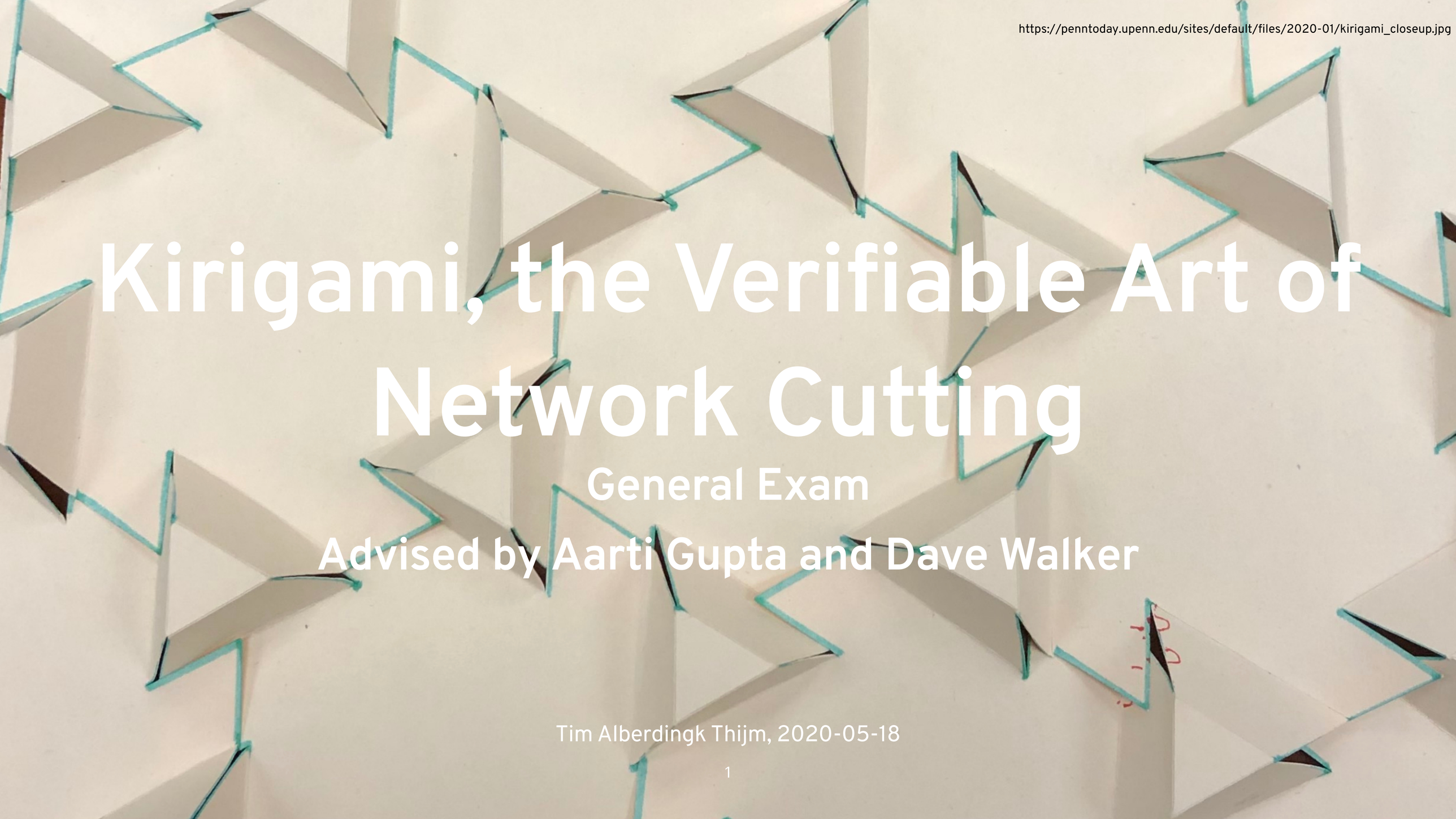


https://penntoday.upenn.edu/sites/default/files/2020-01/kirigami_closeup.jpg

Kirigami, the Verifiable Art of Network Cutting

General Exam

Advised by Aarti Gupta and Dave Walker

Tim Alberdingk Thijm, 2020-05-18

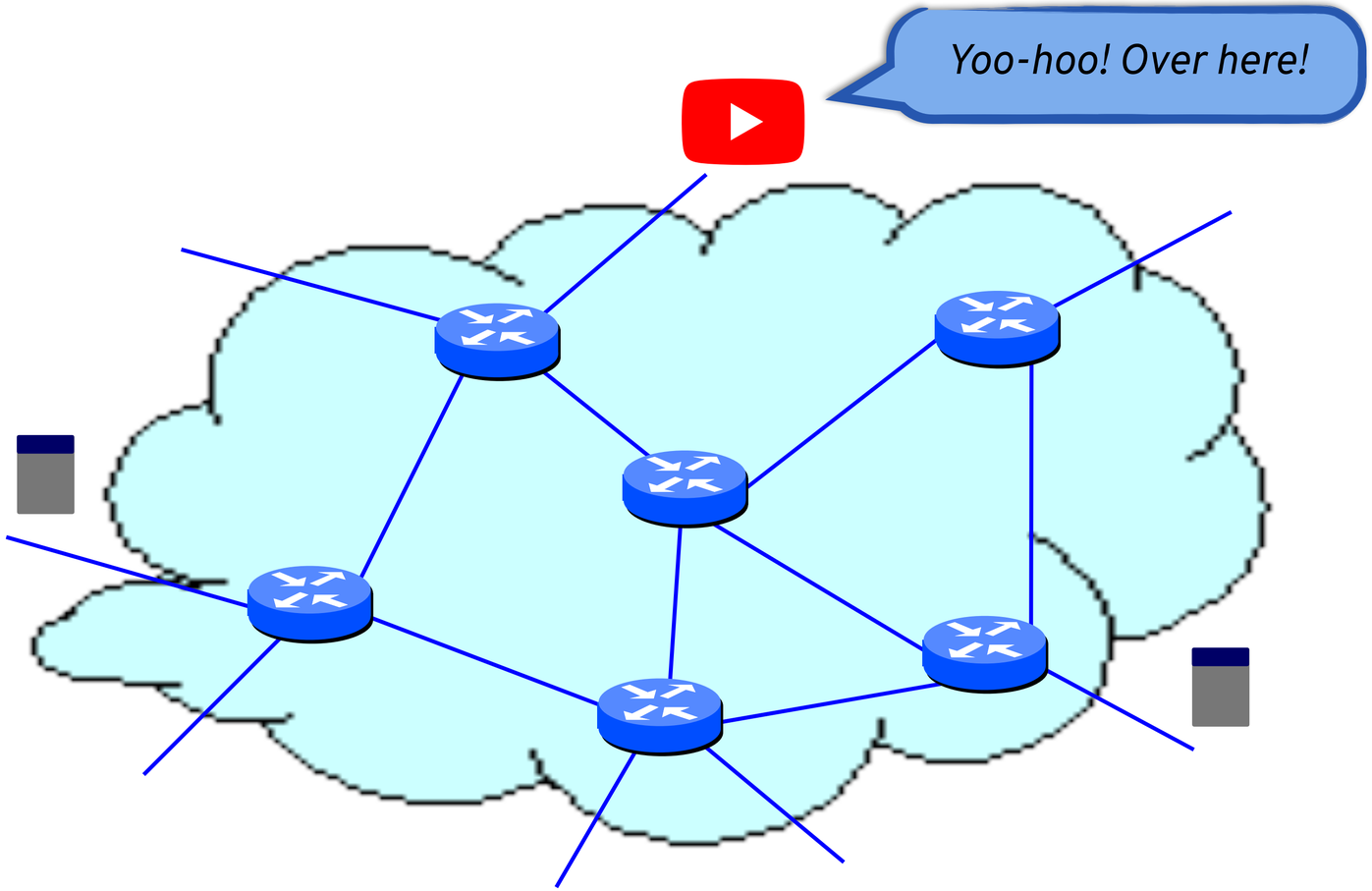
Network Routing

A (Simplified) Control Plane Protocol

Some images from Jen Rexford's COS561 slides

Network Routing

A (Simplified) Control Plane Protocol



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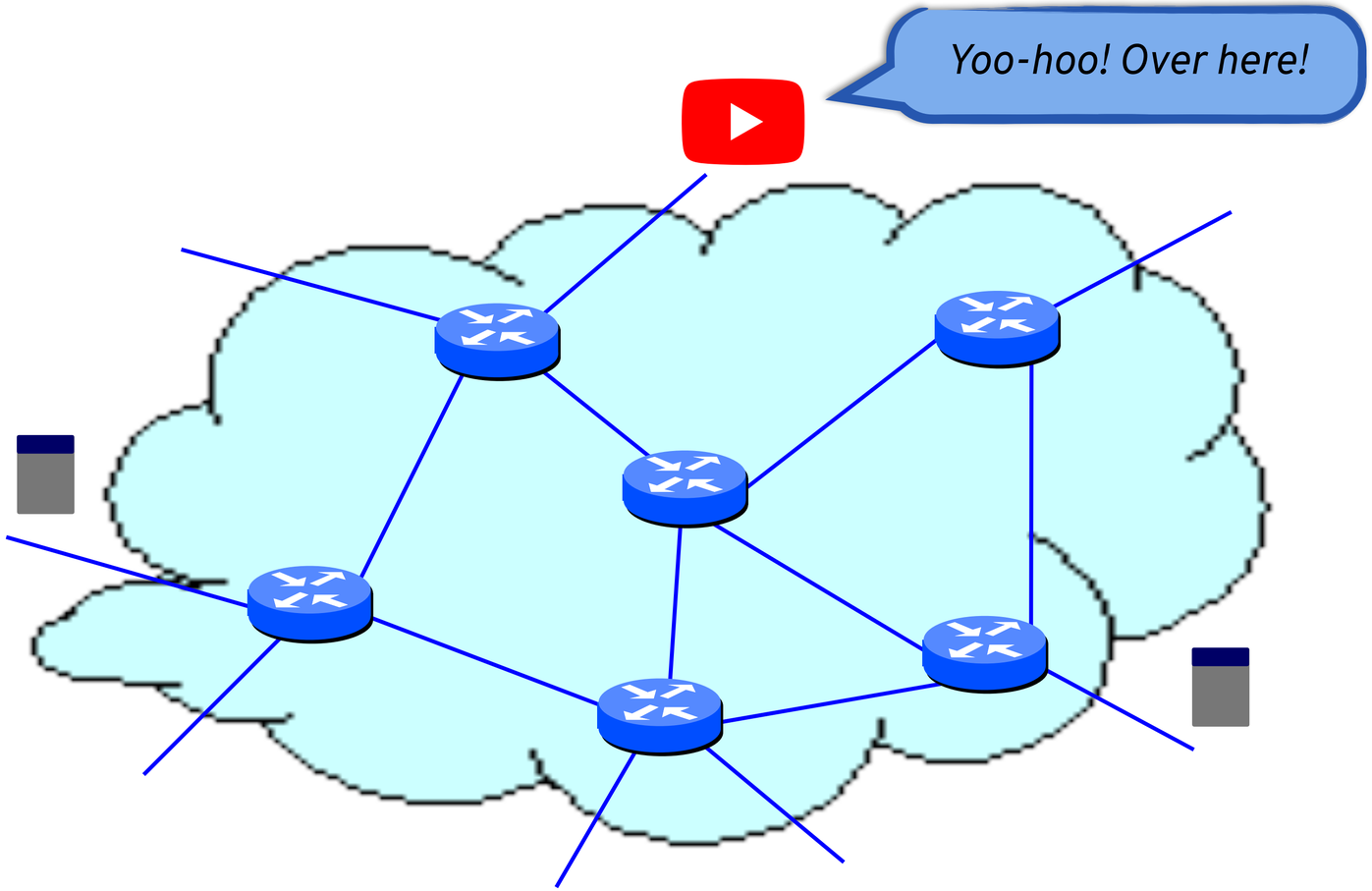
Network Routing

A (Simplified) Control Plane Protocol

Routers can:

- *Send messages*
- *Receive messages*
- *Compare routes by incentives*



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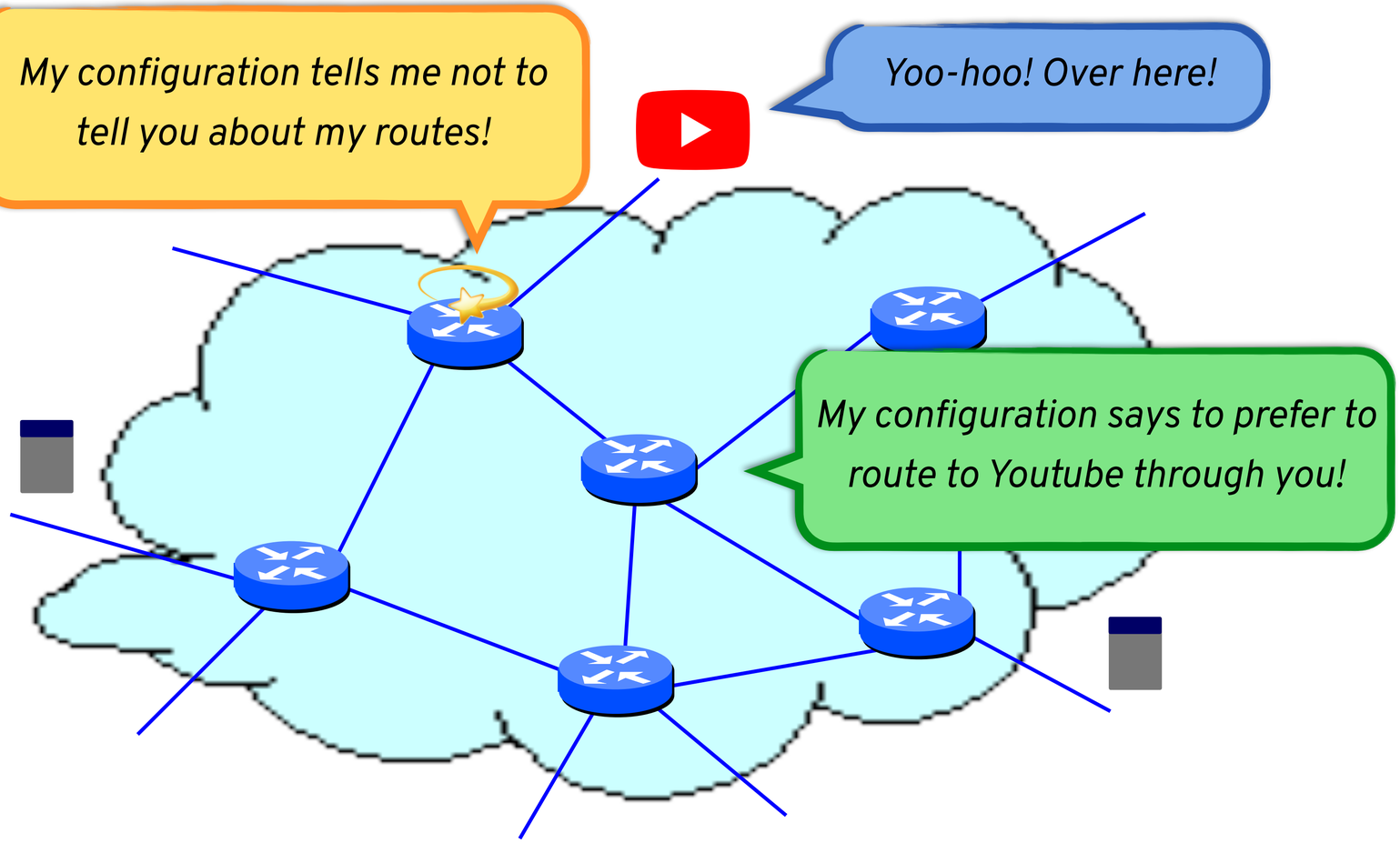

