https://penntoday.upenn.edu/sites/default/files/2020-01/kirigami_closeup.jpg

Kirigami, the Verifiable Art of Network Cutting

Tim Alberdingk Thijm, Ryan Beckett, Aarti Gupta, David Walker

ICNP 2022

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AWS revenue jumps 33%, but growth slows

As enterprises face a possible recession, will uptake of cloud services slow?

By Anirban Ghoshal
Senior Writer, InfoWorld | JUL 29, 2022 1:56 PM PDT

NEWS

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Routers flooded with internet traffic in filter blunder, watchdog told
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Mon 25 Jul 2022 // 18:45 UTC
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Analyzing Distributed Control Planes

Lots of great work, including…

- **Batfish** [Fogel et al., NSDI 2015]
- **Bagpipe** [Weitz et al., OOPSLA 2016]
- **Minesweeper** [Beckett, Gupta, Mahajan, Walker, SIGCOMM 2018]
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But all these tools must **analyze entire network at once**!

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But all these tools must **analyze entire network at once**!

Modularity Is Essential

Cloud providers have networks with **millions of nodes,**

and they are growing…

Thinking about our networks **one piece at a time** makes them

easier to reason over, and

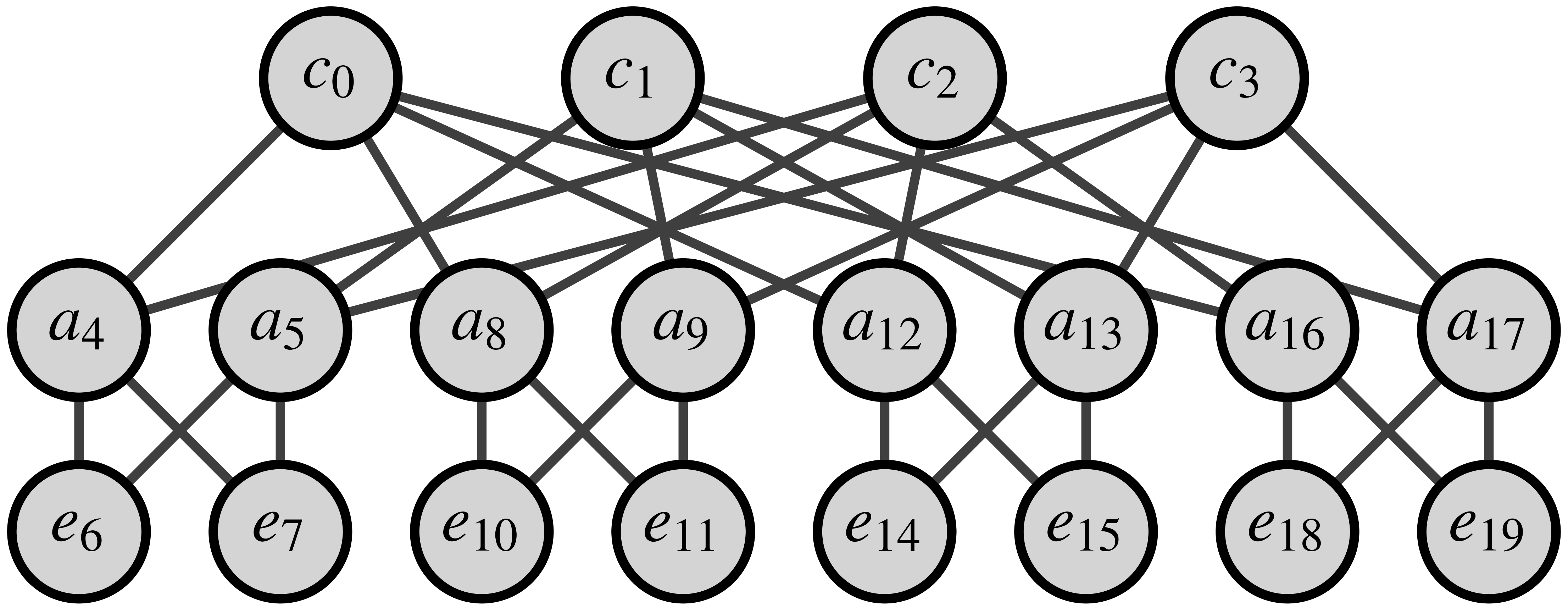
supports **incremental changes and updates**

Modular Network Verification

Identify the network's **components**

Annotate component boundaries with an **interface**

Break up the network into **fragments** to analyze separately



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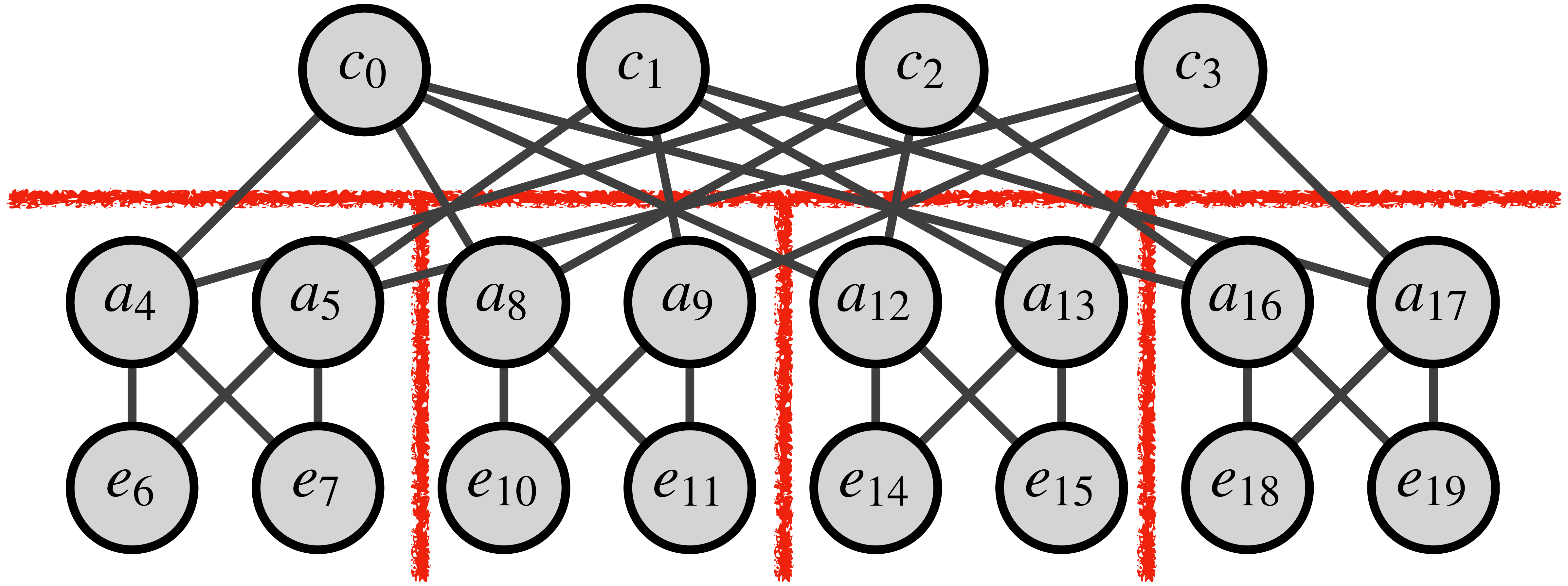

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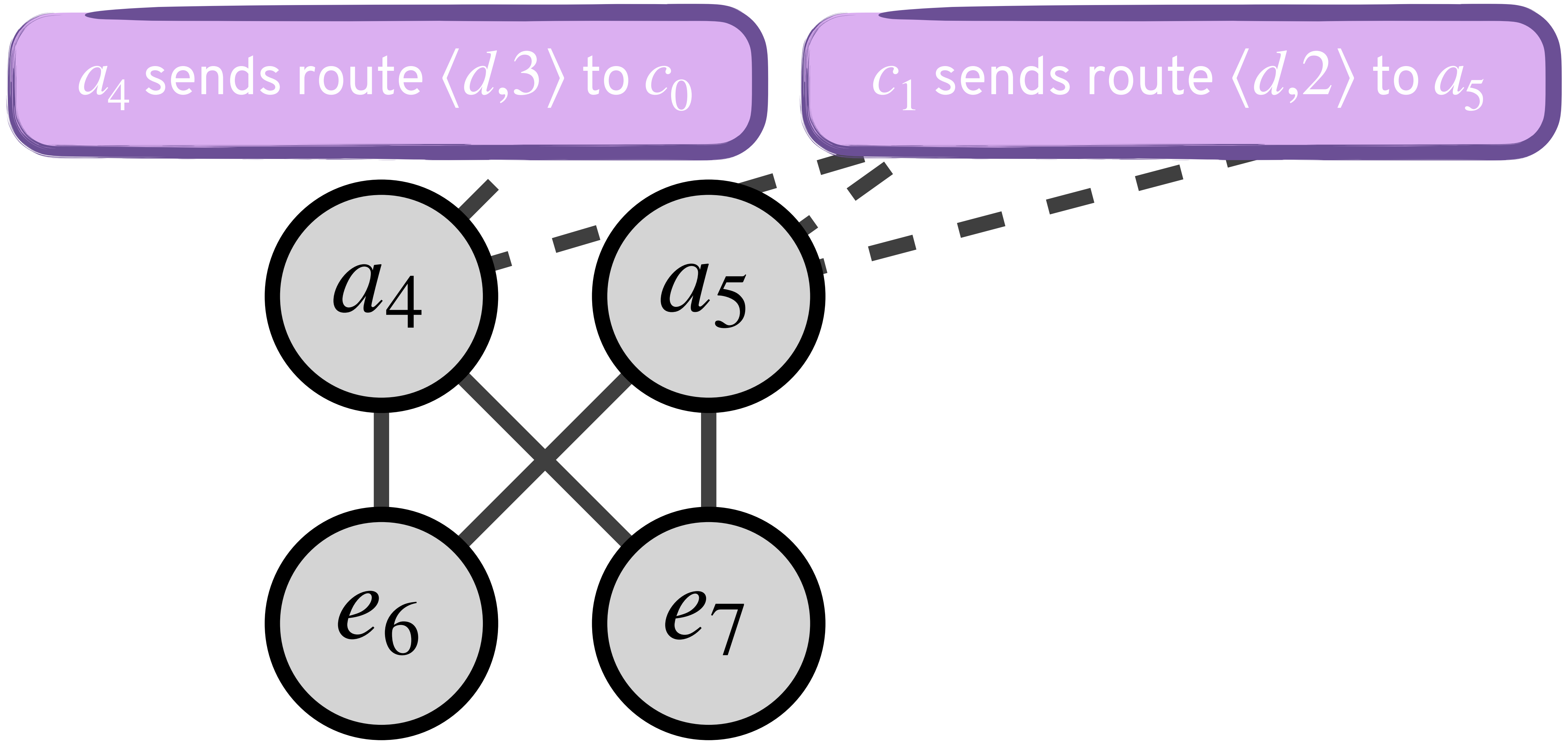

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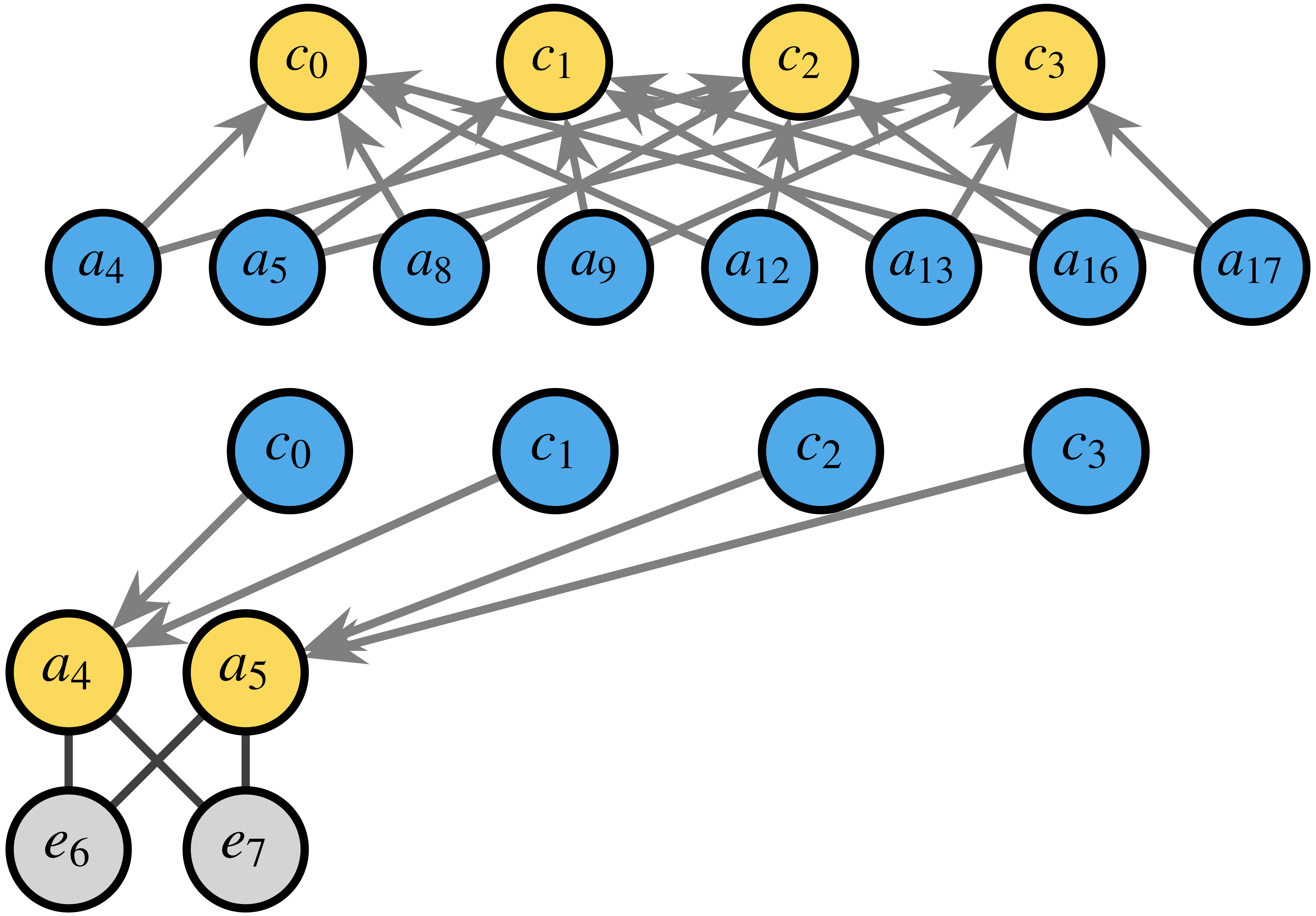


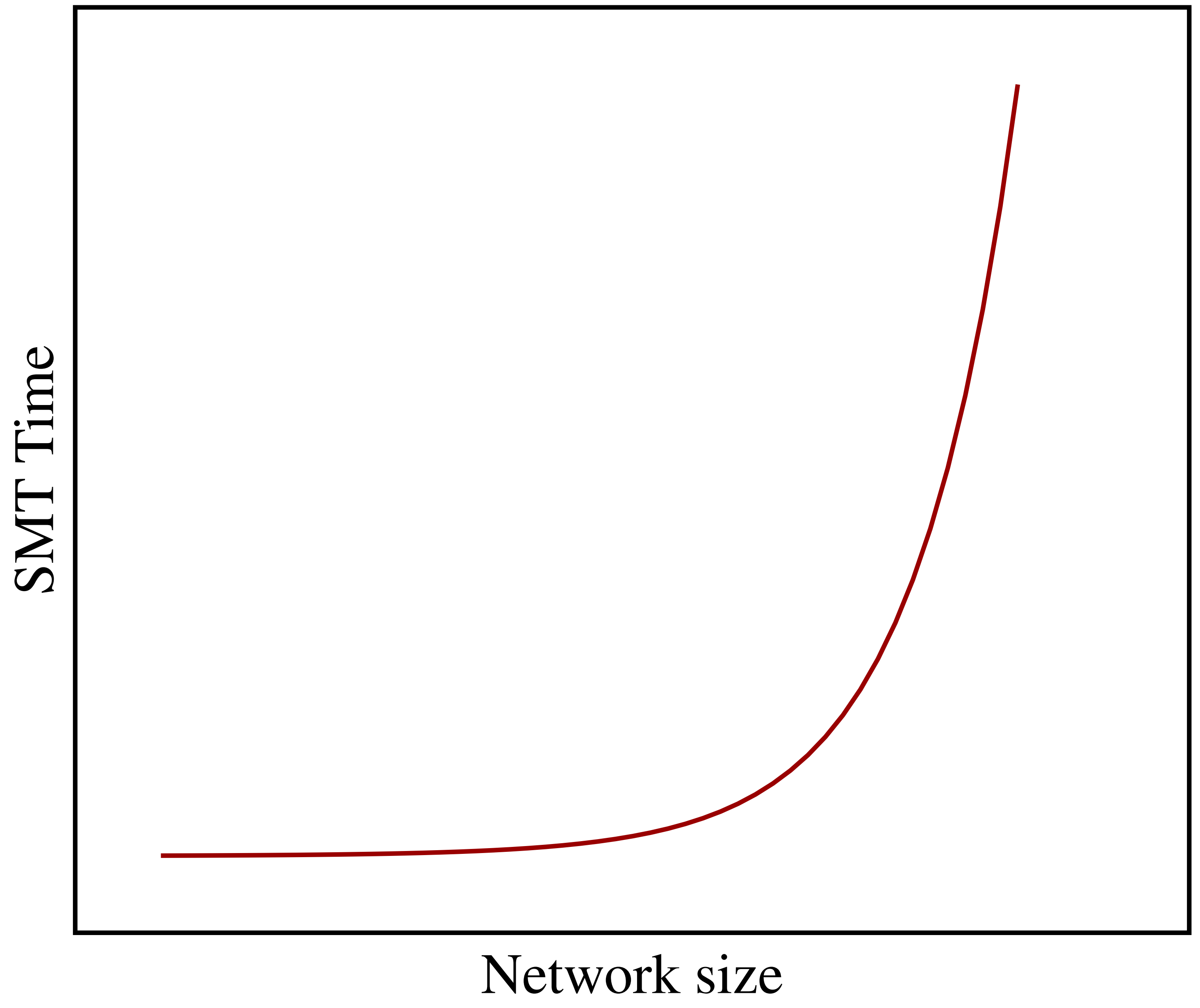
Modular Network Verification

Satisfiability Modulo Theories (SMT)-based verification time

- **Nonlinear** in size of network (worst case **exponential**)
- **Bottlenecks** analysis (NP-complete problem)

