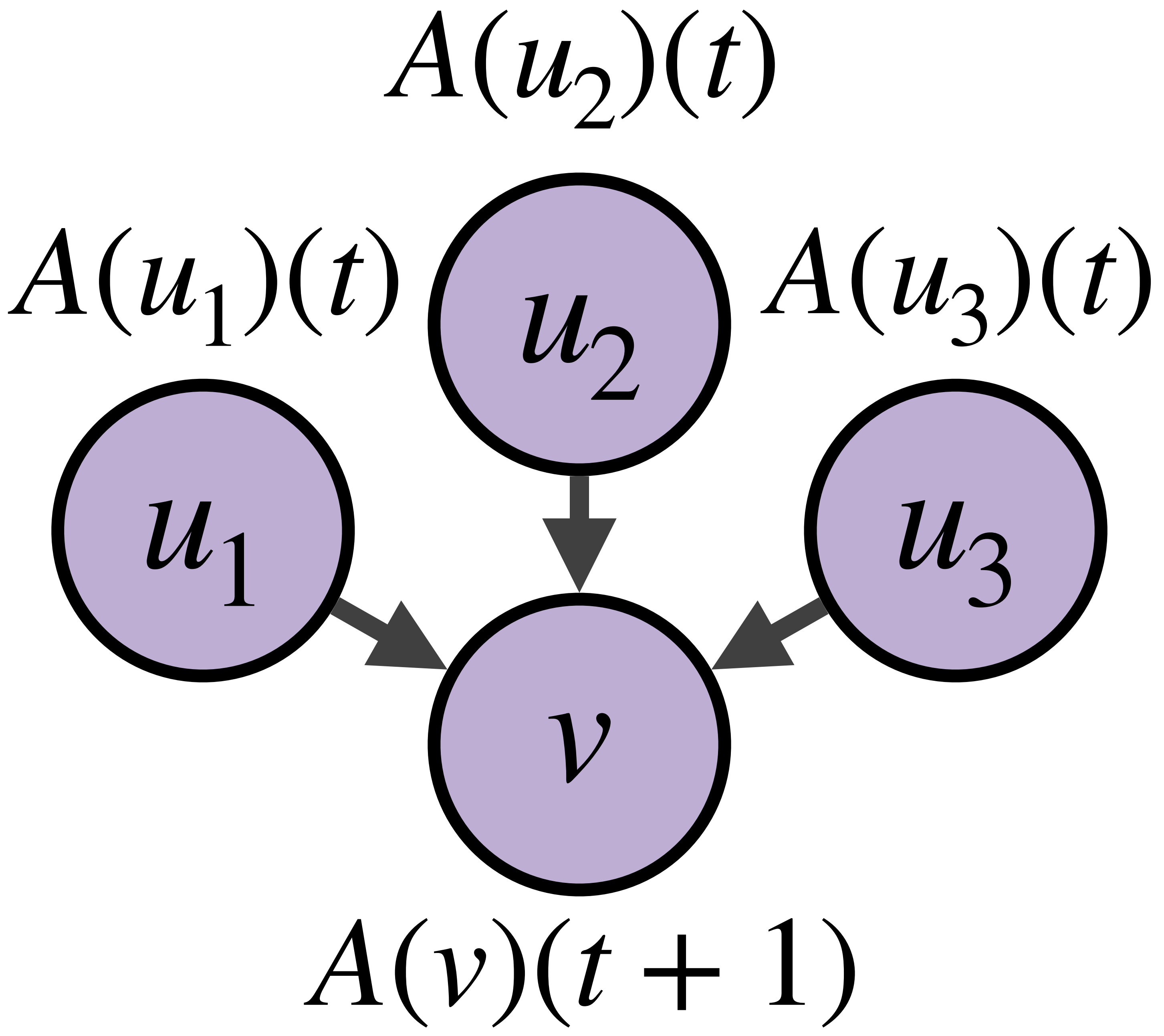
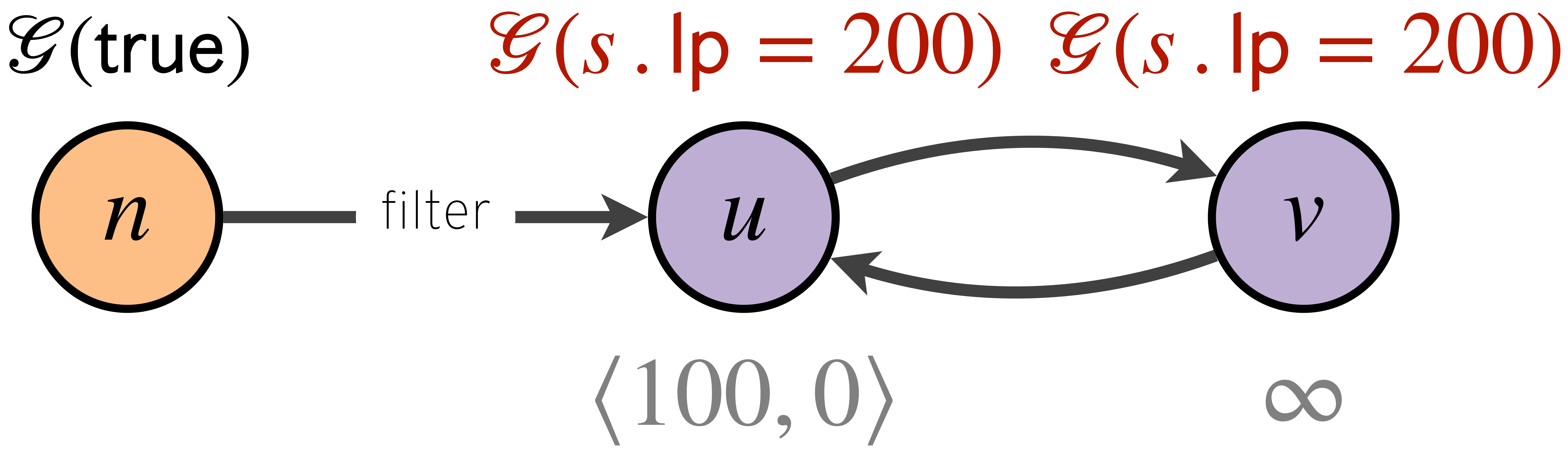


inductive check: for all times t, interfaces at time t+1 holds given interfaces from time t

temporal interface A over-approximates the states of the node v **at time** t with a set of states $A(v)(t)$

Preventing Interference



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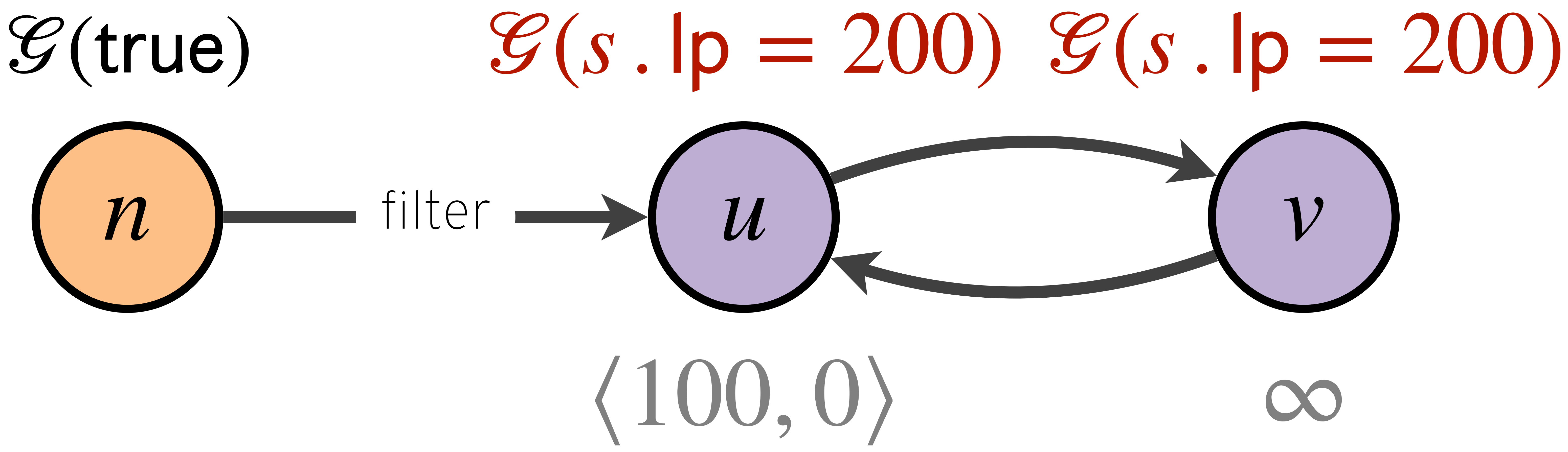
$\mathcal{G}P$ (**globally** P): at every point in time, the predicate P holds



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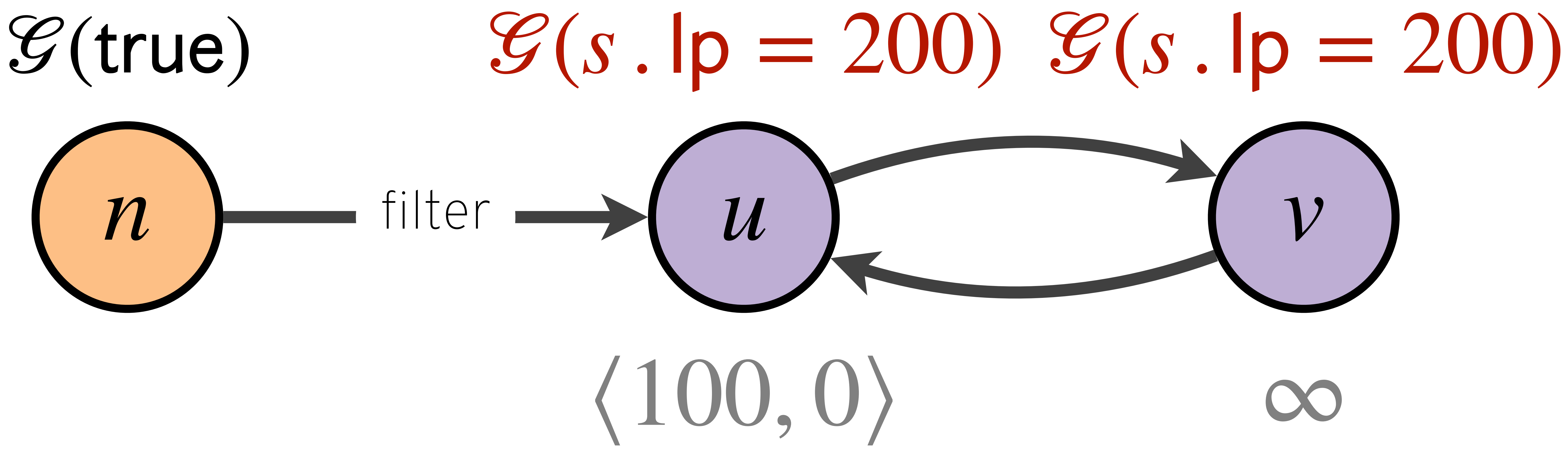
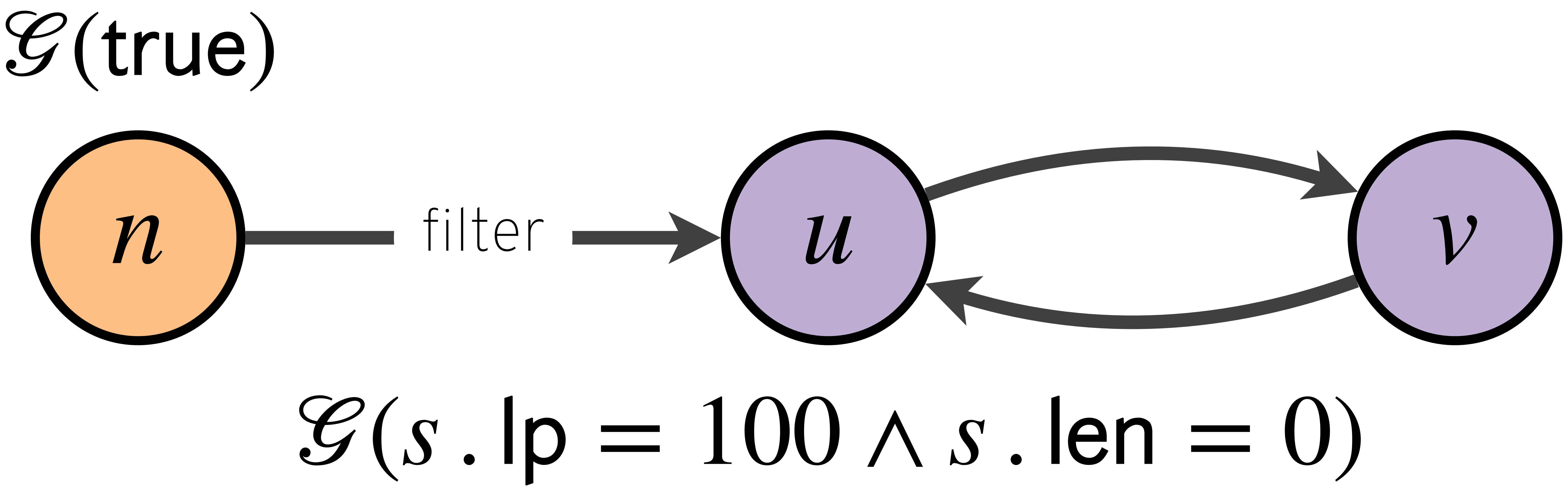
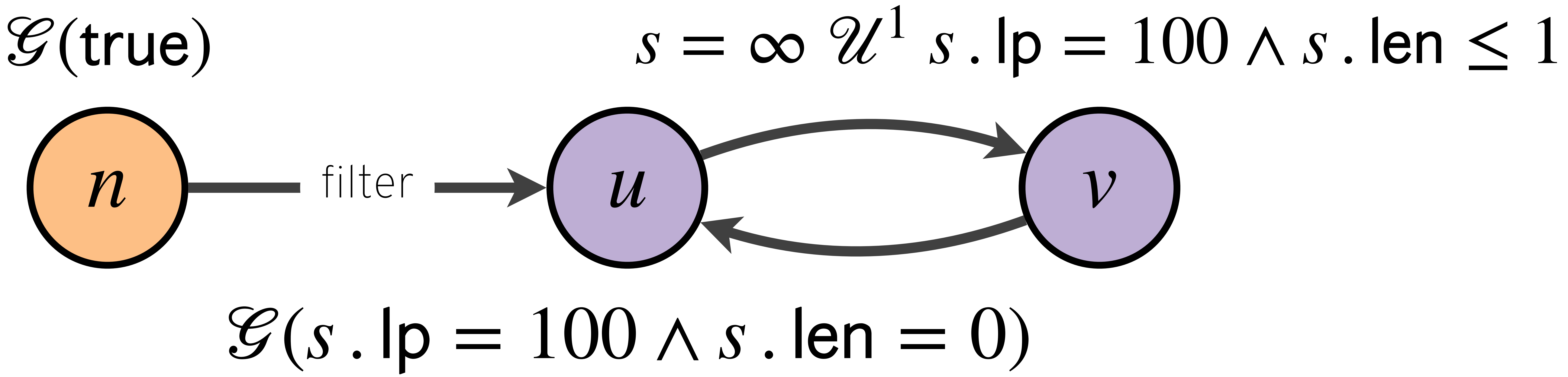


Base checks fail: interfaces $A(u)$ and $A(v)$ do not hold for initial routes at time 0

Proving Path Length



Proving Path Length

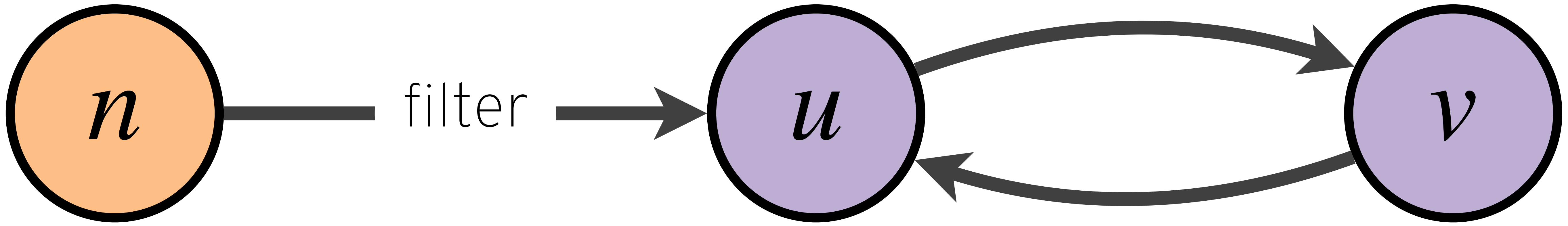


Proving Path Length

$P\ \mathcal{U}^t\ Q$ (P **until** Q **at** t): until time t, P holds; at and after t, Q holds

$\mathcal{G}(\text{true})$

$s = \infty\ \mathcal{U}^1\ s\,.\,\text{lp} = 100 \wedge s\,.\,\text{len} \leq 1$



$\mathcal{G}(s\,.\,\text{lp} = 100 \wedge s\,.\,\text{len} = 0)$

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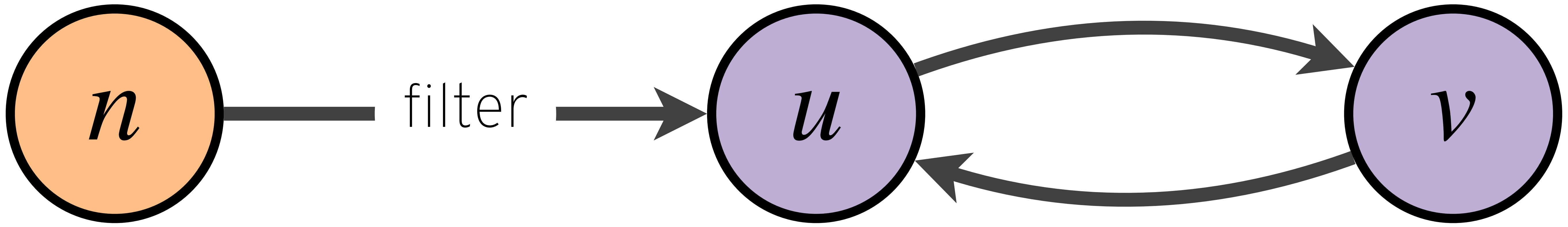