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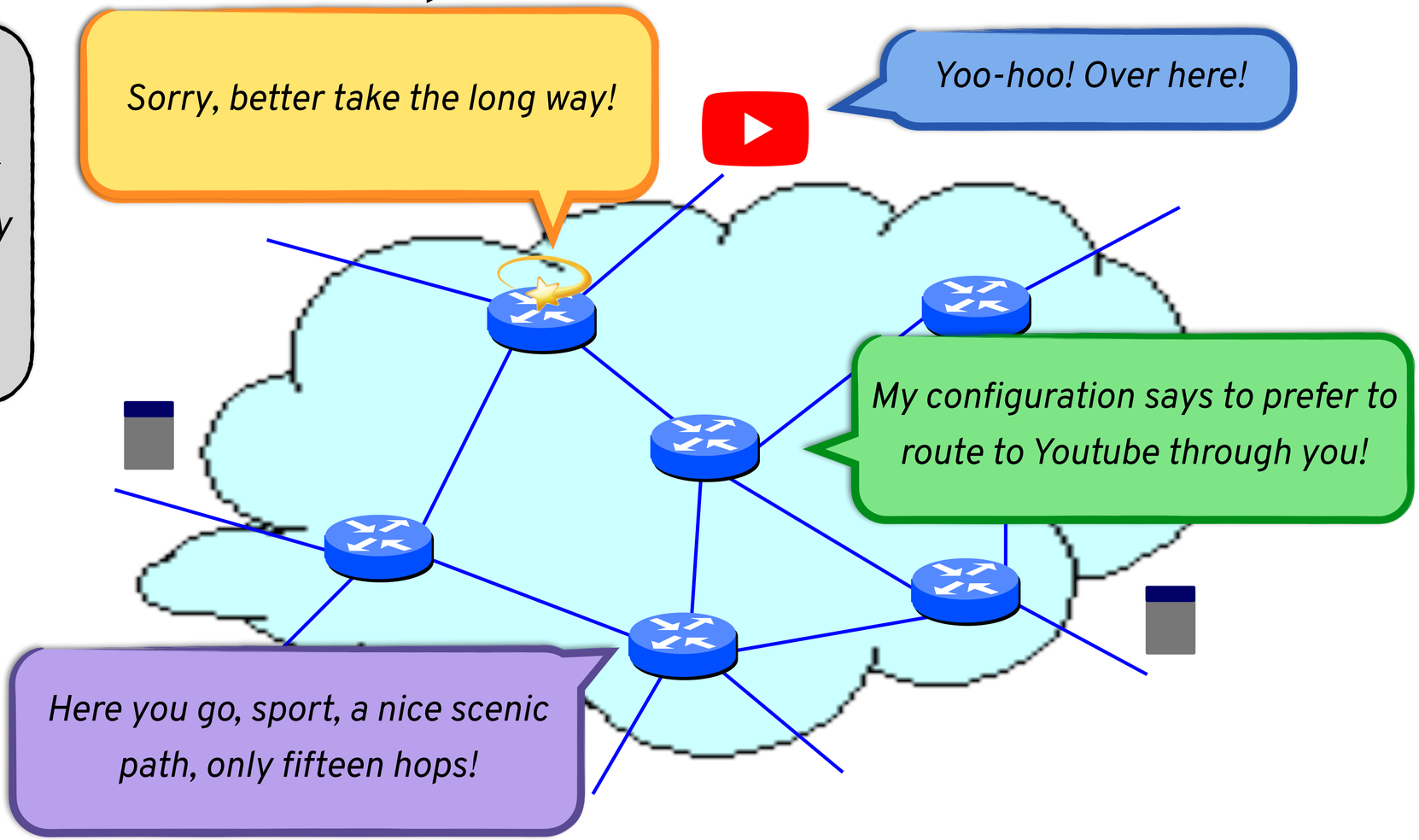

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Network Routing

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Routers can:

- *Send messages*
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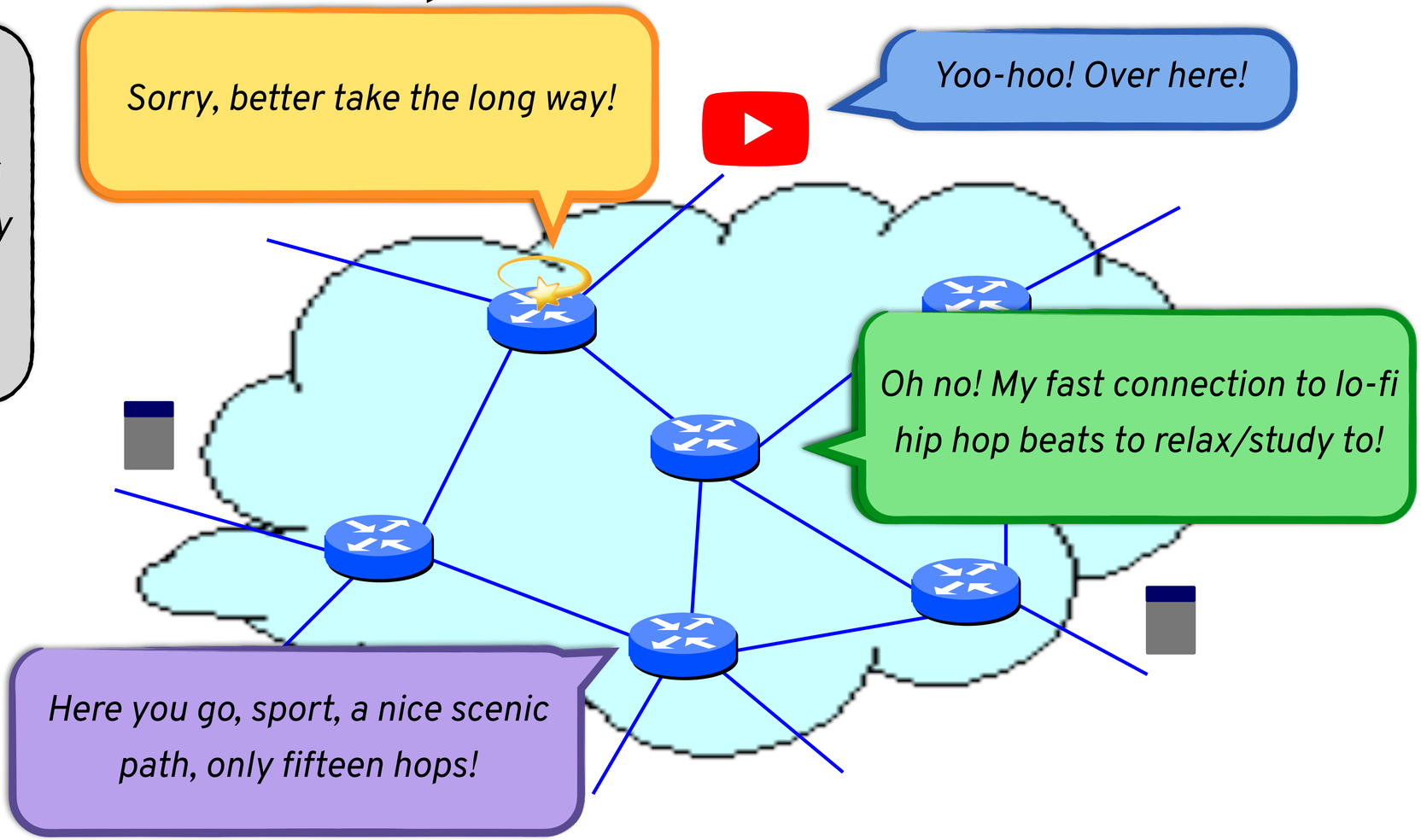

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Solver-Aided Network Verification

In A Nutshell

[Beckett et al., SIGCOMM 2017]

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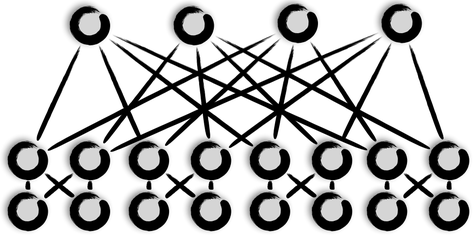
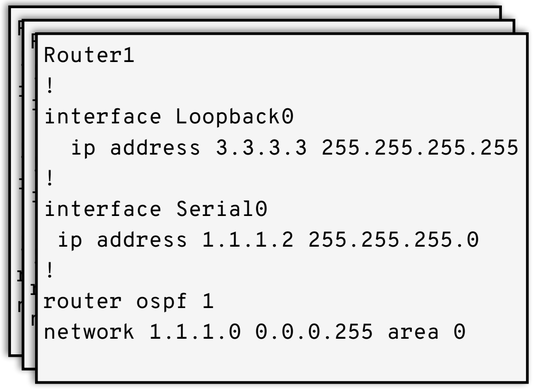
Solver-Aided Network Verification

In A Nutshell





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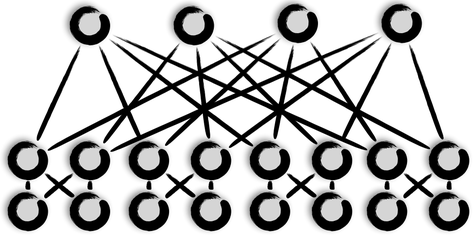

```
Router1
!
interface Loopback0
  ip address 3.3.3.3 255.255.255.255
!
interface Serial0
 ip address 1.1.1.2 255.255.255.0
!
router ospf 1
network 1.1.1.0 0.0.0.255 area 0
```

$$\varphi_1 \wedge \varphi_2 \wedge \ldots \wedge \varphi_n$$

[Beckett et al., SIGCOMM 2017]

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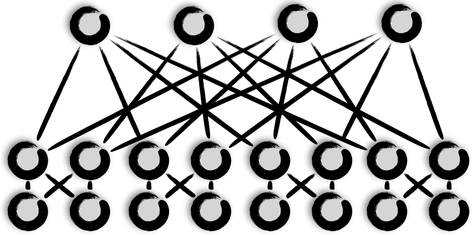

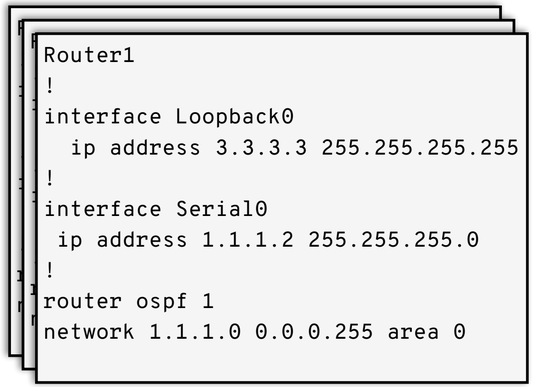

P

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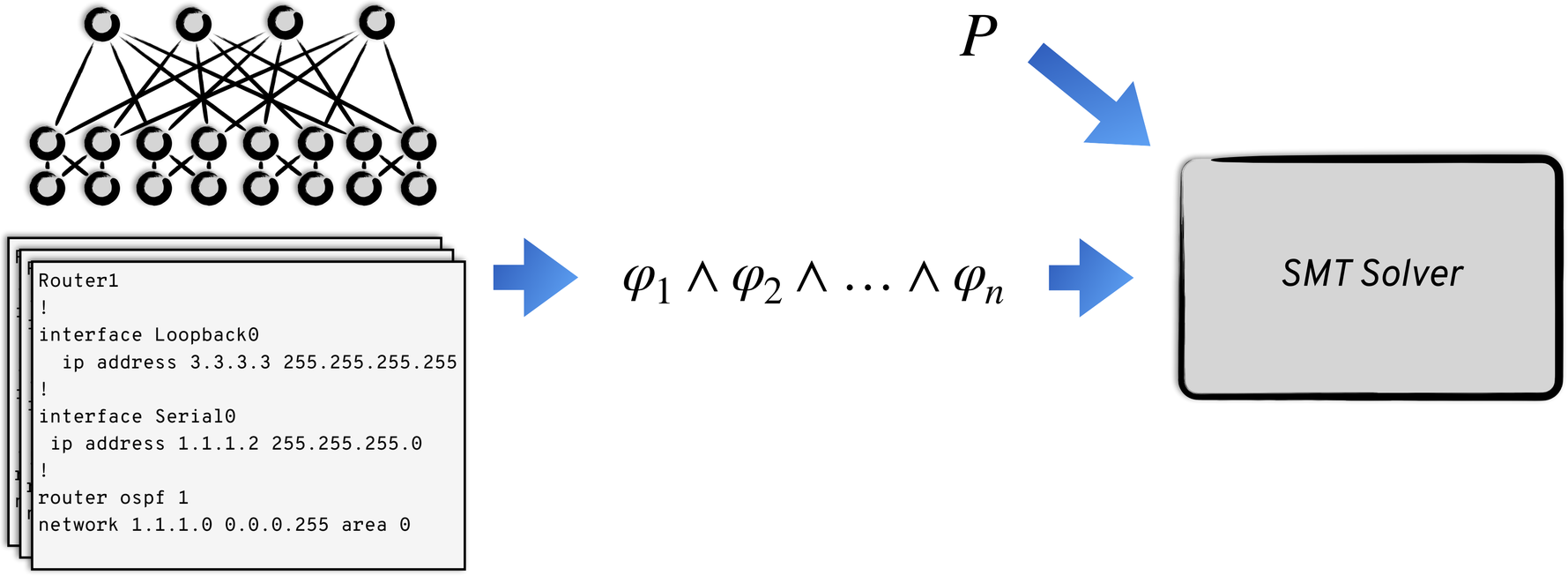

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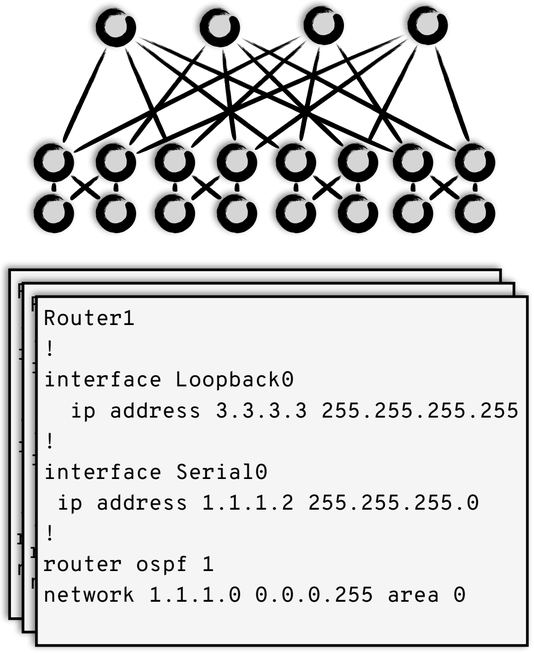

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$\varphi_1 \wedge \varphi_2 \wedge \ldots \wedge \varphi_n$

P

SMT Solver

Verified ✓

[Beckett et al., SIGCOMM 2017]

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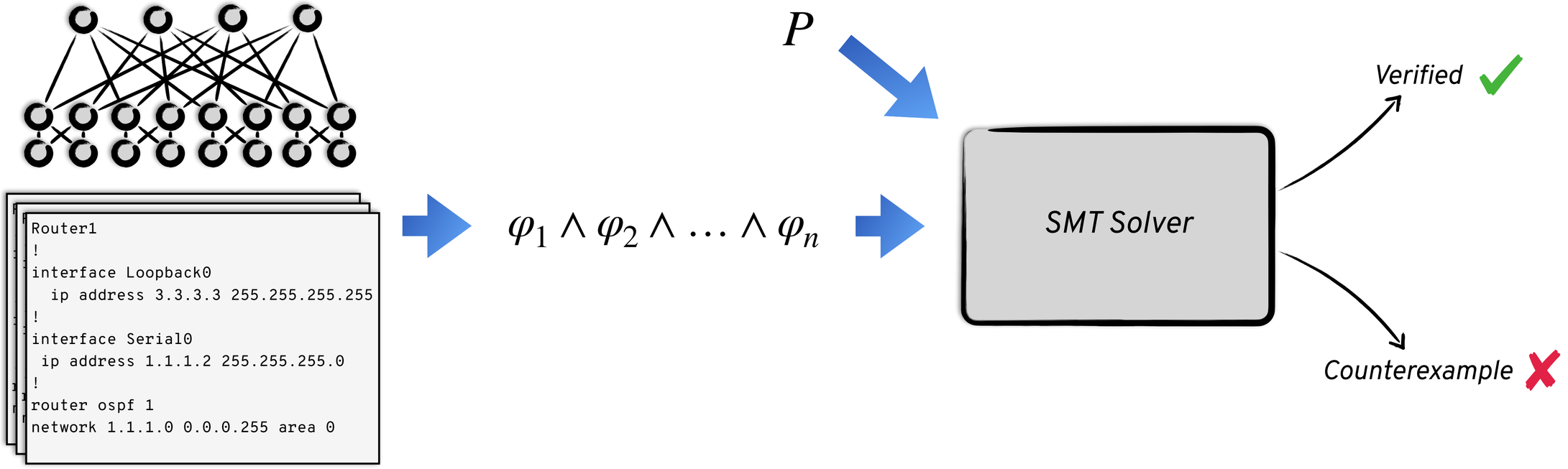

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SMT Verification Scalability

[Beckett et al., SIGCOMM 2017]

SMT Verification Scalability

- # SMT Variables $\propto$ Network Size

[Beckett et al., SIGCOMM 2017]

SMT Verification Scalability

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- Time to check certain properties can be exponential in the number of variables!