Splitting up network takes **linear time**

- ...but with **better-than-linear** improvements!
- Our experiments saw SMT times **improve by over 100,000x**



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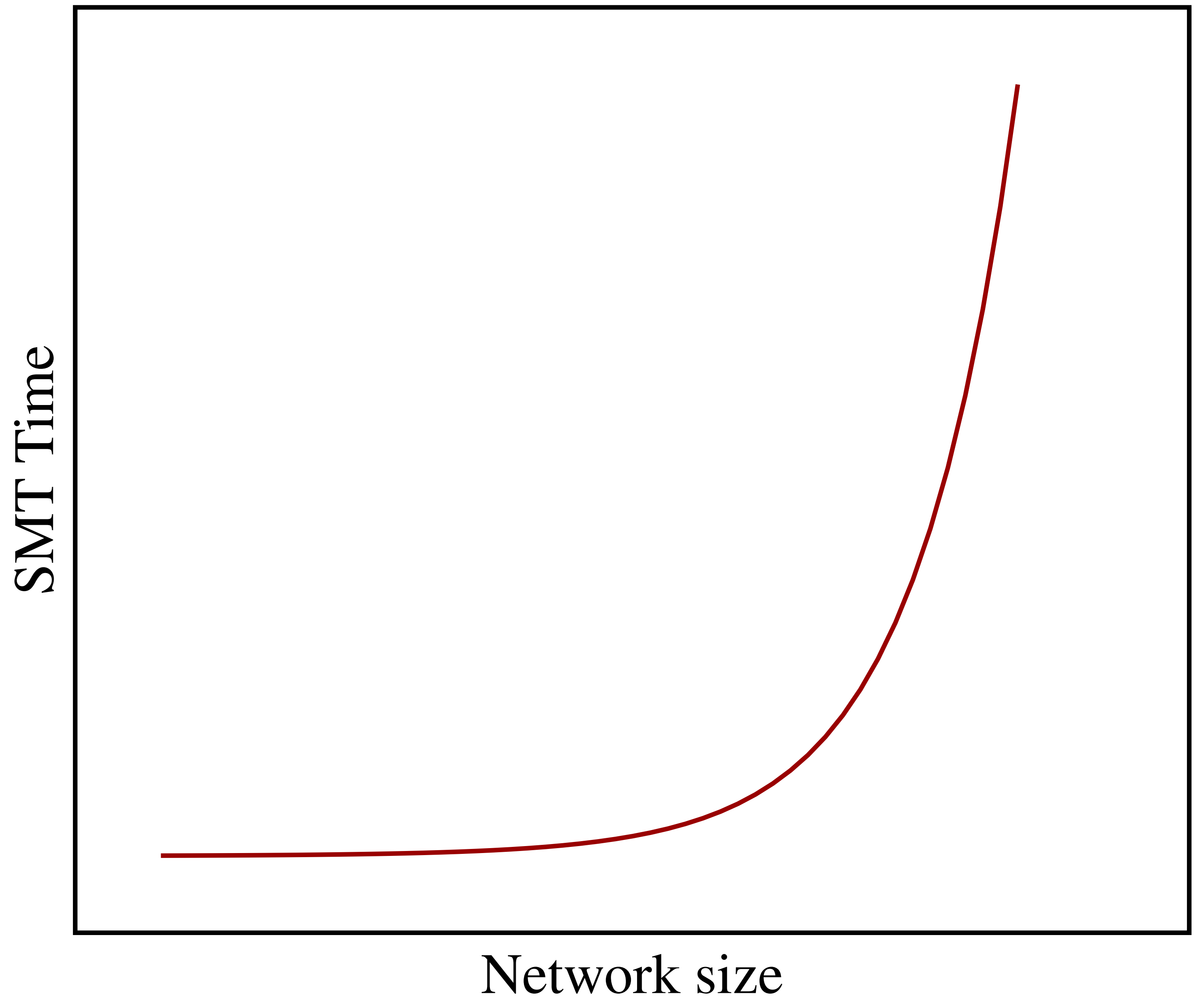

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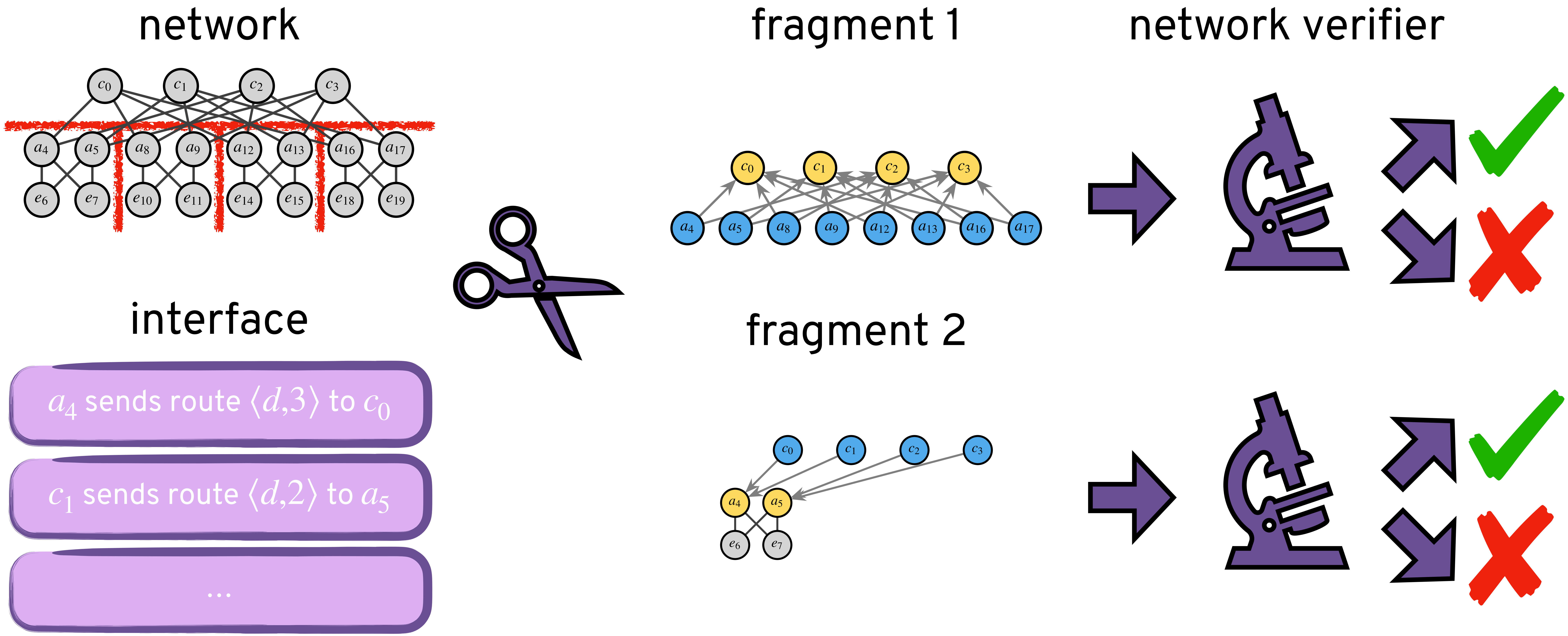

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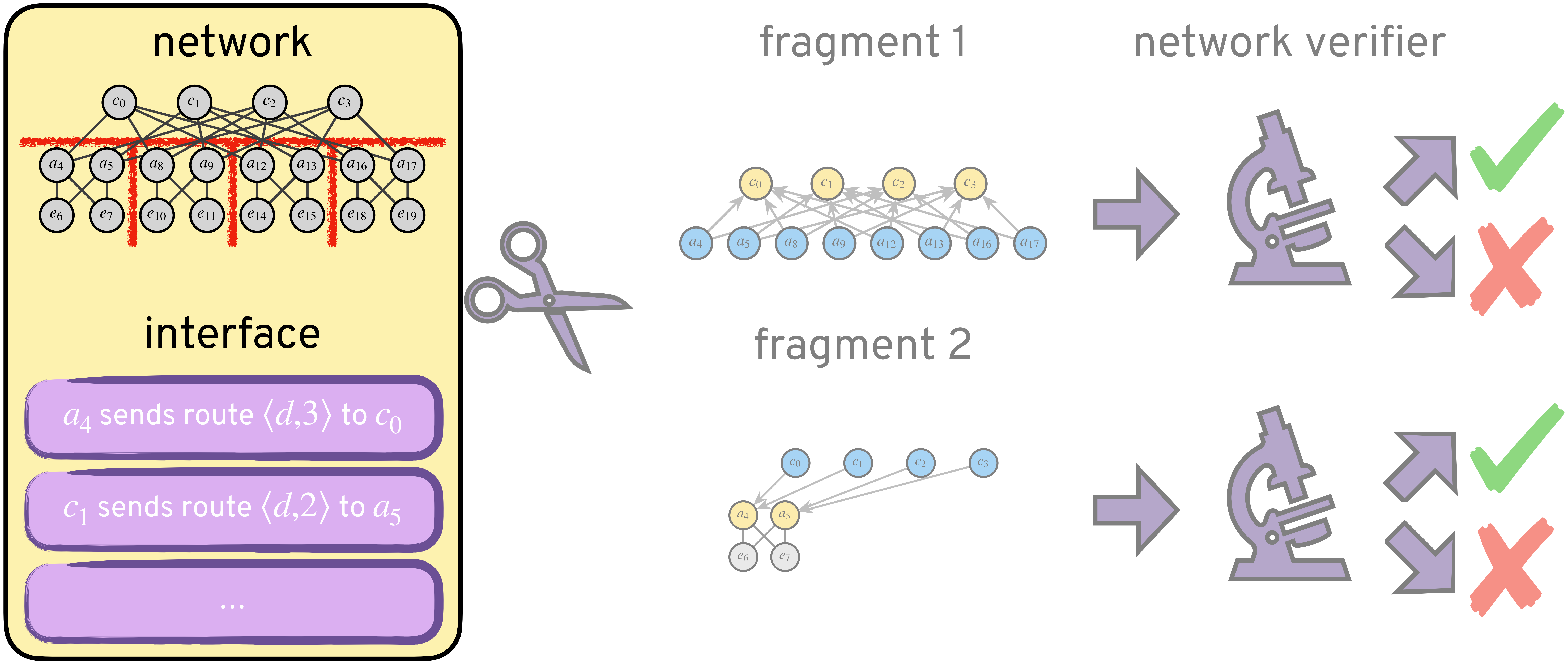

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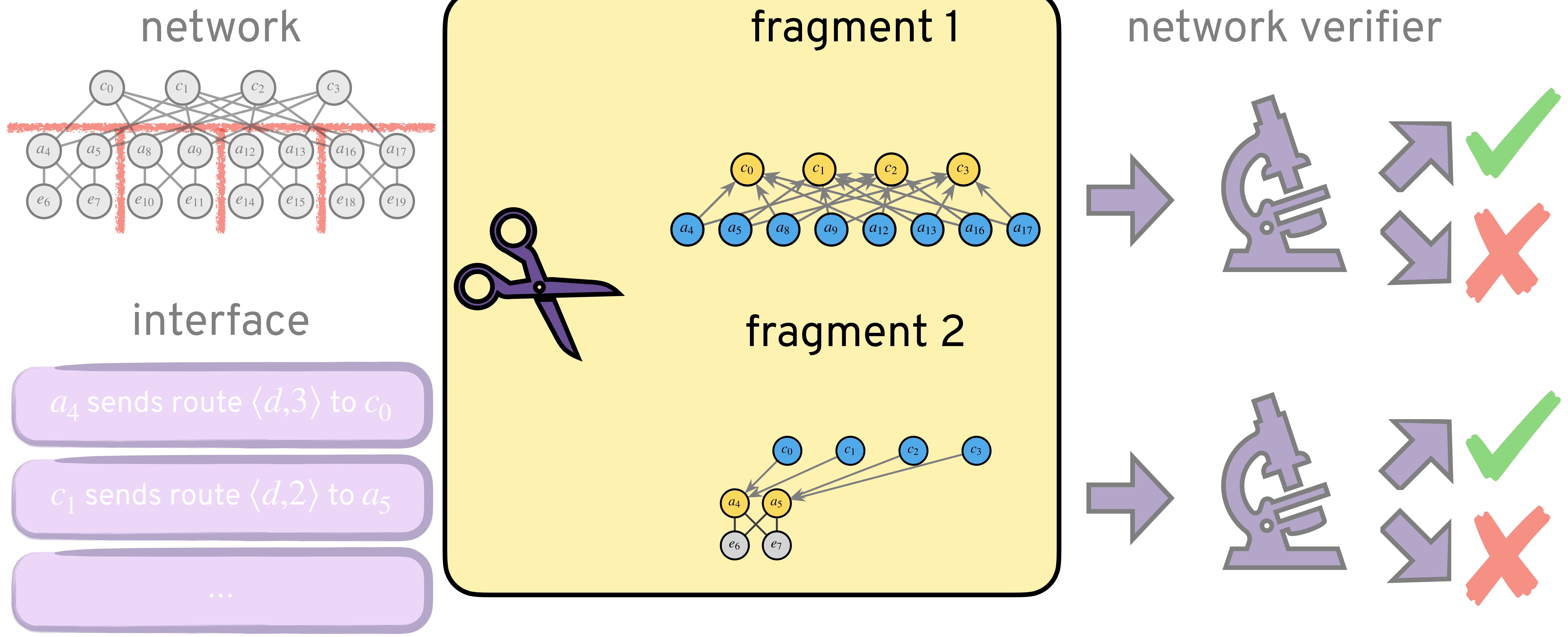
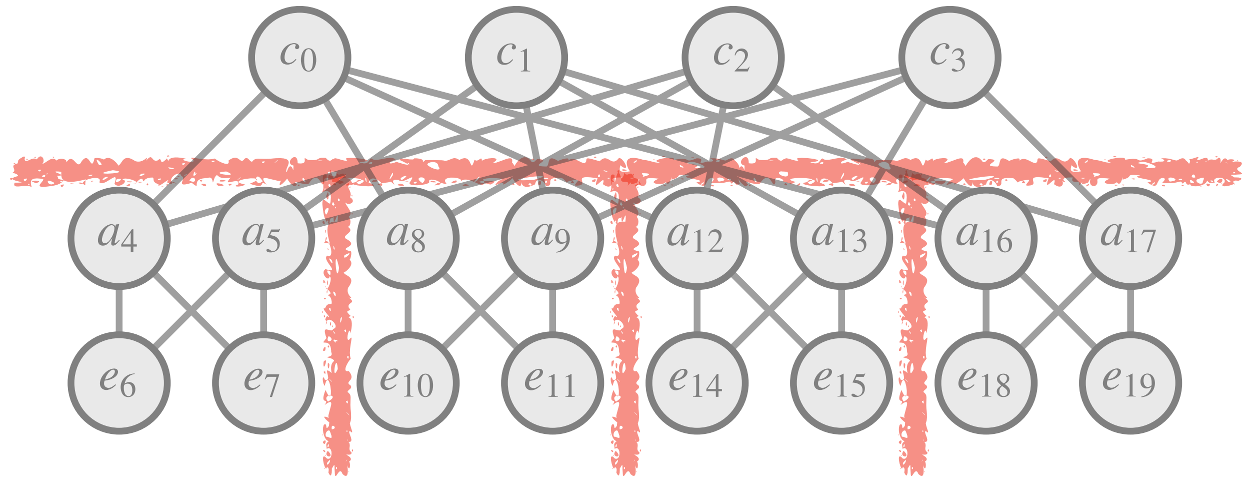