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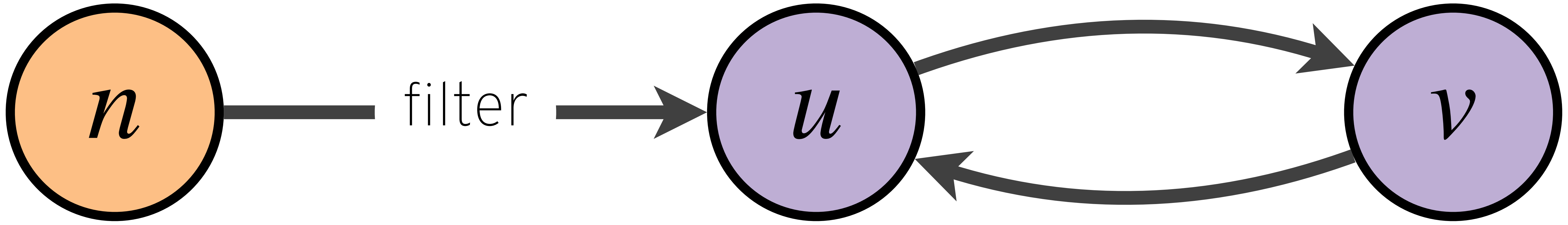
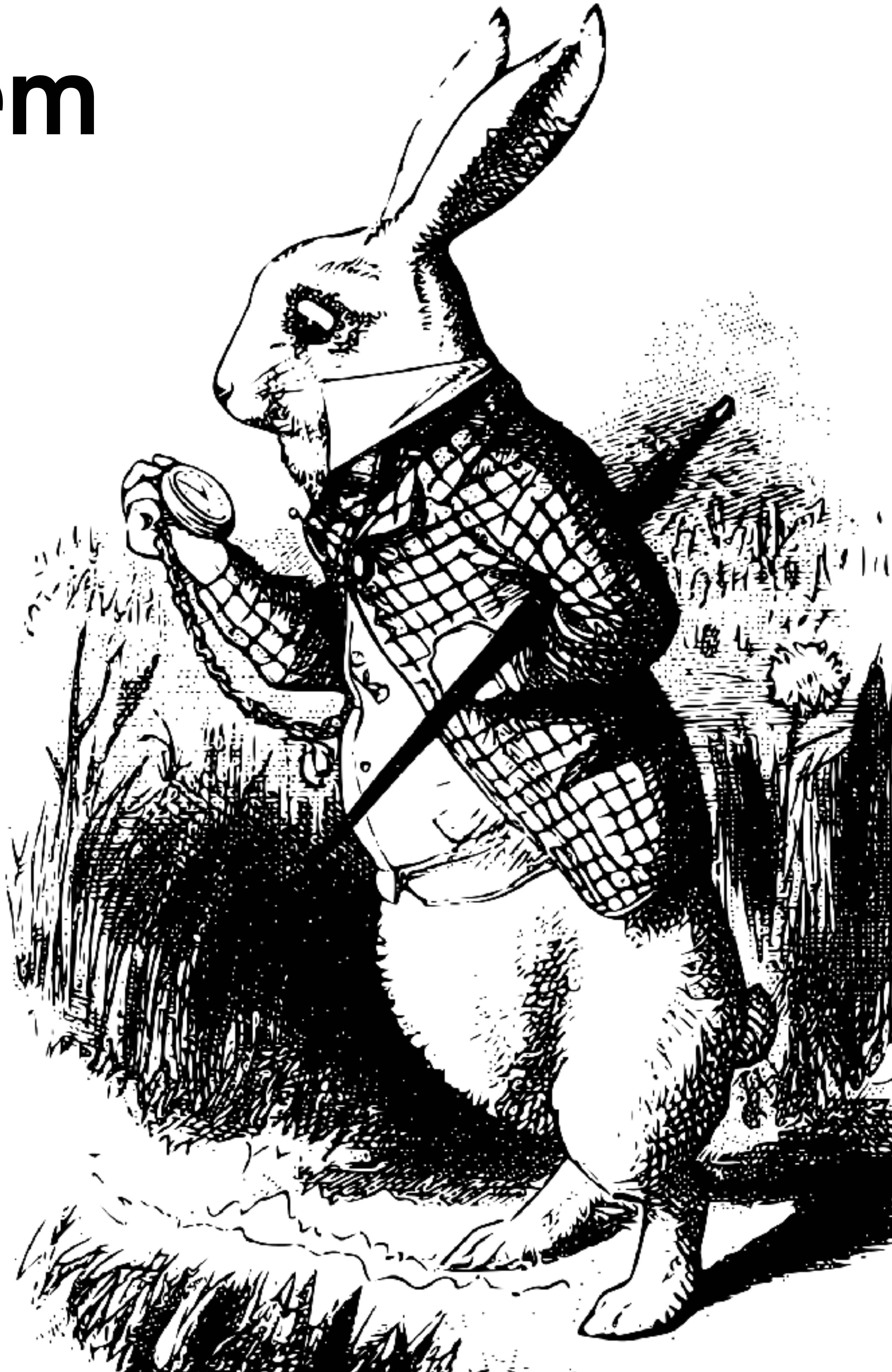


at time 1, v has a route with lp $= 100$ and len ≤ 1

$\mathcal{G}(s\,.\,\text{lp} = 100 \wedge s\,.\,\text{len} = 0)$

Soundness Theorem



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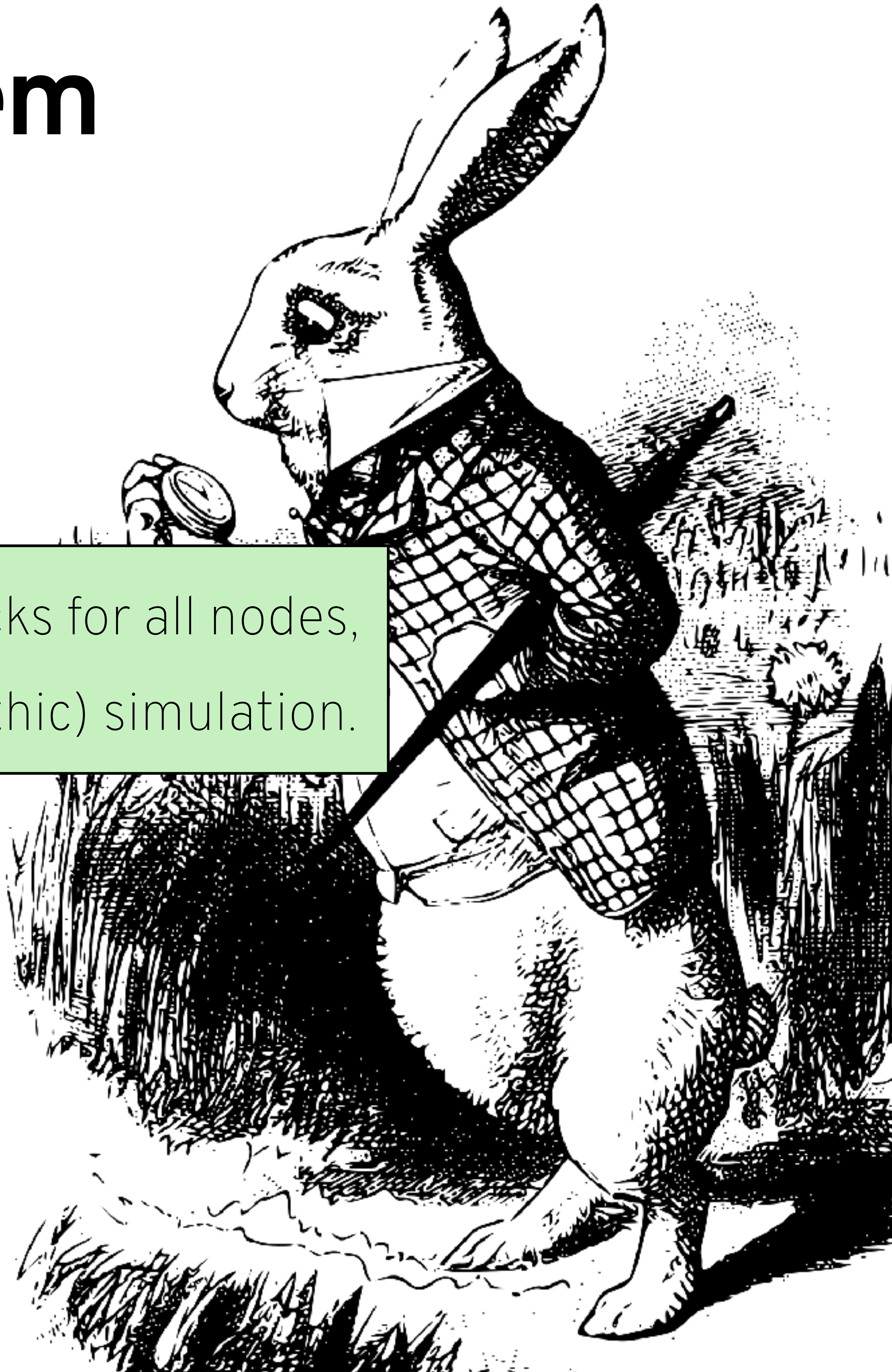
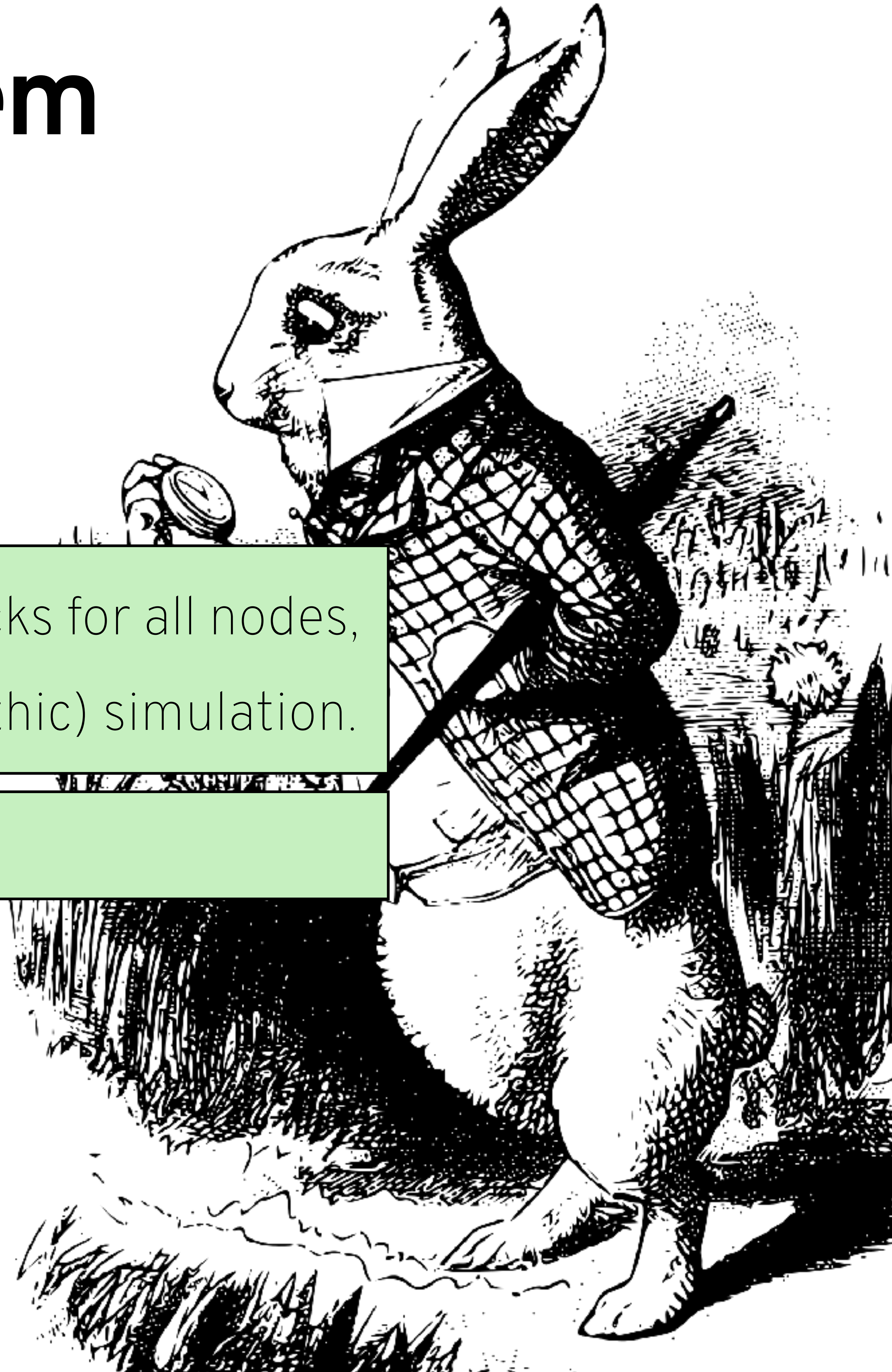


If interface A satisfies the base and inductive checks for all nodes, then A includes all states computable via (monolithic) simulation.

Soundness Theorem



If interface A satisfies the base and inductive checks for all nodes, then A includes all states computable via (monolithic) simulation.

Proof by induction on time.

How to Use Timepiece

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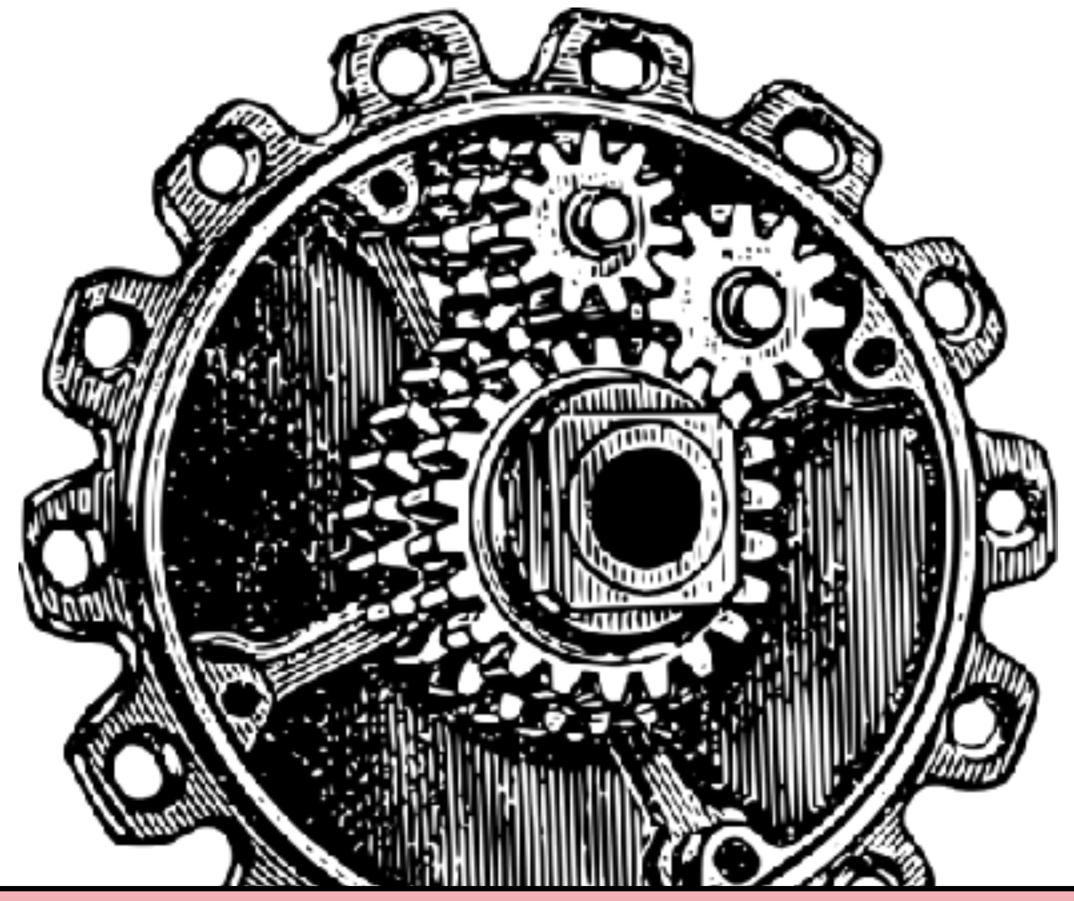

define network semantics in C# or via configurations (via Batfish)

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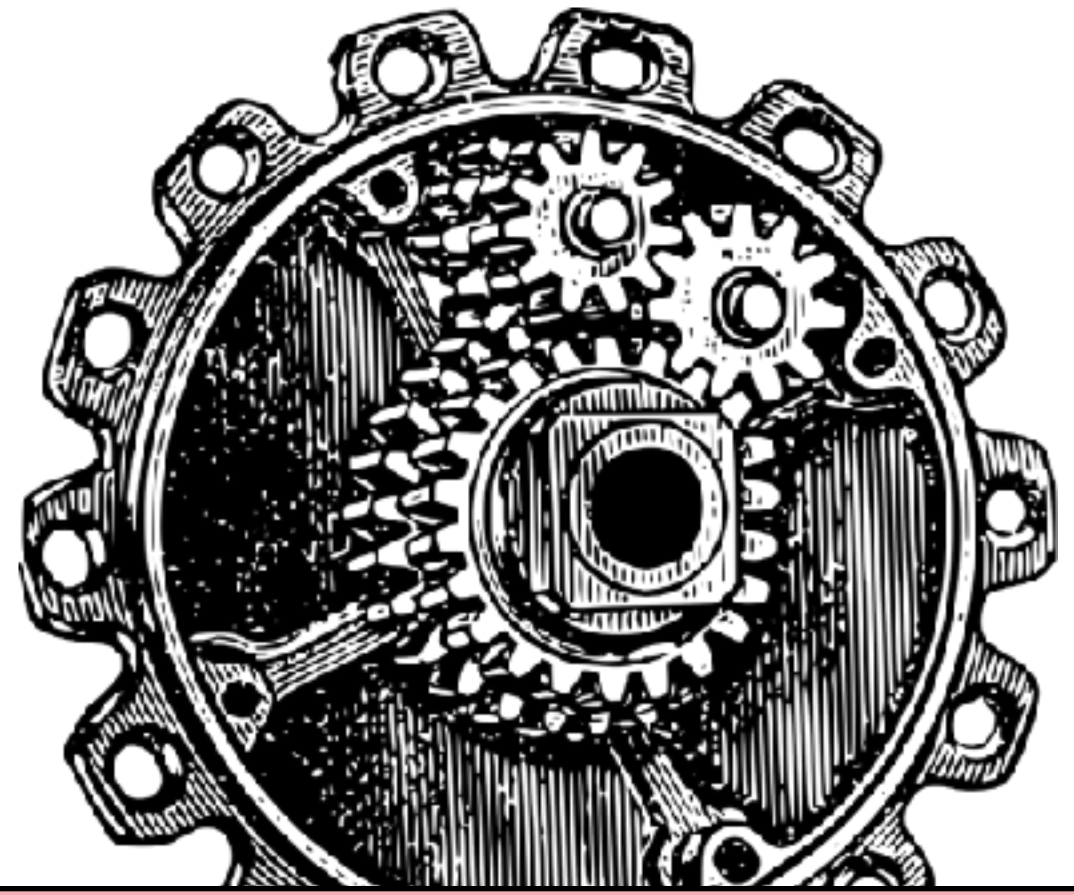