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SMT Verification Scalability

- # SMT Variables ∝ Network Size
- Time to check certain properties can be exponential in the number of variables!

(lower is better)

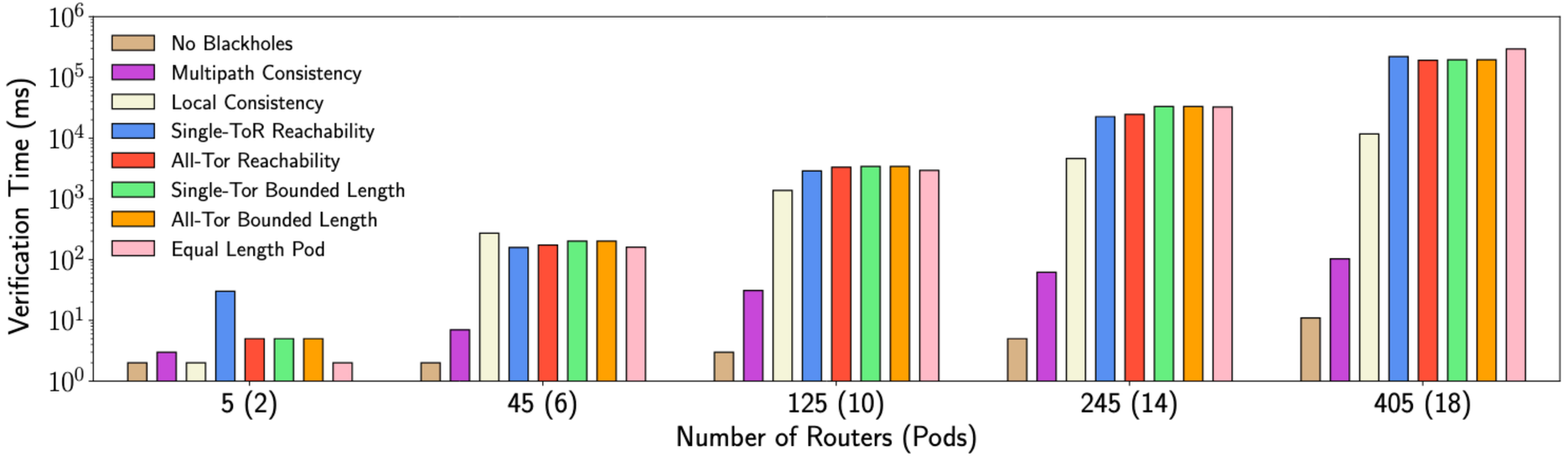

Figure 8: Verification time for synthetic configurations for different properties and network sizes.

[Beckett et al., SIGCOMM 2017]

SMT Verification Scalability

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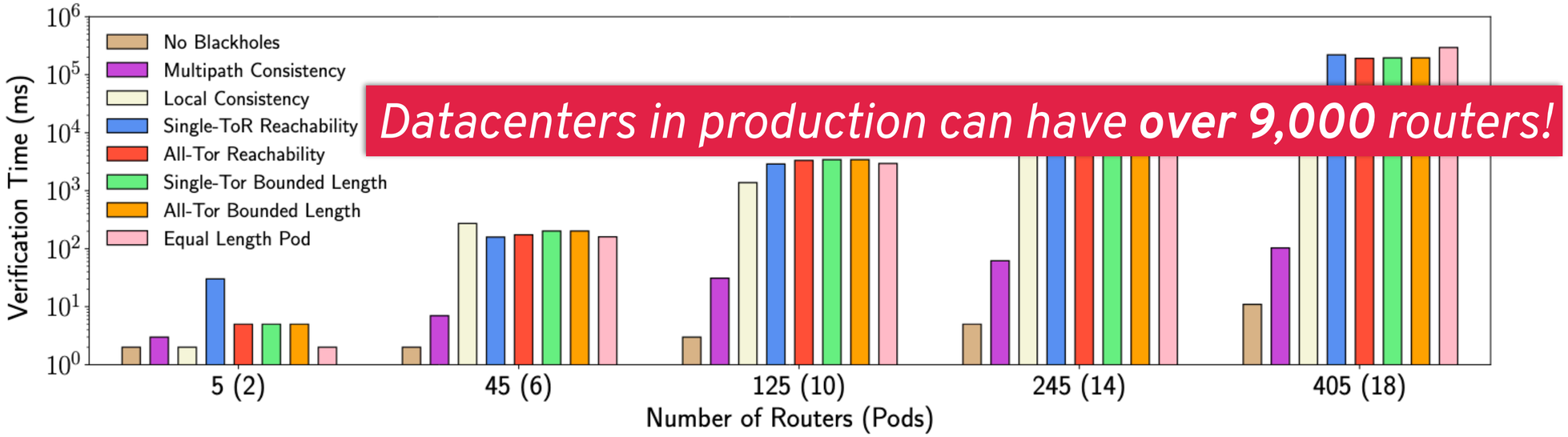
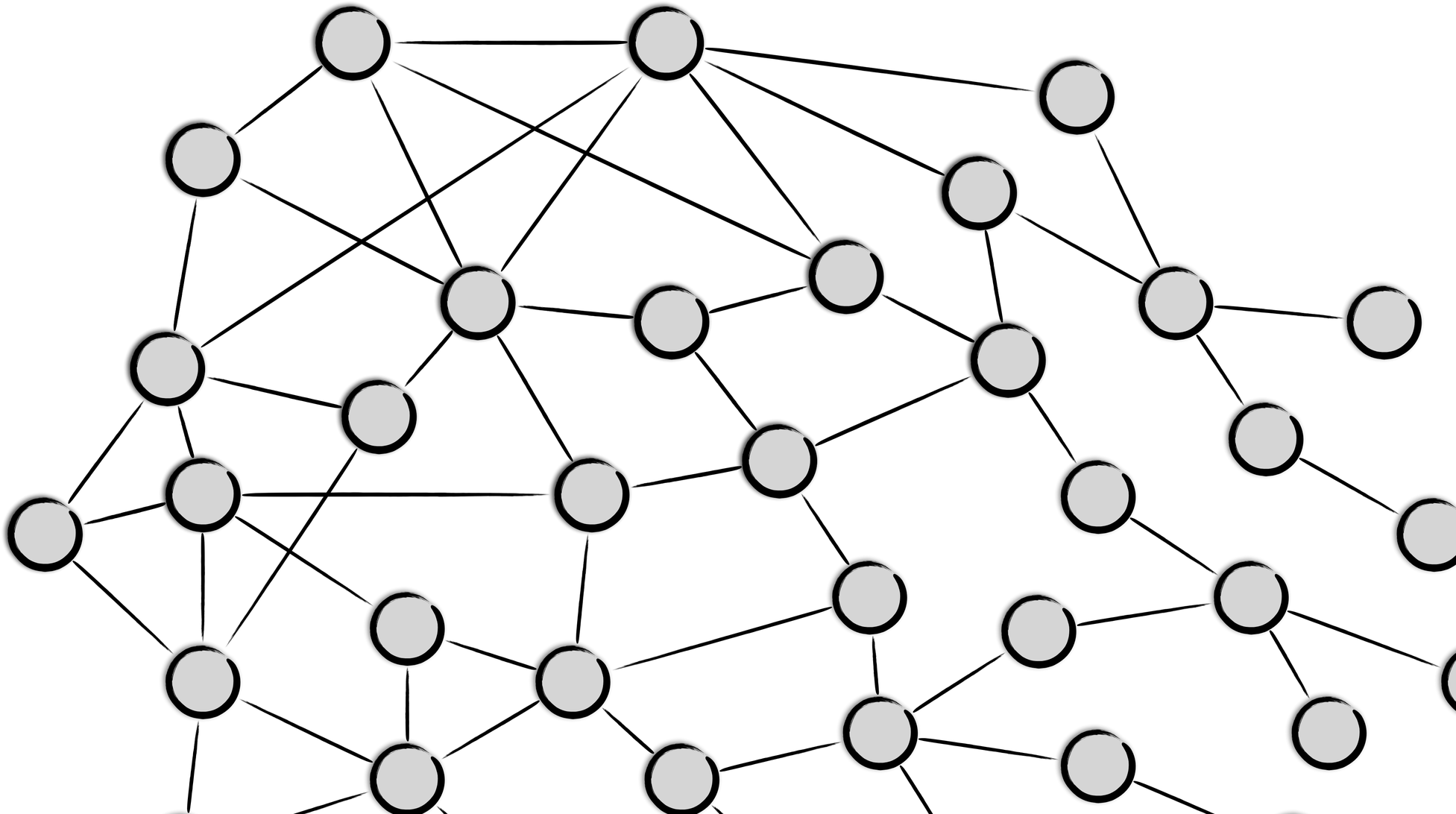


Figure 8: Verification time for synthetic configurations for different properties and network sizes.

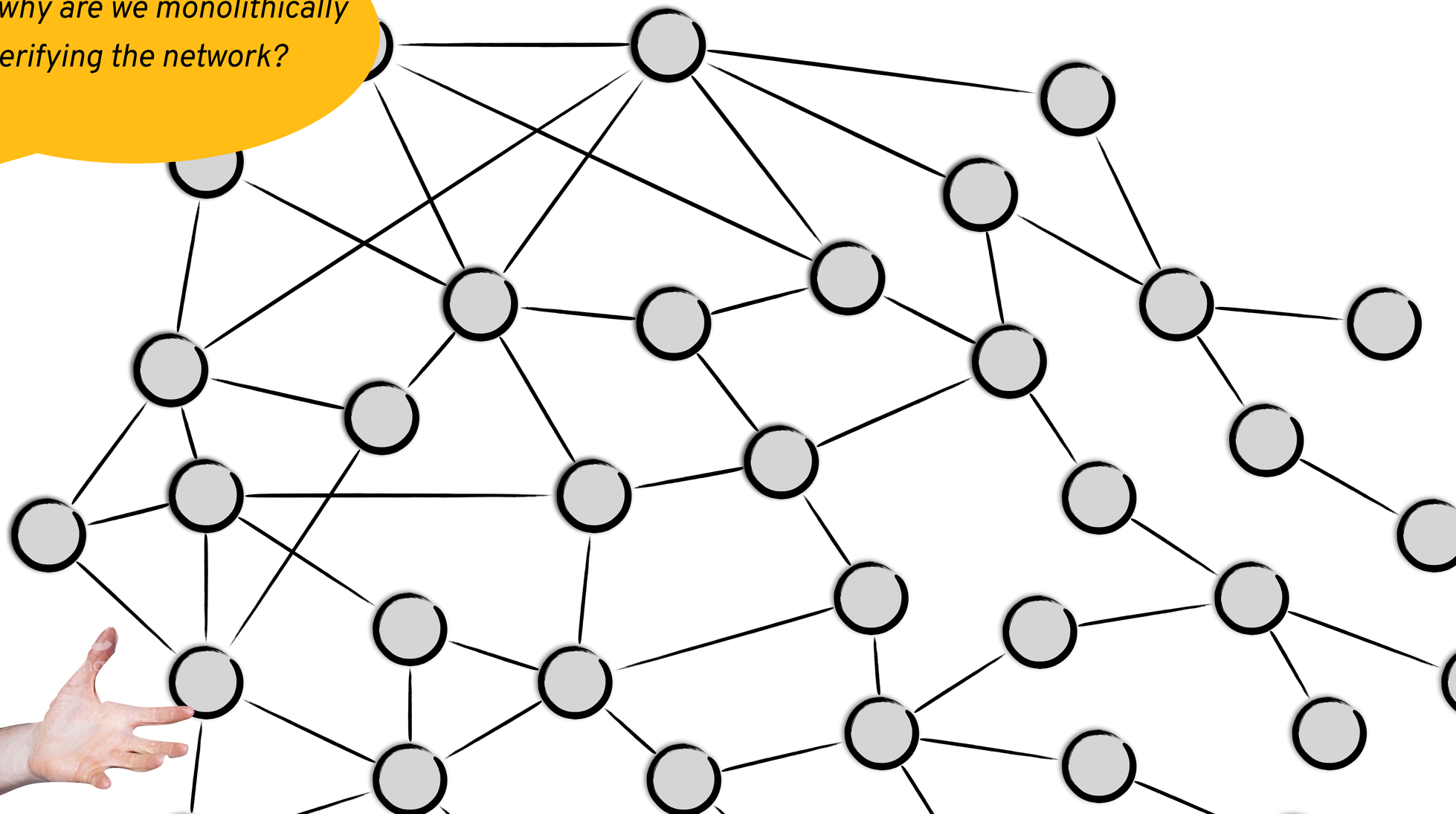
[Beckett et al., SIGCOMM 2017]

Is All Hope Lost?



Is All Hope Lost?

Wait, why are we monolithically verifying the network?



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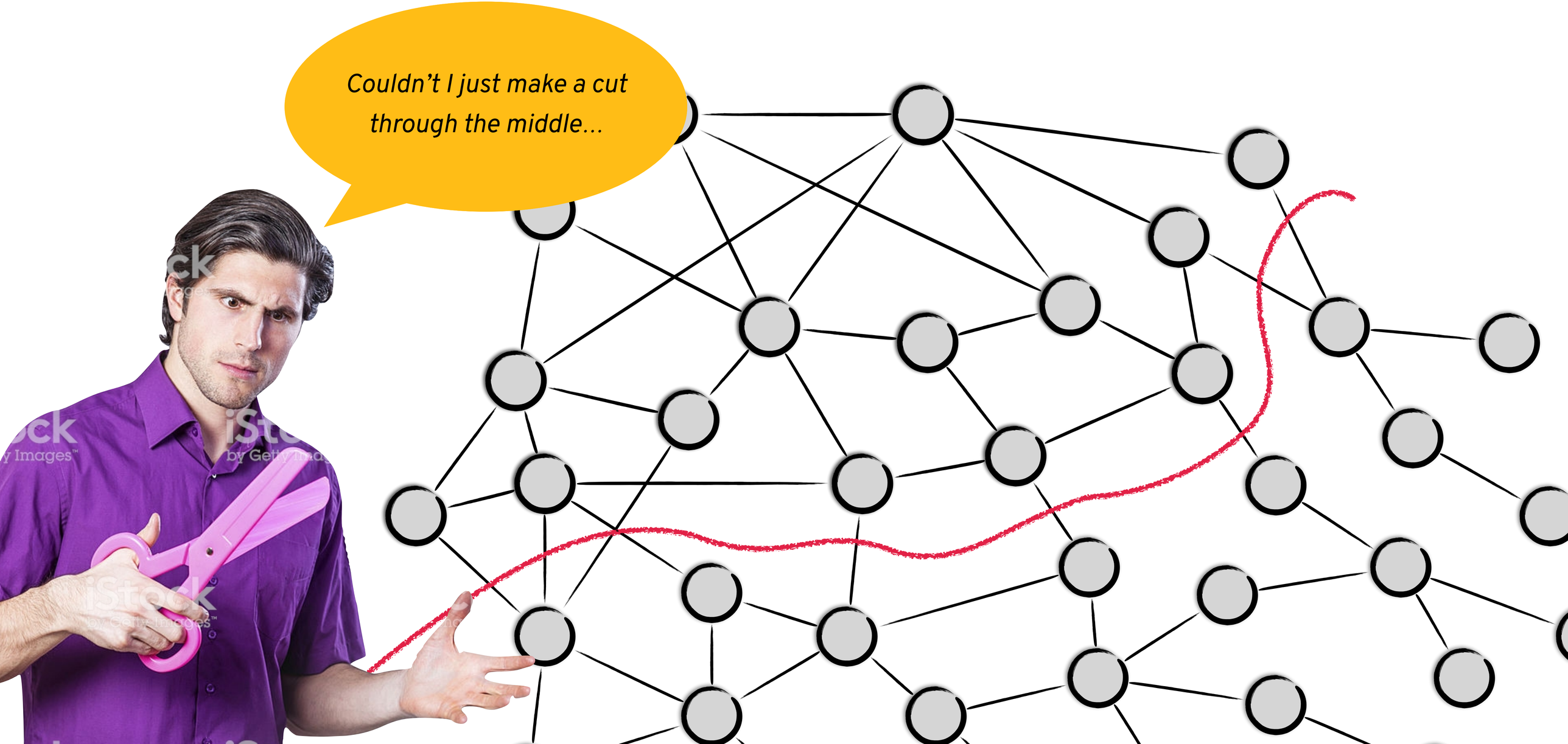