Modular Network Verification

network

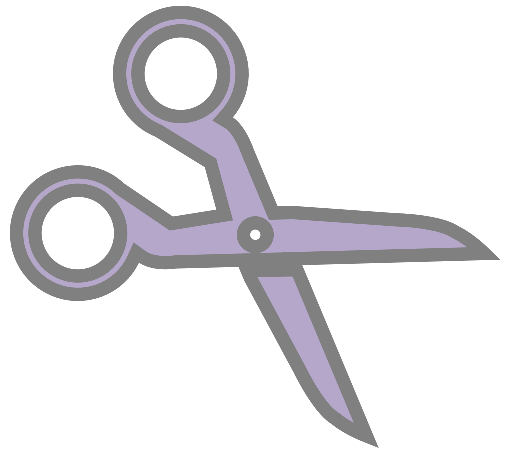


interface

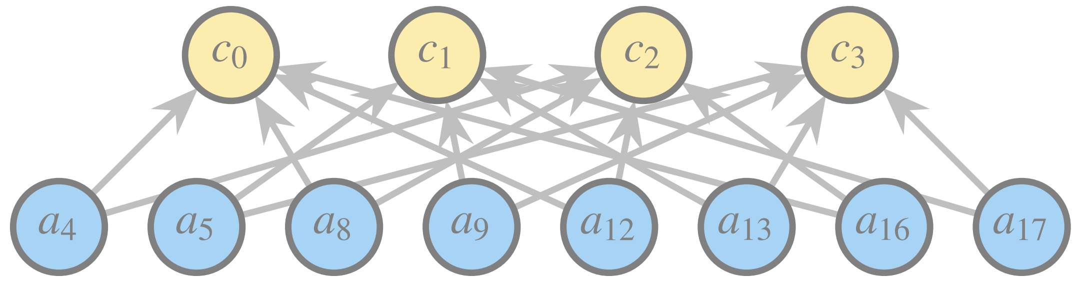
a_4 sends route $\langle d,3 \rangle$ to c_0

c_1 sends route $\langle d,2 \rangle$ to a_5

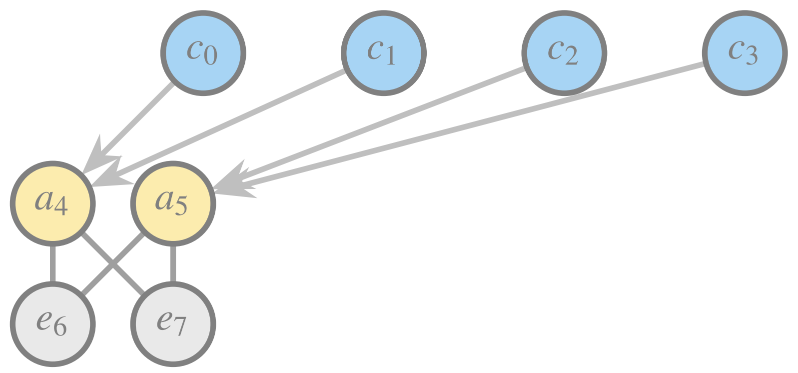
…

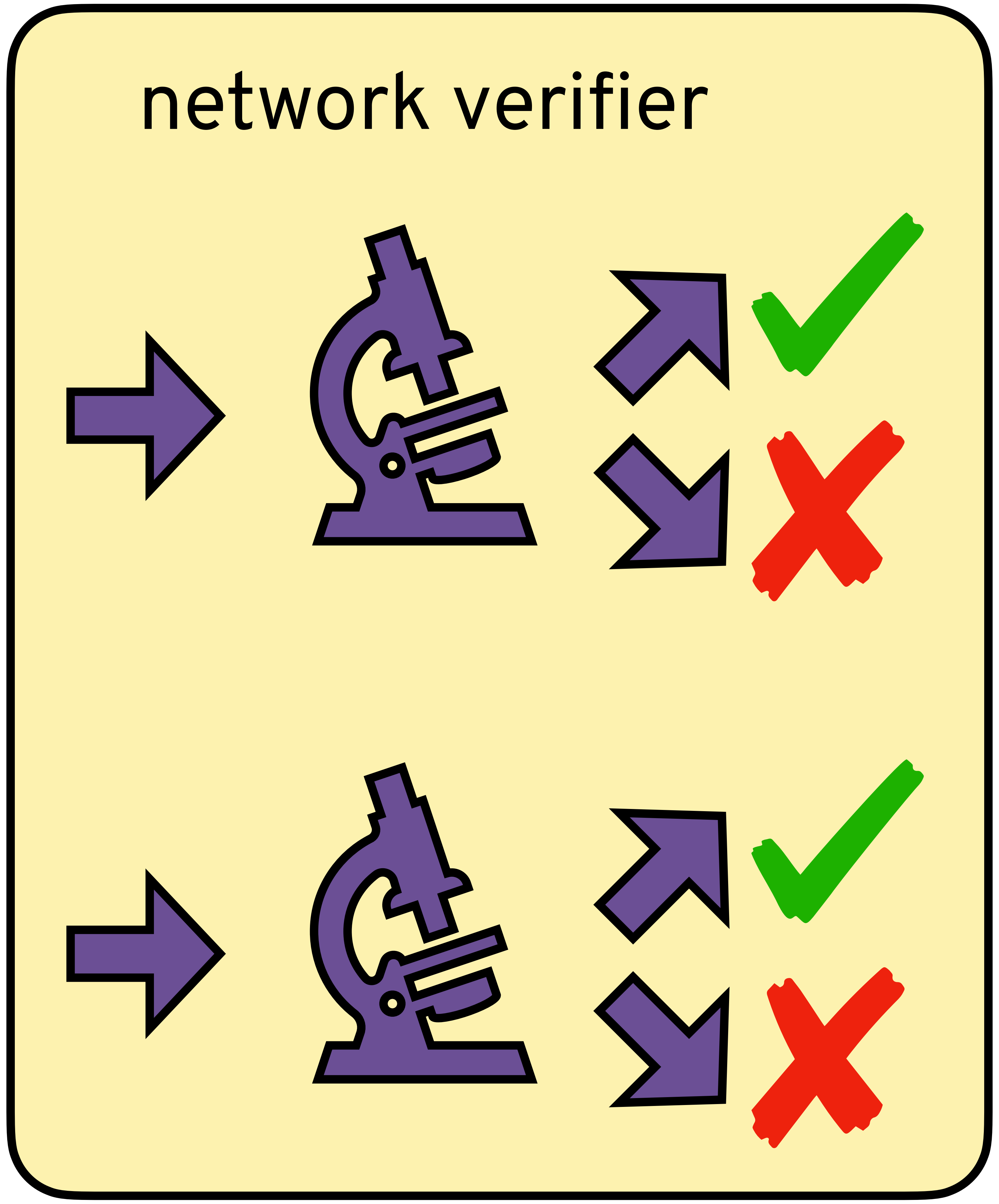


fragment 1



fragment 2





Modular Network Verification

network

Verification counterexamples **localized** to particular fragments.

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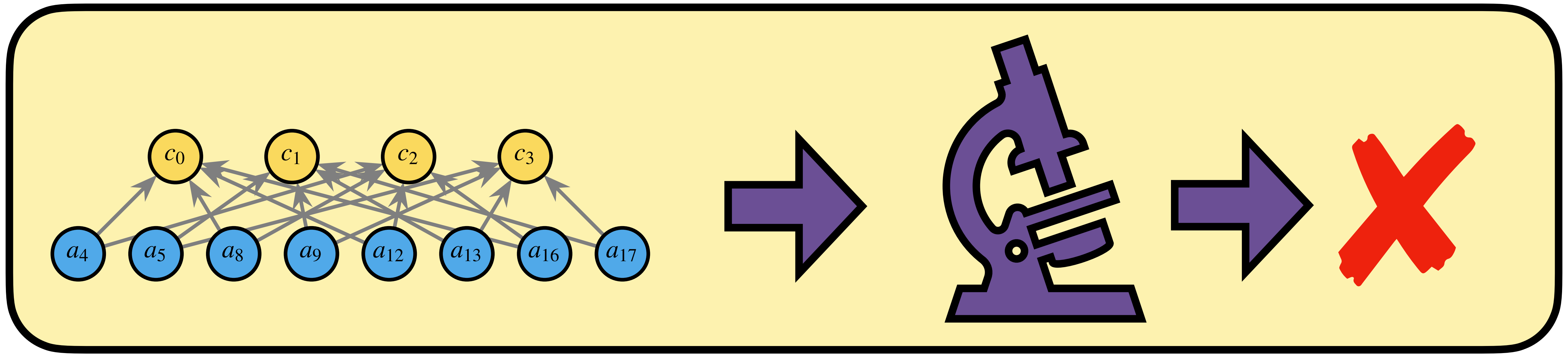
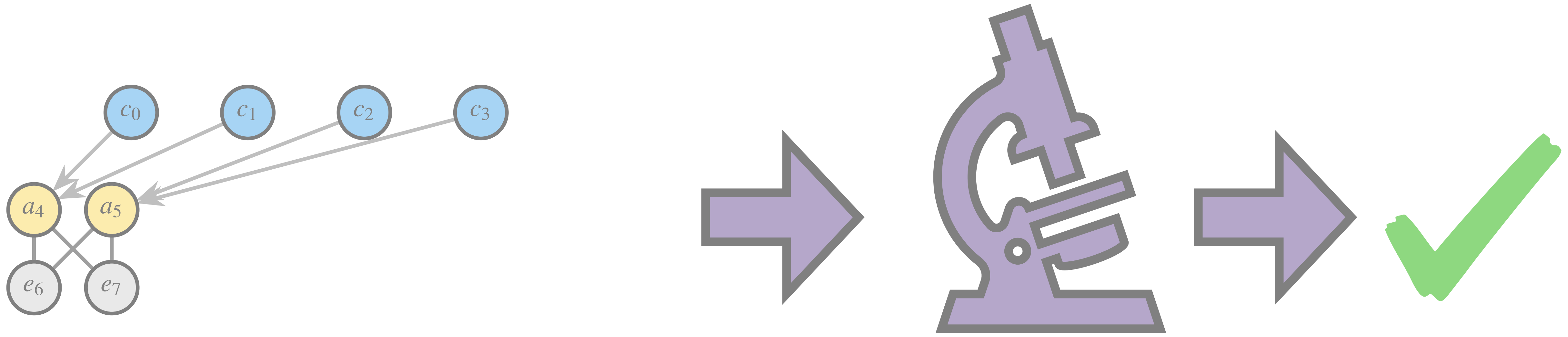
…

fragment 1

network verifier

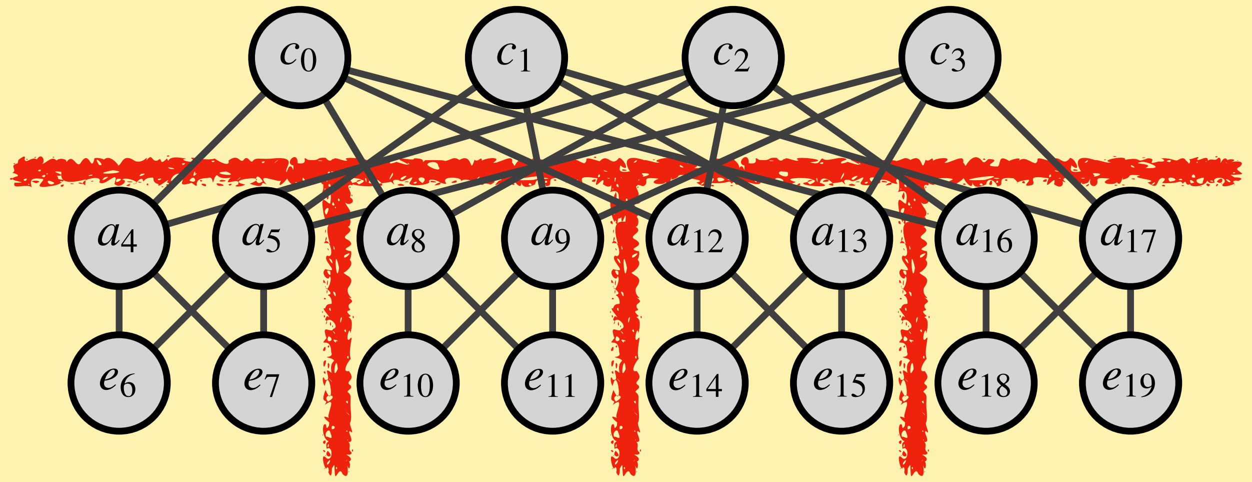


fragment 2



Modular Network Verification

network



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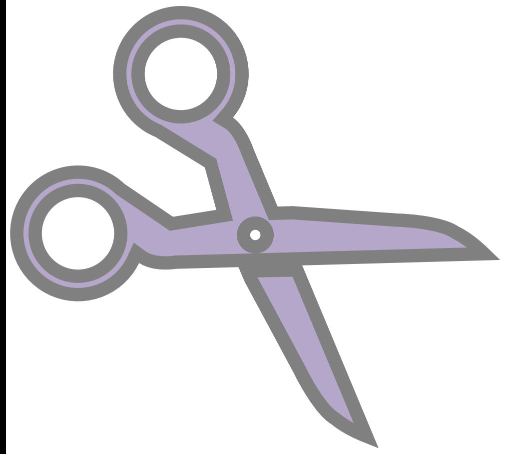

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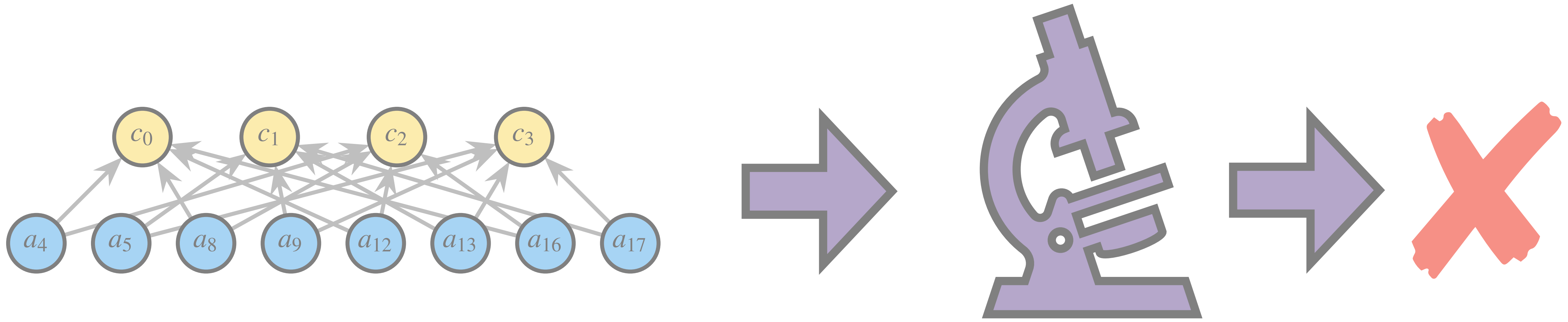
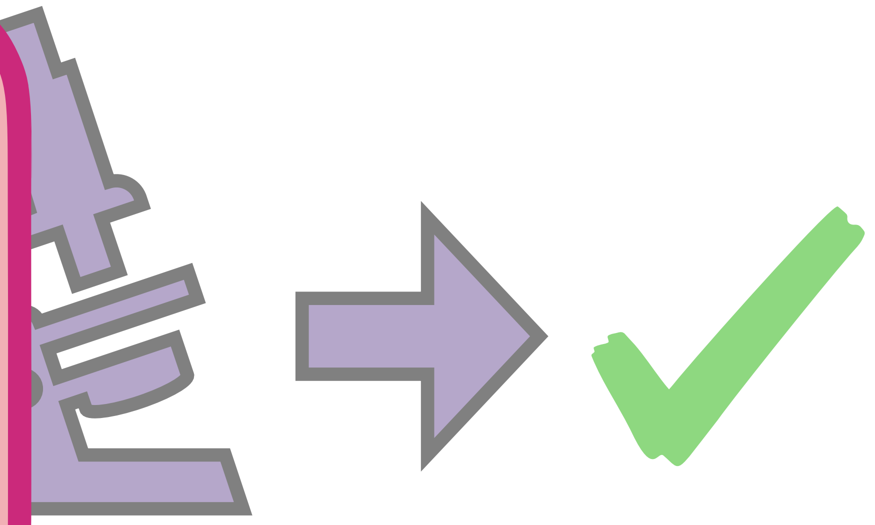


fragment 2



Users can specify **arbitrary cuts** for fragments of different granularities, accommodating annotation cost.

Our Contributions

A **theory of network interfaces and fragments**

based on **assume-guarantee reasoning,**

proved fragment verification **sound and complete** *w.r.t.* monolithic verification