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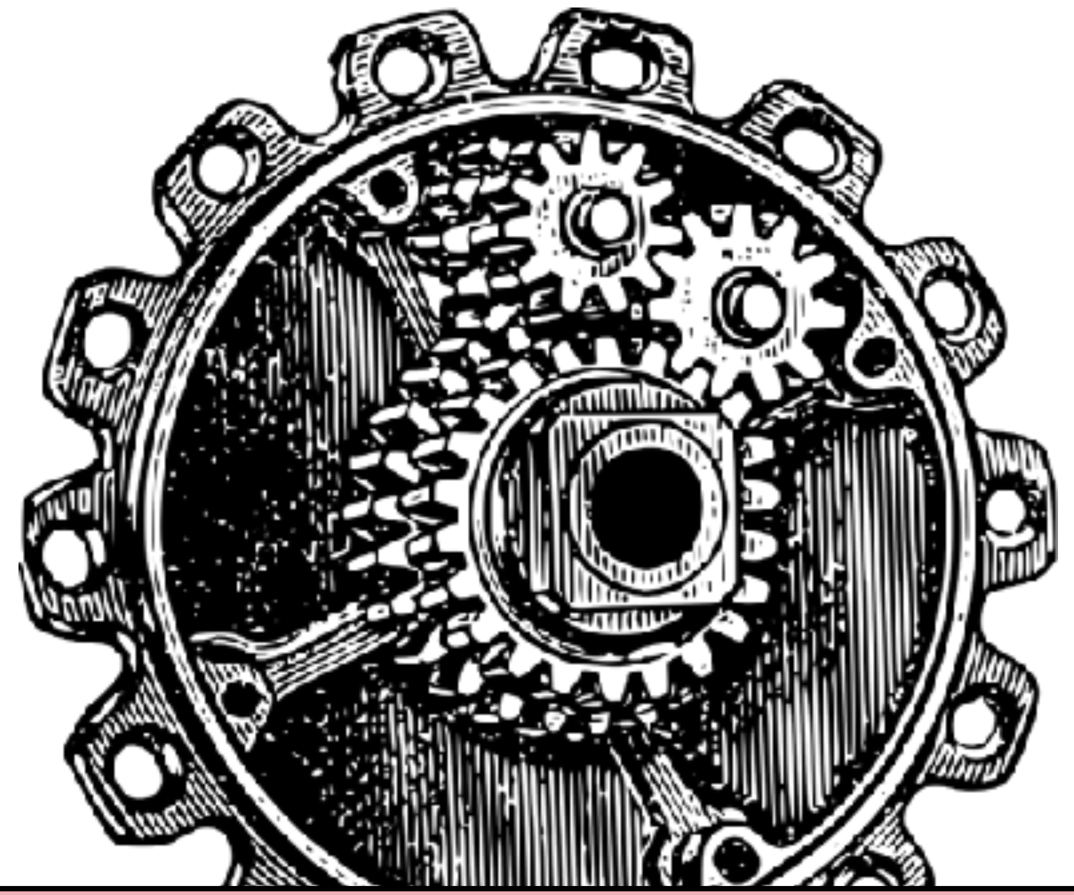
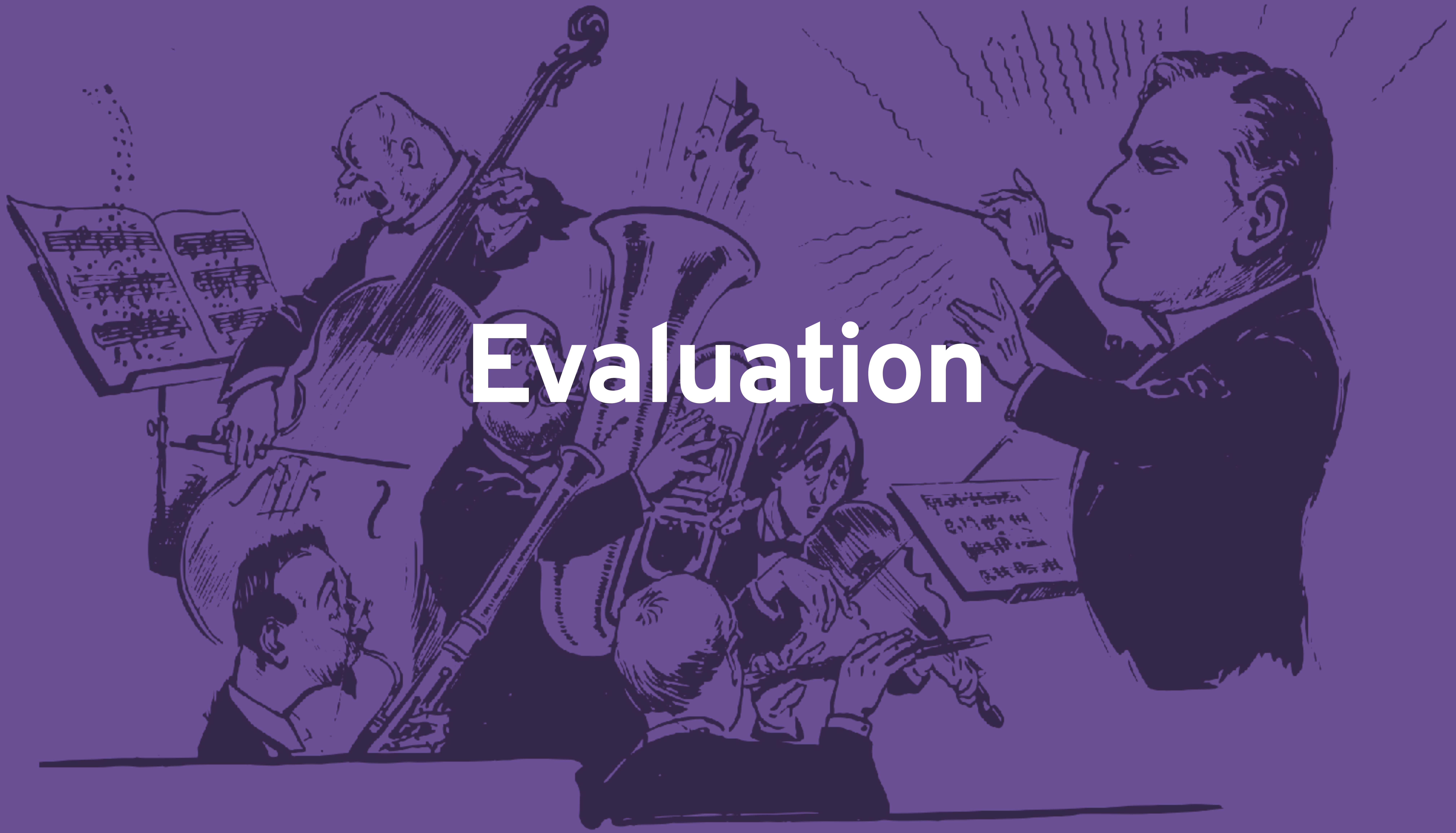


define network semantics in C# or via configurations (via Batfish)

write interfaces using C# library of temporal operators ($\mathscr{G}, \mathscr{U}^t, \mathscr{F}^t$)

check VCs *in parallel* on every node using Satisfiability Modulo Theories (SMT) solver

Evaluation



Evaluation

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does Timepiece scale to large networks?

does Timepiece handle complex policies?

how easy is it to write invariants for different properties?

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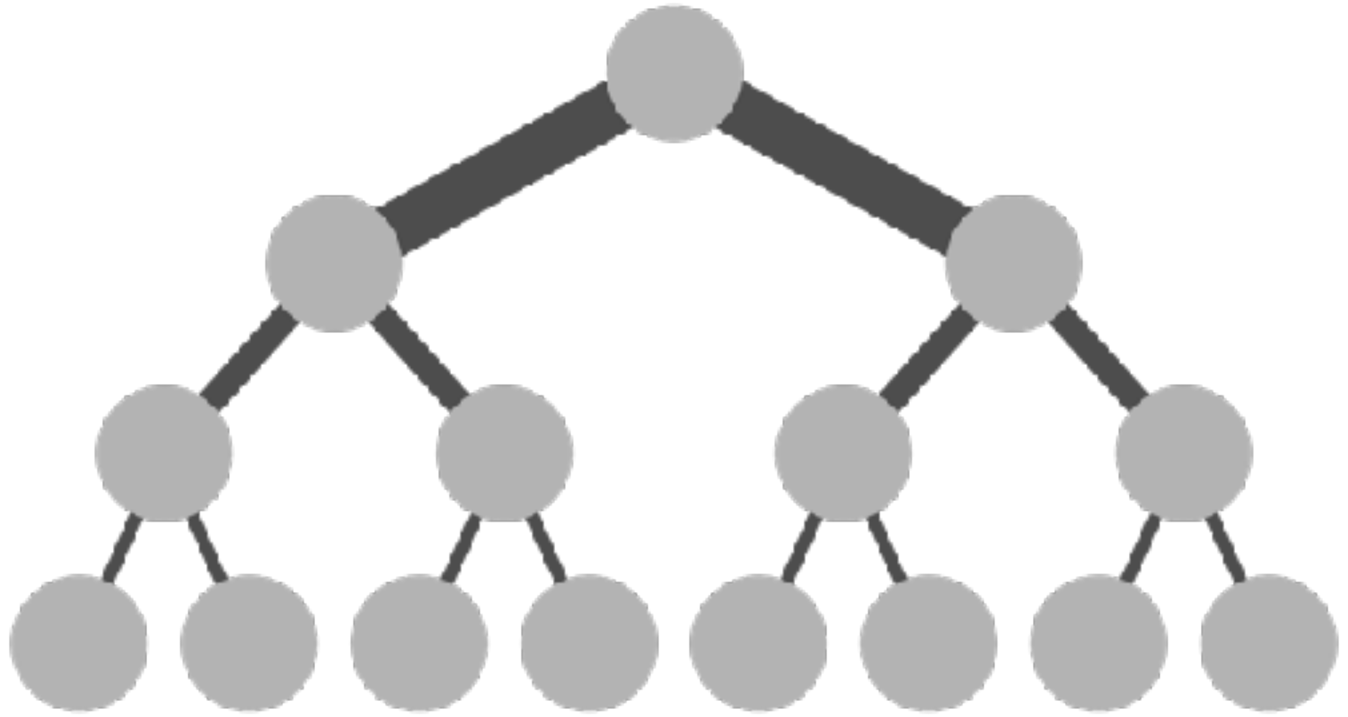

Fat-tree data center networks
C# model of eBGP routing protocol
20–2000 nodes

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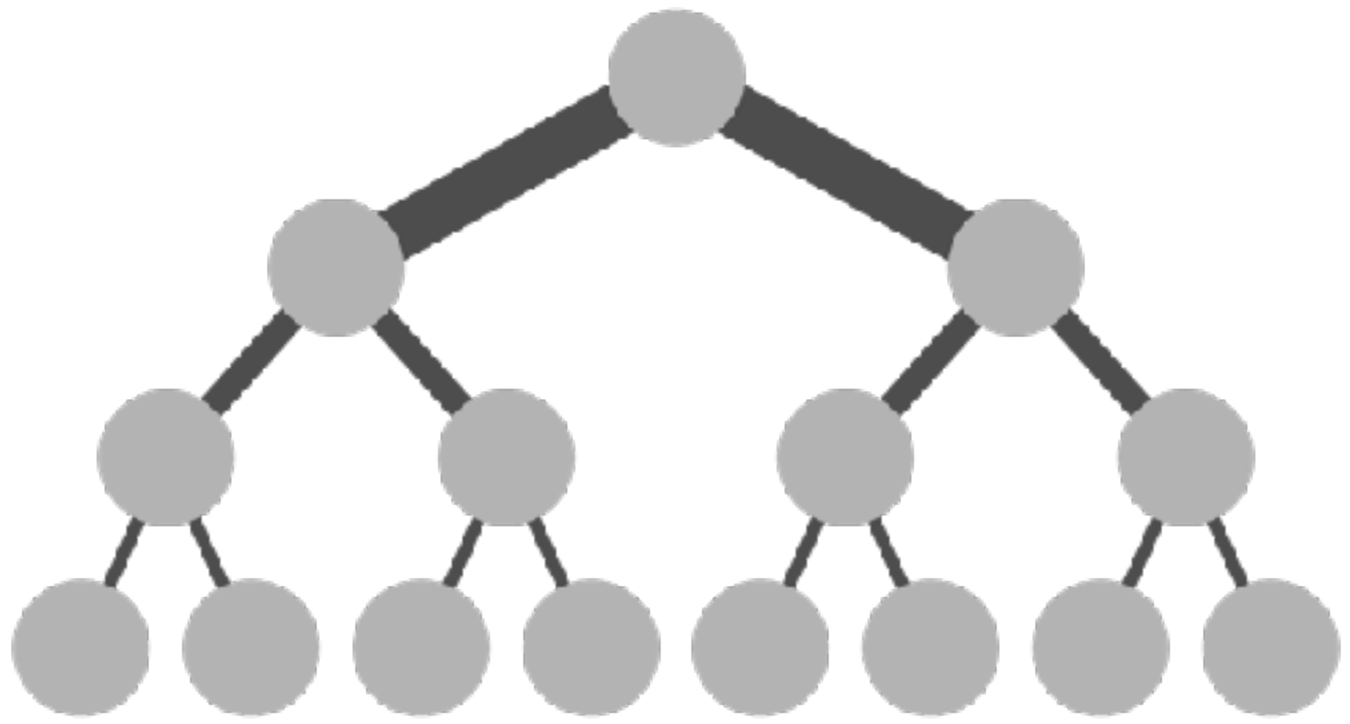

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Internet2 wide-area network

102,753 lines of Juniper configuration code

263 nodes (10 internal, 253 external)

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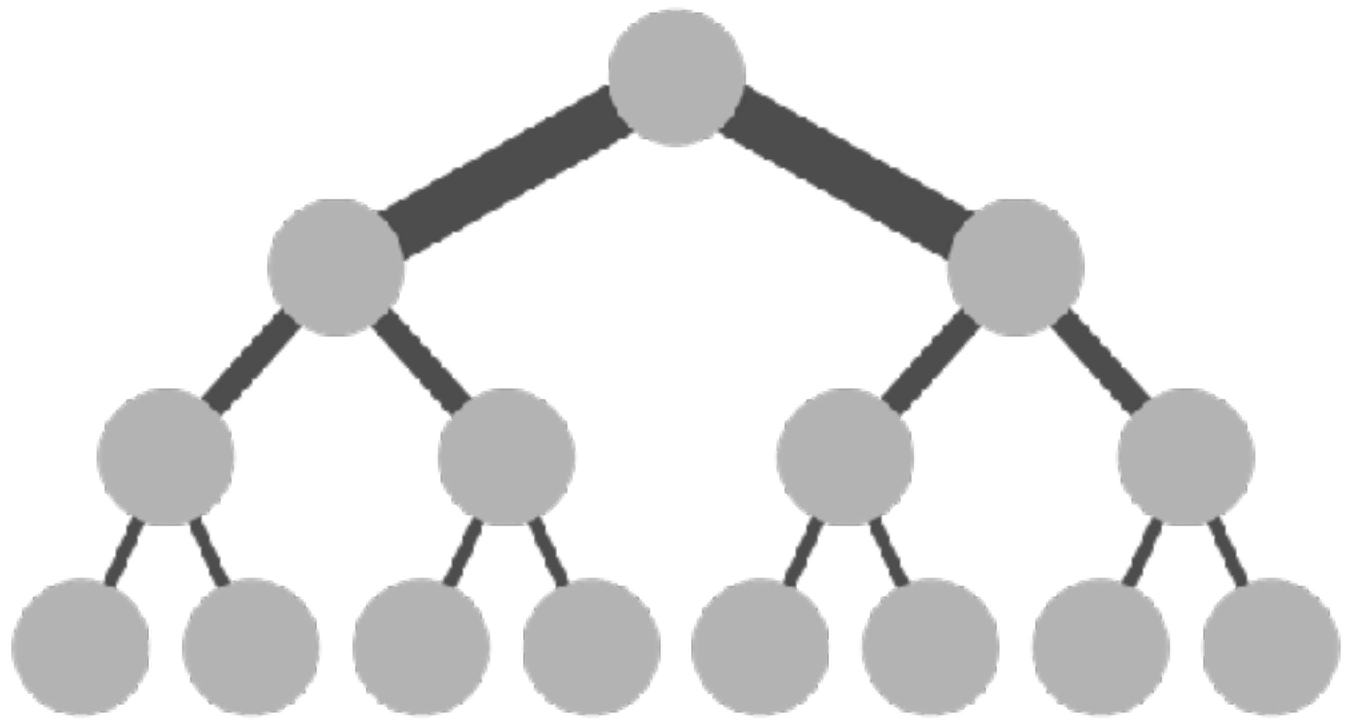

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Reachability | Path length
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Evaluation

on Microsoft Azure D96s VM with 96 vCPUs and 384GB RAM

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Benchmark
Reachability
Path length
Valley freedom
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Evaluation

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Benchmark	Network LoC
Reachability	81
Path length	88
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Evaluation

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Benchmark	Network LoC	Annotation LoC
Reachability	81	3
Path length	88	7
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Benchmark	Network LoC	Annotation LoC	Nodes	Monolithic time
Reachability	81	3	2000	14s
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BGP misconfiguration/attack:
a “hijacker” node announces it has a path to a prefix it doesn’t own, misleading others to route through the hijacker