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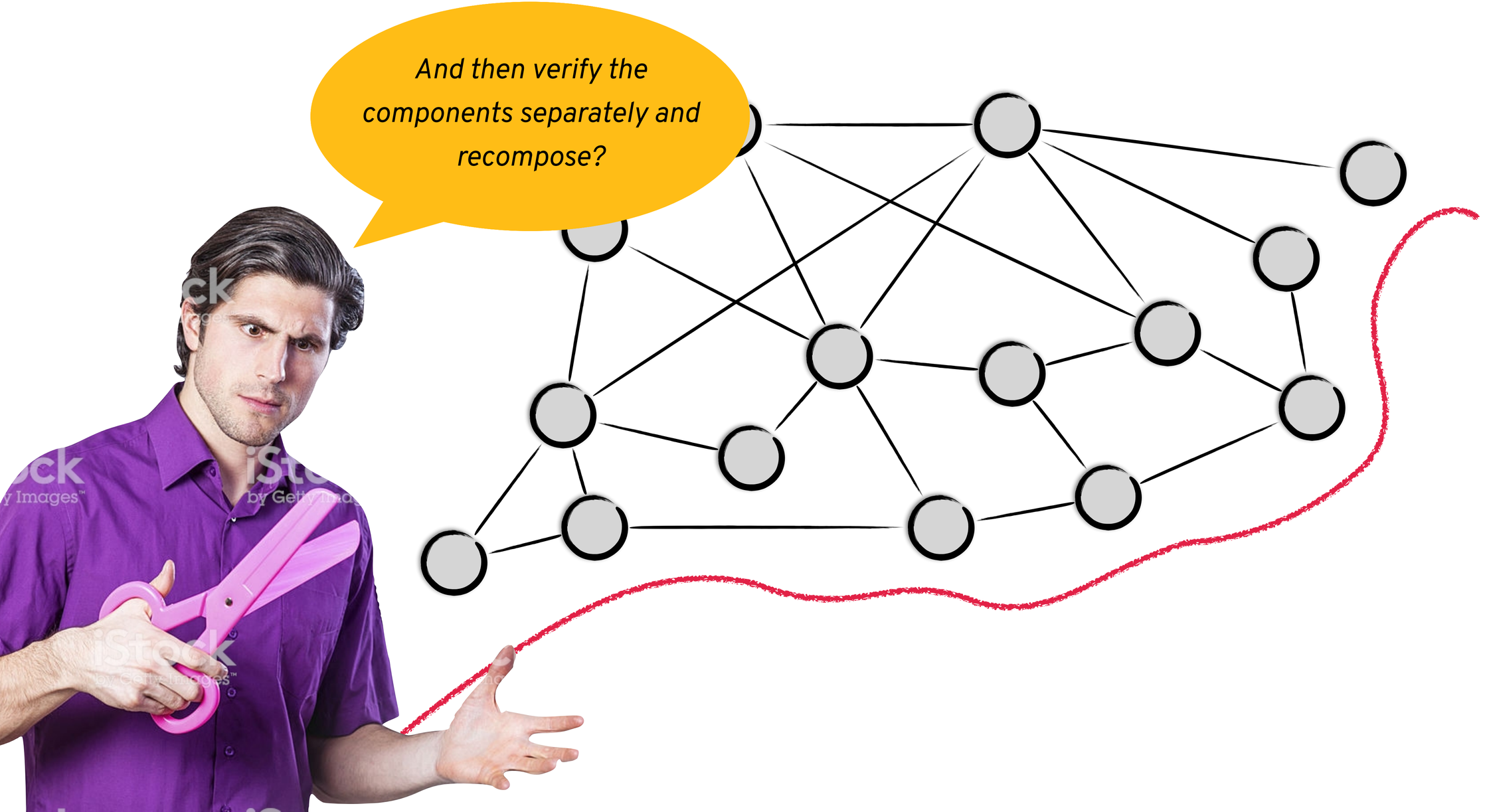

In other words…

Can we use the inherent *compositional design* of networks to *verify them compositionally*?

In other words…

Can we

co

rks

to

tionally?

Compositional Verification: verify each component separately, such that correctness of the monolithic system is guaranteed!

Roadmap

Opening up the Stable Routing Problem

The Kirigami Algorithm

Implementing Kirigami in NV

Results and Future Directions

Opening up the Stable Routing Problem

The Stable Routing Problem (SRP)

(Prior Work)

[Beckett et al., SIGCOMM 2018]
[Griffin and Sobrinho, SIGCOMM 2005]
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The Stable Routing Problem (SRP)

(Prior Work)

$$R = (\quad , \quad , \quad , \quad , \quad)$$

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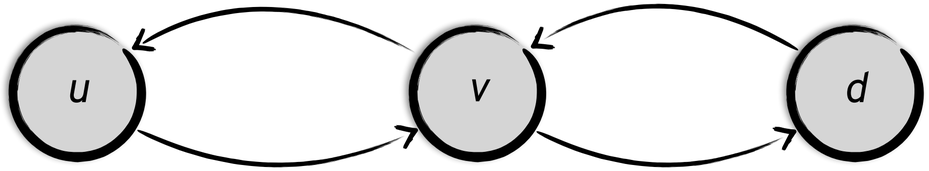

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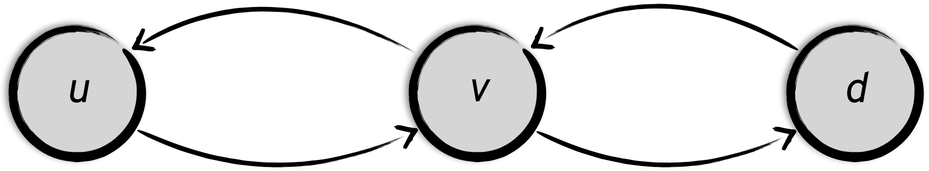
The Stable Routing Problem (SRP)

(Prior Work)

topology of network

$$R = (\ G,\ A,\quad ,\quad ,\quad)$$

set of attributes



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The Stable Routing Problem (SRP)

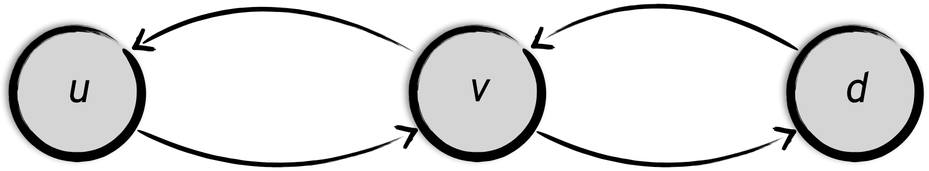
(Prior Work)

topology of network

$$R = (\ G,\ A, \mathbf{init},\quad ,\qquad\qquad)$$

set of attributes

initial attribute at each node



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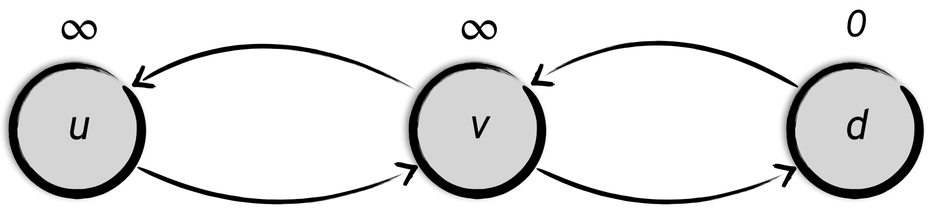

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The Stable Routing Problem (SRP)

(Prior Work)

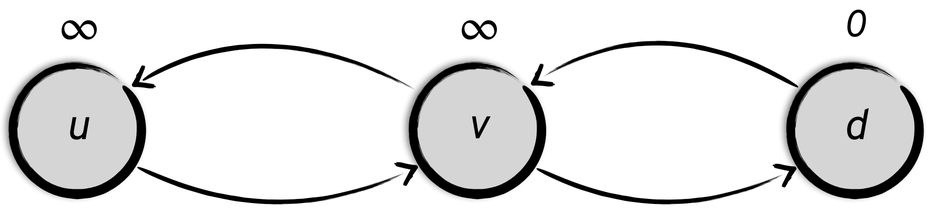
how to merge received attributes

topology of network

$$R = (G, A, \mathbf{init}, \oplus, \quad)$$

set of attributes

initial attribute at each node



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The Stable Routing Problem (SRP)

(Prior Work)

how to merge received attributes

topology of network

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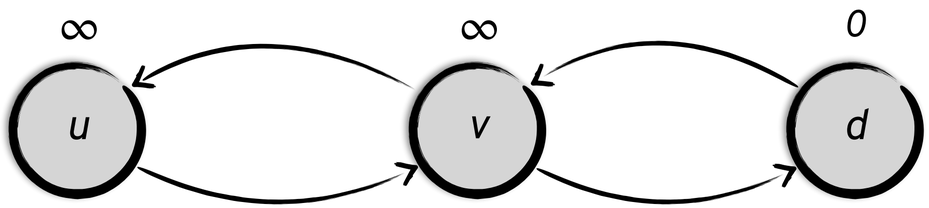

set of attributes

how to transfer attributes along edges

initial attribute at each node

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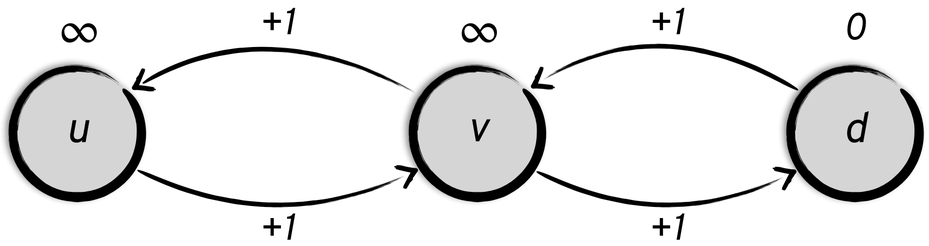

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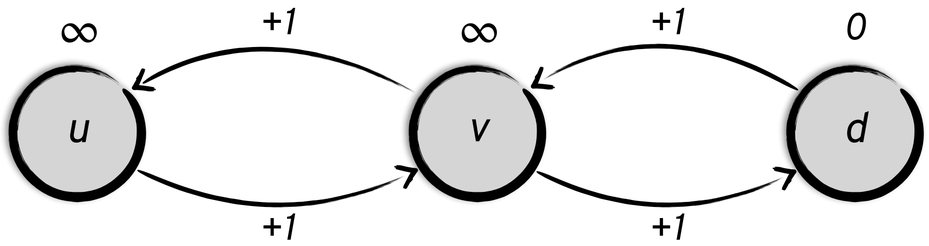

Can every router reach the destination d in under 10 hops?

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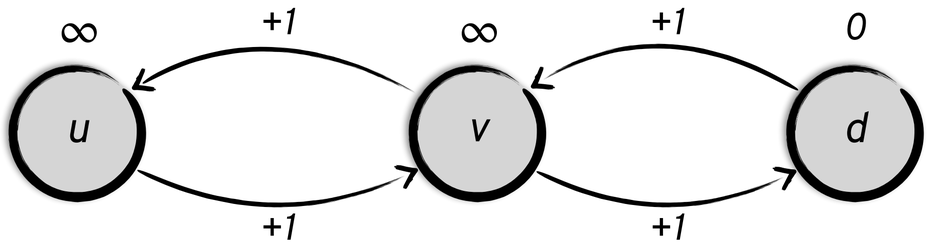

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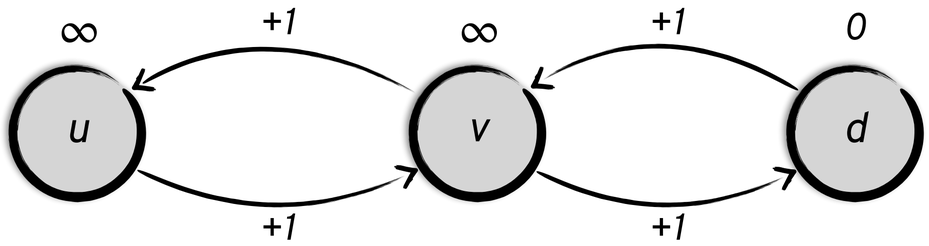
$$\text{init}(n) = \text{if } n = d \text{ then } 0 \text{ else } \infty$$
$$a \oplus b = \min(a, b)$$
$$\text{trans}(e, x) = x + 1$$

Step: 0



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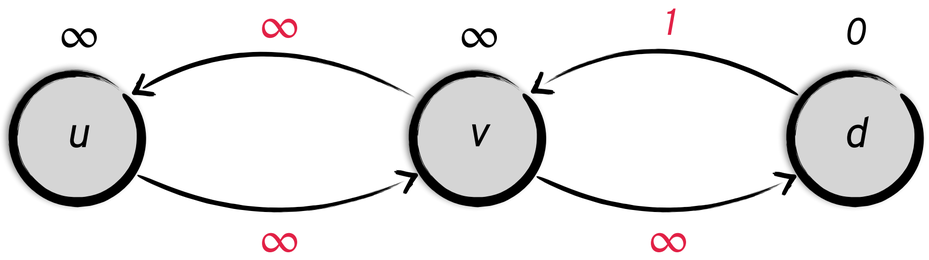
Step: 1



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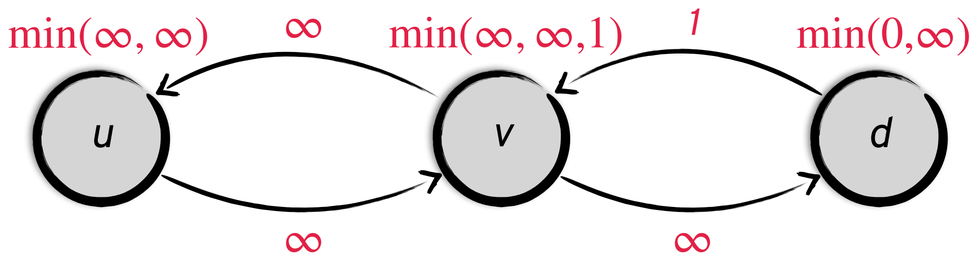

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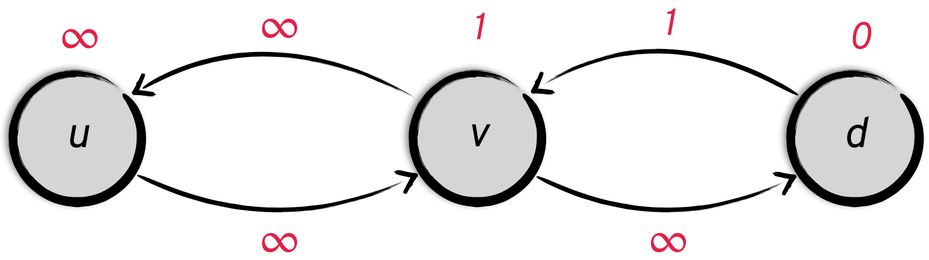

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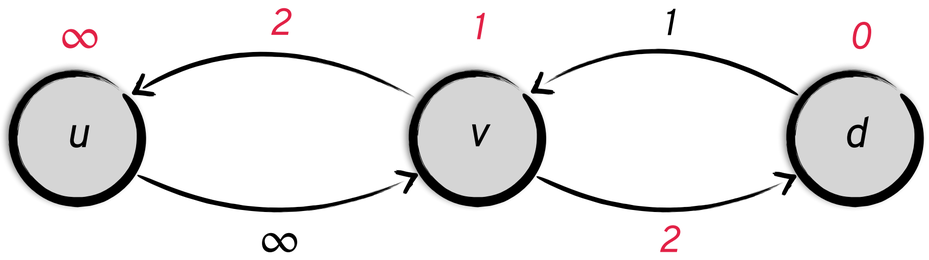
Step: 2



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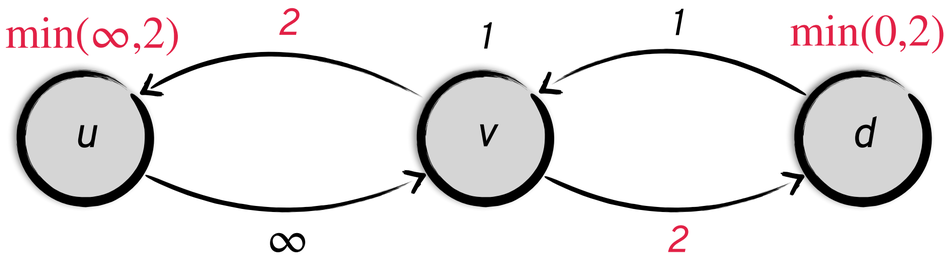

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The Stable Routing Problem (SRP)

(Prior Work)