A **checking procedure** to verify properties using fragments

and to check if a given **interface is correct**

An extension **Kirigami** for the **network verification language NV**

evaluated on benchmarks, with over **100,000x improvement in SMT time**

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Roadmap

An Example Modular Verification Problem

A Theory of Network Fragments

Implementation

Evaluation

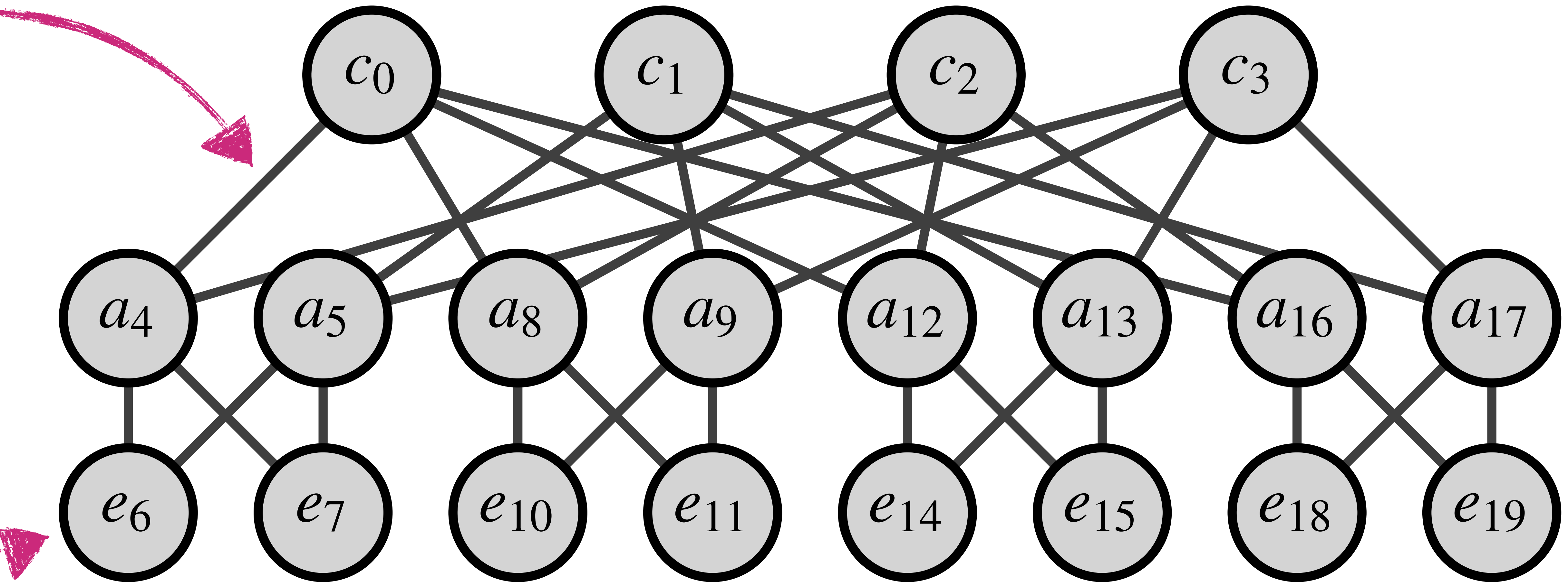
Takeaways

Verifying a Data Center

The Stable Routing Problem

topology graph with nodes V and edges E

$$G = (V, E)$$



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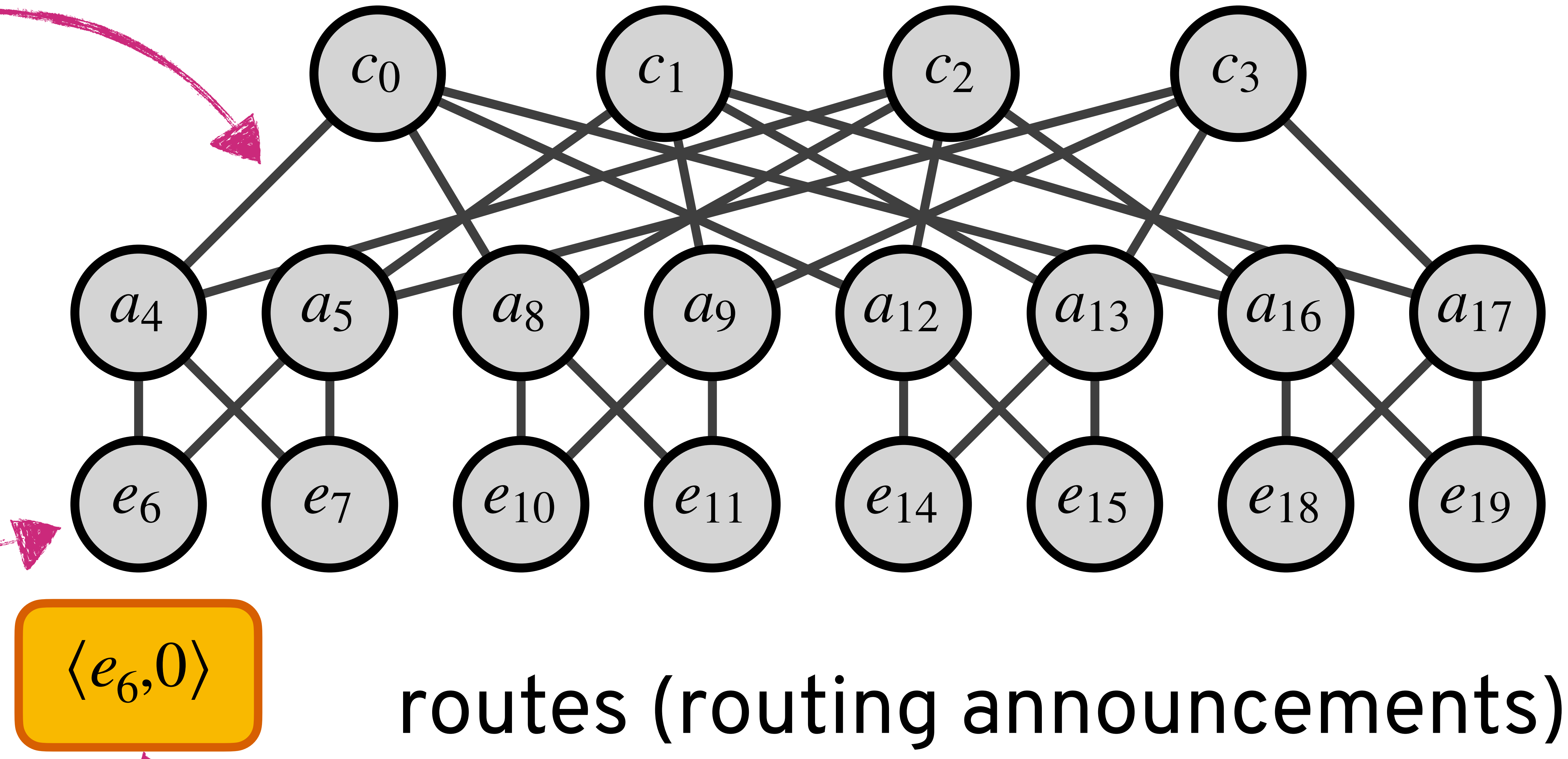
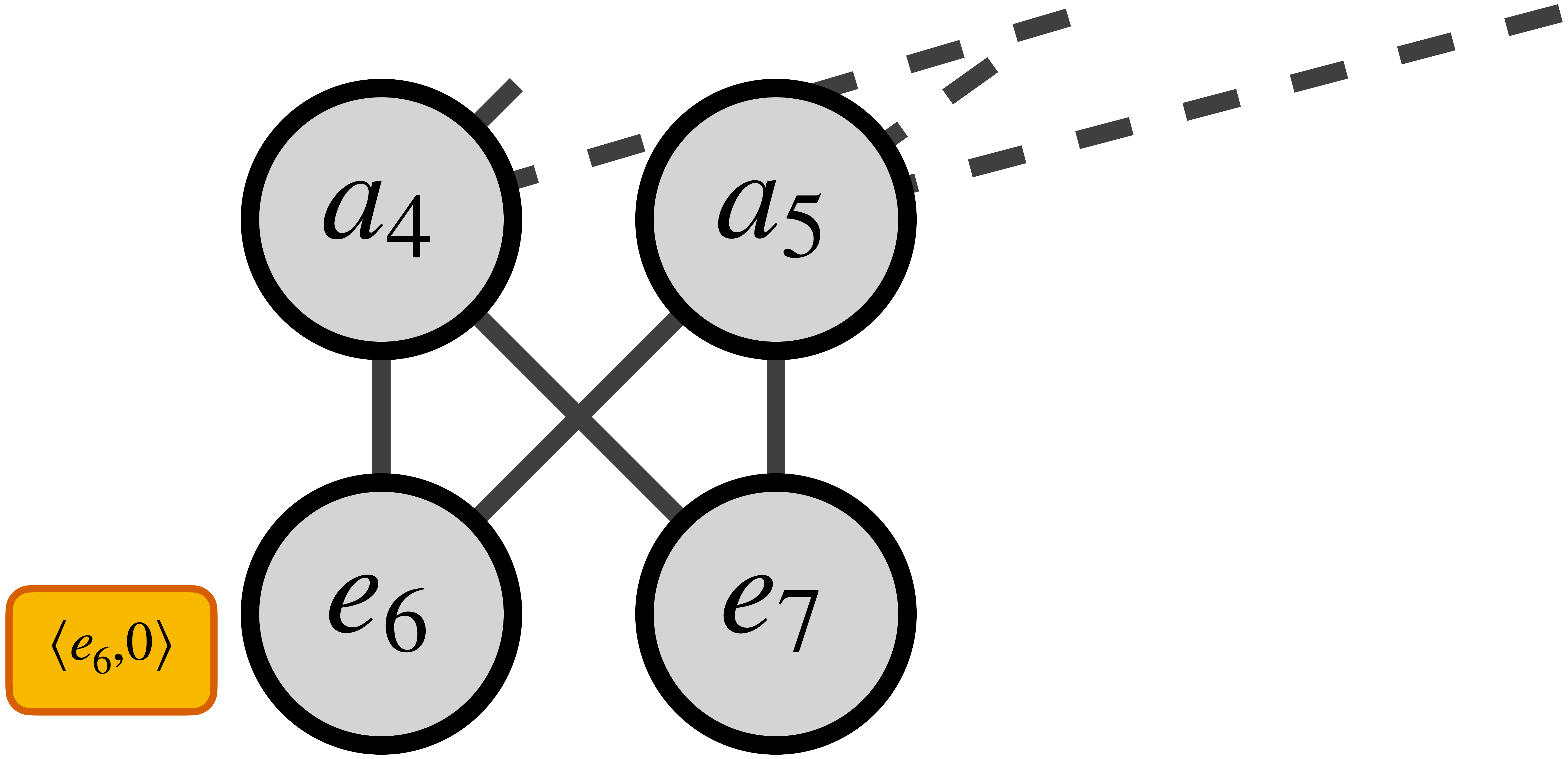


routes (routing announcements) $\langle p, x \rangle$:

identifier p and a cost metric x

Verifying a Data Center

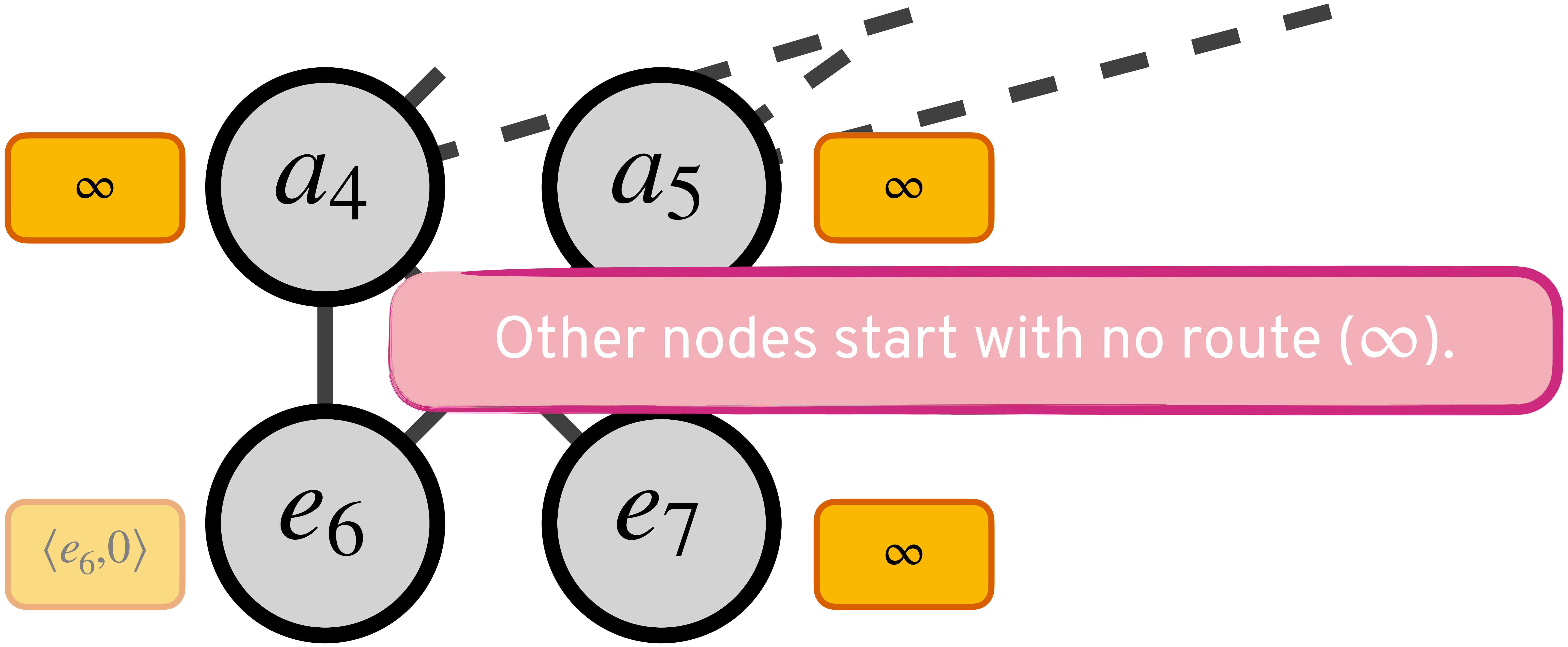
The Stable Routing Problem



Suppose e_6 announces a route to itself.

Verifying a Data Center

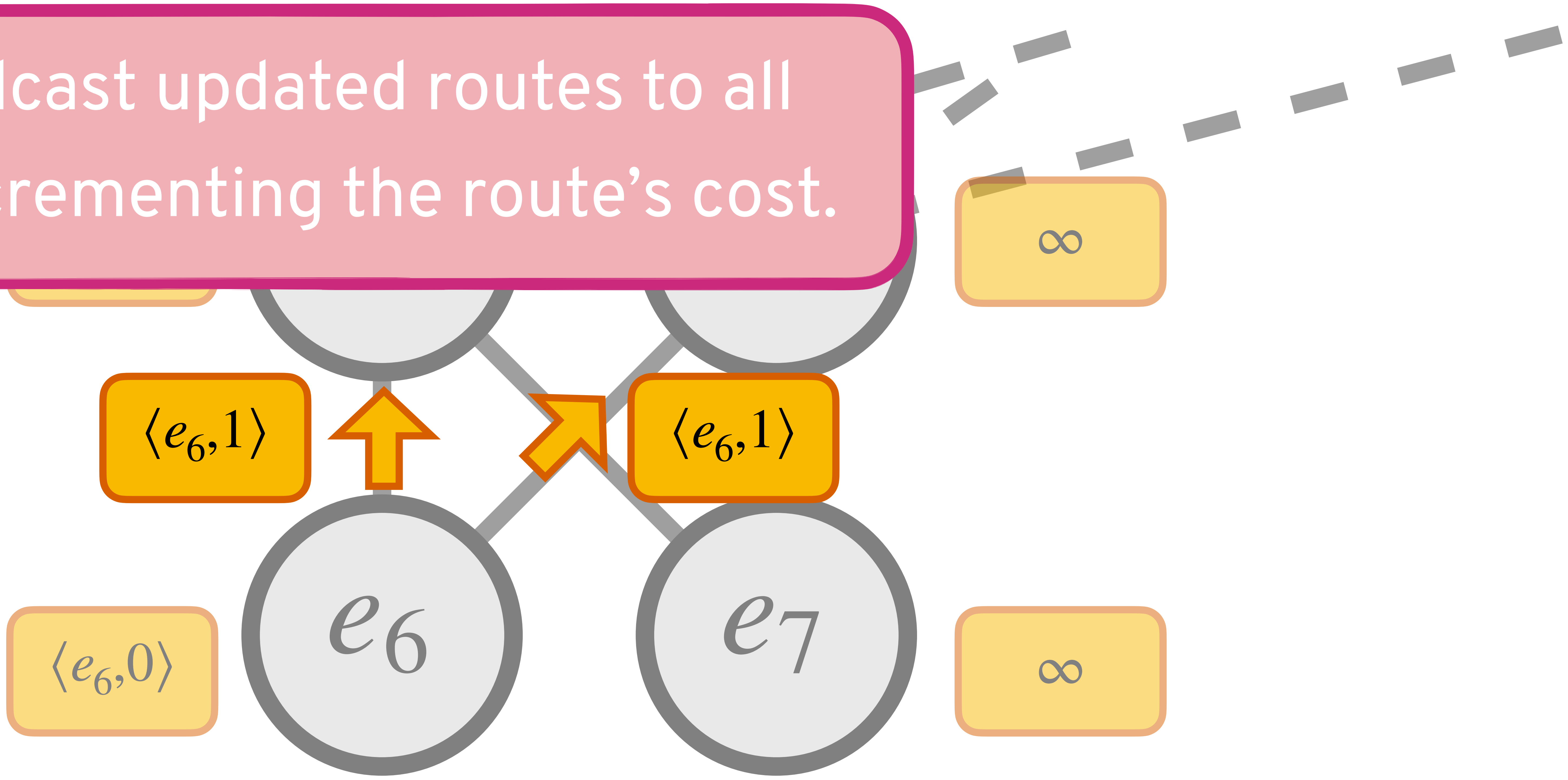
The Stable Routing Problem



Verifying a Data Center

The Stable Routing Problem

Nodes broadcast updated routes to all neighbors, incrementing the route's cost.