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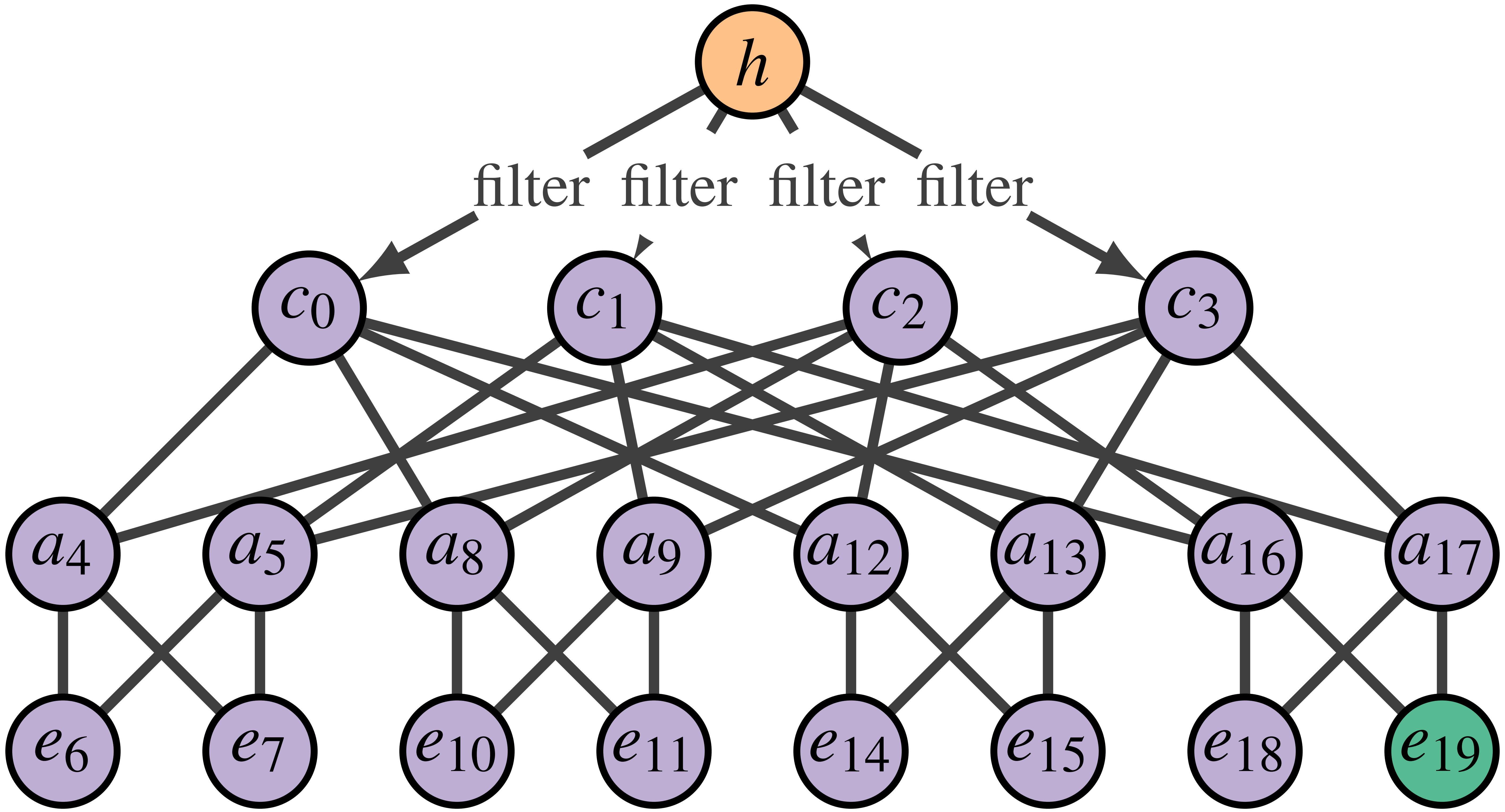

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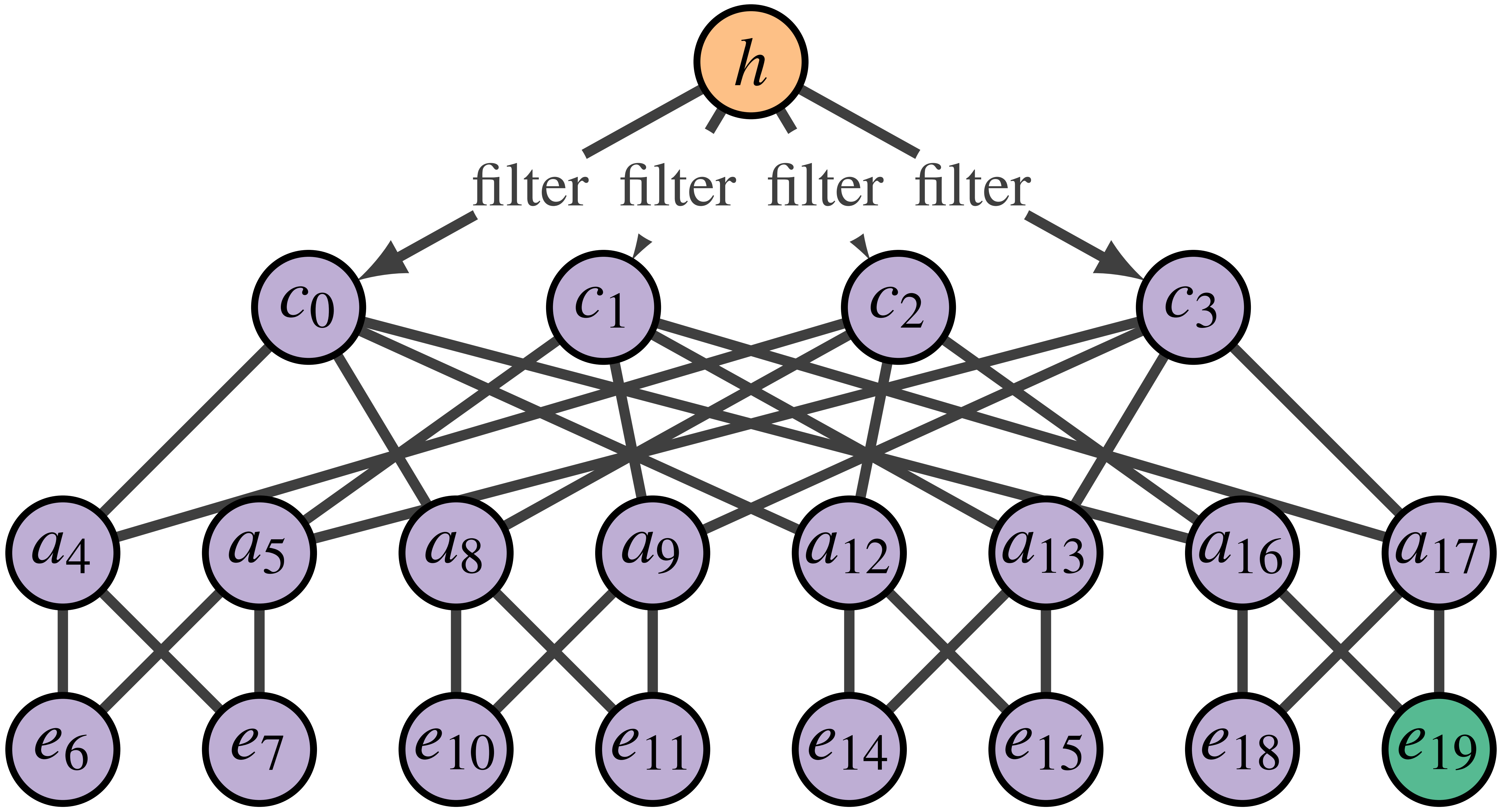

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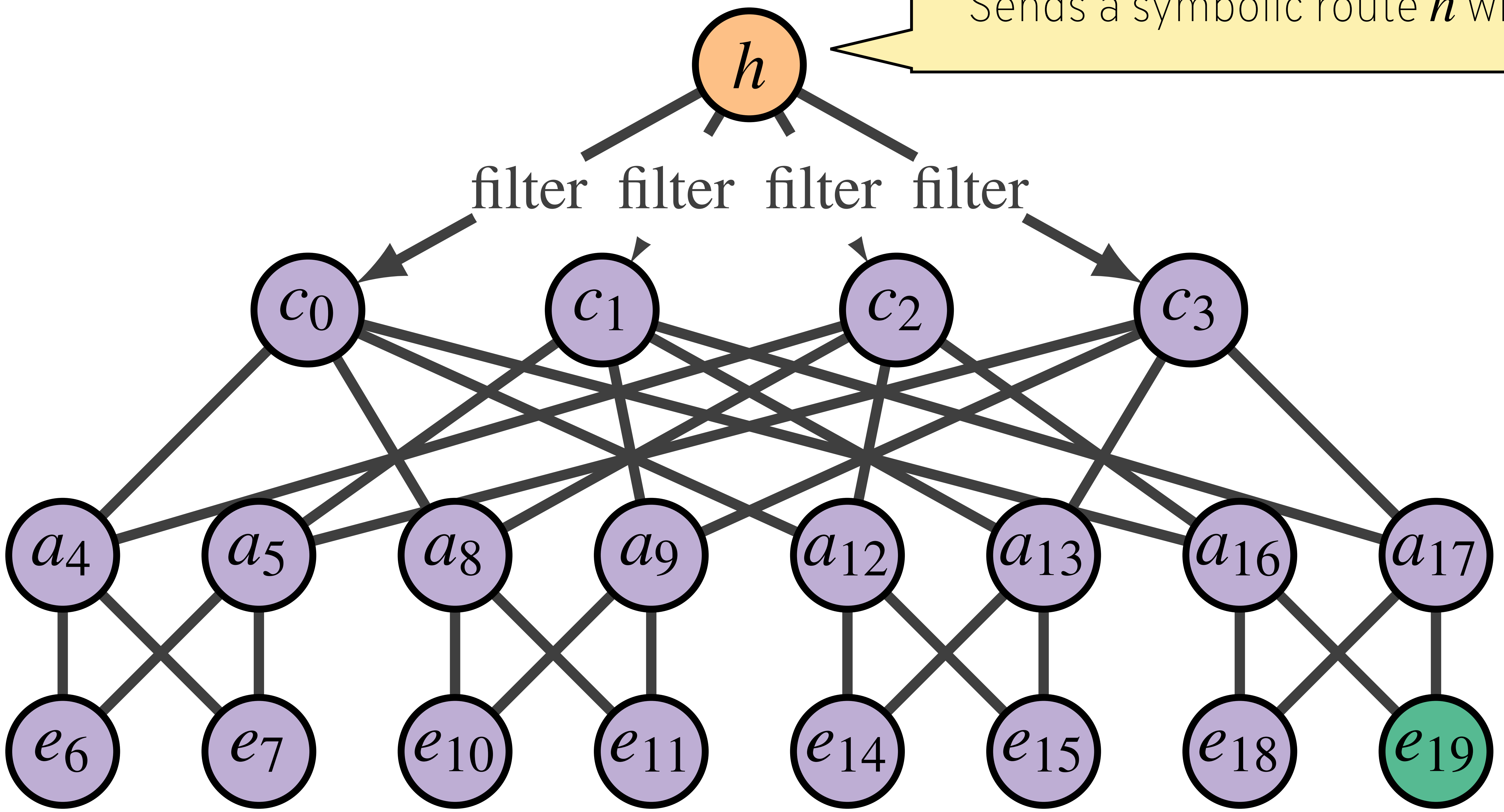

Sends a symbolic route h with **tag** true

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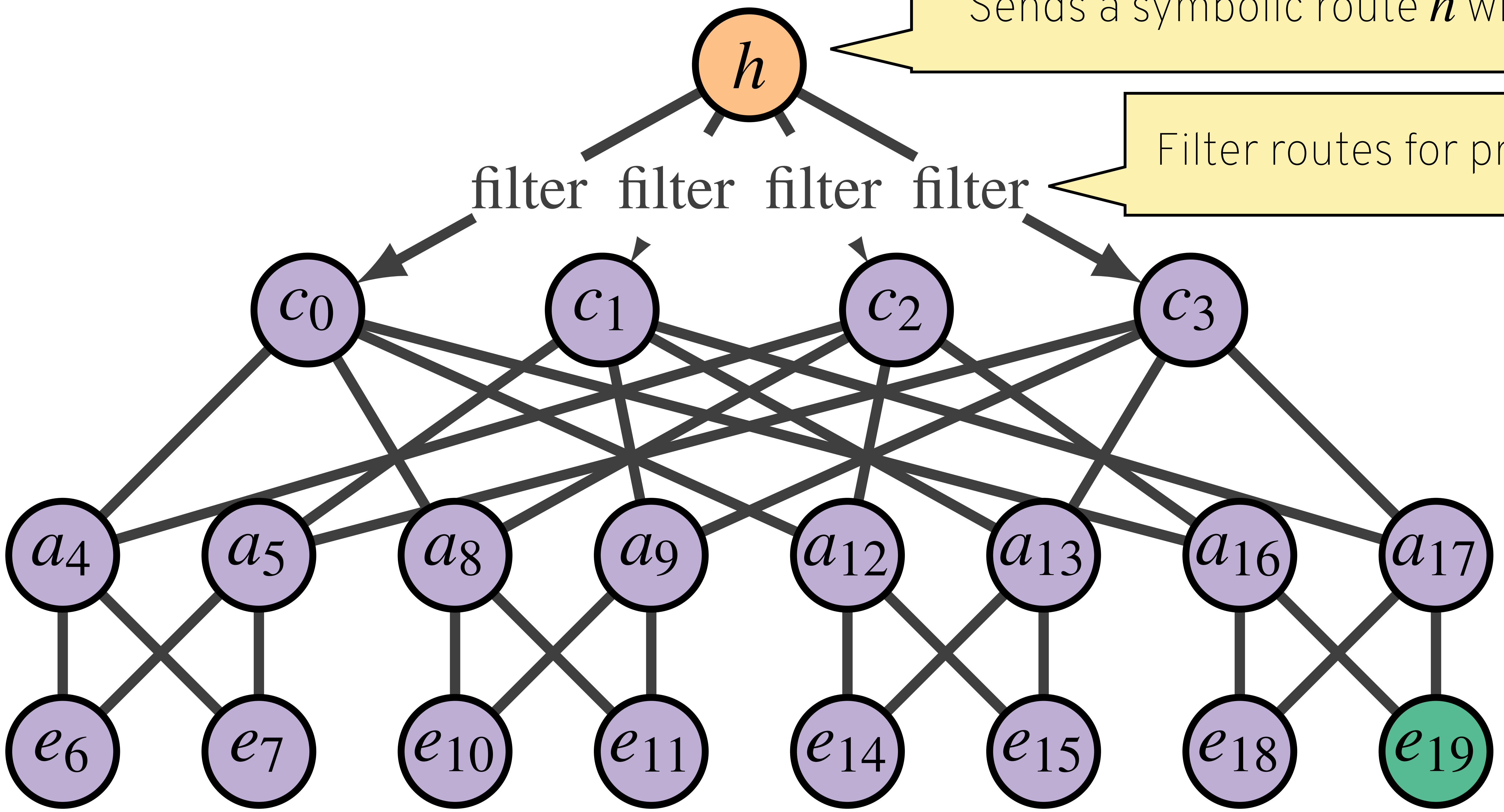
Filter routes for prefix p



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Fat-tree Hijack Filtering

Converged routes for prefix p should not come from h

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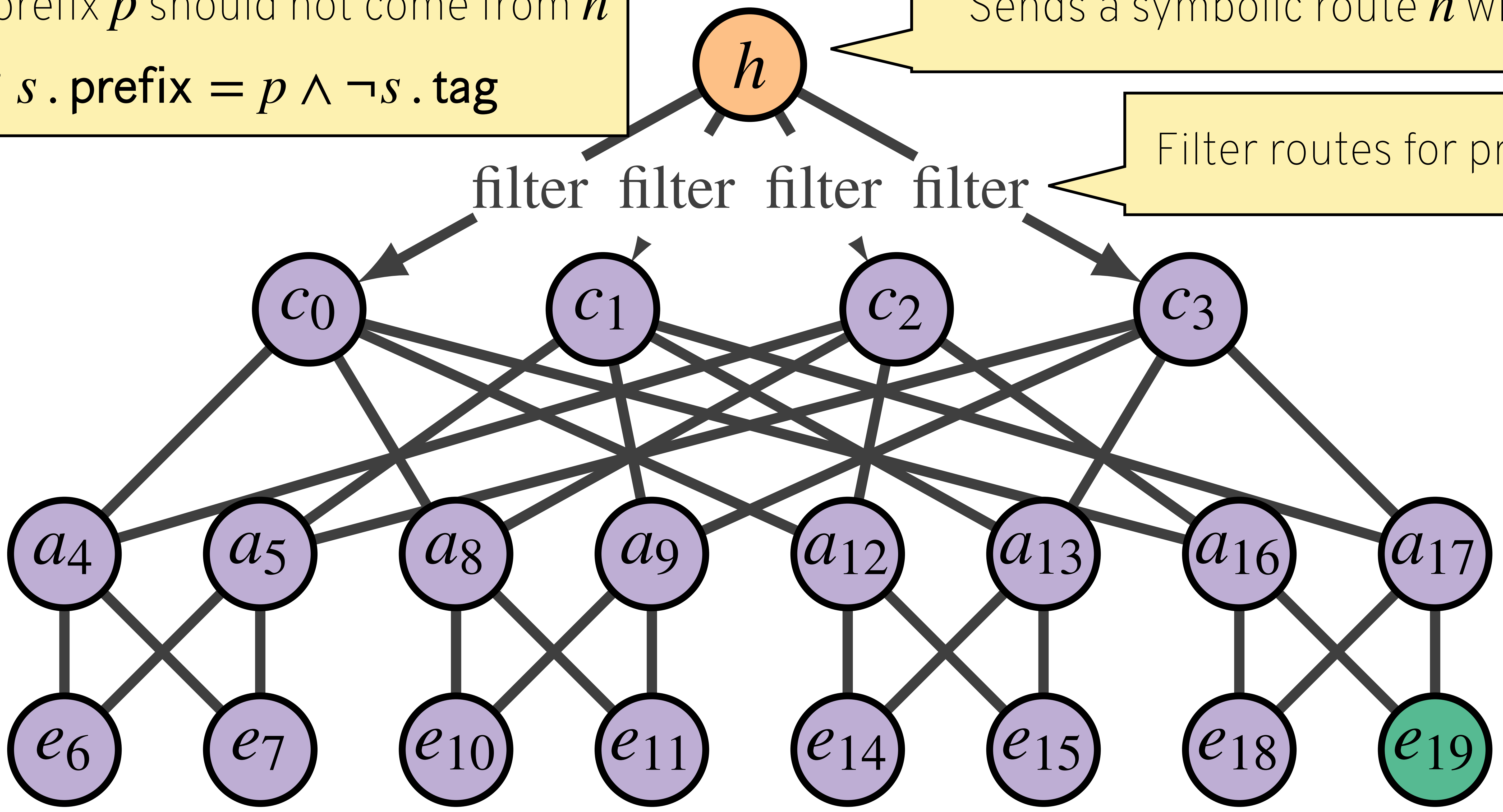