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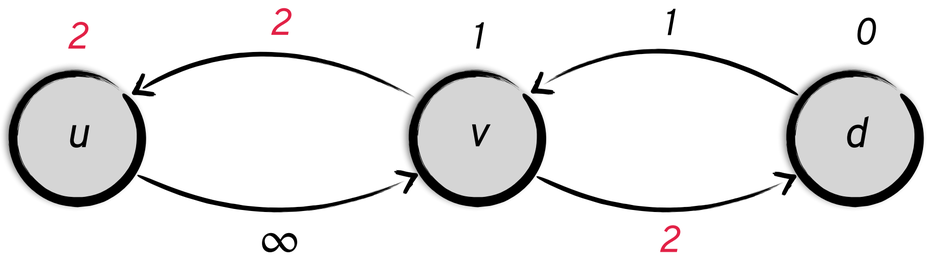

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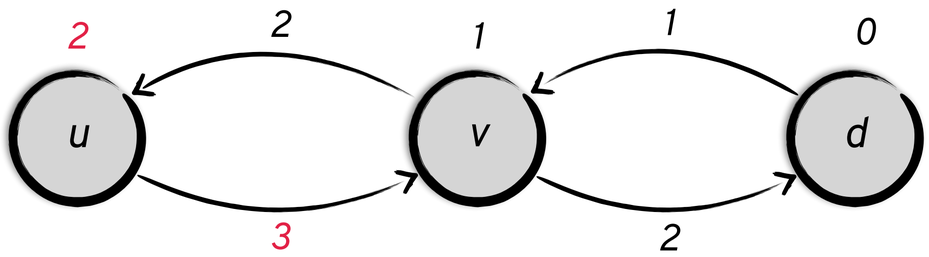

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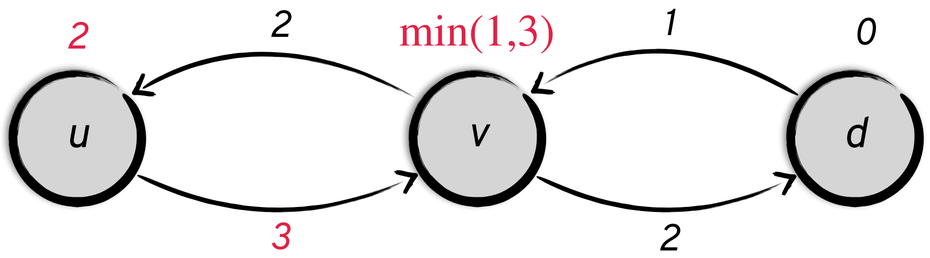

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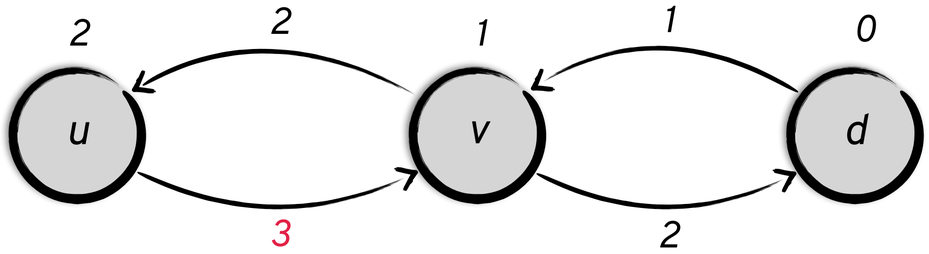

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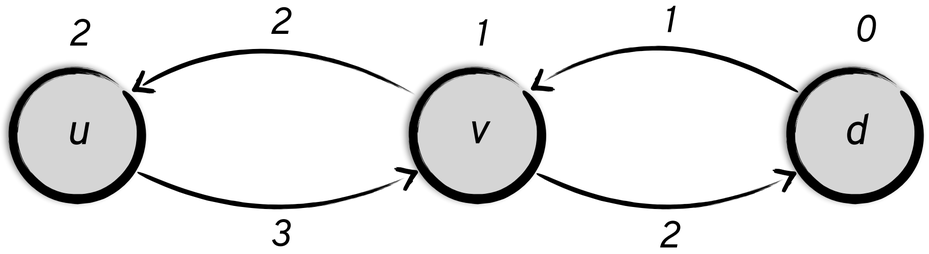

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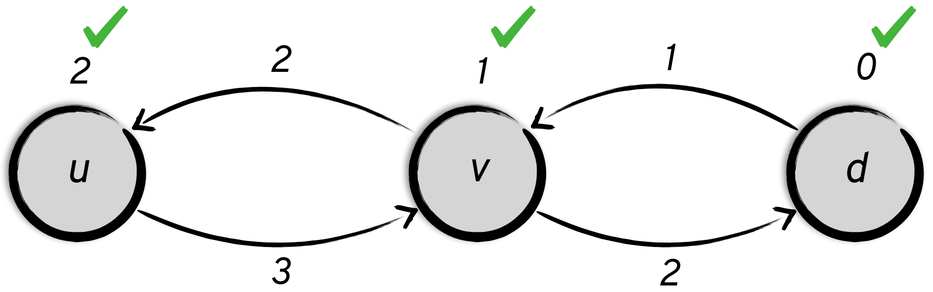

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captures *converged* solutions:

$$\mathscr{L}(u) = 2$$
$$\mathscr{L}(v) = 1$$
$$\mathscr{L}(d) = 0$$

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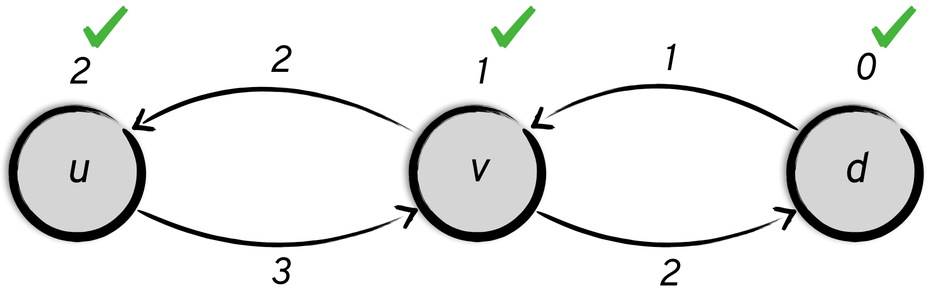

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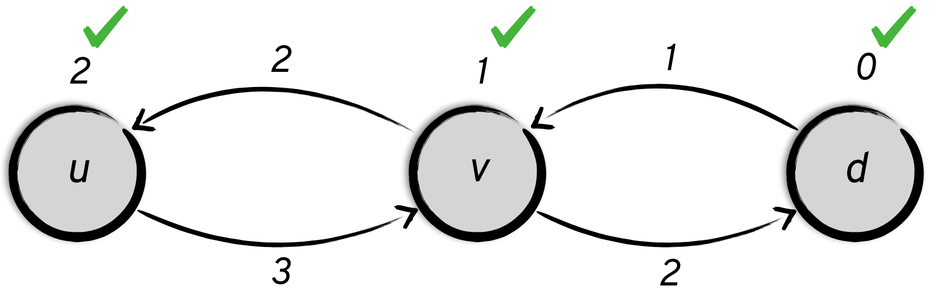

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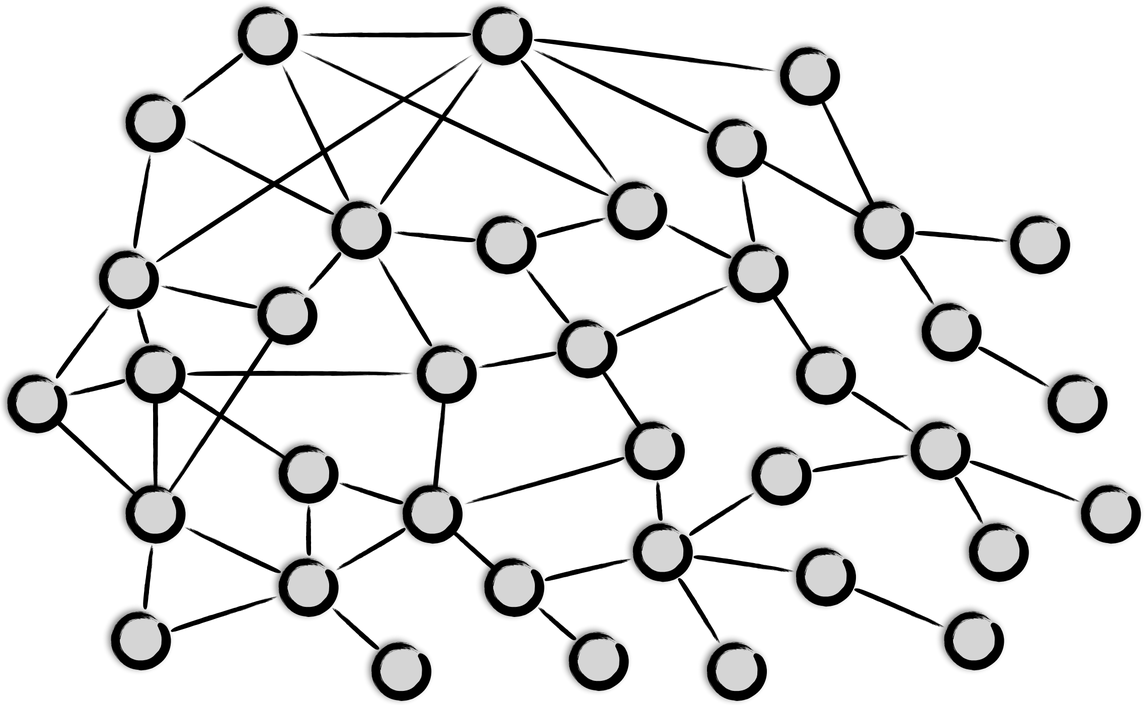
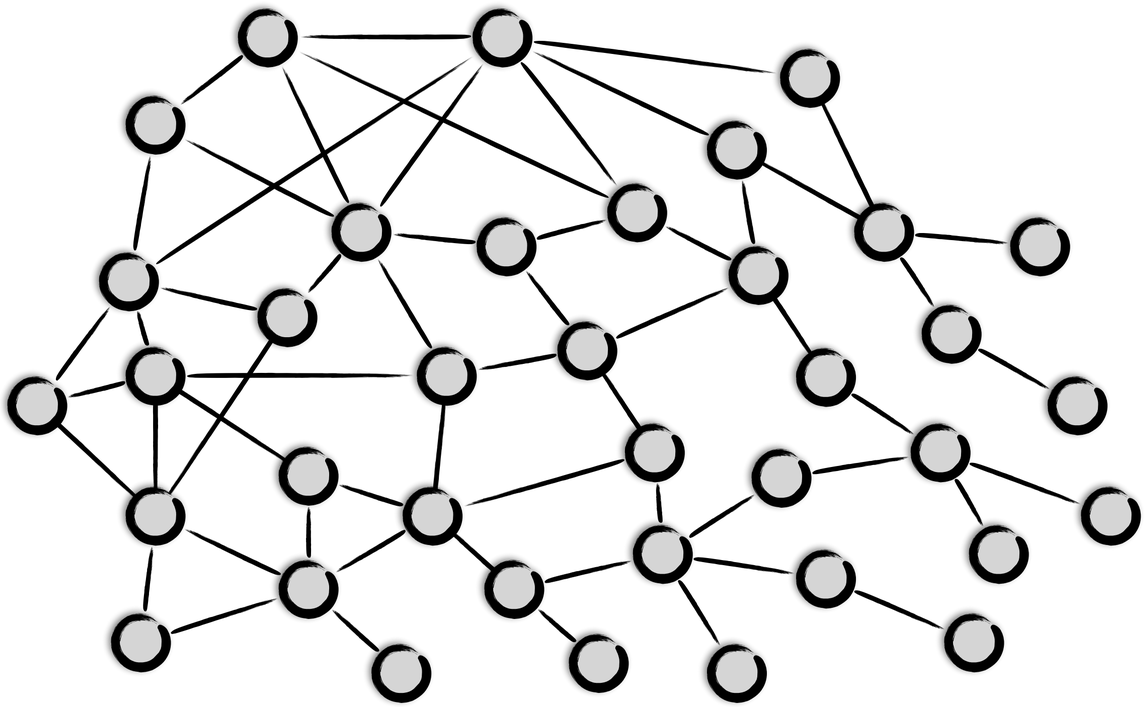


Verifying SRPs Compositionally

- Identify a cut-set of edges as forming an *interface*



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- Identify a cut-set of edges as forming an *interface*
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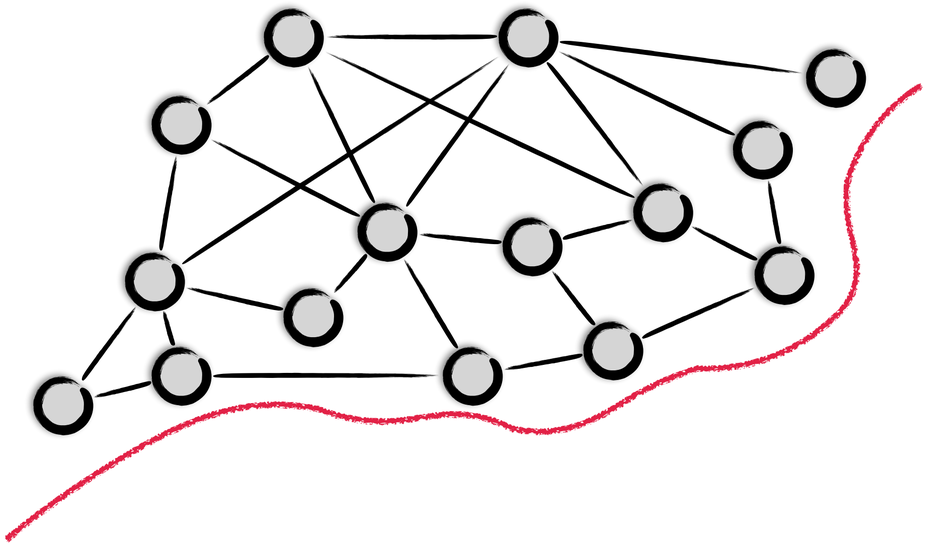

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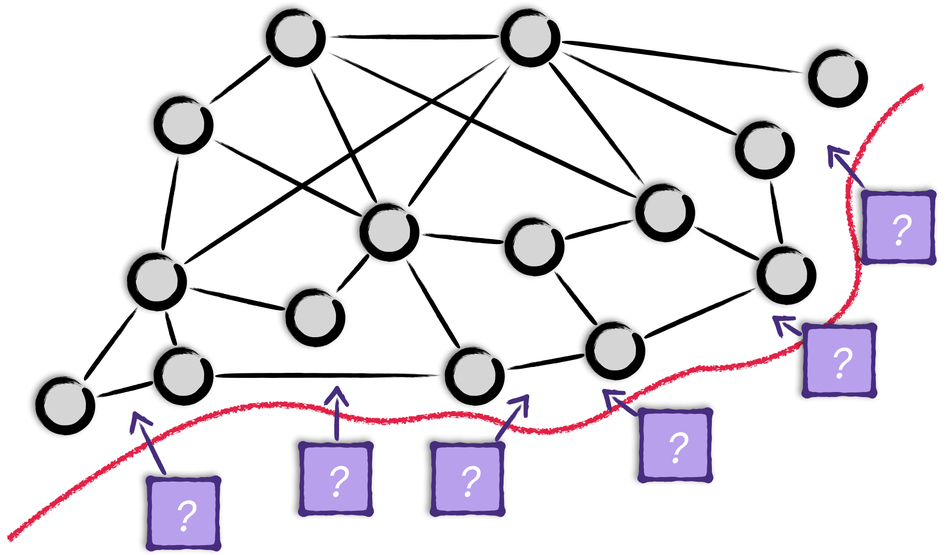