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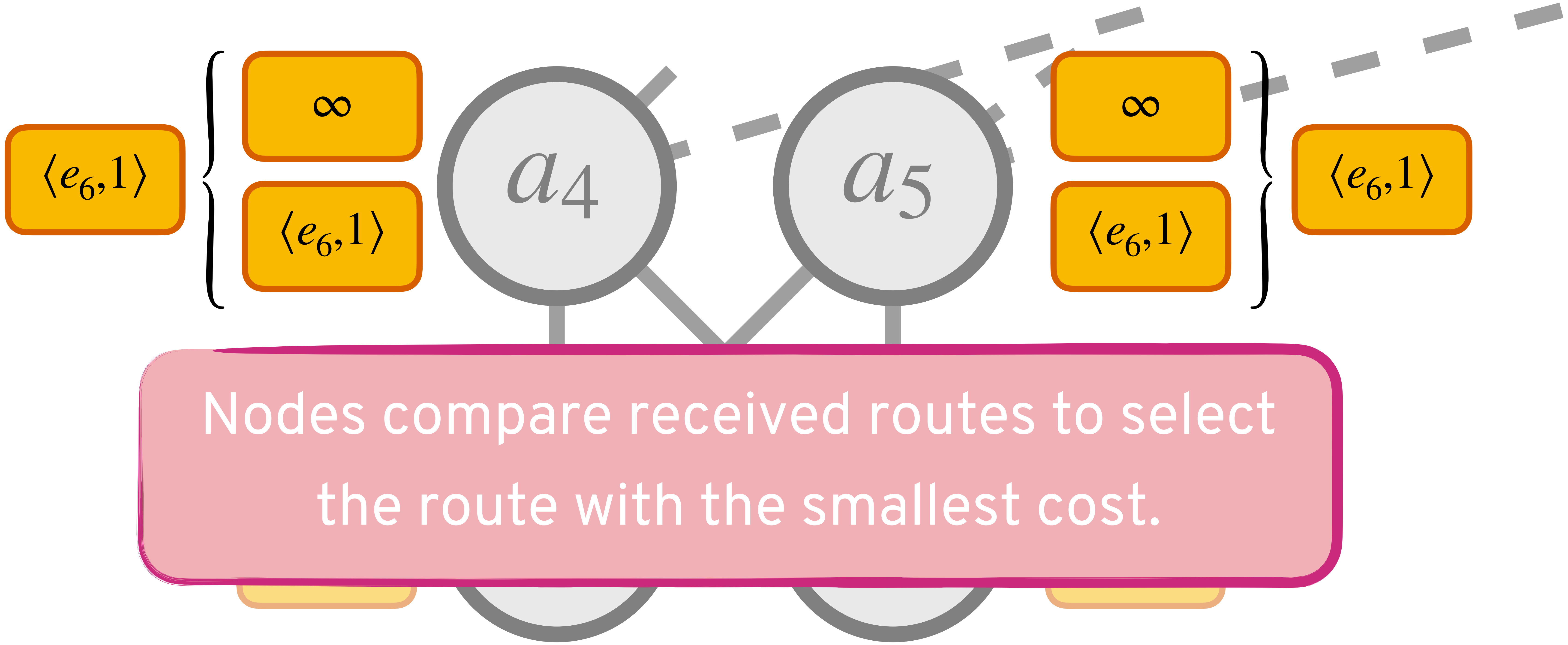
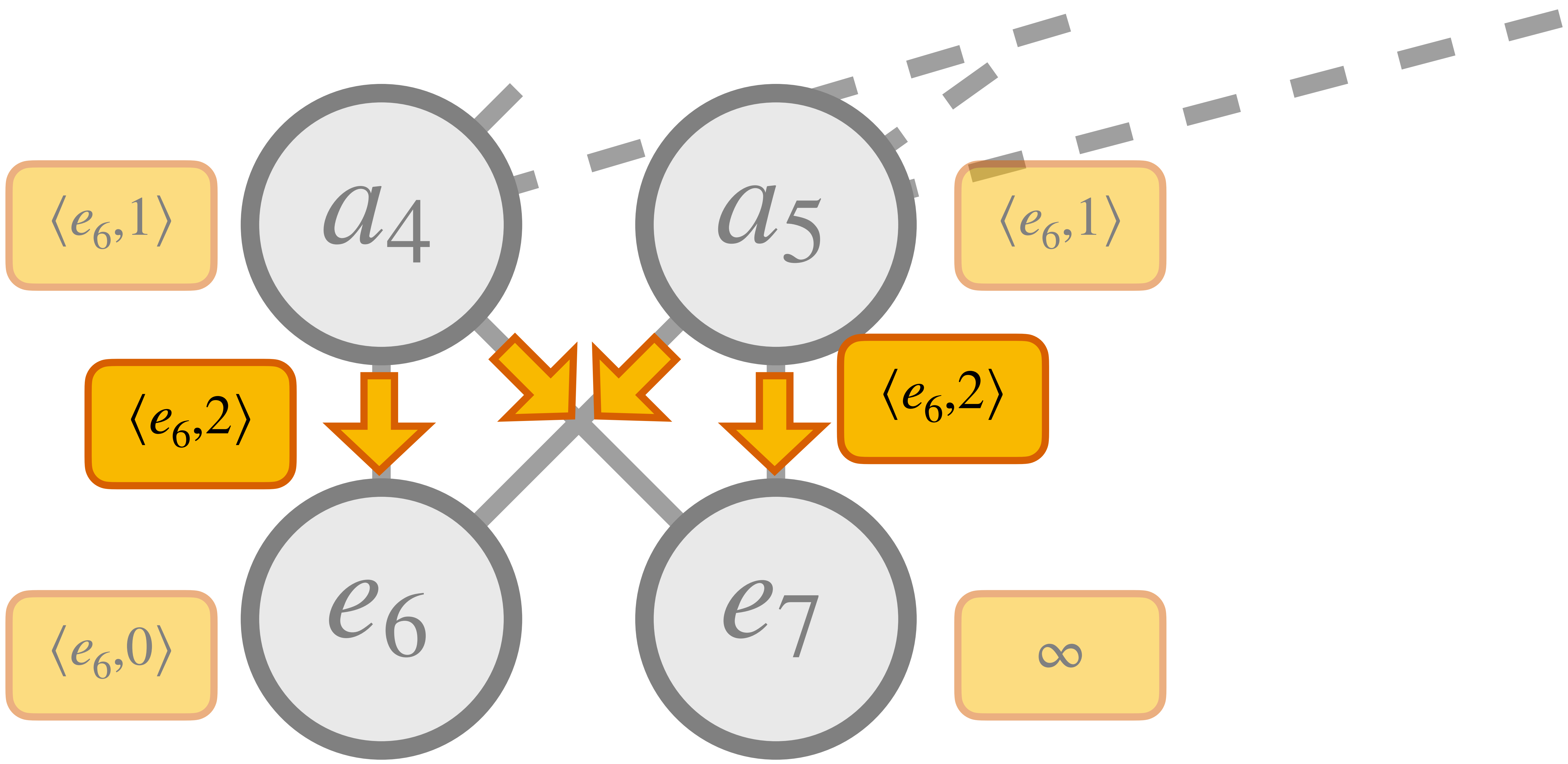


Nodes compare received routes to select the route with the smallest cost.

Verifying a Data Center

The Stable Routing Problem

…and so on…



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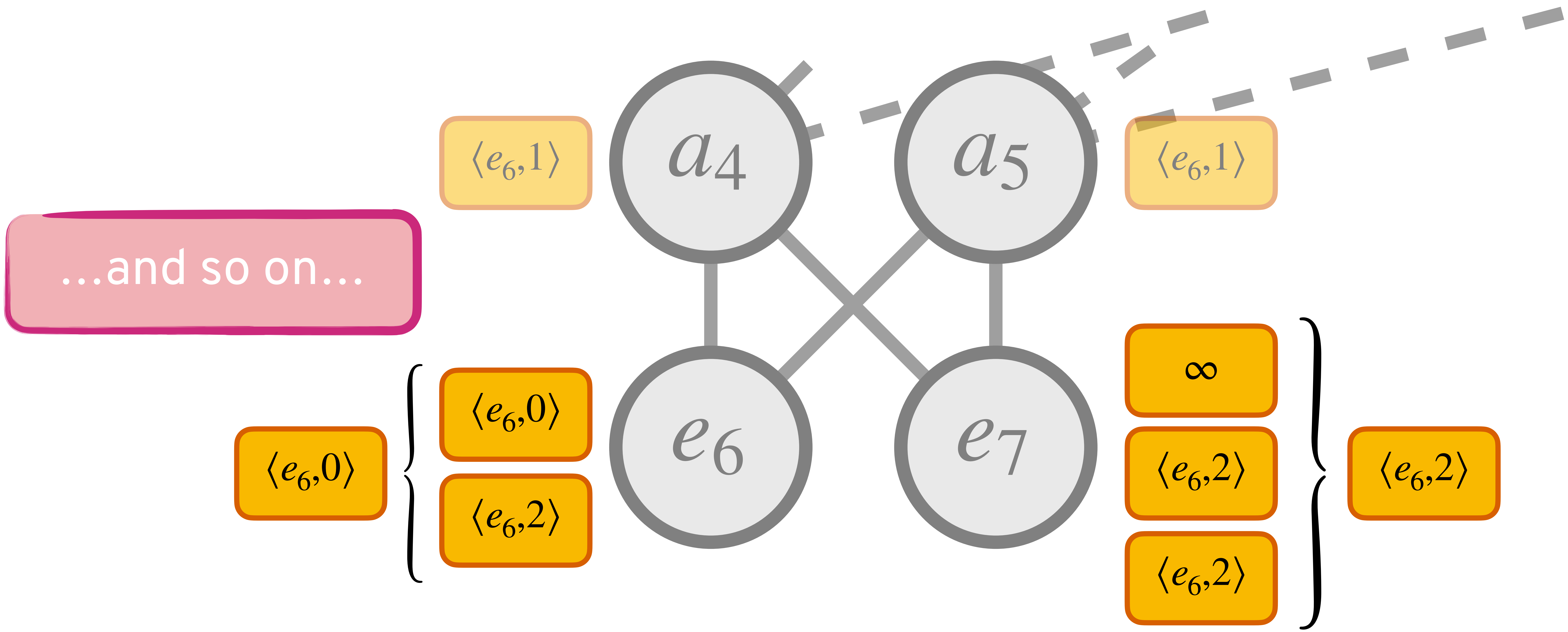

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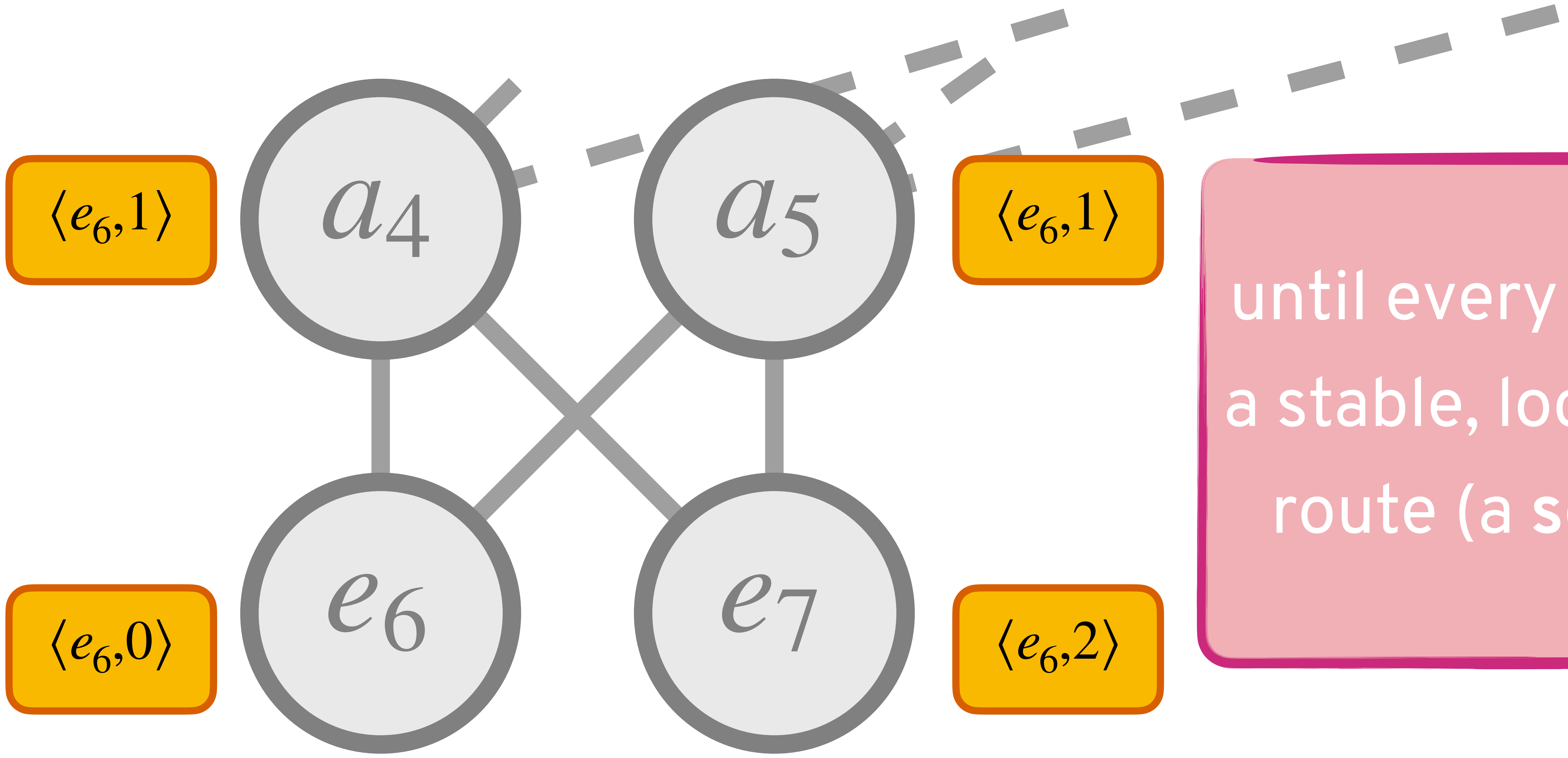


until every node has a stable, locally-best route (a **solution**)

Verifying a Data Center

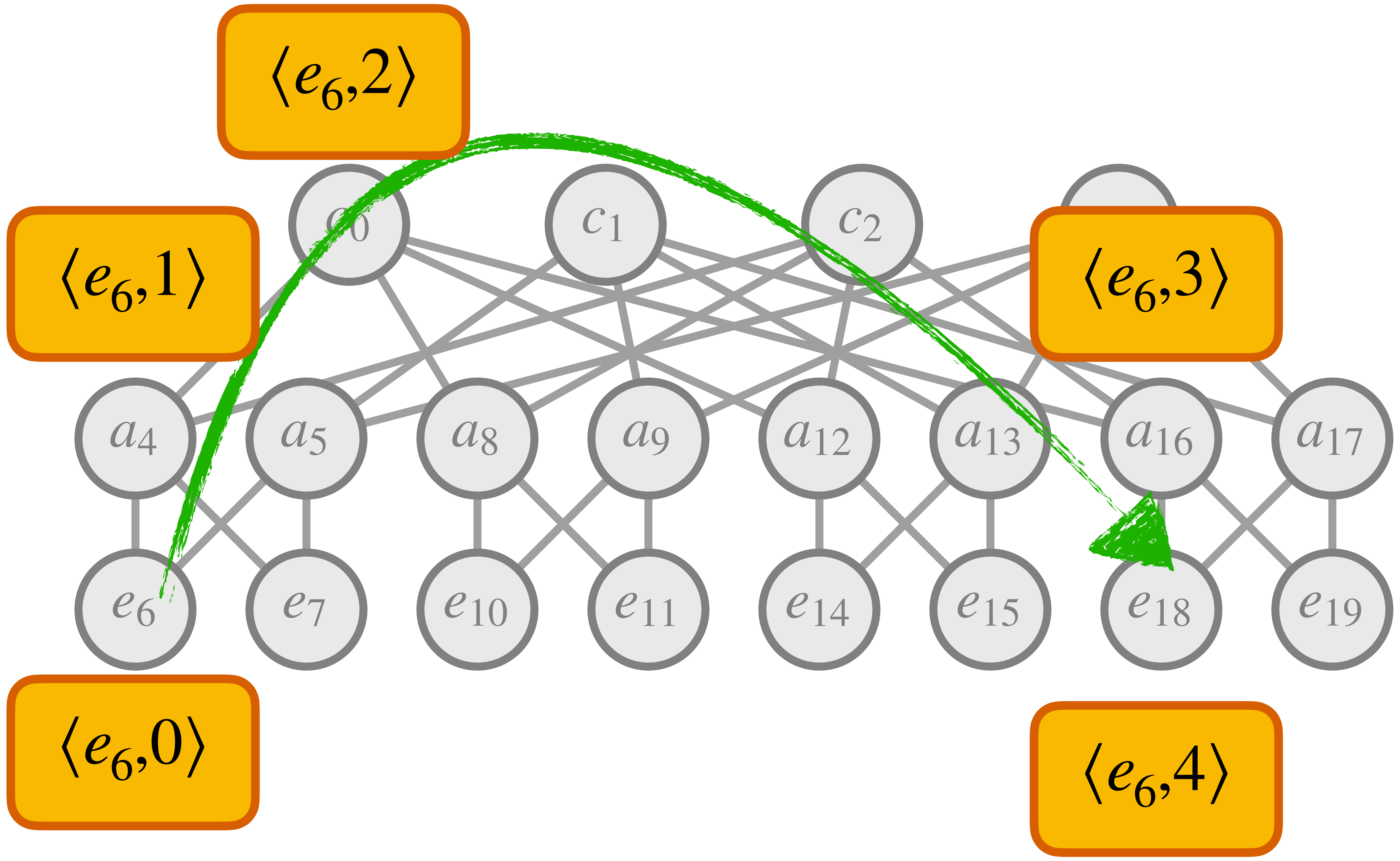
The Stable Routing Problem

Routing converges to **network solution**

Check **properties** on nodes' solutions

- **all-pairs path length**

  for any choice of identifier p, all nodes converge to a route $\langle p, x \rangle$ with a metric $x \leq 4$.



Verifying a Data Center

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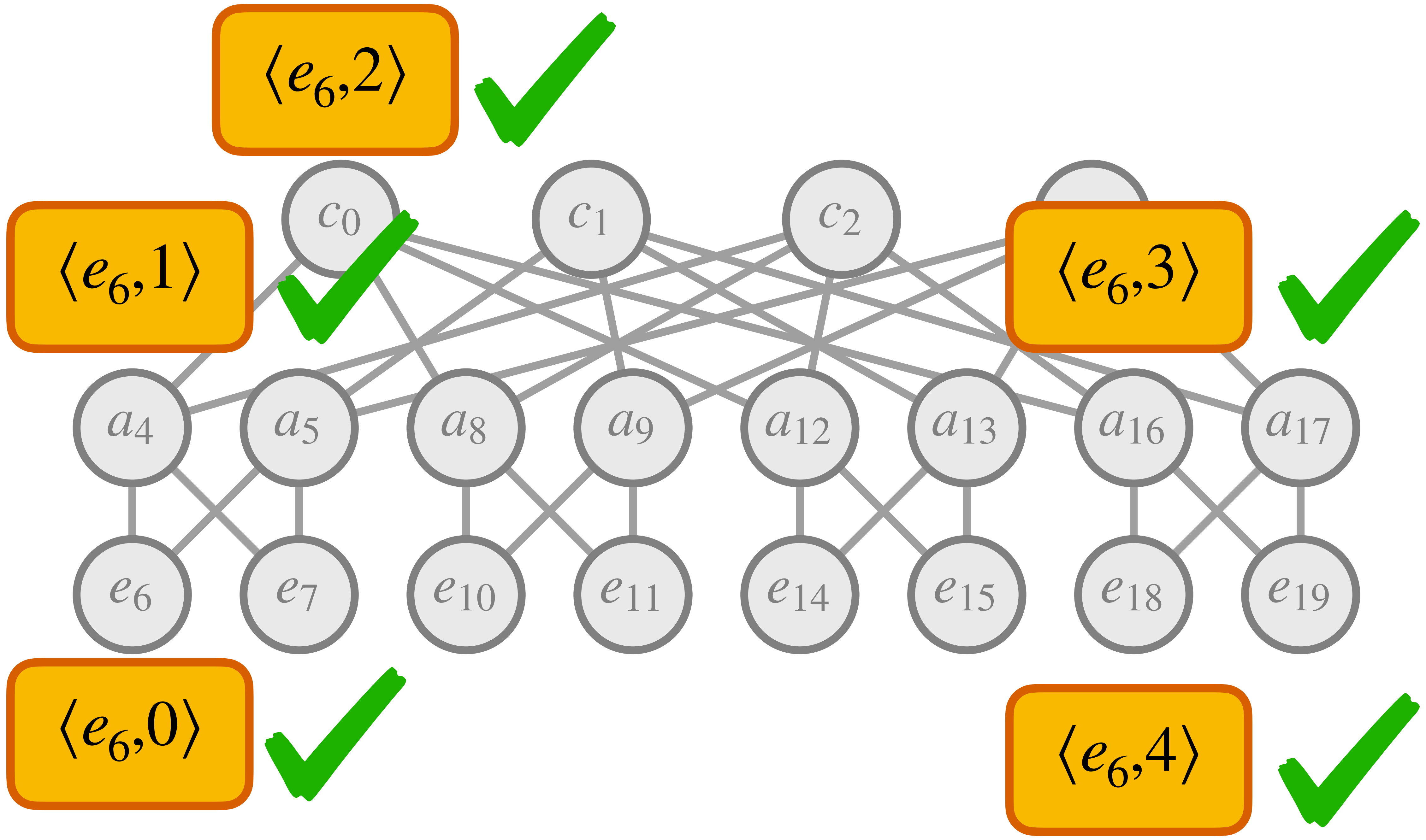