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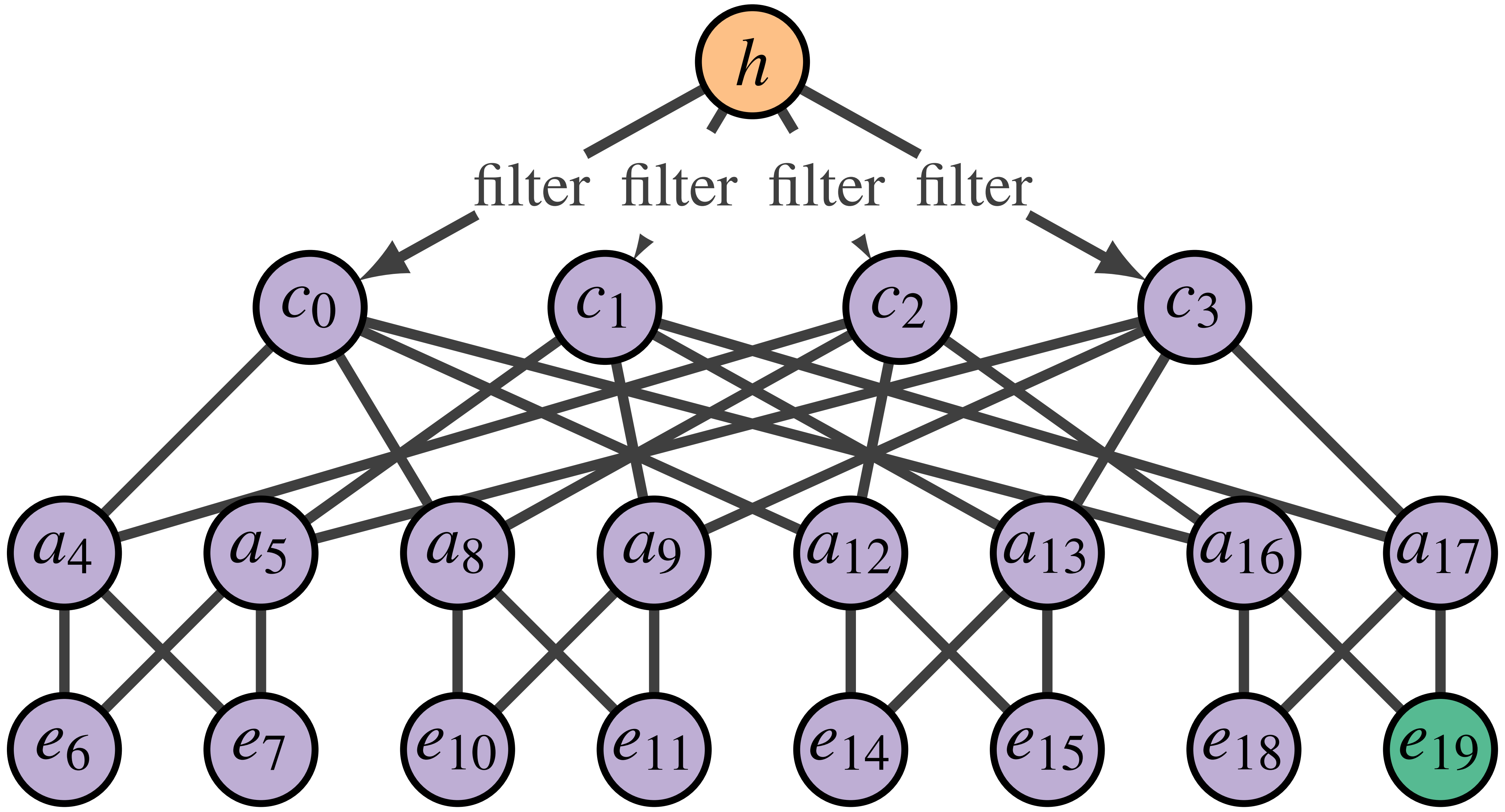
Interface **composes** an "eventual invariant" with a "safety invariant"



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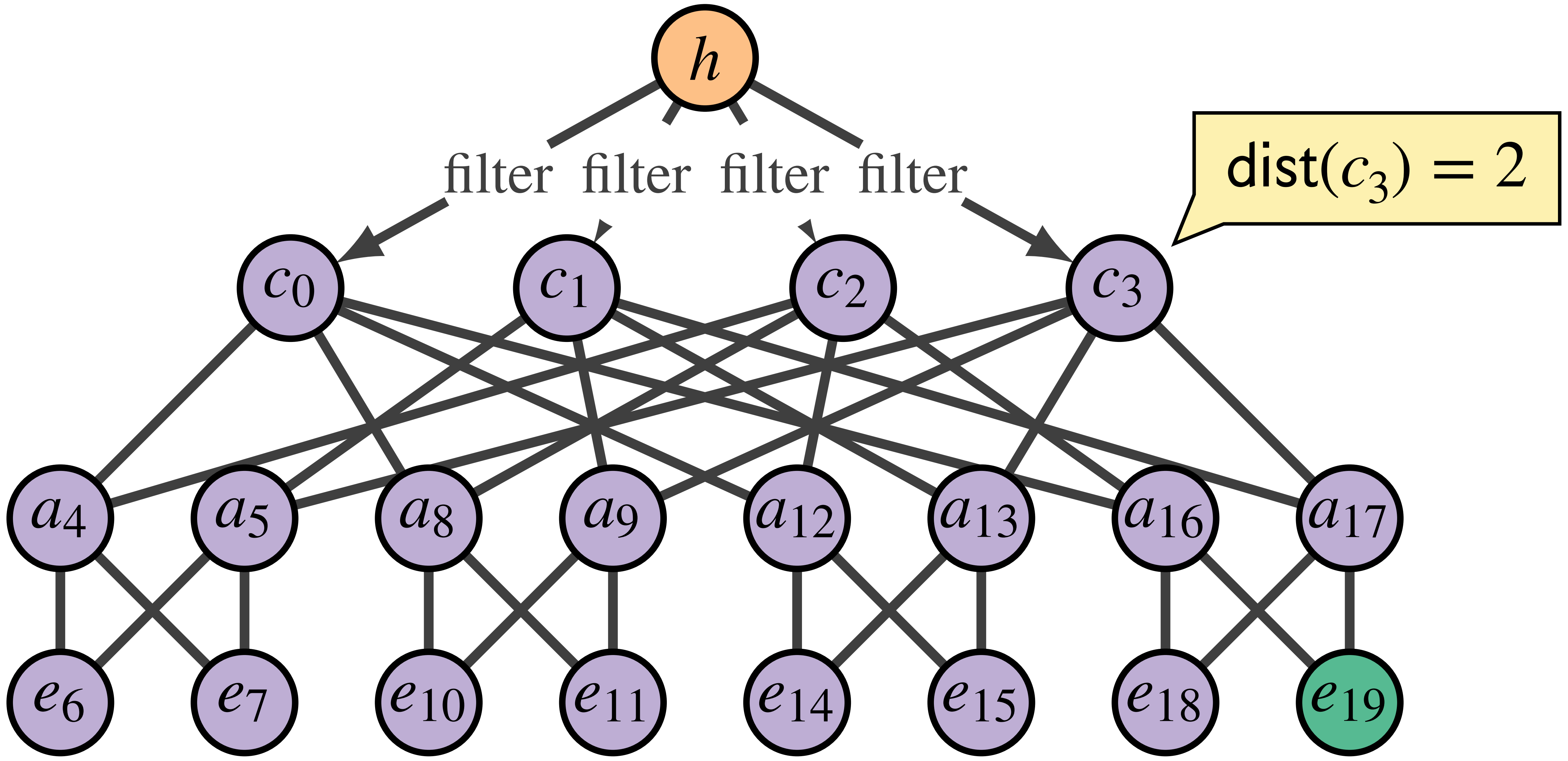

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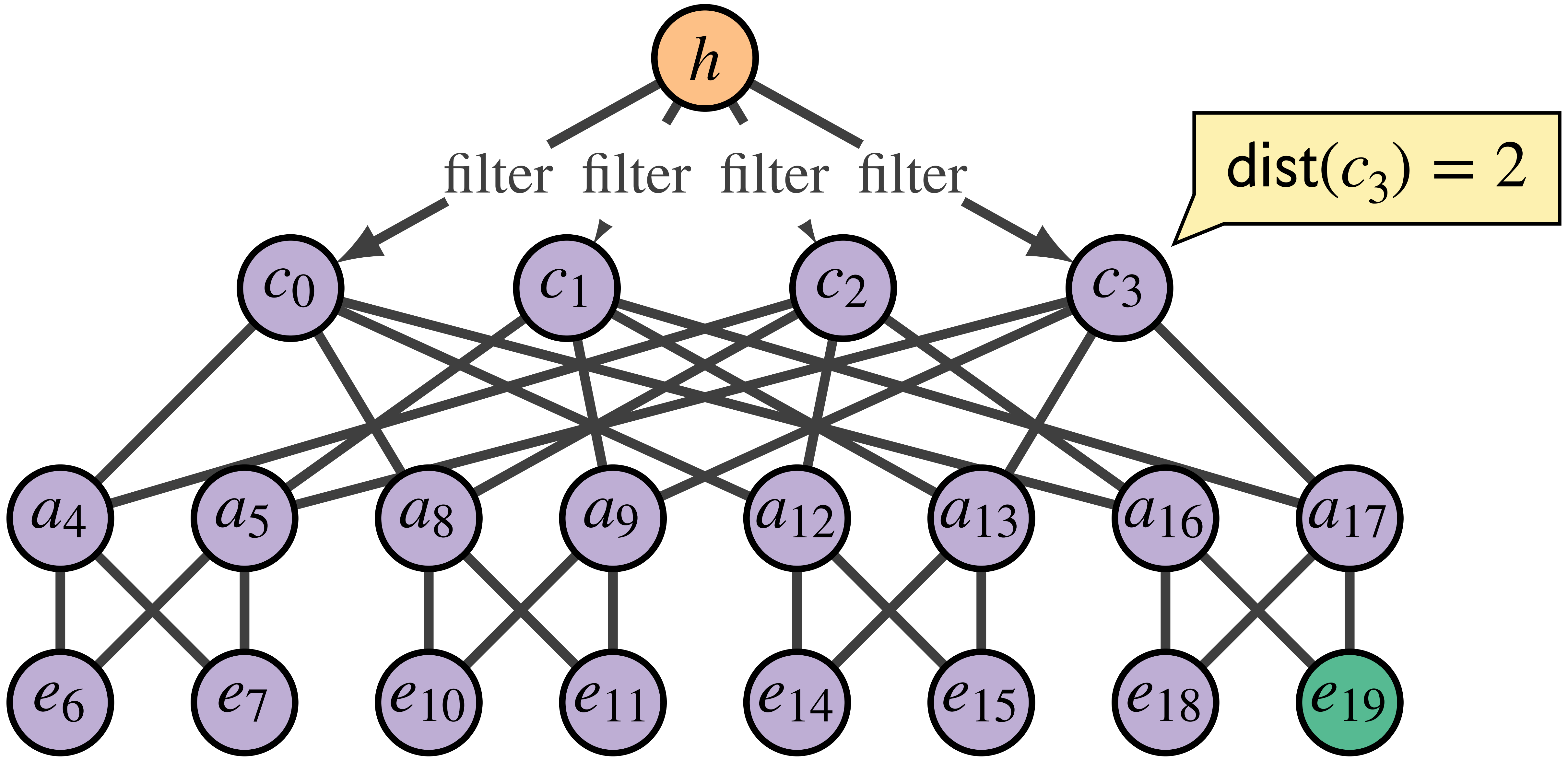

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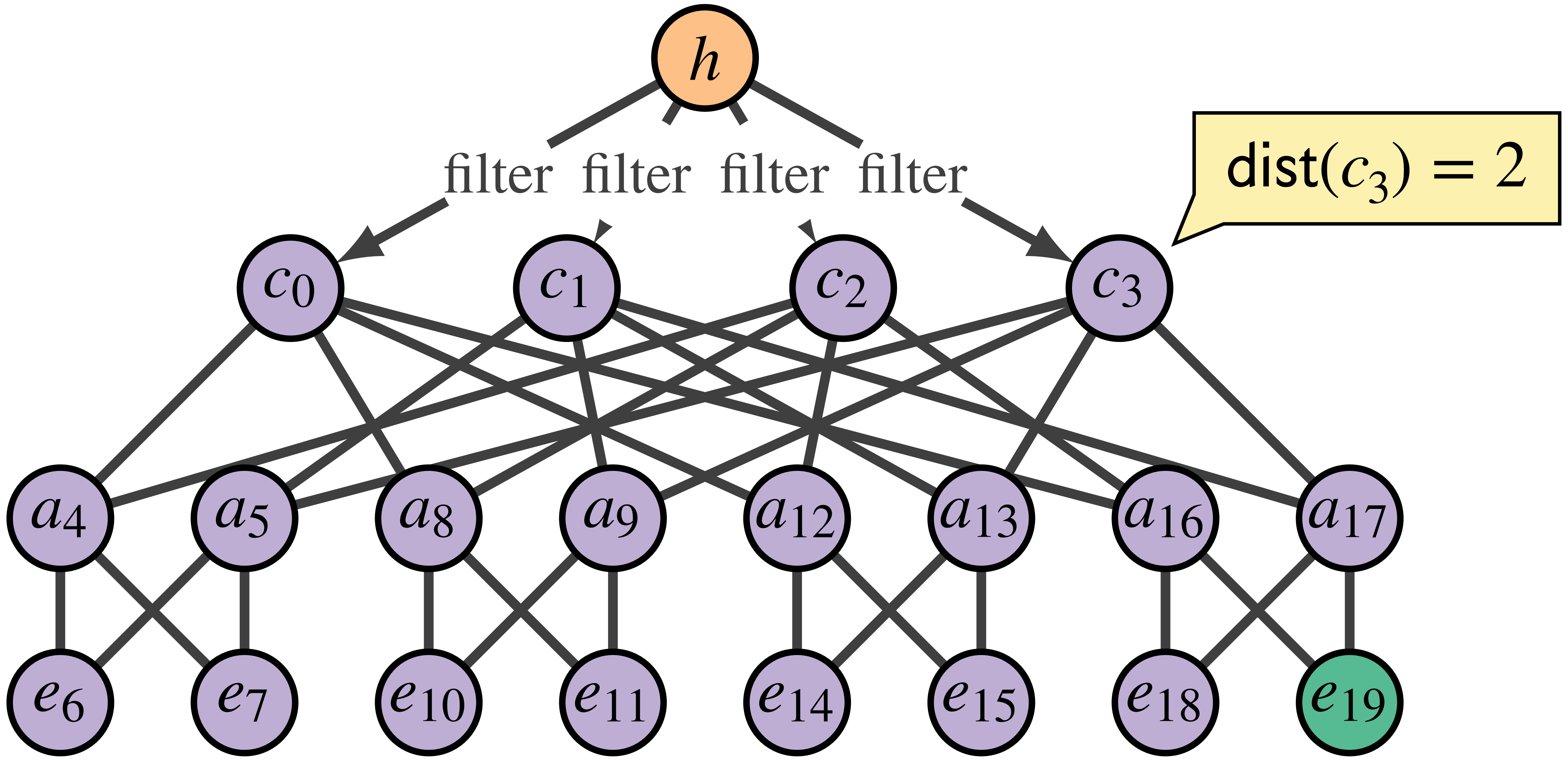
Nodes **never** use hijacking routes