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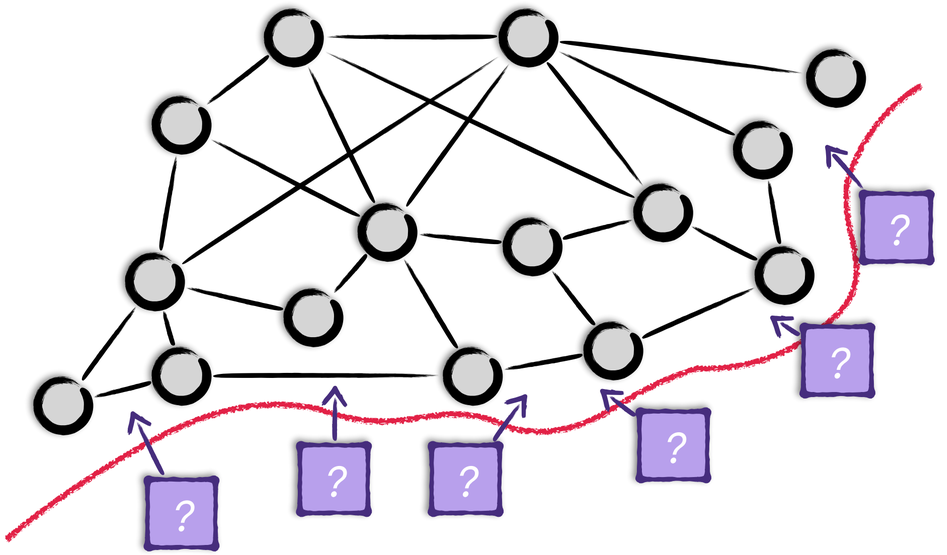
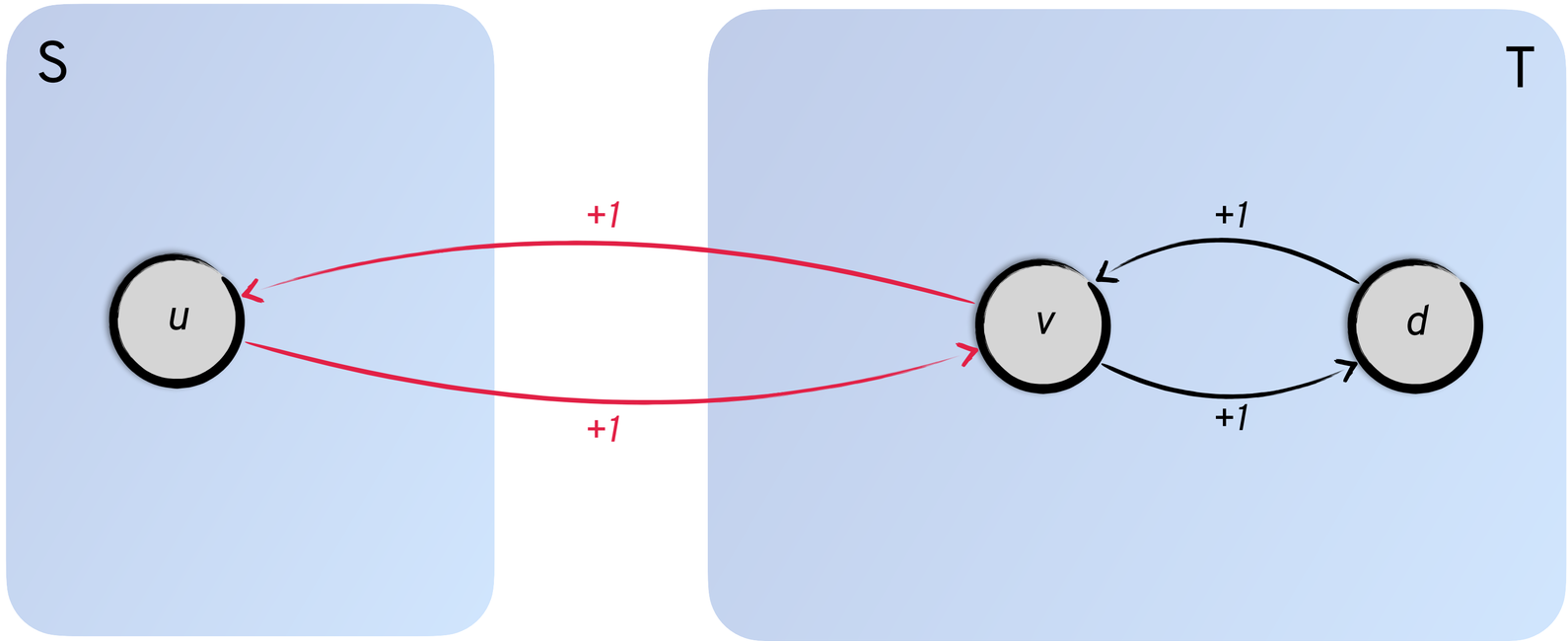
- Verify the components using hypotheses, and then demonstrate that this suffices to prove the monolithic network correct



Open SRPs



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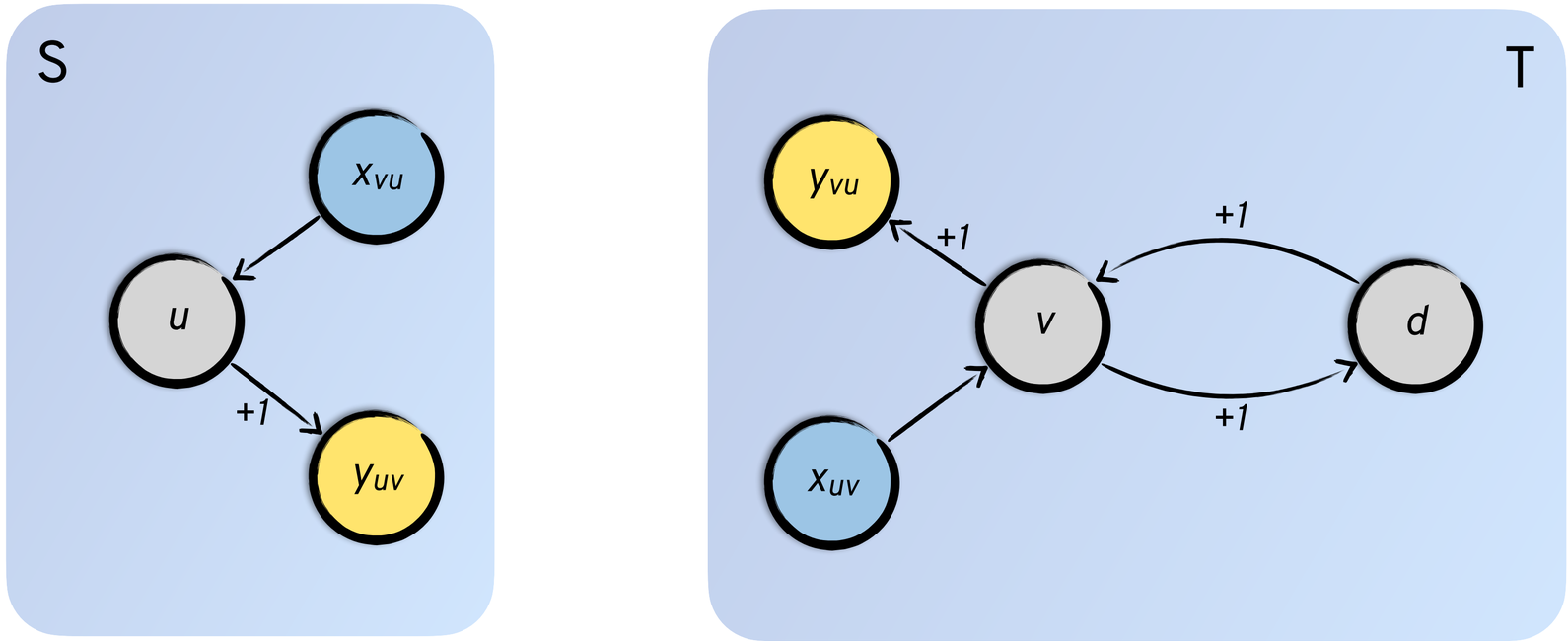

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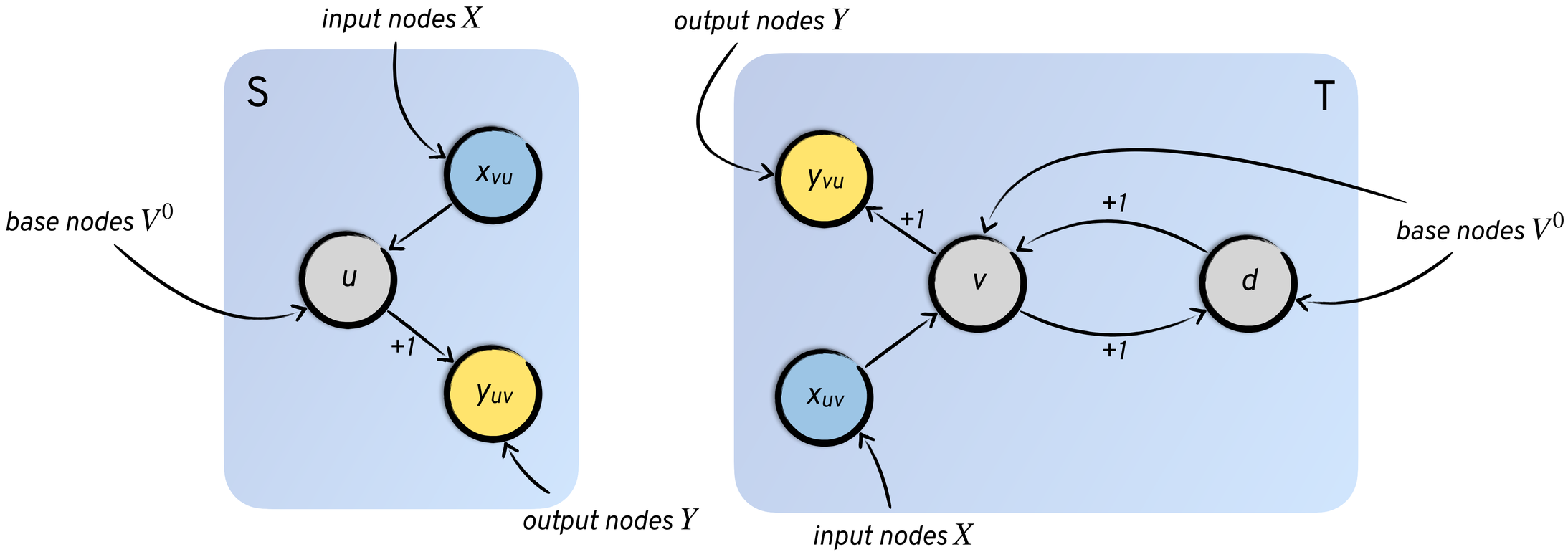
input nodes X
S
x_{vu}
base nodes V^0
u
+1
y_{uv}
output nodes Y
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T
y_{vu}
+1
+1
base nodes V^0
v
d
+1
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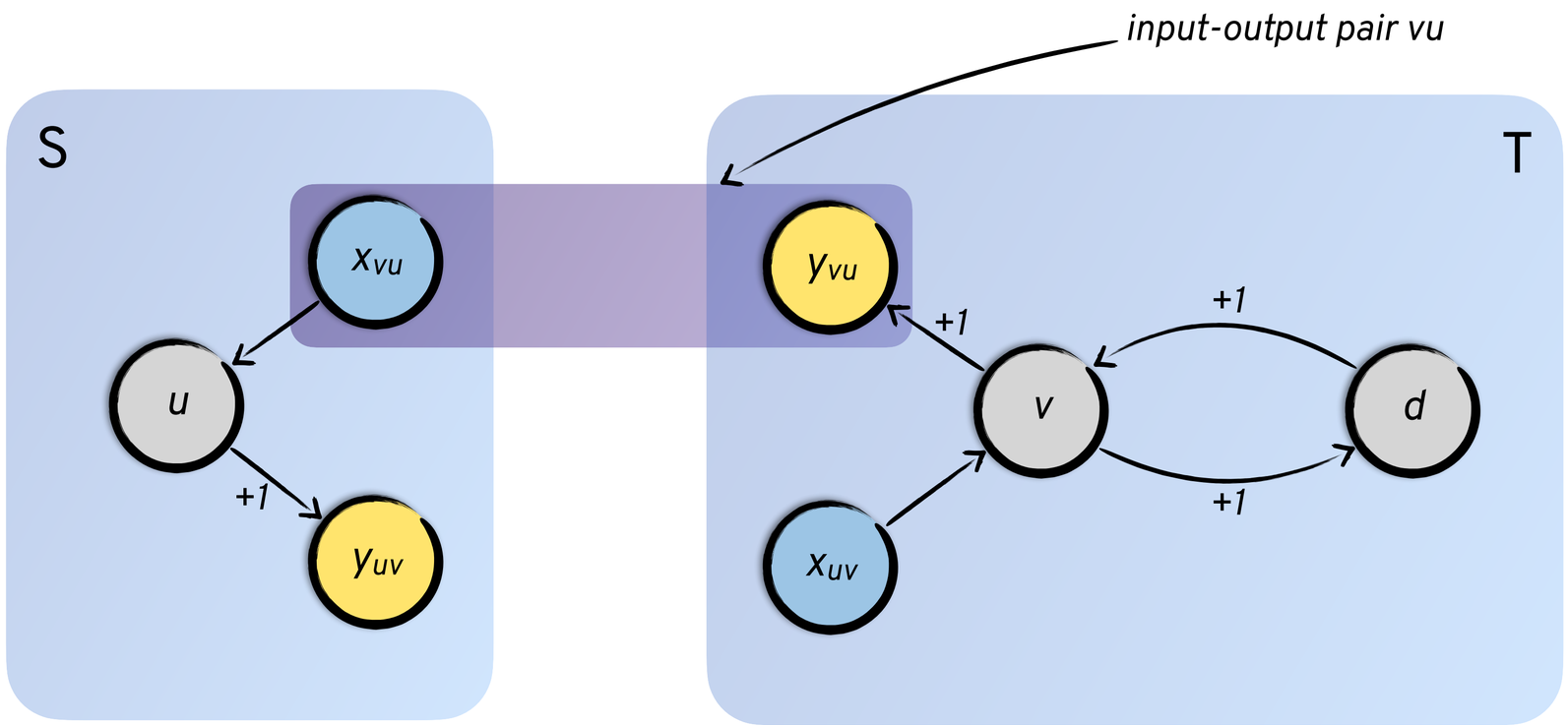

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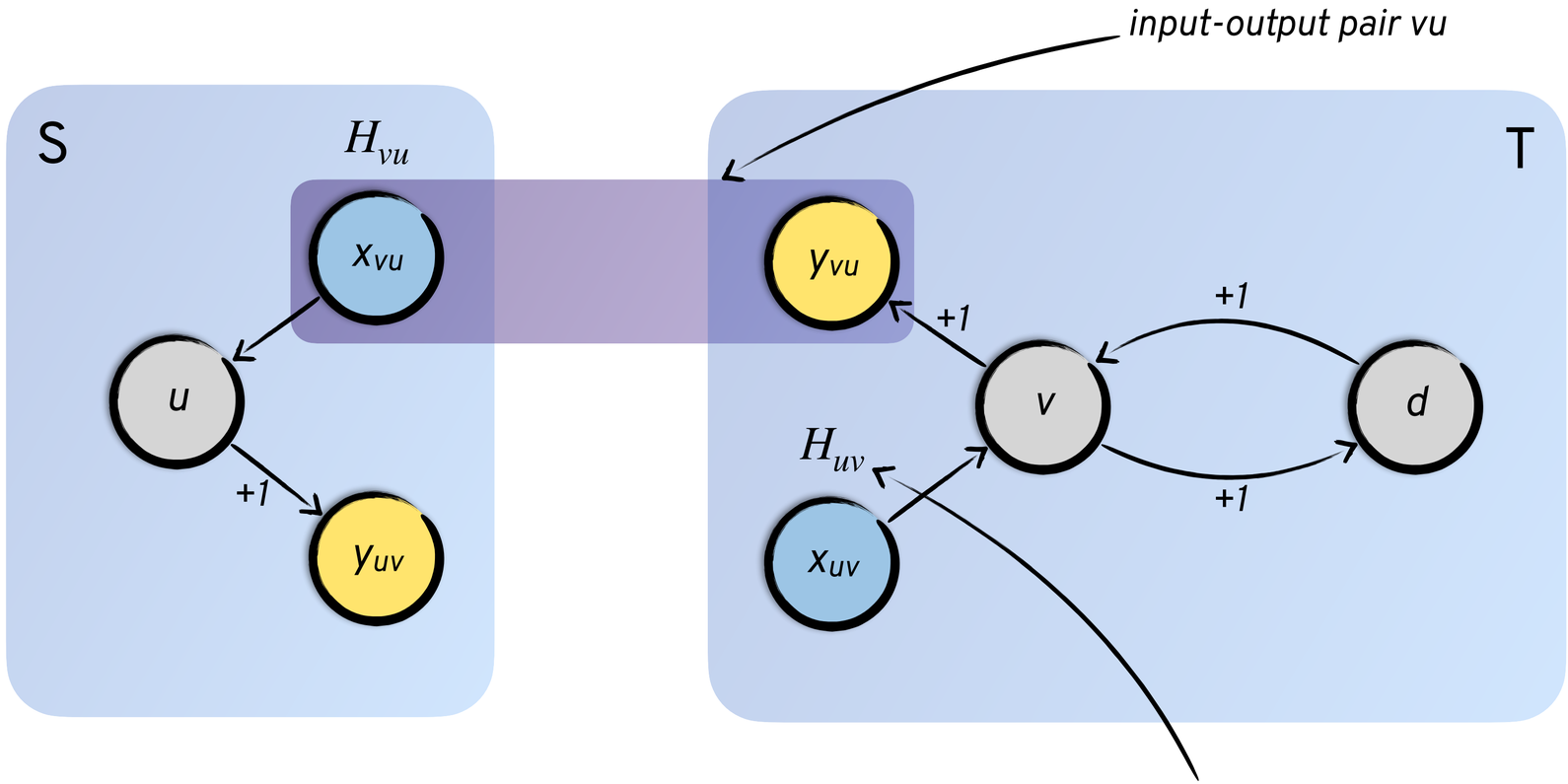