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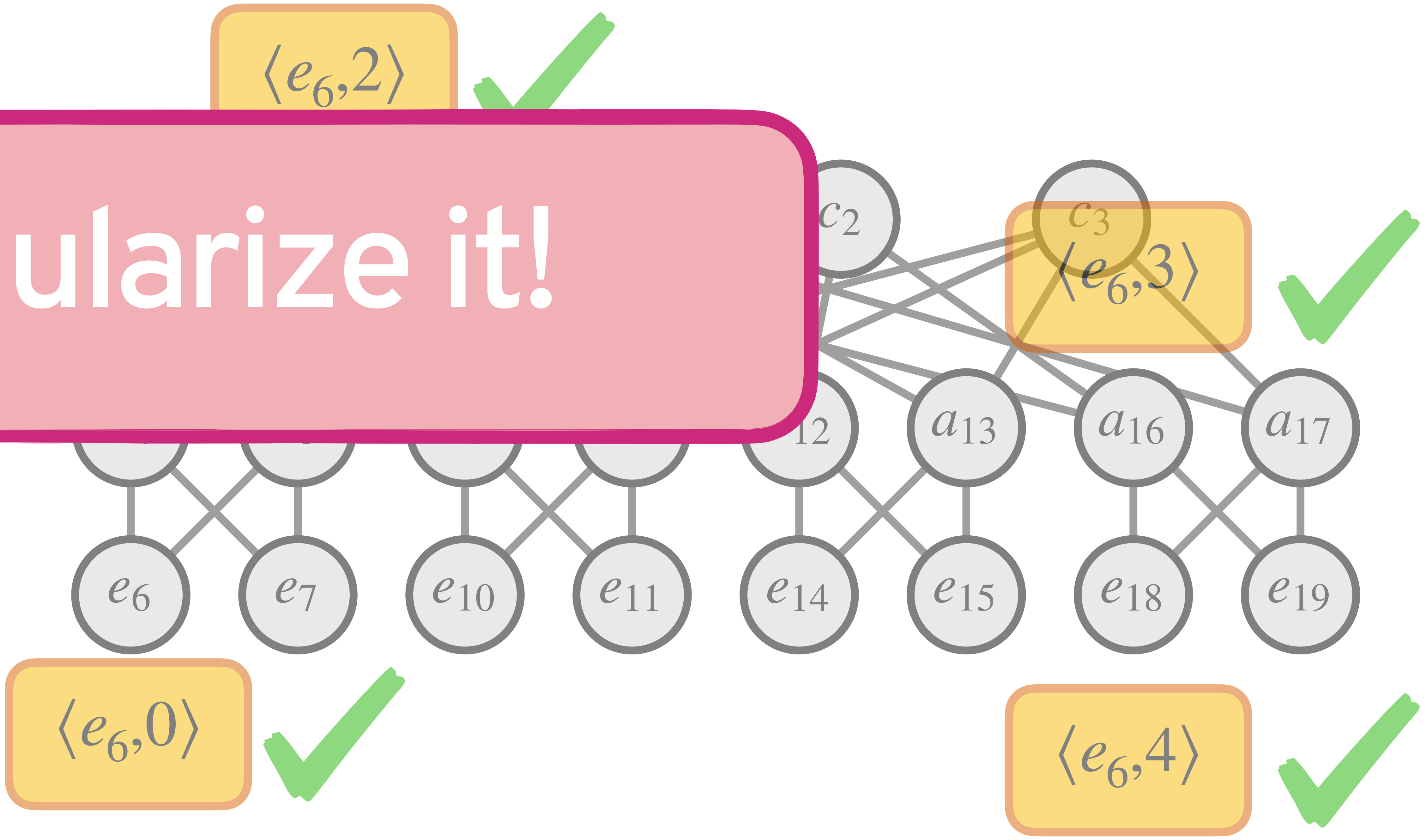


Let's modularize it!

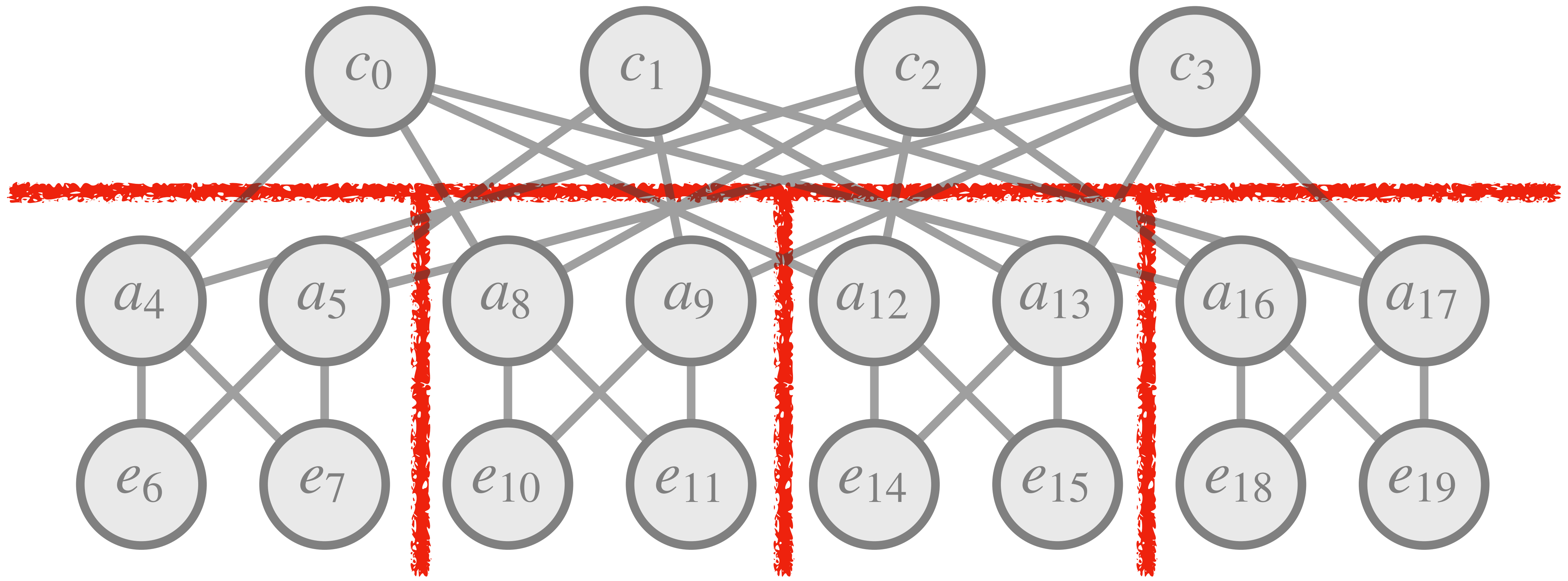
Cutting Down Fattrees

Cut fattree SRP S into **fragments**

- each pod i in its own fragment $T_{\text{p}i}$,
- spine nodes in a fragment T_{spines}

Represent **routes that cross the cut**

- **interface** annotating every cut edge



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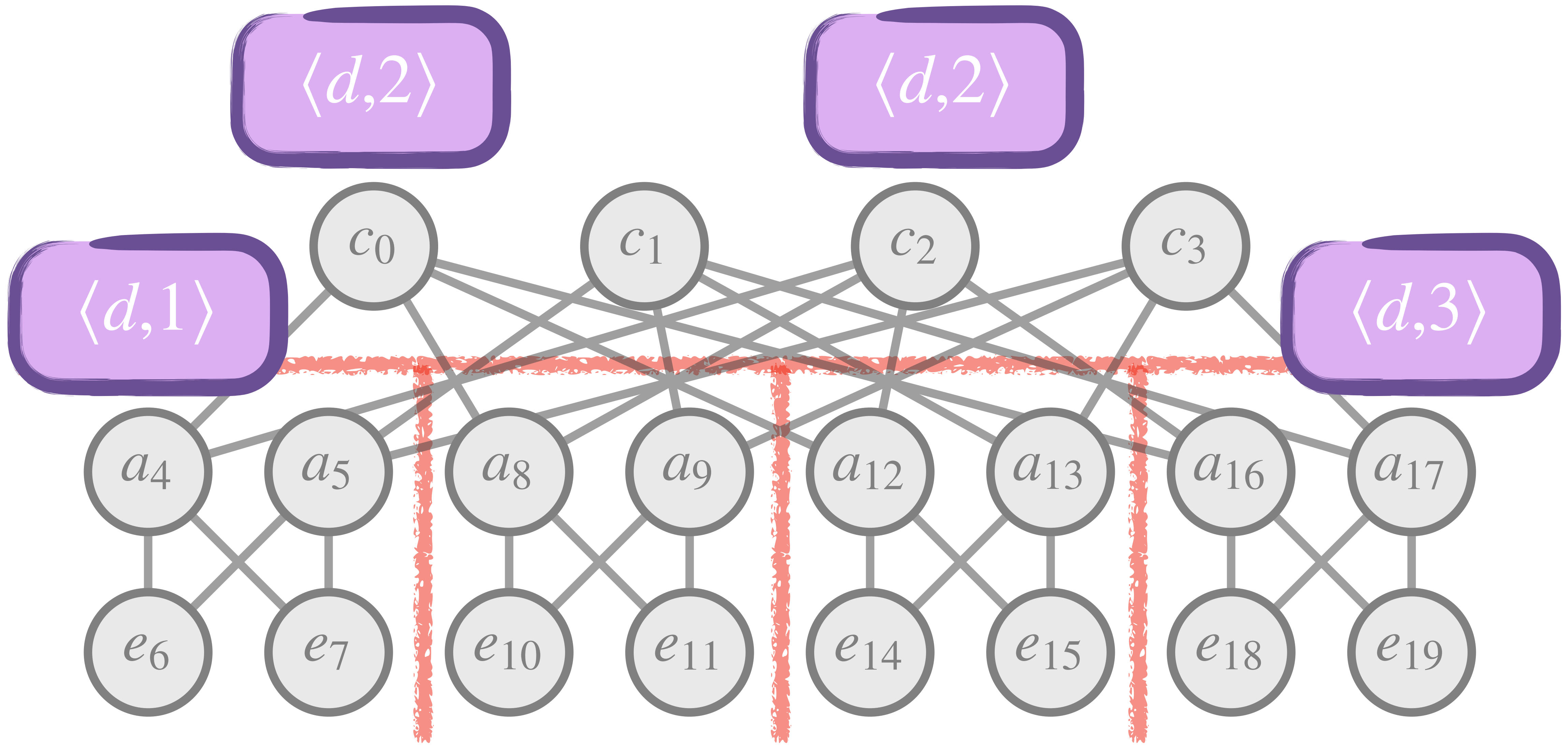

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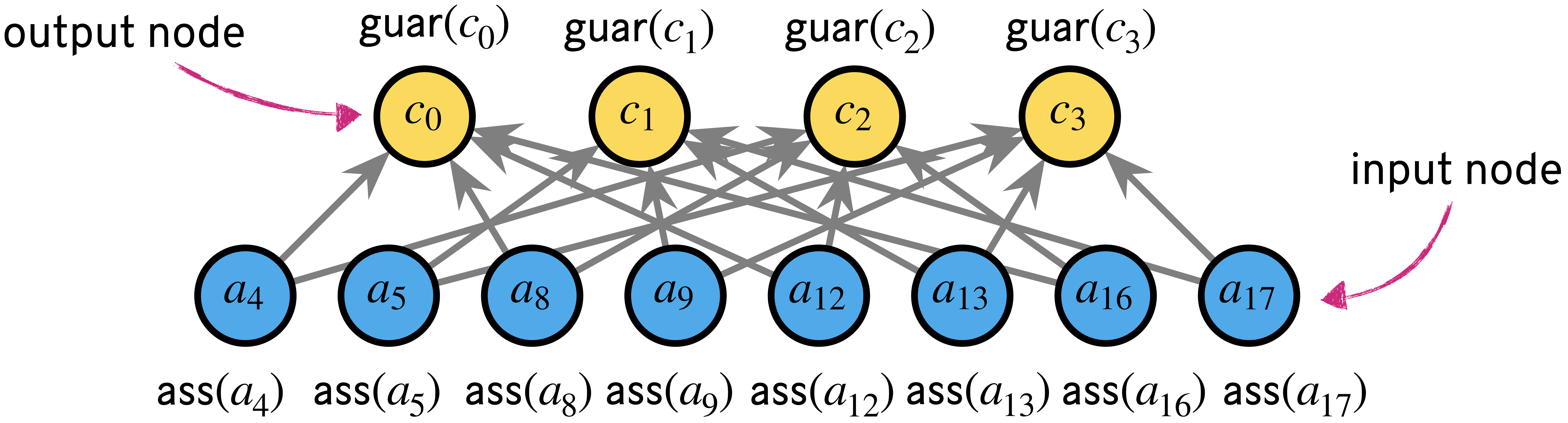

Interface defines

input nodes: assume the annotated route,

output nodes: guarantee (check) node converges to the annotated route

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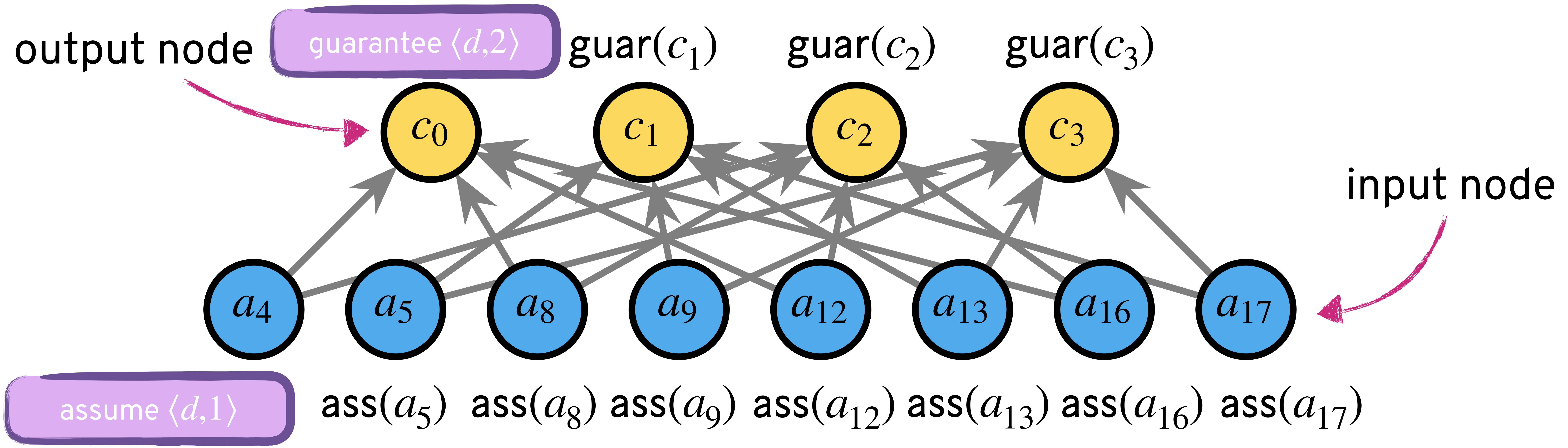