$\mathcal{G}(s.\mathsf{prefix} = p \rightarrow \neg s.\mathsf{tag})$



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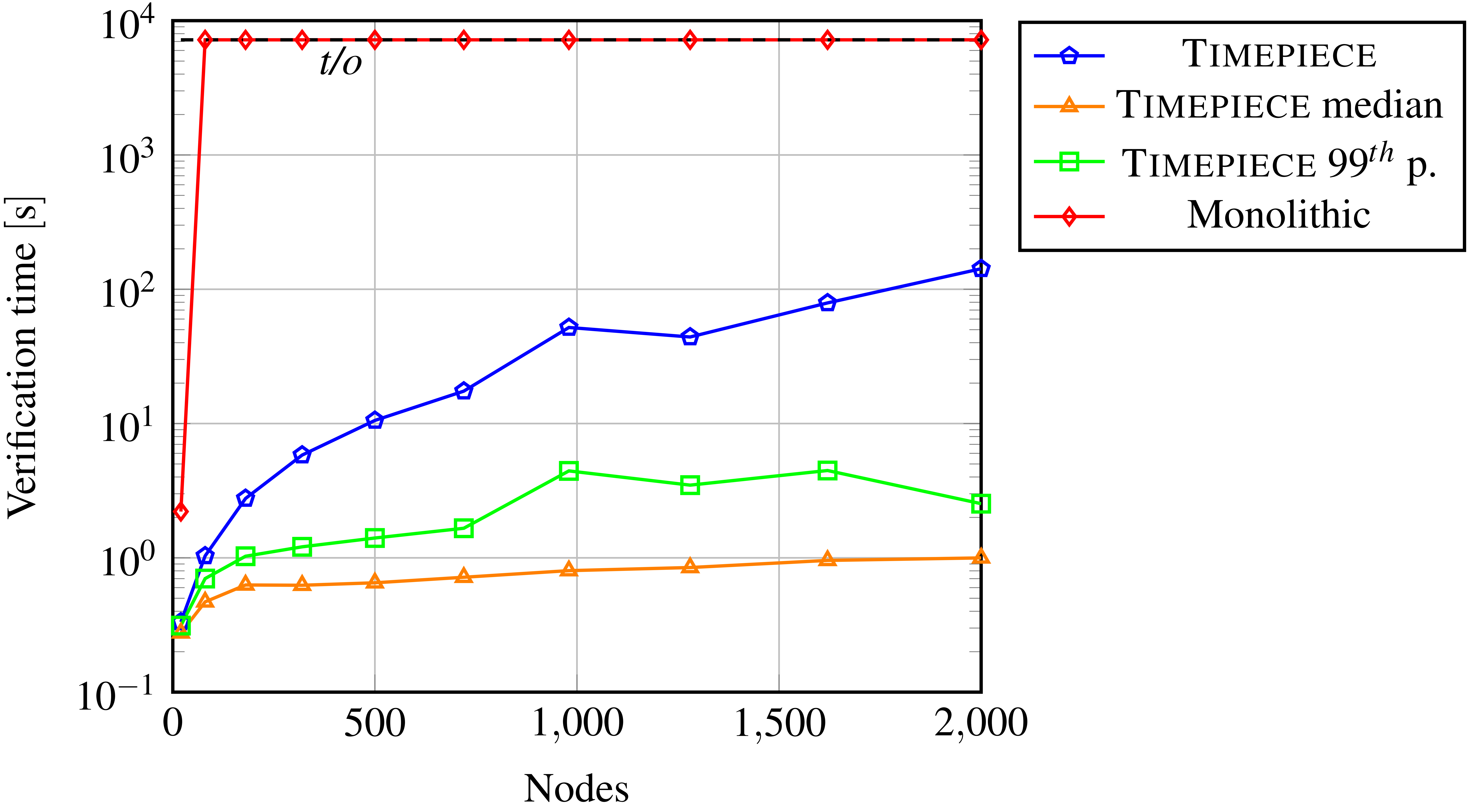
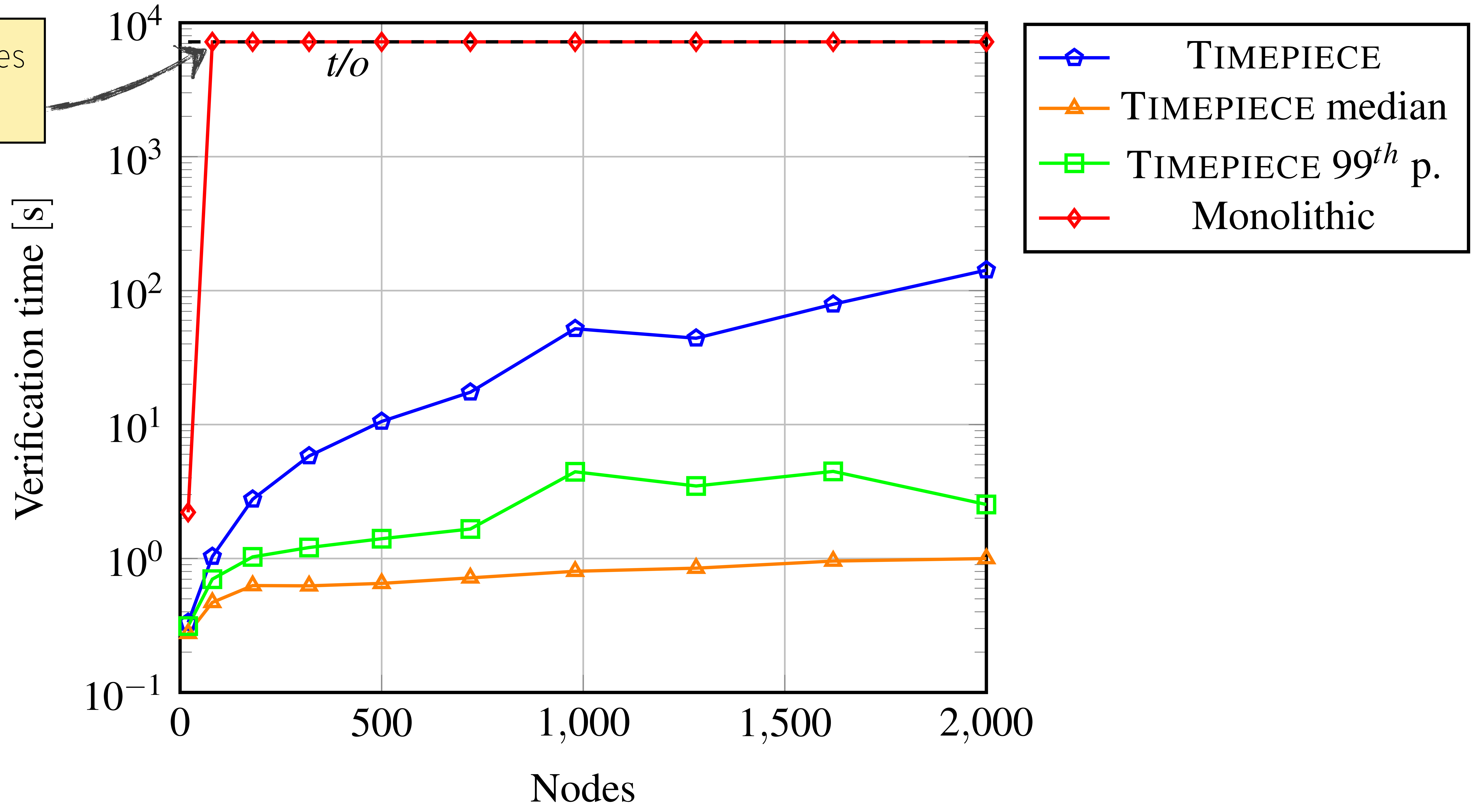


Fat-tree Hijack Filtering

Monolithic verification times out (>2h) at 80 nodes



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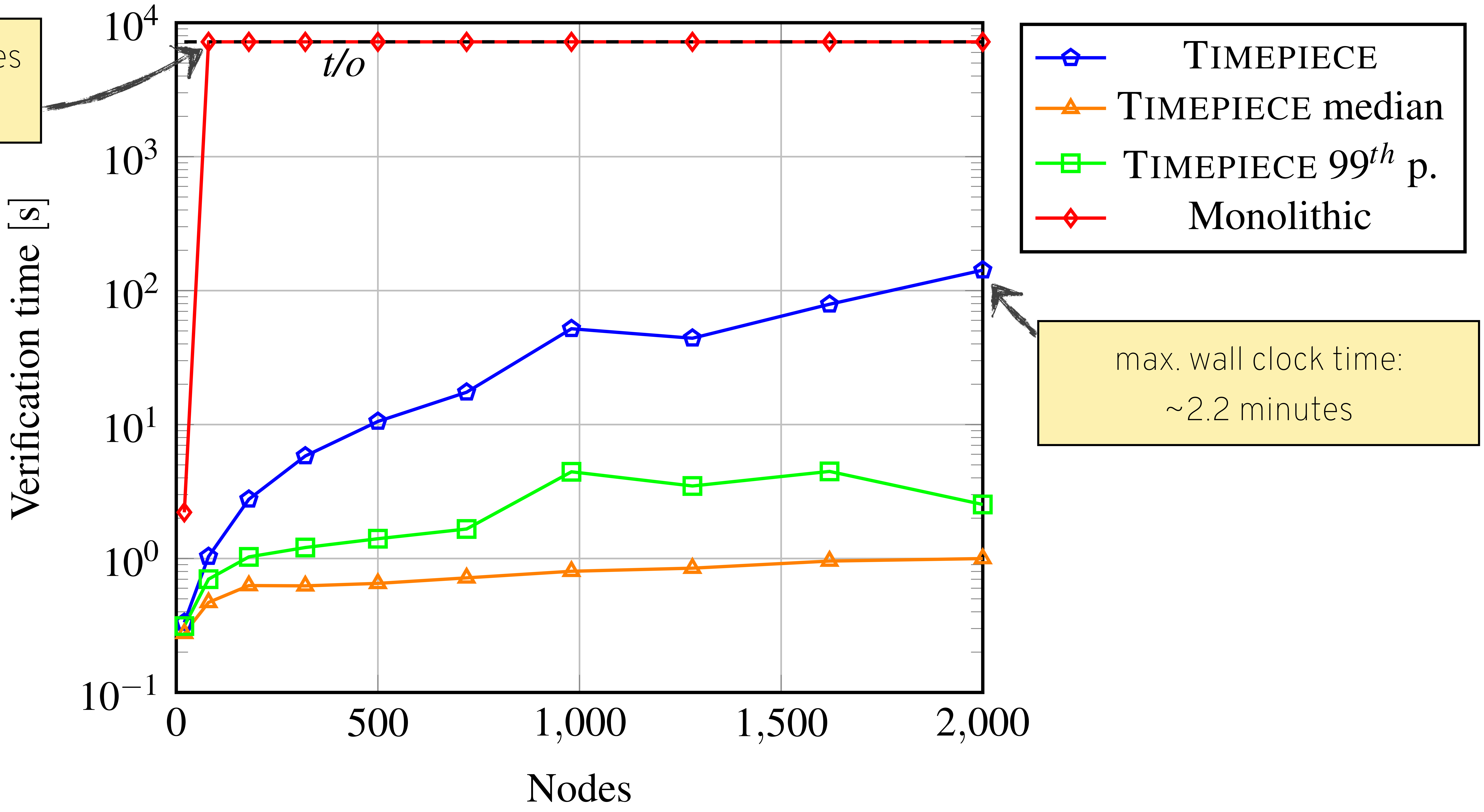

max. wall clock time: ~2.2 minutes

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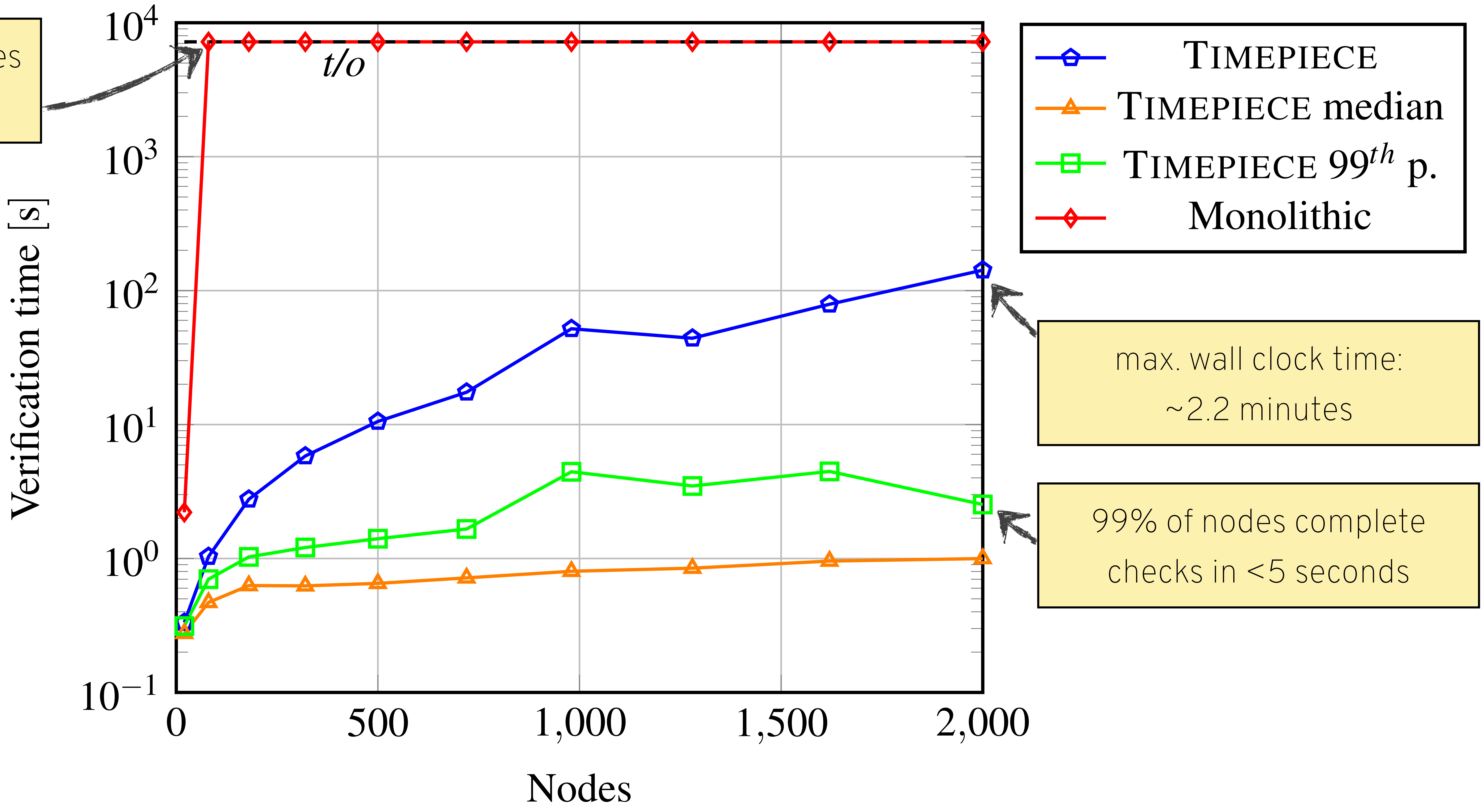

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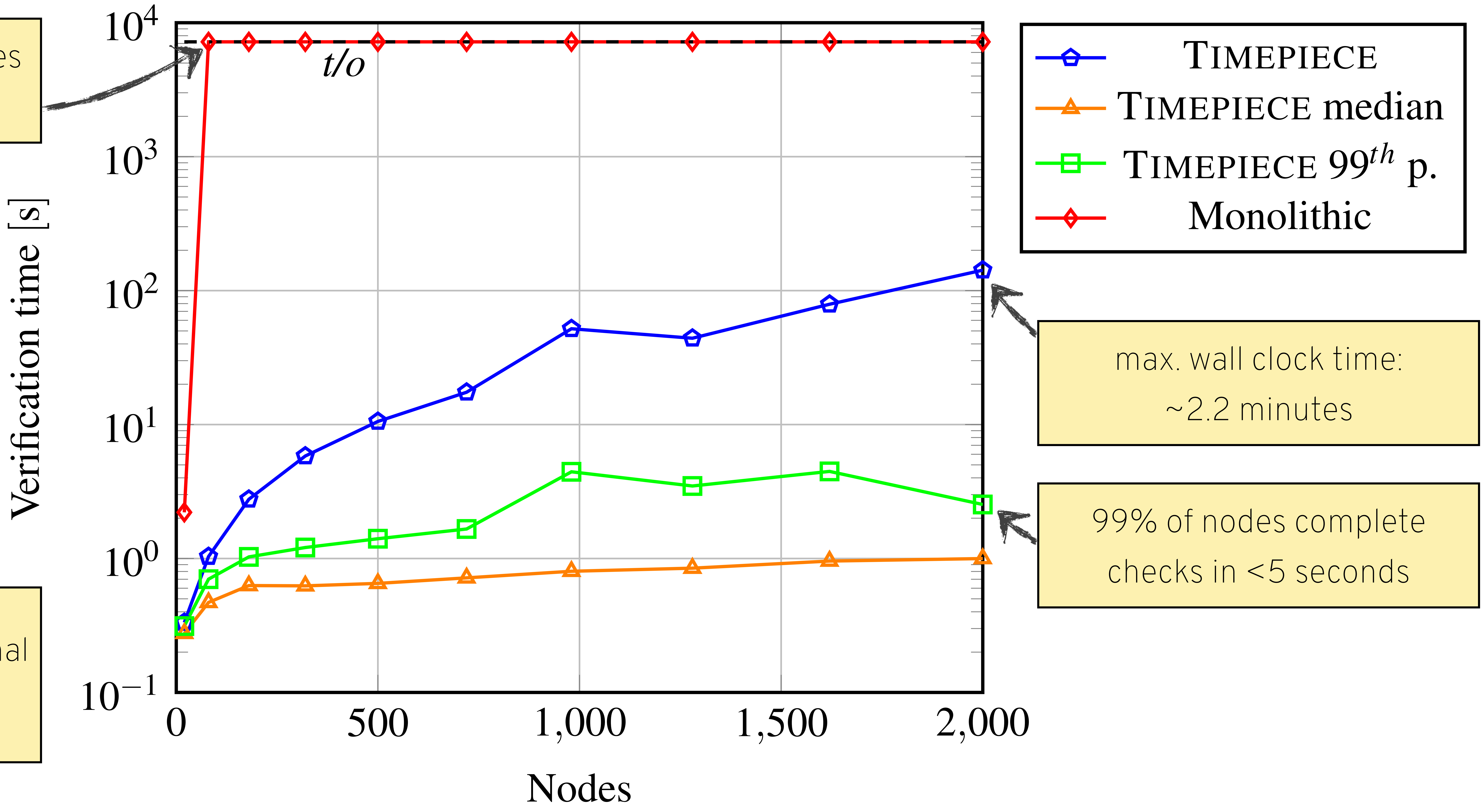
99% of nodes complete checks in <5 seconds