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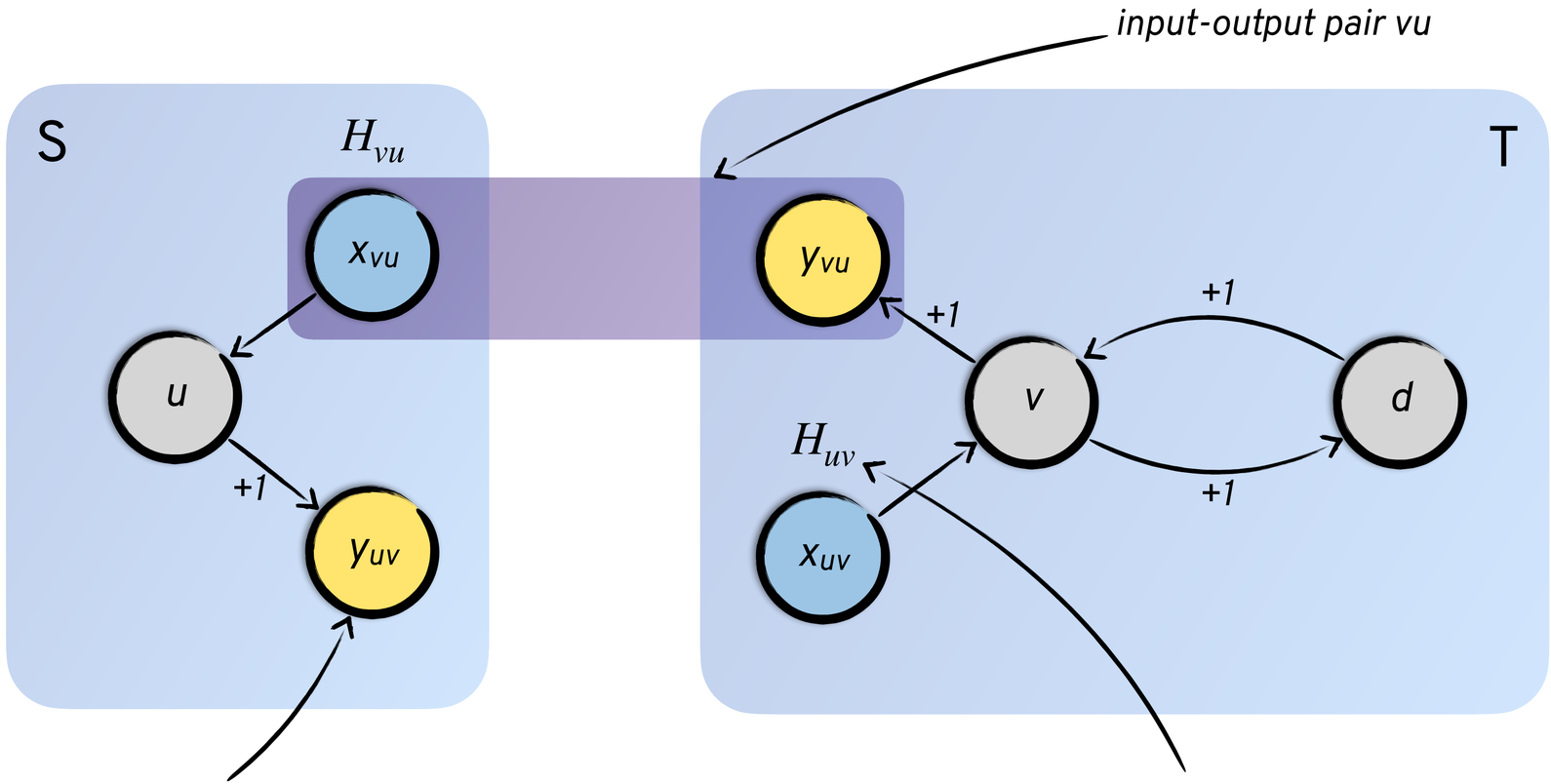

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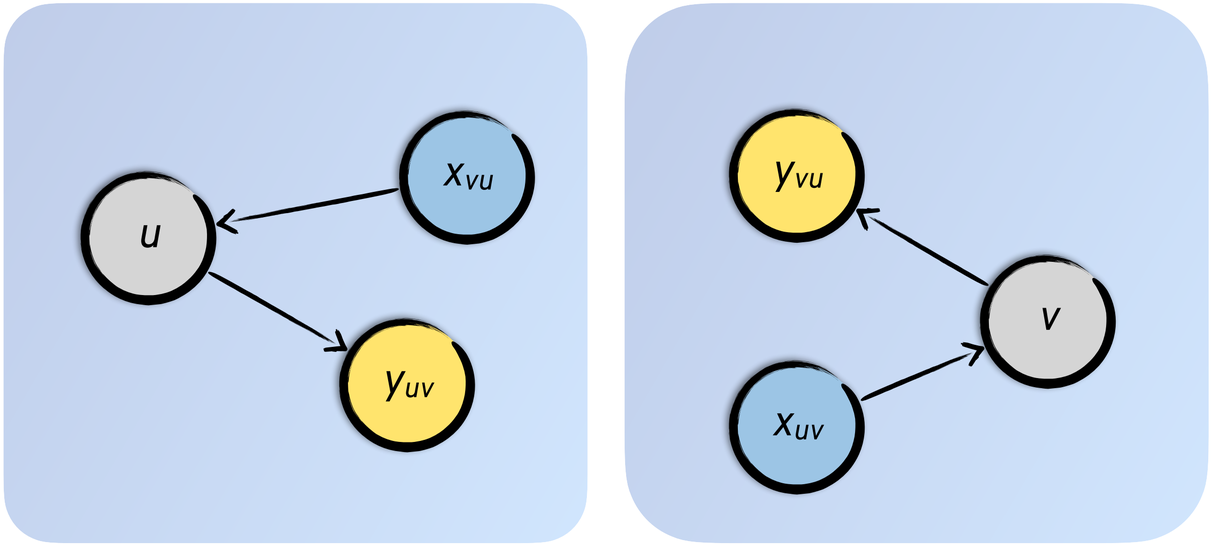
The Kirigami Algorithm

Interfaces



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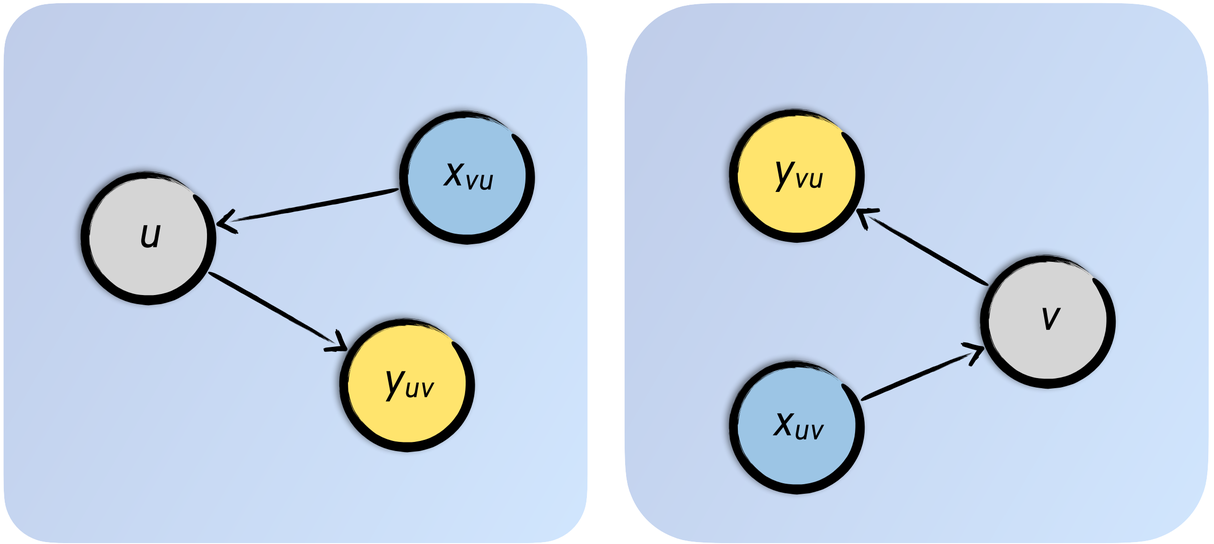

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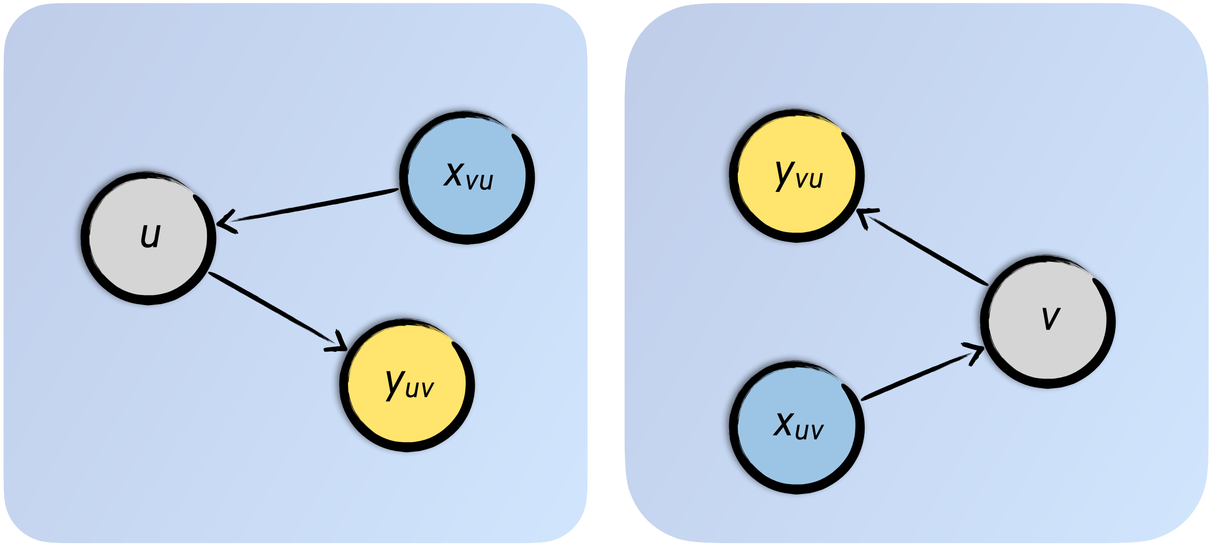

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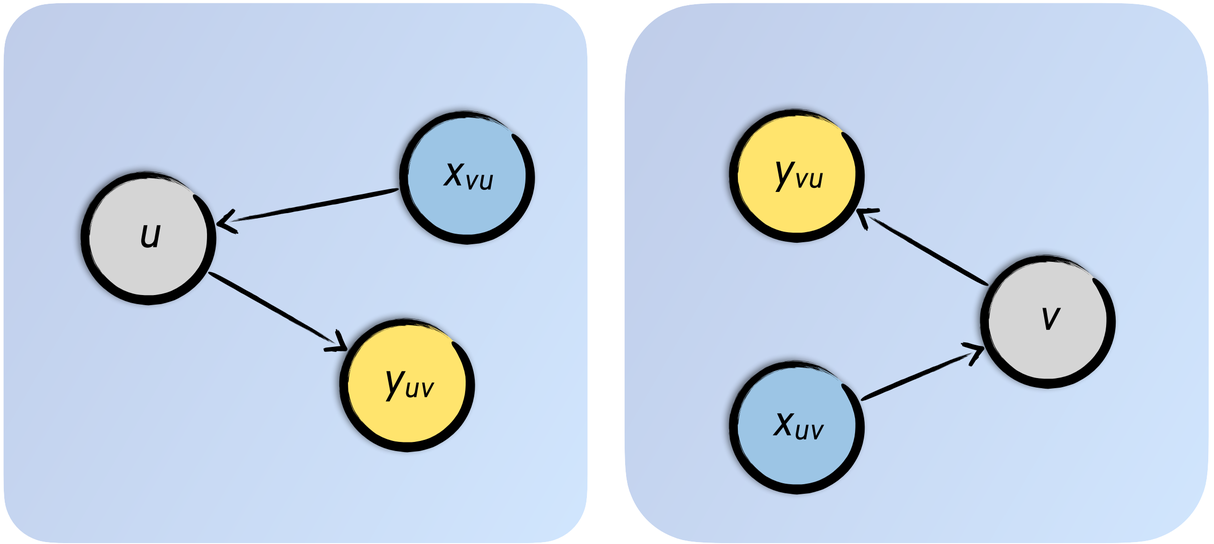

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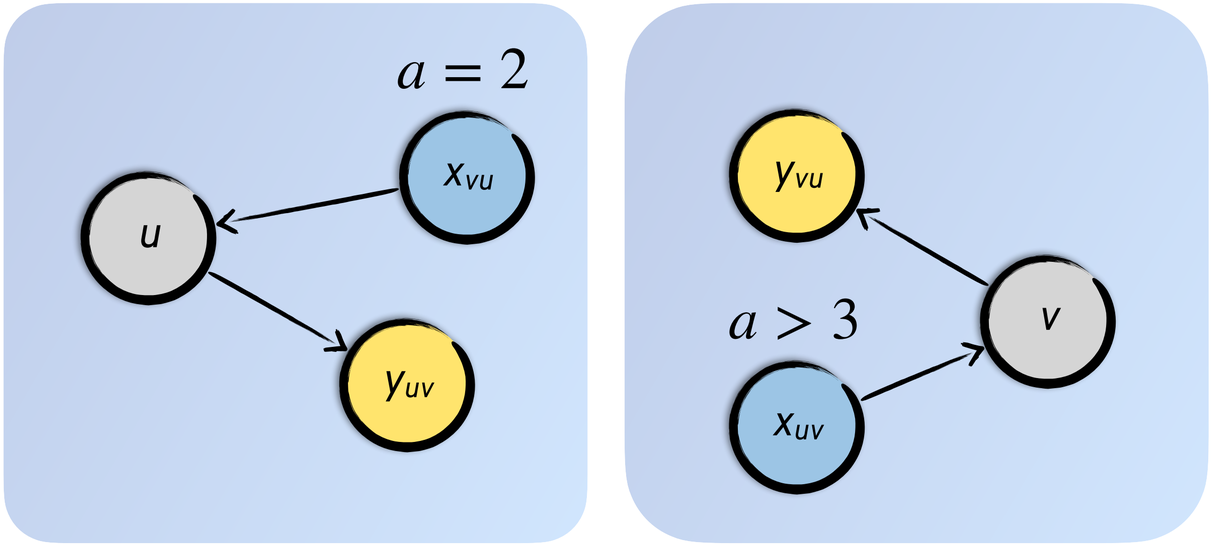

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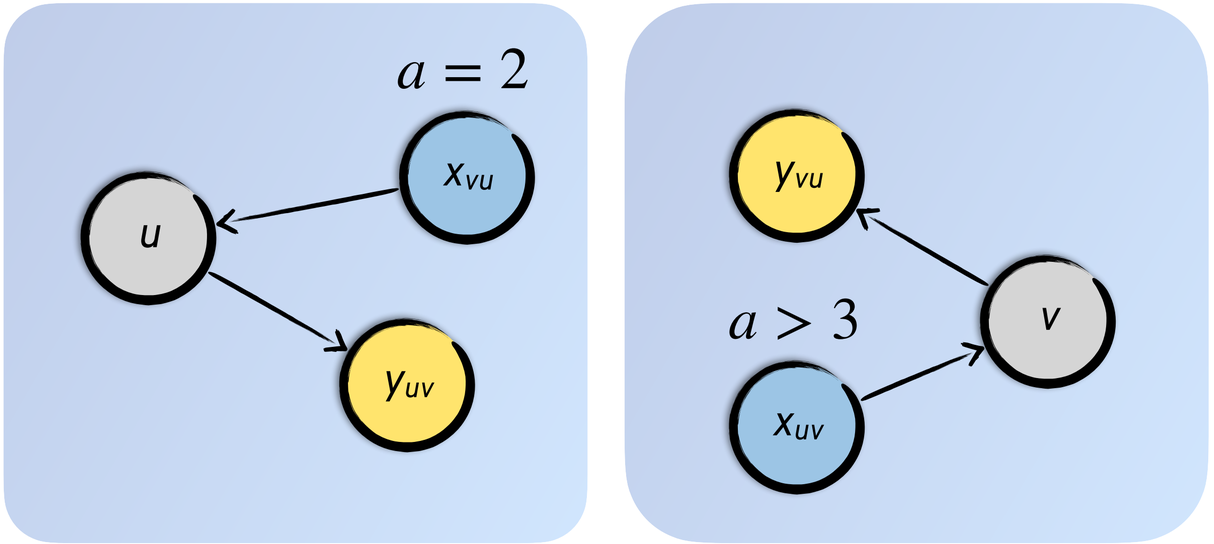