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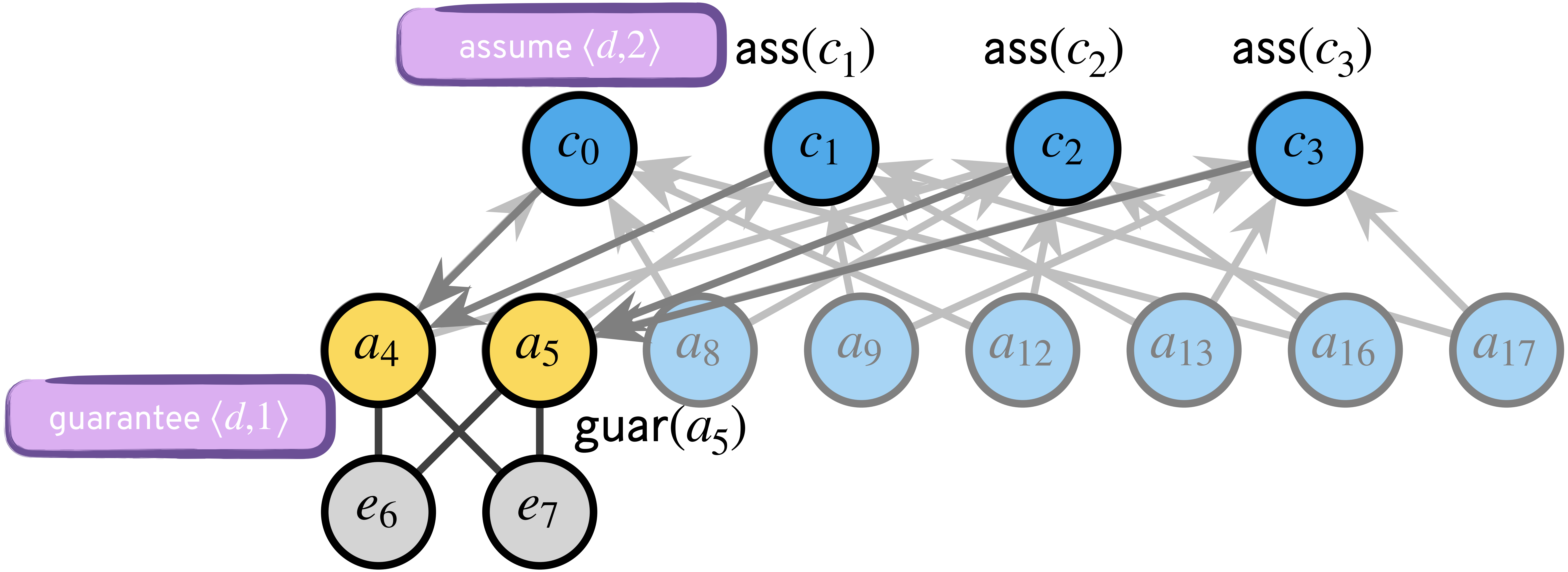
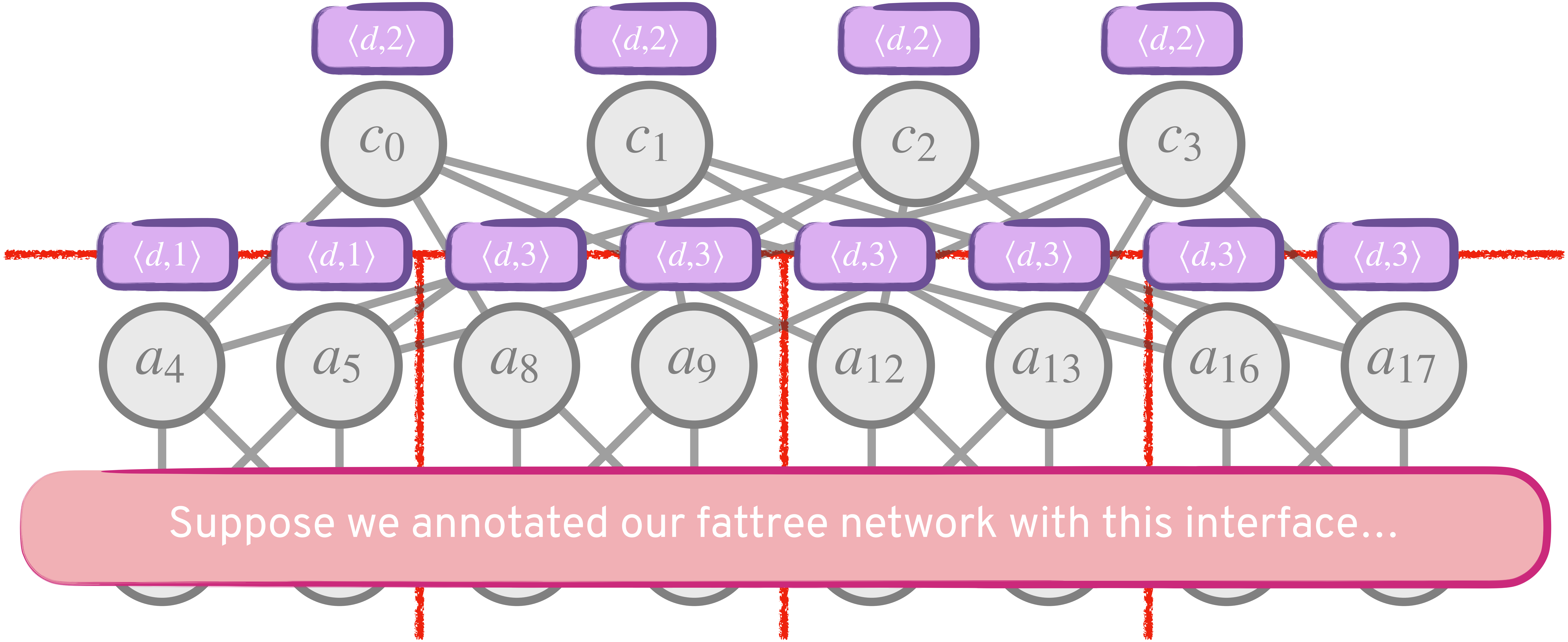


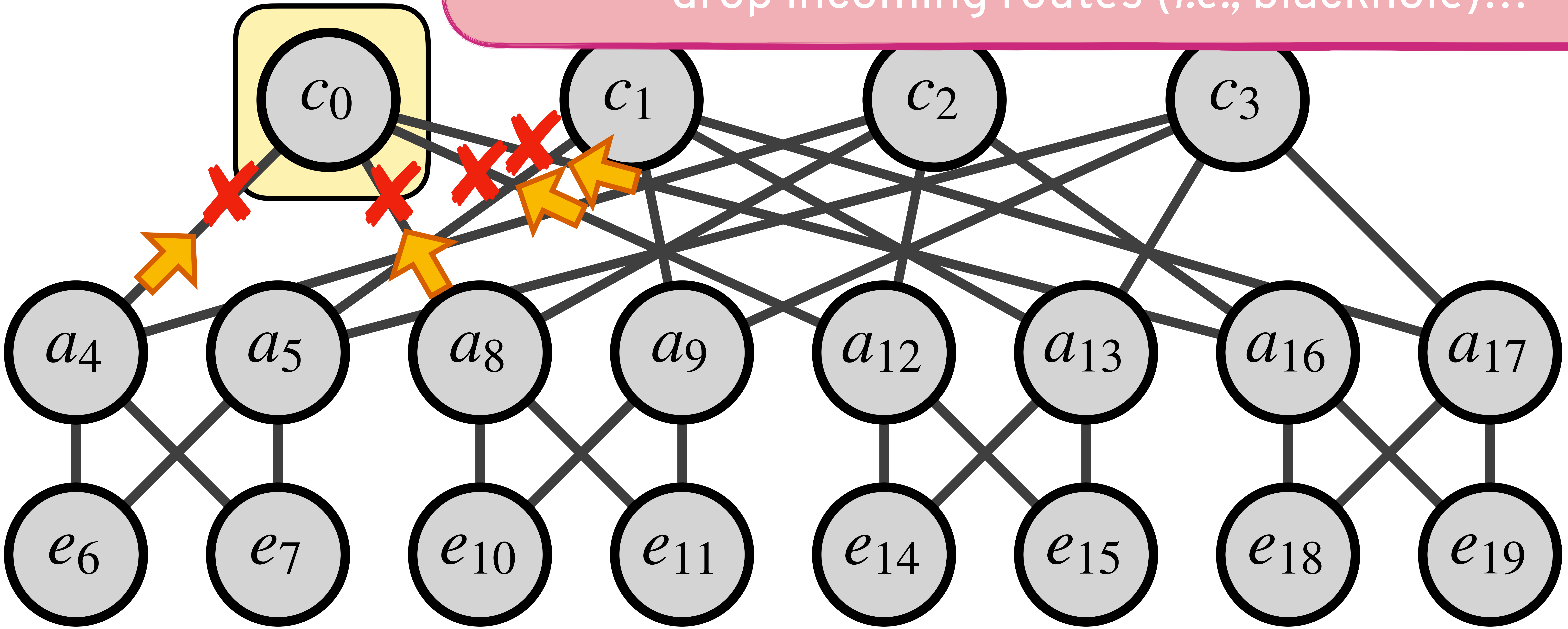
If we **assume** an annotation in one fragment, we **guarantee** it in another.

Catching Bugs with Modular Verification



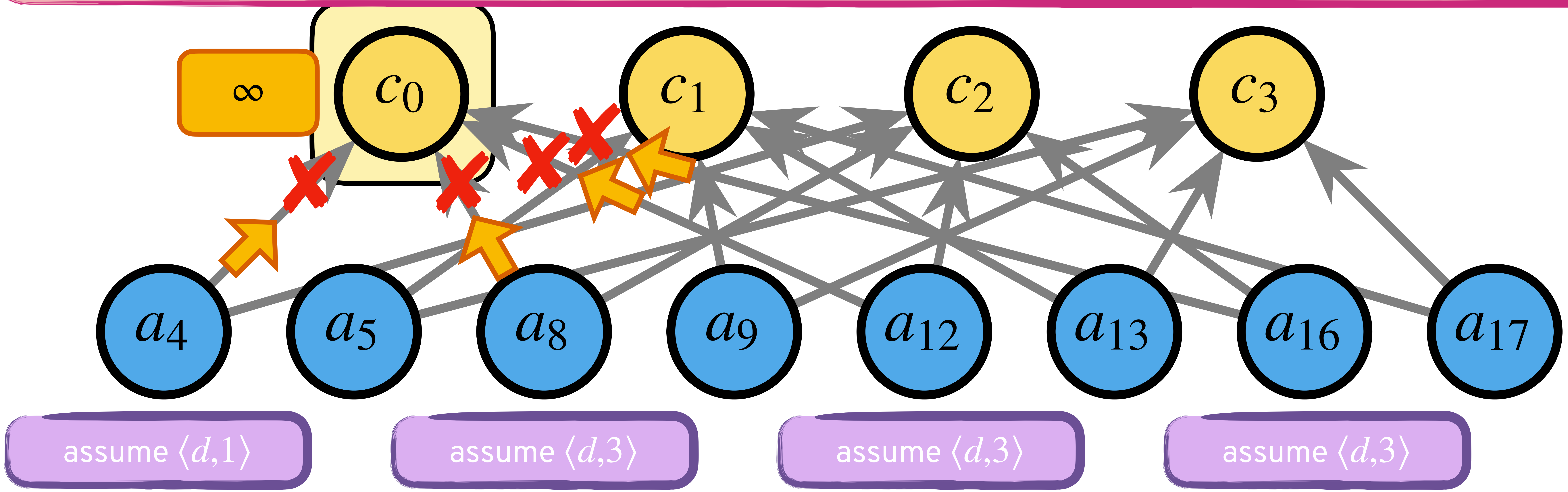
Catching Bugs with Modular Verification

Imagine c_0 is reconfigured incorrectly, causing it to drop incoming routes (*i.e.*, blackhole)...



Catching Bugs with Modular Verification

Given the assumptions on c_0's input nodes, it will converge to the ∞ route.



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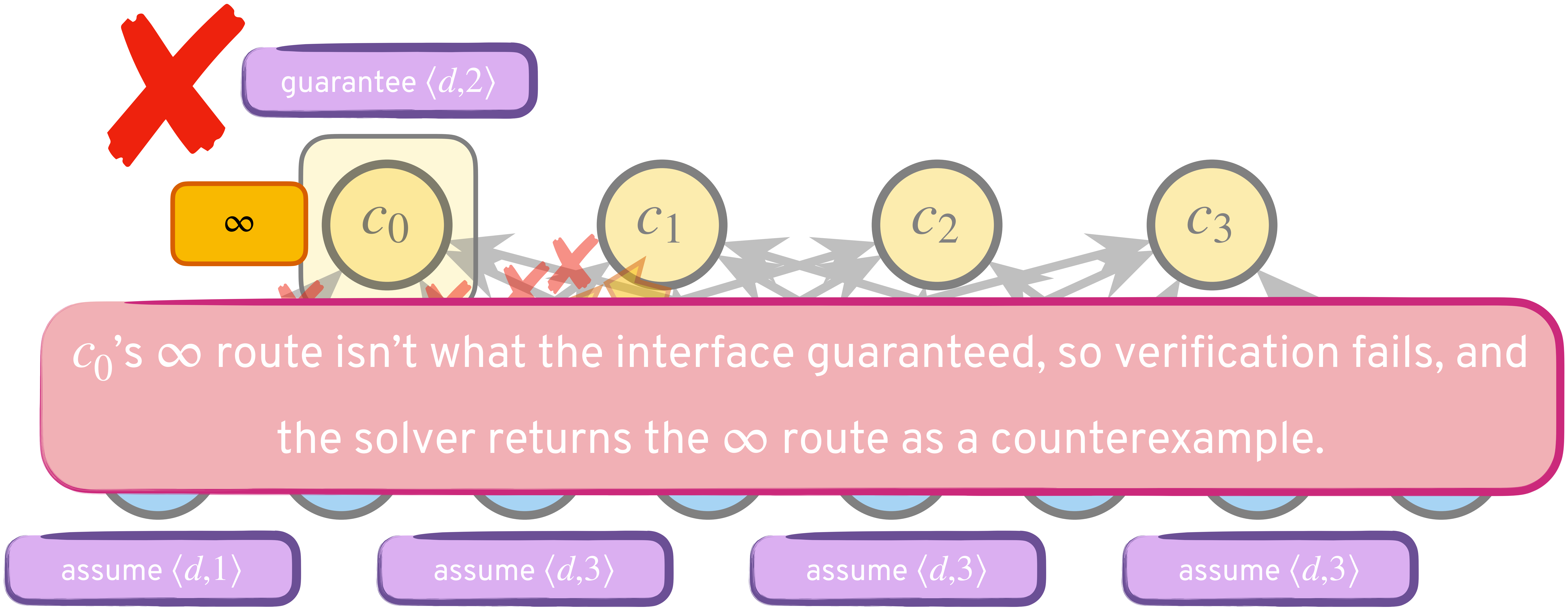
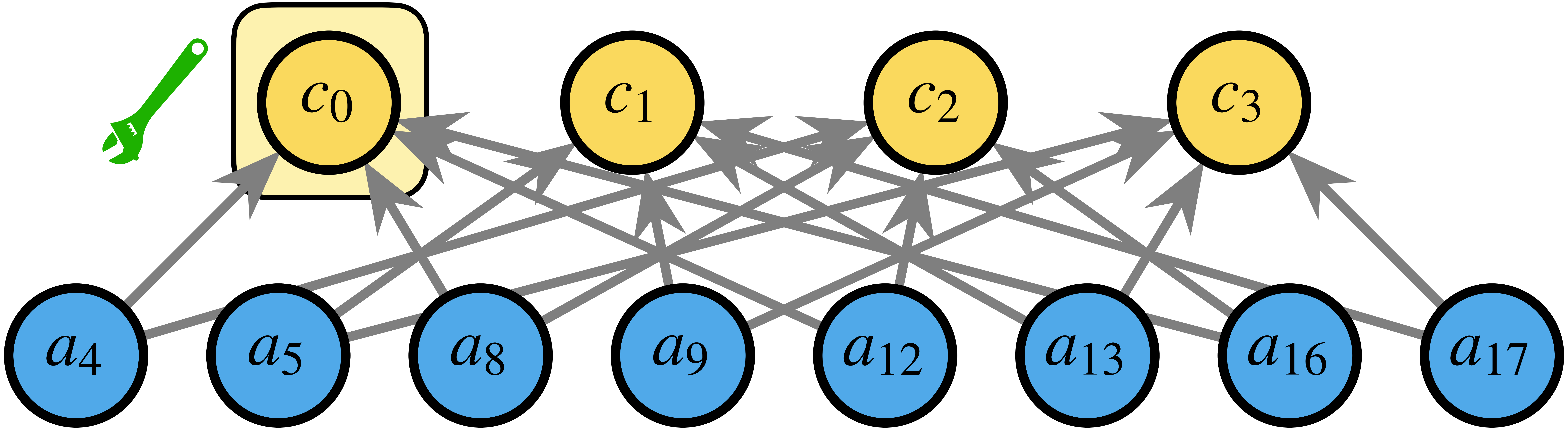


c_0’s ∞ route isn’t what the interface guaranteed, so verification fails, and the solver returns the ∞ route as a counterexample.

Catching Bugs with Modular Verification



We can now identify and fix the bug at c_0,

without checking any other fragment!

A Theory of Network Fragments

Proven sound

if we cut SRP S using interface I into fragments $T_1, T_2, \ldots,$

if the fragments have solutions, their combined solutions are a solution to S.

Proven complete

if we cut SRP S using interface I into fragments $T_1, T_2, \ldots,$

if I annotates the nodes with their solutions in S, the fragments have solutions.

Implementation

Kirigami

- an extension to NV, a network modelling system & analysis tool
- lets users define interfaces in the NV language for their networks

The “end-to-end” NV verification pipeline

- preprocess network
- **if interface defined,** cut into fragments using Kirigami
- encode network/fragments as SMT formulae
- hand off encoding(s) to the Z3 SMT solver to check properties & guarantees

Evaluation

We wanted to find out…

- Does Kirigami **scale better** than NV?
- How do **different cuts** affect verification time?