Fat-tree Hijack Filtering

Monolithic verification times out (>2h) at 80 nodes

verification time proportional to node's degree



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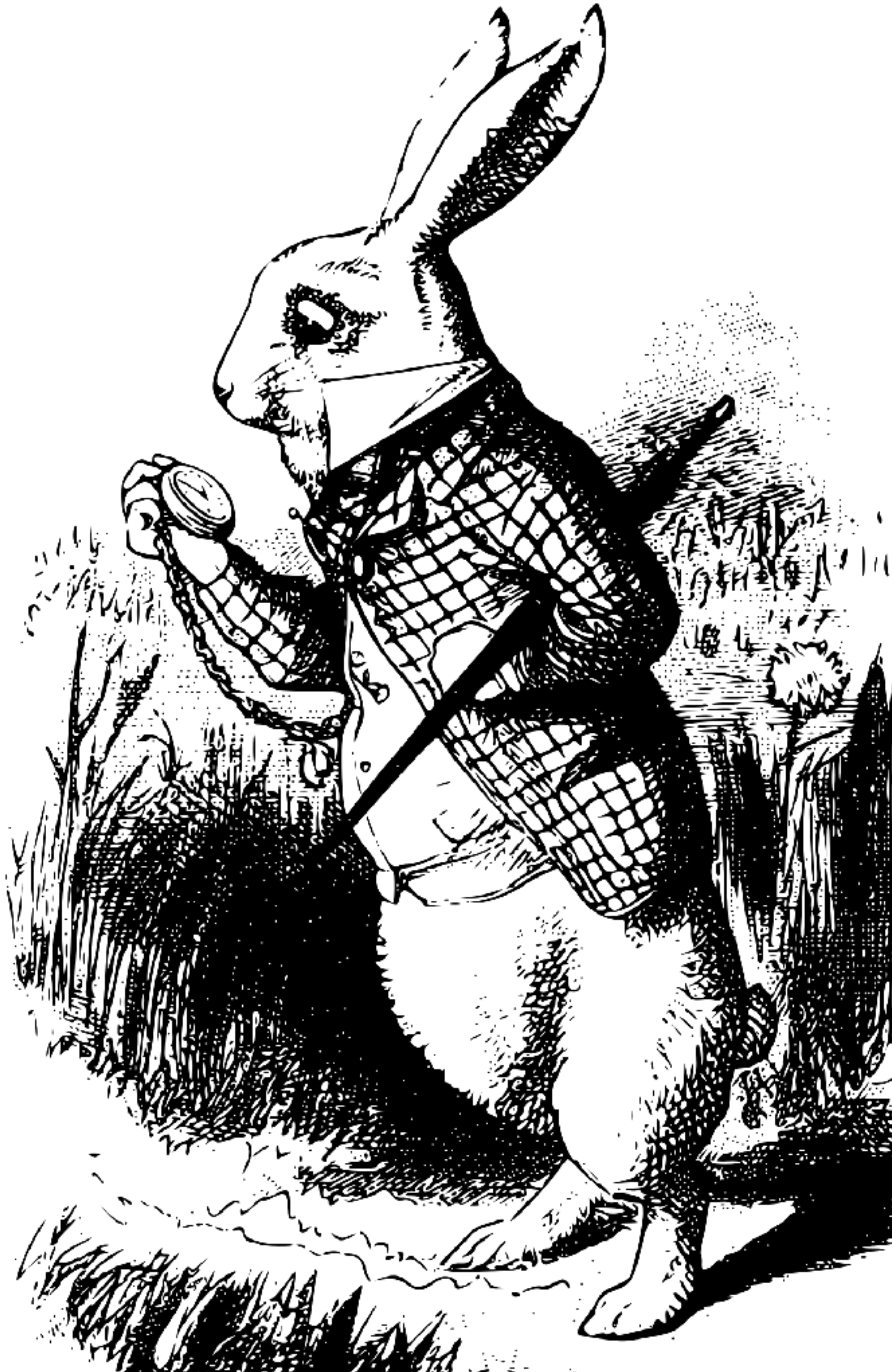
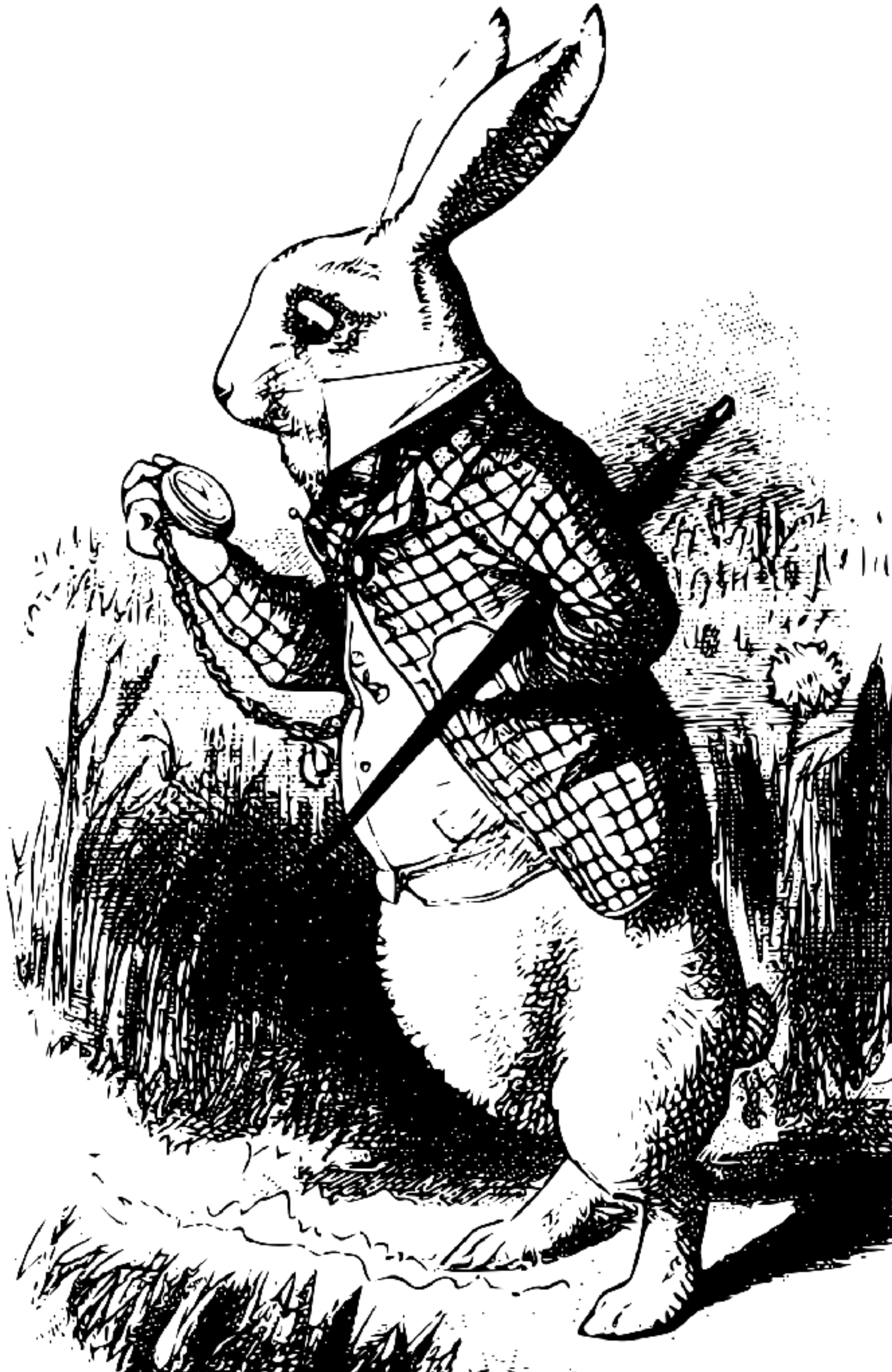
Takeaways



Takeaways

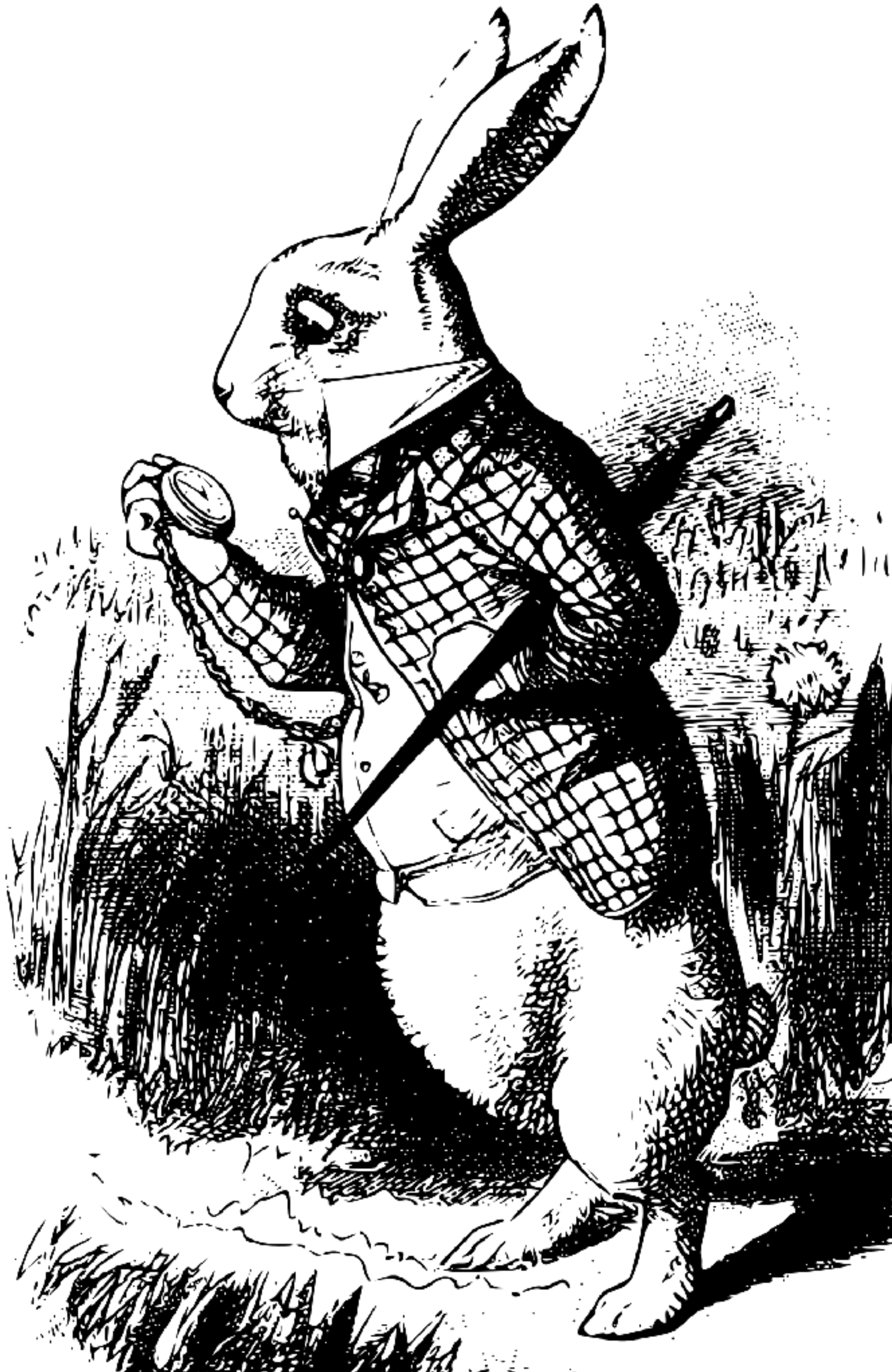
Big, complex control planes need modular tools



Takeaways

Big, complex control planes need modular tools

Temporal invariants provide a **correct basis for modular verification**



Takeaways

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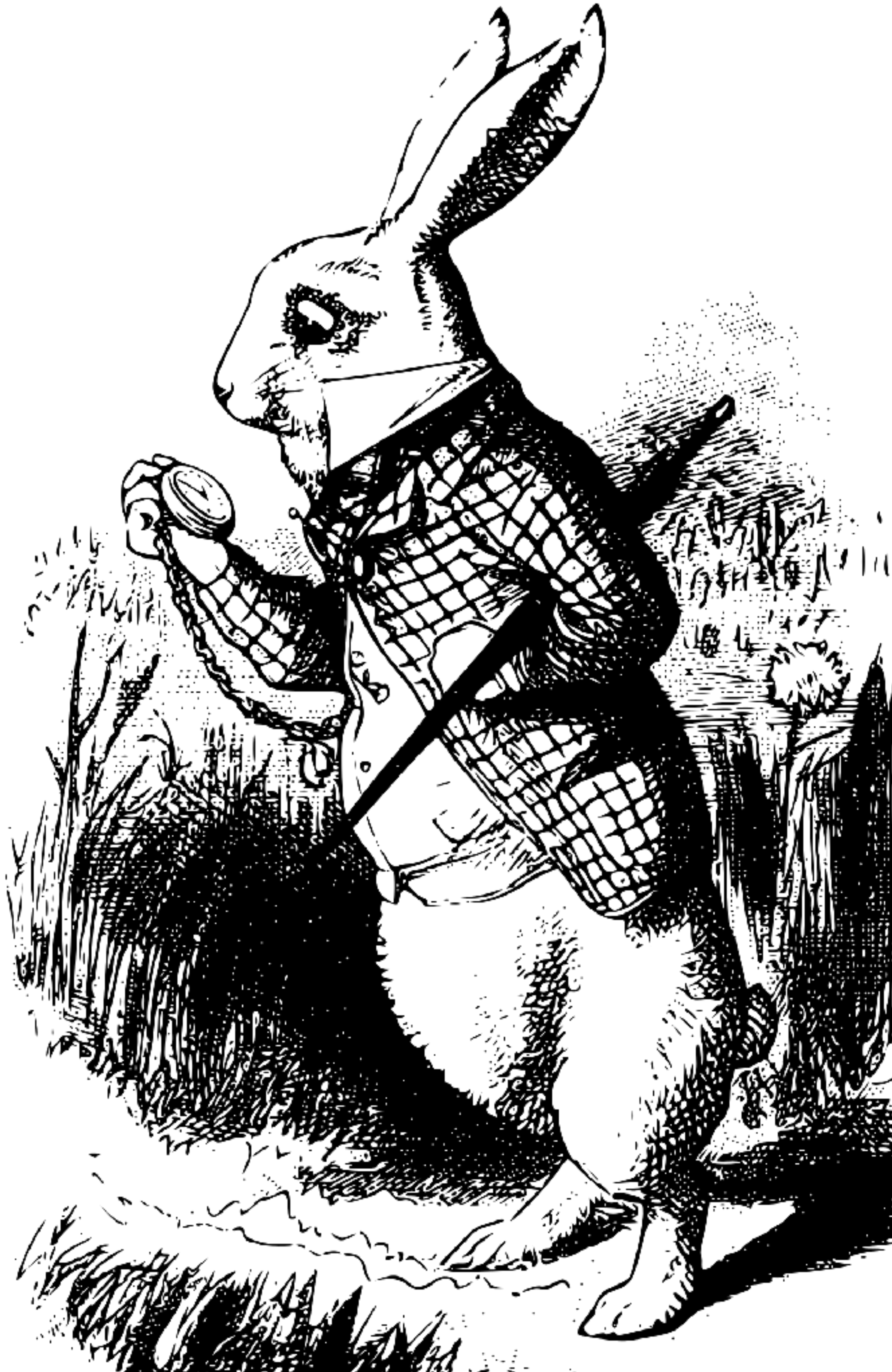
Scale to thousands of nodes & complex policies



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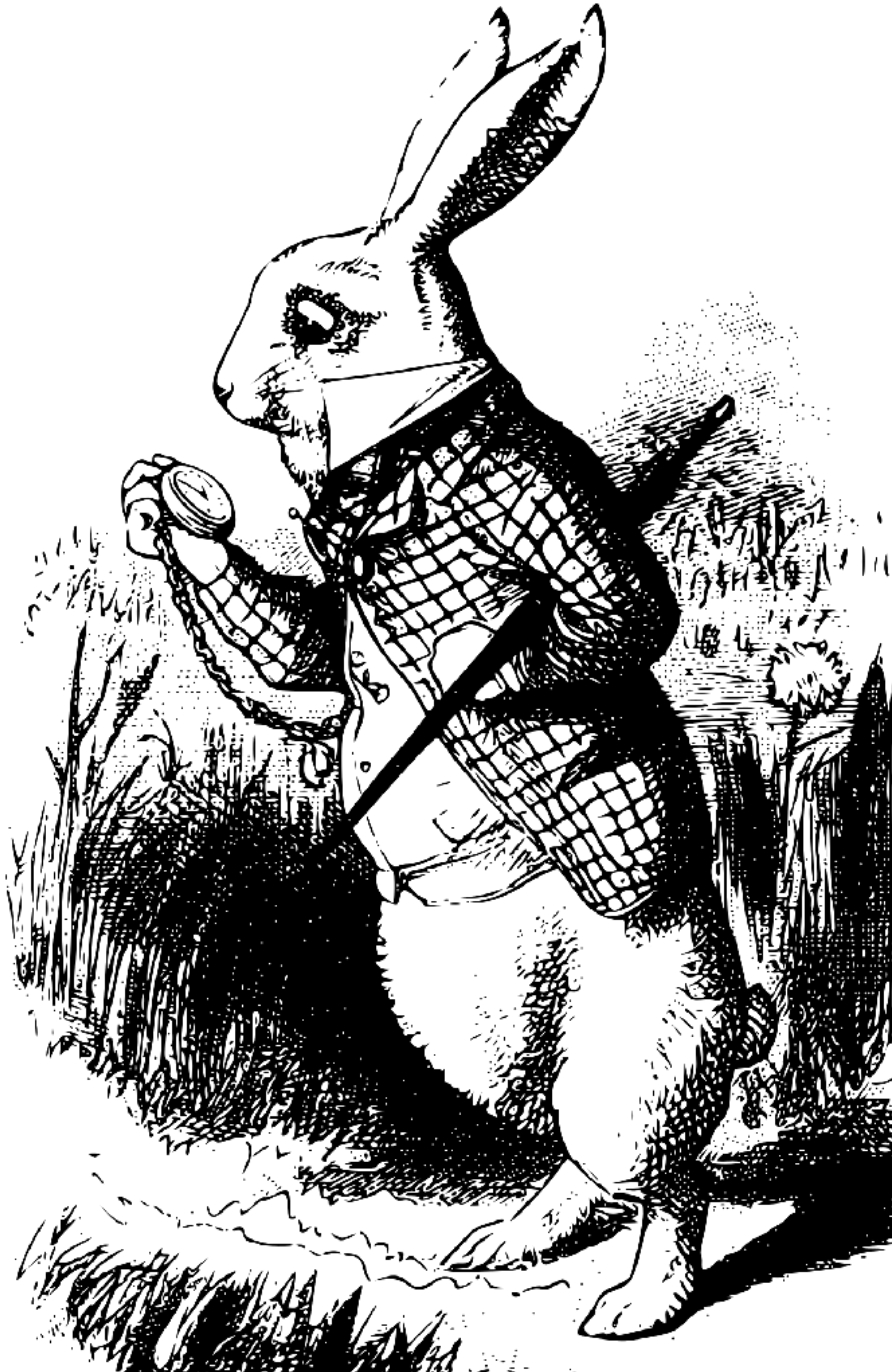
Read the paper to learn more!



Thank You!

I'm looking for a job!

cs.princeton.edu/~tthijm

Our paper

Tim Alberdingk Thijm
Princeton

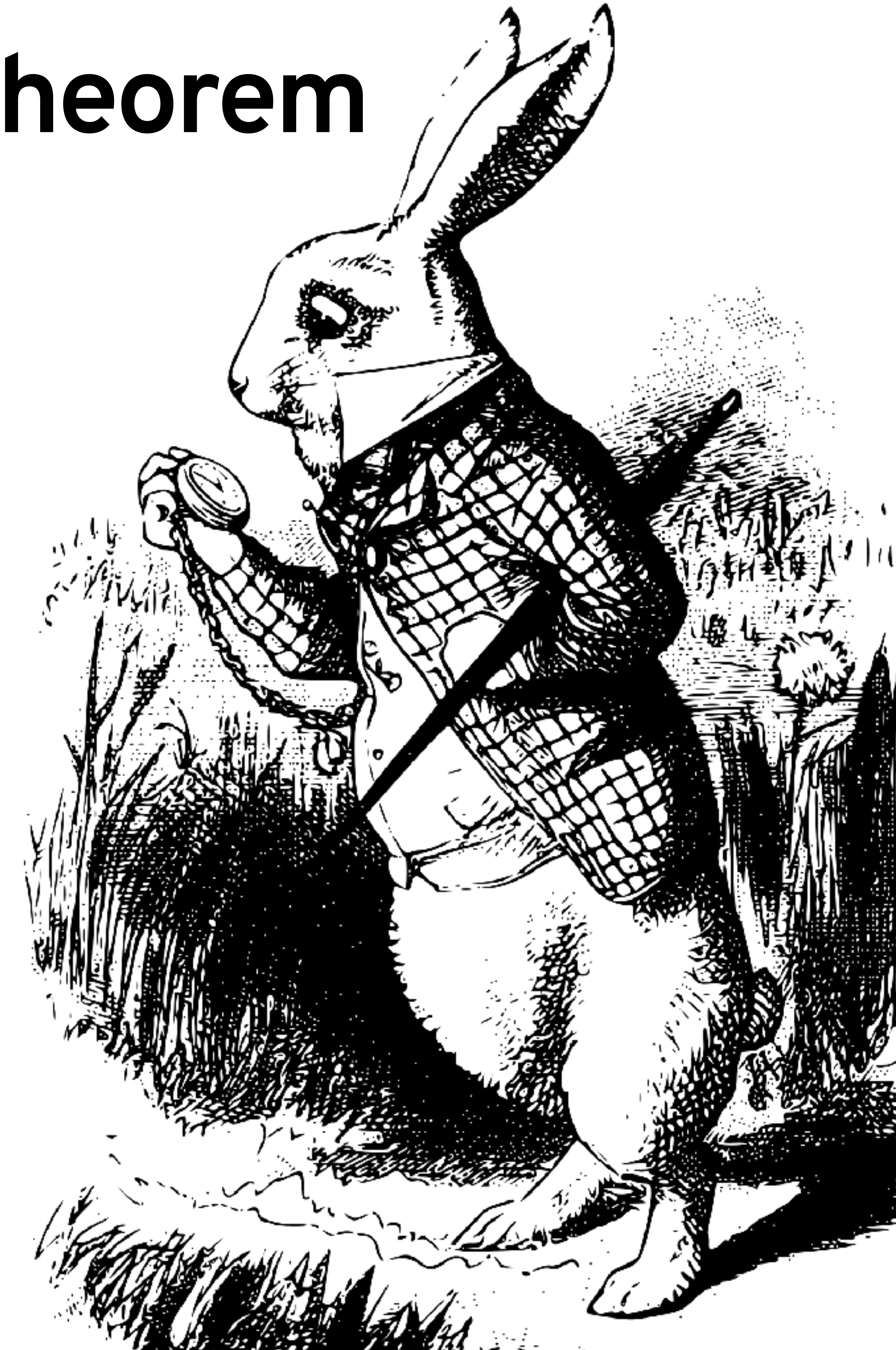
Ryan Beckett
Microsoft Research

Aarti Gupta
Princeton

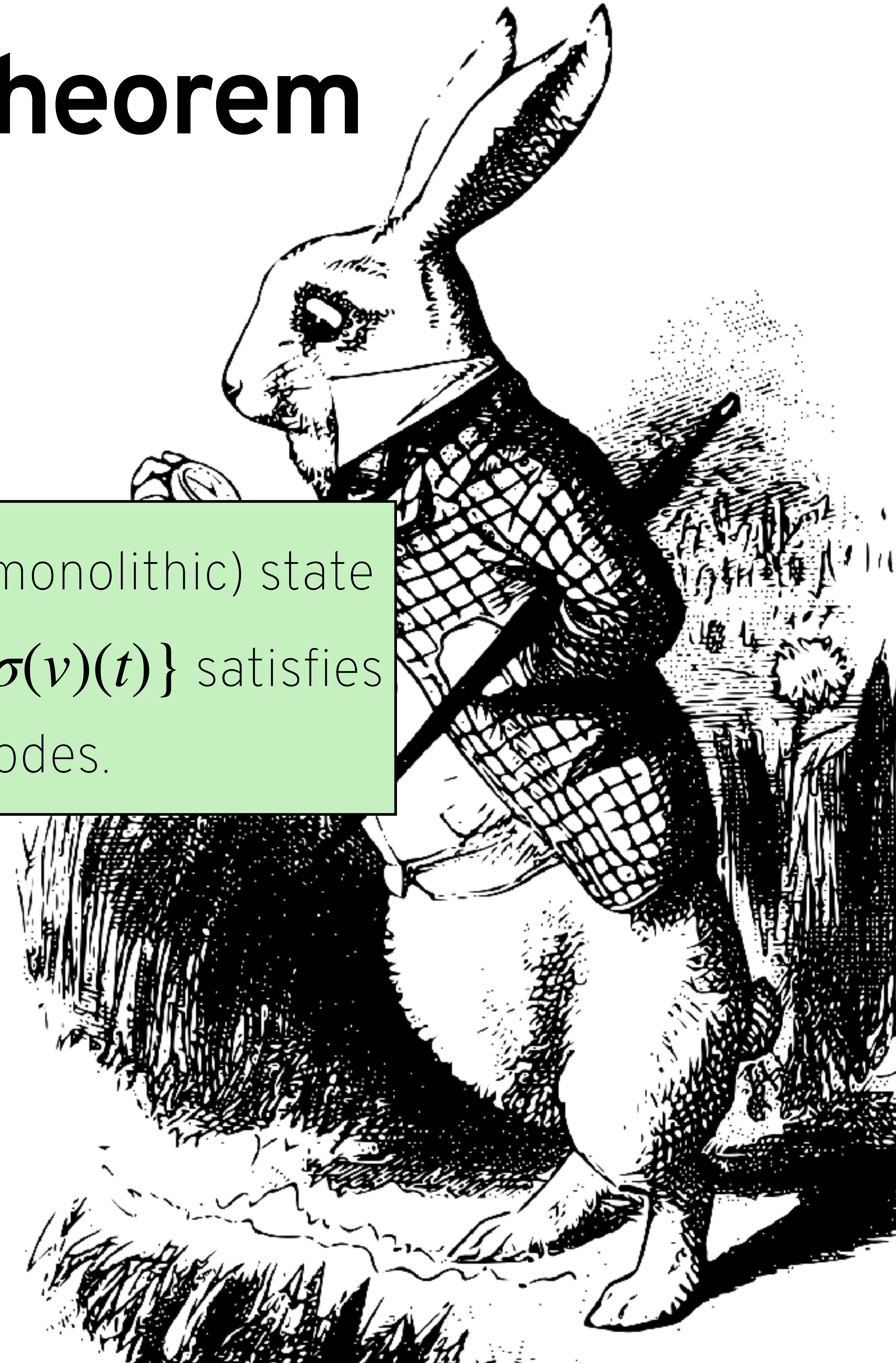
Dave Walker
Princeton

Extra slides

Closed Completeness Theorem



Closed Completeness Theorem



Starting from fixed initial routes, if $\sigma(v)(t)$ is the (monolithic) state of node v at time t, then the interface $A(v)(t) = \{\sigma(v)(t)\}$ satisfies the base and inductive checks for all nodes.

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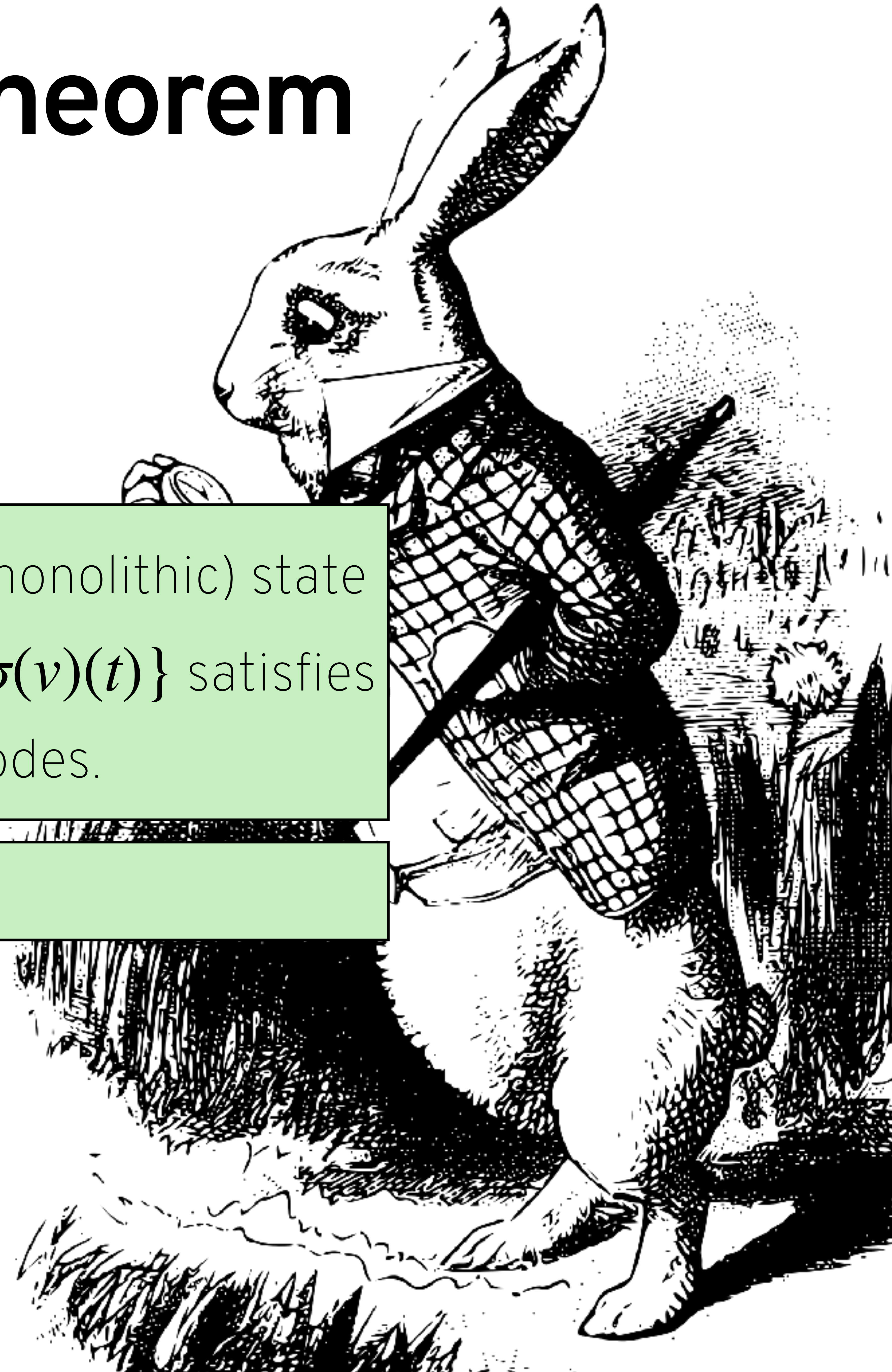

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Evaluation

Evaluation

Benchmark

Reachability

Path length

Valley freedom

Hijack filtering

No transit

Evaluation

Benchmark	Nodes
Reachability	20-2000
Path length	20-2000
Valley freedom	20-2000
Hijack filtering	20-2000
No transit	263

Evaluation

Benchmark	Nodes	Network LoC
Reachability	20-2000	81
Path length	20-2000	88
Valley freedom	20-2000	89
Hijack filtering	20-2000	146
No transit	263	88 (+102,753)

Evaluation

Benchmark	Nodes	Network LoC	Annotation LoC
Reachability	20-2000	81	3
Path length	20-2000	88	7
Valley freedom	20-2000	89	12
Hijack filtering	20-2000	146	21
No transit	263	88 (+102,753)	5

Evaluation

Benchmark	Nodes	Network LoC	Annotation LoC	Monolithic hits 2h timeout?
Reachability	20-2000	81	3	No (fixed dest.) 80 nodes (symbolic dest.)
Path length	20-2000	88	7	80 nodes (fixed dest.) 20 nodes (symbolic dest.)
Valley freedom	20-2000	89	12	180 nodes
Hijack filtering	20-2000	146	21	80 nodes (fixed dest.) 20 nodes (symbolic dest.)
No transit	263	88 (+102,753)	5	Yes

Evaluation

Benchmark	Nodes	Network LoC	Annotation LoC	Monolithic hits 2h timeout?	Modular verification time
Reachability	20-2000	81	3	No (fixed dest.) 80 nodes (symbolic dest.)	28s (fixed 2000 nodes) 336s (symbolic 2000 nodes)
Path length	20-2000	88	7	80 nodes (fixed dest.) 20 nodes (symbolic dest.)	1204s (fixed 2000 nodes) 3953s (symbolic 2000 nodes)
Valley freedom	20-2000	89	12	180 nodes	398s (fixed 2000 nodes) 3506s (symbolic 1280 nodes)
Hijack filtering	20-2000	146	21	80 nodes (fixed dest.) 20 nodes (symbolic dest.)	142s (2000 nodes) 2196s (symbolic 2000 nodes)
No transit	263	88 (+102,753)	5	Yes	38s

Related Work

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Satisfiability Modulo Theories (SMT)-based verification

Scalable Verification of Border Gateway Protocol Configurations with an SMT Solver

Konstantin Weitz Doug Woos Emina Torlak
Michael D. Ernst Arvind Krishnamurthy Zachary Tatlock
University of Washington, USA
{weitzkon, dwoos, emina, mernst, arvind, ztatlock}@cs.washington.edu

A General Approach to Network Configuration Verification

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simulation-based verification

Plankton: Scalable network configuration verification through model checking

Santhosh Prabhu, Kuan-Yen Chou, Ali Kheradmand, P. Brighten Godfrey, Matthew Caesar
University of Illinois at Urbana-Champaign

Tiramisu: Fast Multilayer Network Verification

Anubhavnidhi Abhashkumar*, Aaron Gember-Jacobson†, Aditya Akella*
University of Wisconsin - Madison, Colgate University†*

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A General Approach to Network Configuration Verification

Ryan Beckett, Princeton University
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simulation-based verification

Plankton: Scalable network configuration verification through model checking

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Tiramisu: Fast Multilayer Network Verification

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modular SMT-based verification

LIGHTYEAR: Using Modularity to Scale BGP Control Plane Verification

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Kirigami, the Verifiable Art of Network Cutting

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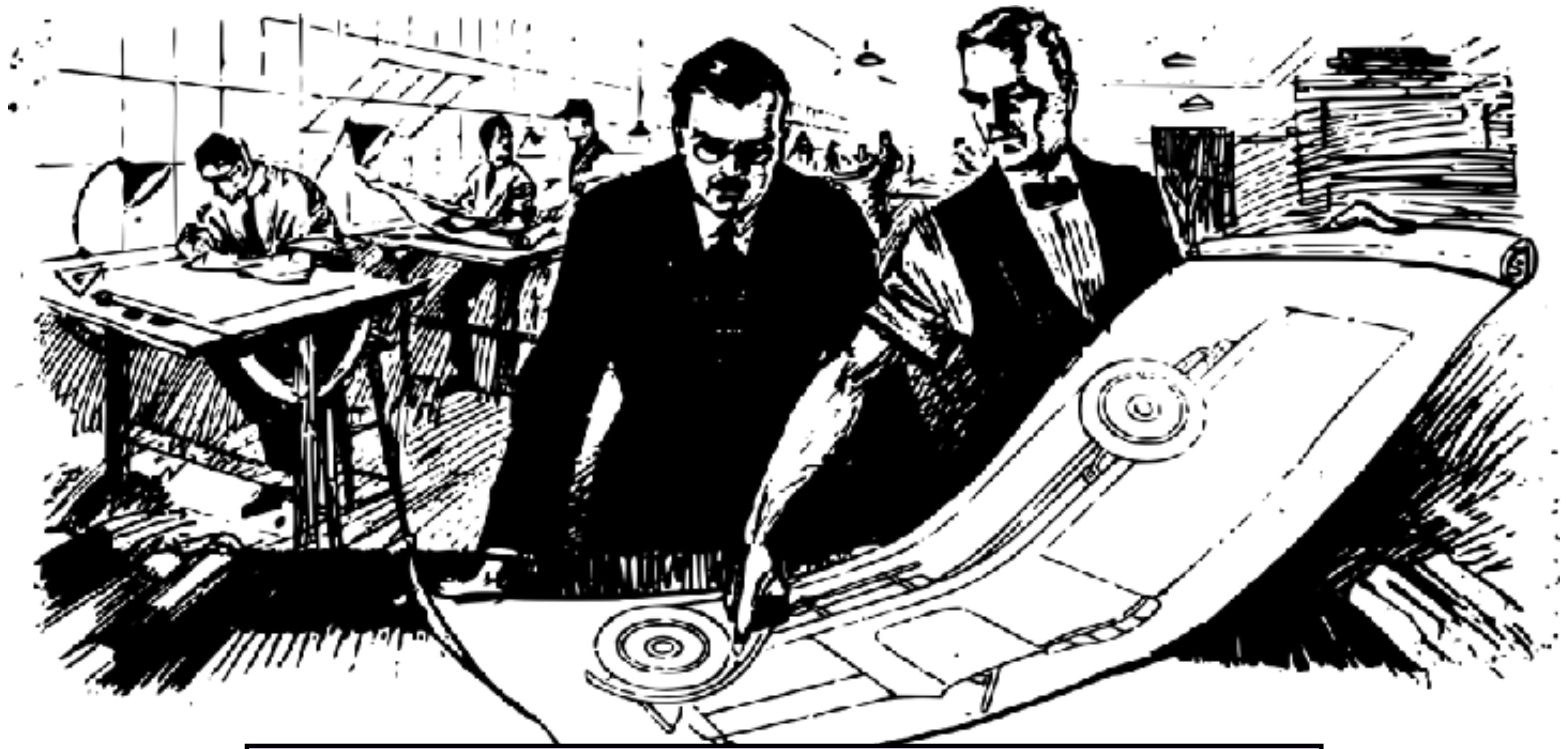
Challenges



finding the correct invariants

synchronous network semantics