Evaluated on a variety of benchmarks

- Fattrees, random networks, wide-area networks
- Simple shortest-path, valley-free routing, 1-node fault tolerance
- Single-node reachability, all-ToR reachability

Kirigami improves maximum Z3 solve time by **up to 100,000x**, and end-to-end NV verification time by **up to 10x.**

All-ToR Reachability

Evaluation set-up

k-fattree topologies

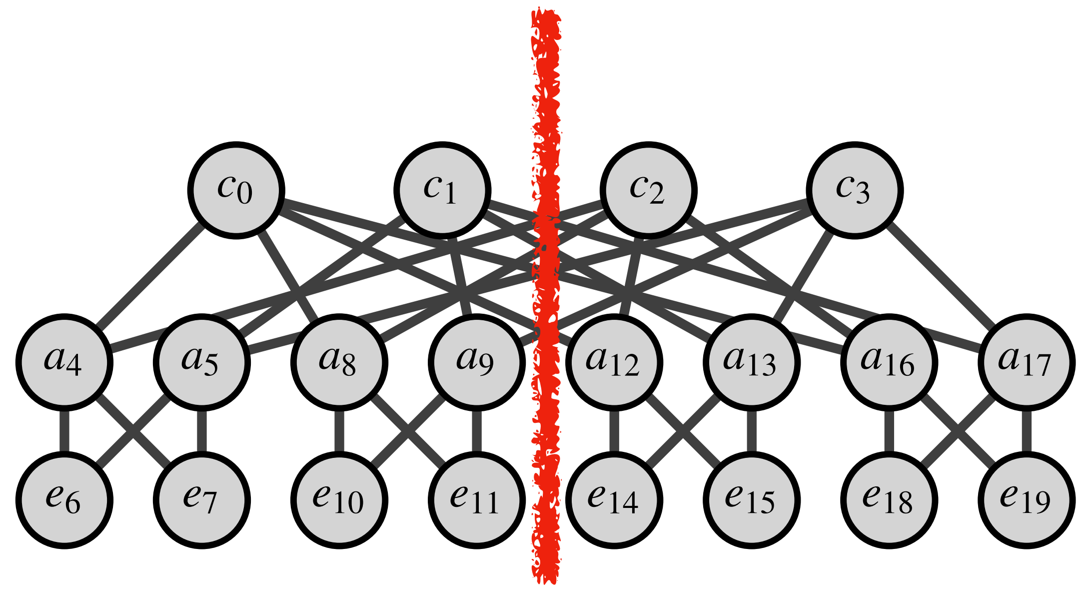
- 20 (k=4) to 500 (k=20) nodes

Simple shortest-path Border Gateway Protocol (BGP) routing to a *symbolic destination ToR node*

4 different cuts considered for fattrees

- Finer cuts require **more annotations**, but should take **less time to solve**
- Generated annotations using a script, using node tier and pod to determine shortest path to destination

vertical



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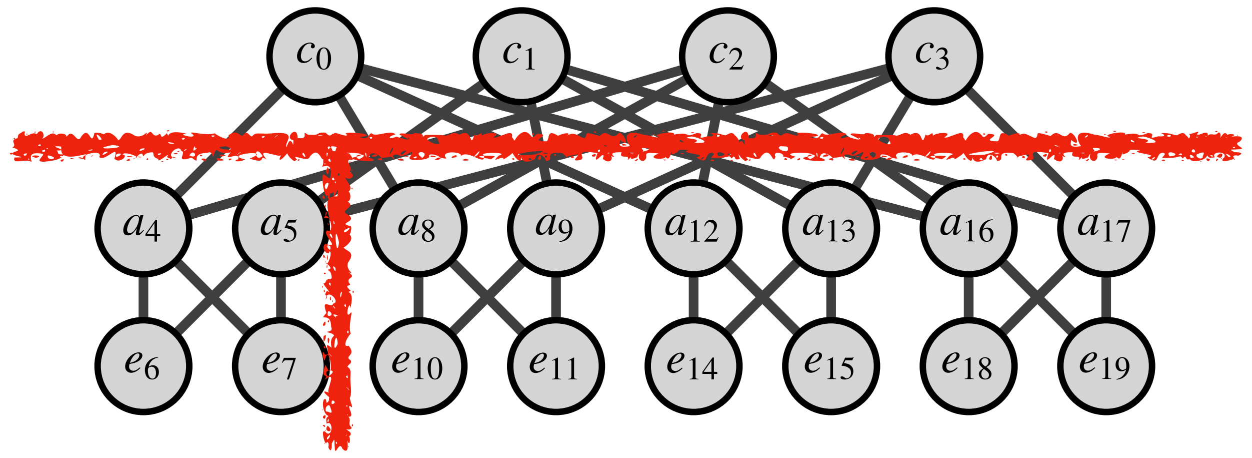
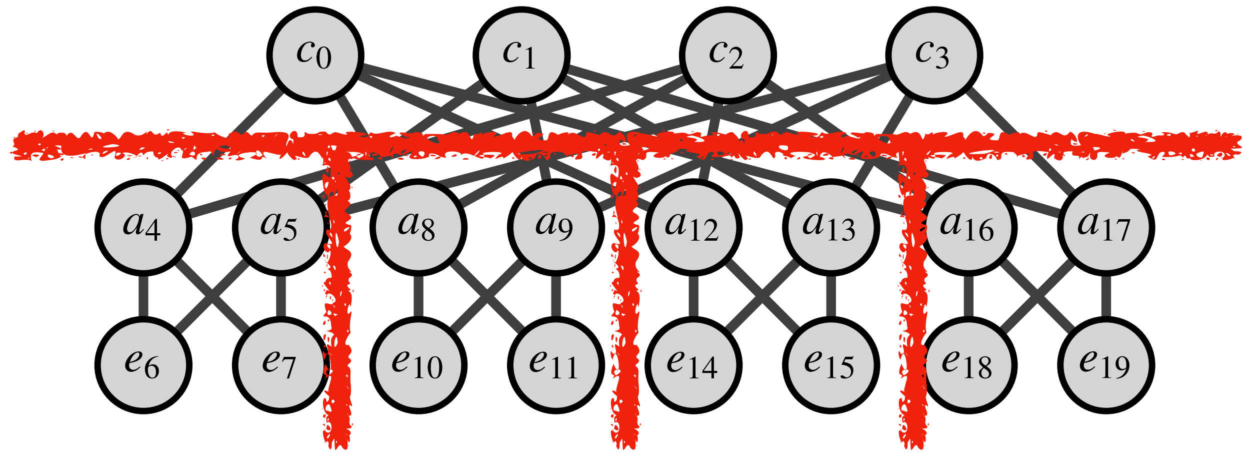
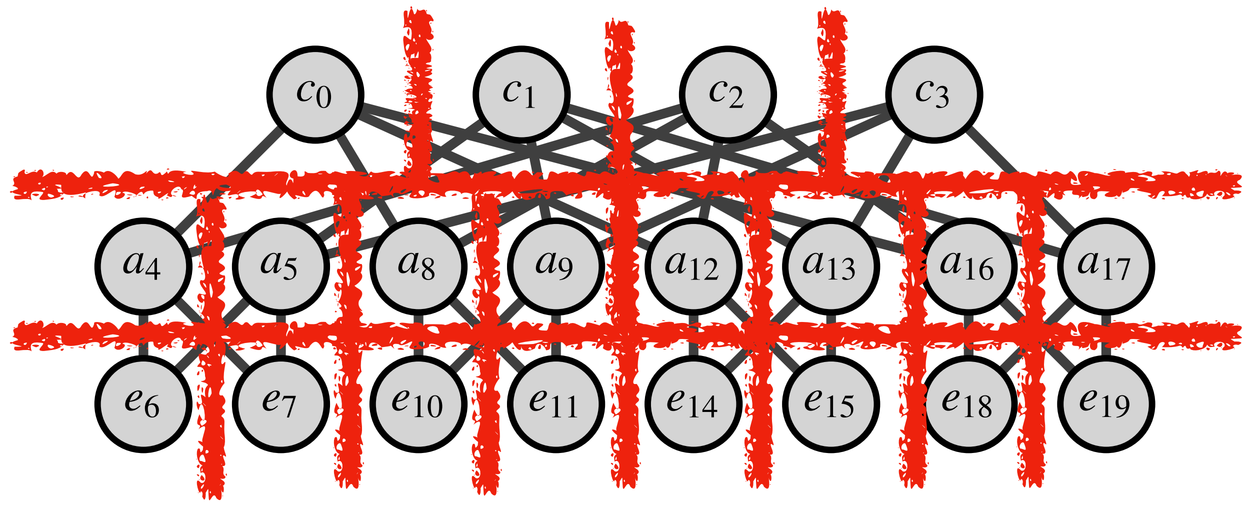


pods



full



All-ToR Reachability

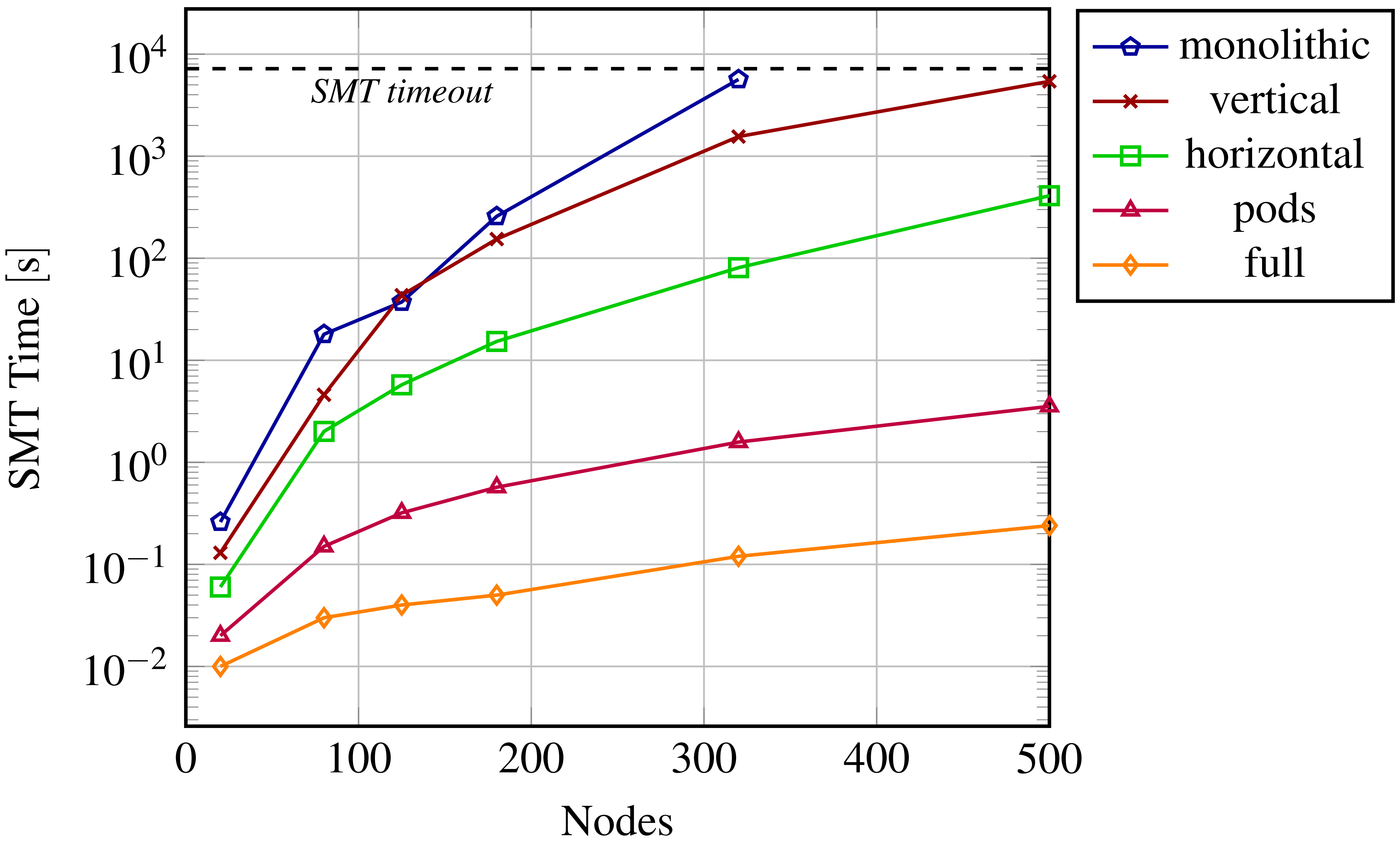
SMT Performance

Time taken by the **slowest SMT query** among all fragments (1 query/fragment)

Smaller fragments ⇒ faster queries

- At 500 nodes, monolithic benchmark times out after 2h
- … pods queries take at most 3.54s
- … full query take at most 0.24s

SMT results are similar across other benchmarks



All-ToR Reachability

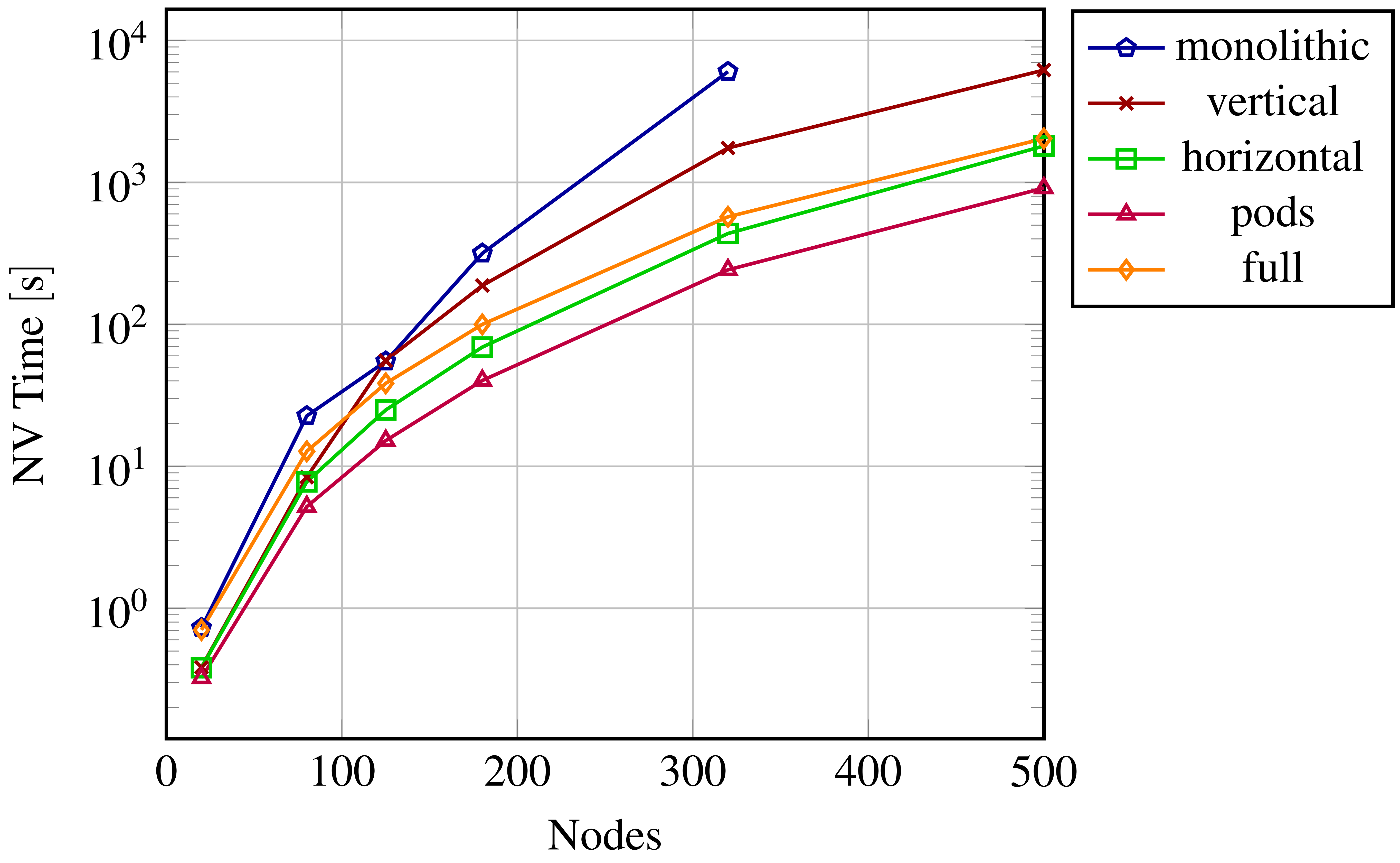
End-to-end Performance

Time taken by **NV verification pipeline**

Parallelized over 32 CPU cores, 128GB/core

Partitioned networks **scale past monolithic**

- At 320 nodes, ~10x speedup
- At 500 nodes, full cut spends 87% of time cutting network
- Pods cut fully parallelizable, balances cutting time with solving time to achieve best overall time



Practical Kirigami Usage

Annotations are a **small burden** relative to writing the rest of the config

- Users should **annotate during development**

Caveat: how difficult is it to come up with the **correct annotations**?

- Easiest in a **highly-structured network** such as a data center
- May need to **cut more granularly** to obtain interface with correct guarantees
- Counterexamples can help **refine interface** if annotations don't match network behavior

Limitations

Assumes networks converge to **unique solutions**

- Uncommon in practice?
- Easy to see for some protocols, *e.g.*, distance-vector protocols

Requires **exact annotations**

- Stable routes ensure we don't admit **spurious (incorrect) annotations**

Takeaways

Modularity has **critical benefits** for network verification

- Makes interactive behavior **explicit and easier to reason about**
- **Localizes** verification and error correction
- **Accelerates and parallelizes** analysis time

Kirigami brings modularity to network control plane verification

- ...with a **sound theoretical framework**
- ...and **proven benefits** on many topologies and policies!

Comparison of Related Work

Tool	Bagpipe (OOPSLA 2016)	Minesweeper (SIGCOMM 2018)	Tiramisu (NSDI 2020)	Plankton (NSDI 2020)	Kirigami (ICNP 2022)
Underlying technique	Encode BGP network to SMT	Encode network to SMT	Simulate policy over multi-layer graph	Use explicit-state model checking over policy model	Cut network, encode fragments to SMT
Arbitrary symbolic reasoning?	Yes	Yes	No	No*	Yes
Scales to large networks?	No	No	Yes	Yes	Yes
Modular?	No	No	No	No	Yes

Ryan Beckett, Aarti Gupta, Ratul Mahajan, and David Walker. A general approach to network configuration verification. In SIGCOMM, August 2017. https://doi.org/10.1145/3098822.3098834

Konstantin Weitz, Doug Woos, Emina Torlak, Michael D. Ernst, Arvind Krishnamurthy, and Zachary Tatlock. Scalable Verification of Border Gateway Protocol Configurations with an SMT Solver. In OOPSLA 2016. http://www.konne.me/assets/bagpipe.pdf

Anubhavnidhi Abhashkumar, Aaron Gember-Jacobson, and Aditya Akella. Tiramisu: Fast multilayer network verification. In NSDI 2020. https://www.usenix.org/system/files/nsdi20-paper-abhashkumar.pdf

Santhosh Prabhu, Kuan-Yen Chou, Ali Kheradmand, Brighten Godfrey, and Matthew Caesar. Plankton: Scalable network configuration verification through model checking. In NSDI 2020. https://www.usenix.org/system/files/nsdi20-paper-prabhu.pdf

A Closer Look at the Implementation

```
include “fat.nv”

(* Associate each node with a fragment *)
let partition node = match node with
  | 0n | 1n | 2n | 3n -> 0 (* spines *)
  | 4n | 5n | 6n | 7n -> 1 (* pod 0 *)
  | 8n | 9n | 10n | 11n -> 2 (* pod 1 *)
  | 12n | 13n | 14n | 15n -> 3 (* pod 2 *)
  | 16n | 17n | 18n | 19n -> 4 (* pod 3 *)

(* Associate each edge with an annotation *)
let interface edge route = match edge with
  | 0~_ | 1~_ | 2~_ | 3~_ -> route = { id = d; cost = 2; }
  | 4~_ | 5~_ ->             route = { id = d; cost = if d >= 4 && d <= 7 then 1 else 3; }
  | 8~_ | 9~_ ->             route = { id = d; cost = if d >= 8 && d <= 9 then 1 else 3; }
  | 12~_ | 13~_ ->           route = { id = d; cost = if d >= 12 && d <= 15 then 1 else 3; }
  | 16~_ | 17~_ ->           route = { id = d; cost = if d >= 16 && d <= 19 then 1 else 3; }
```

Why Exact Annotations?

Limitation of our approach: couldn't we overapproximate?

- Exact routes ensure **spurious annotations are not admitted**

Other modular techniques also require **a well-founded ordering**

- Different tradeoffs to provide this ordering