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An algorithm for checking *interfaces*

[Beckett et al., SIGCOMM 2017]

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$\langle A \rangle M \langle G \rangle$ notation:
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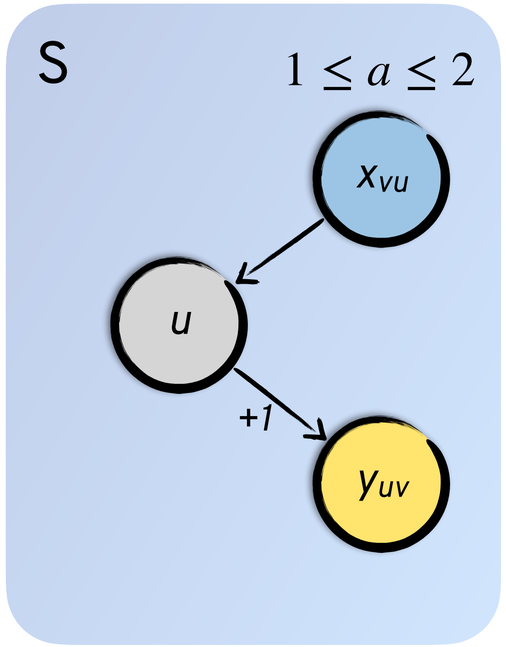
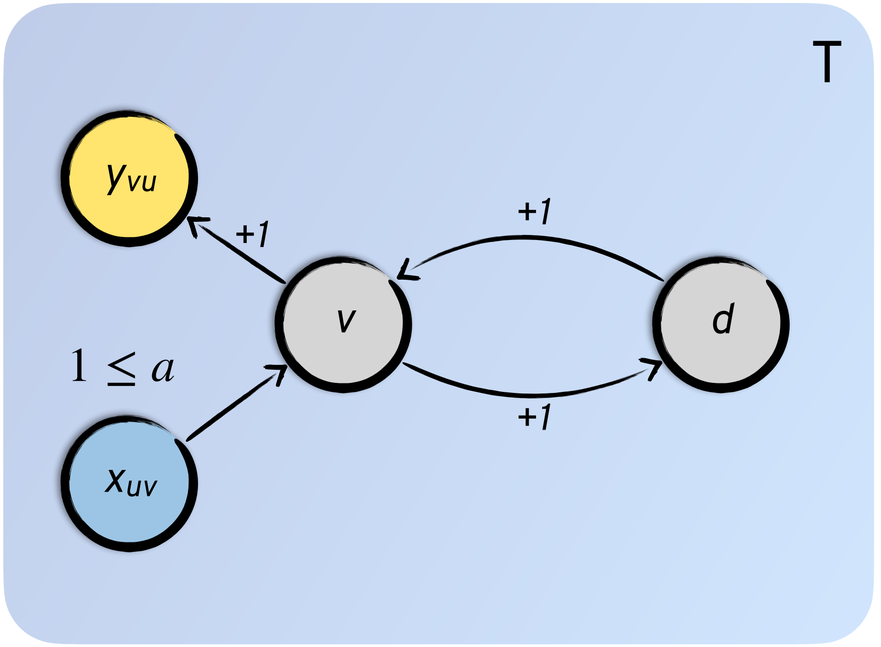
$\langle A \rangle M \langle G \rangle$ *notation:*
assuming A about M's inputs,
M must guarantee G (cf. Hoare triples)

[Beckett et al., SIGCOMM 2017]

Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$



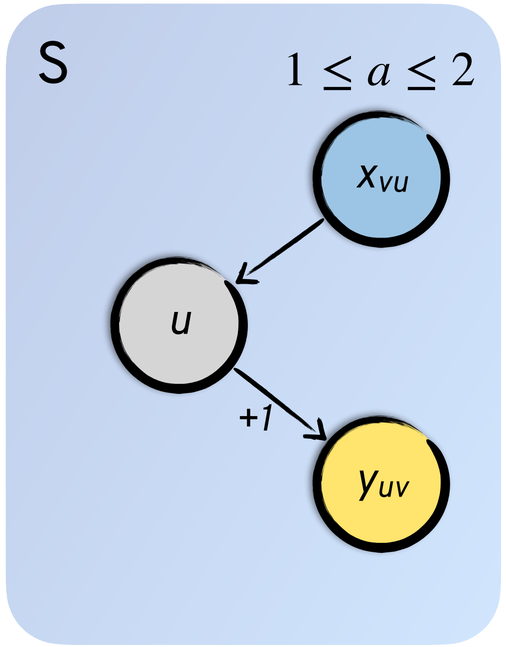


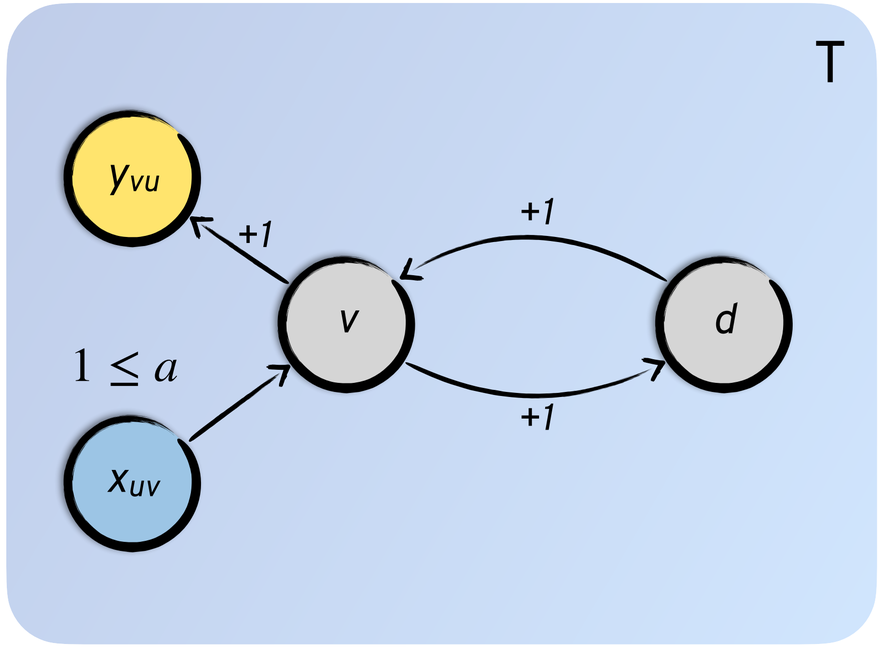
Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

$(v, u, 1 \leq a \leq 2)$

$(u, v, 1 \leq a)$





Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

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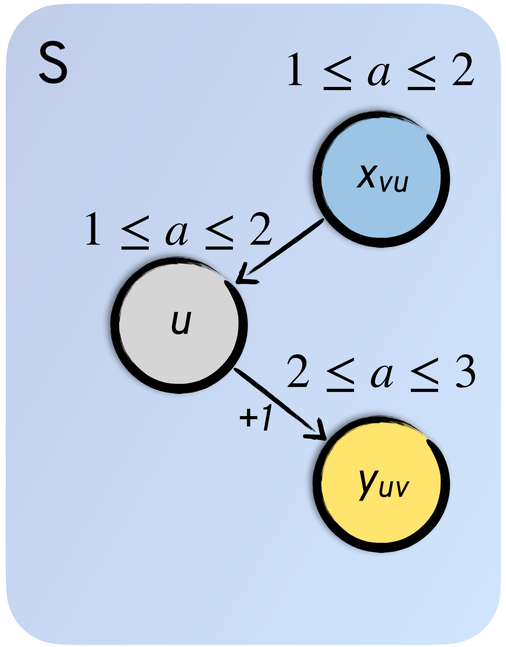
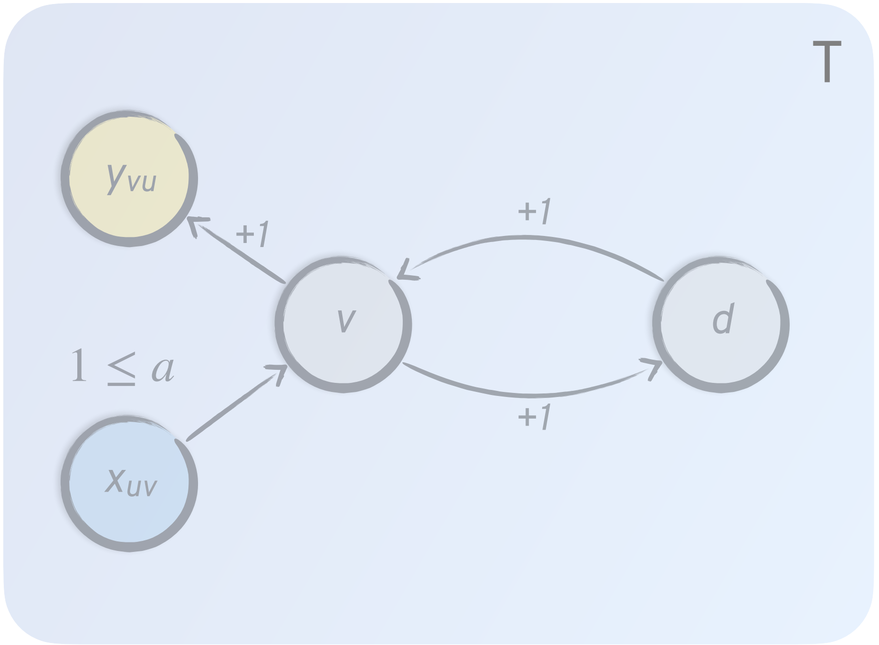
$(u, v, 1 \leq a)$

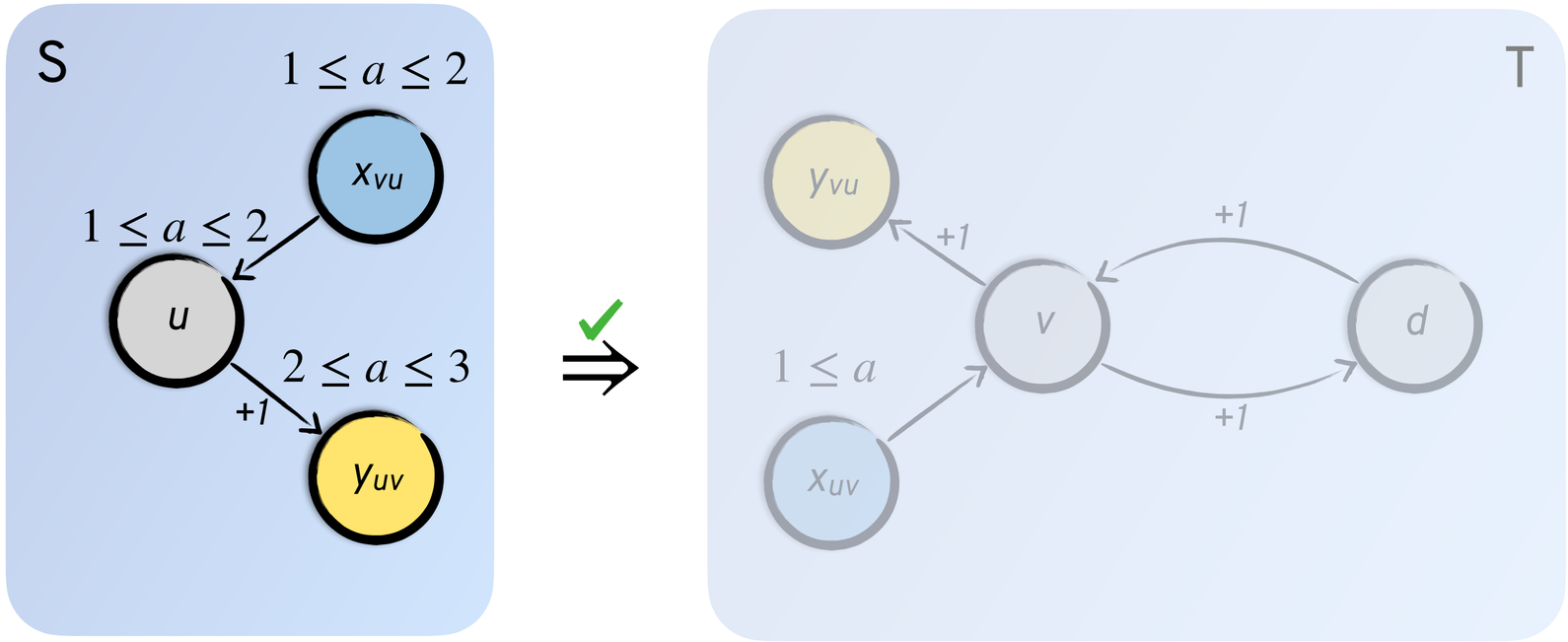




Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

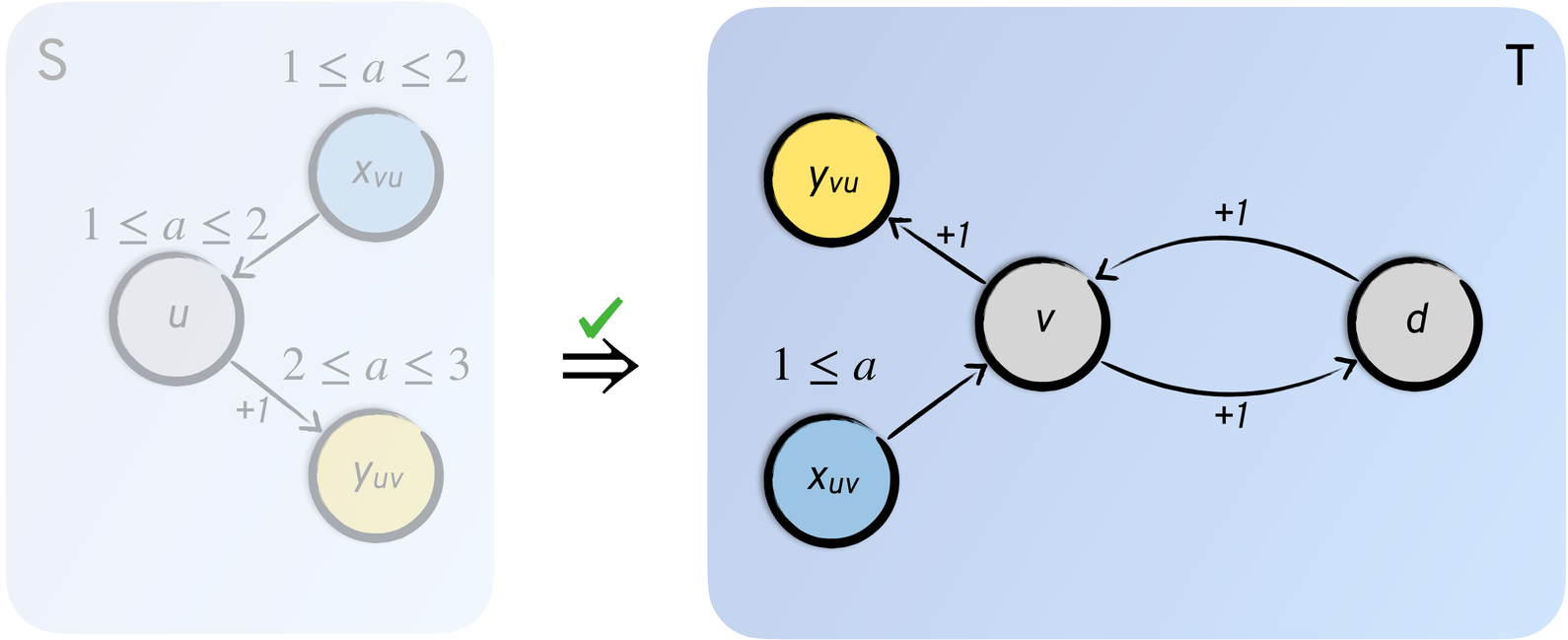
$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$



Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

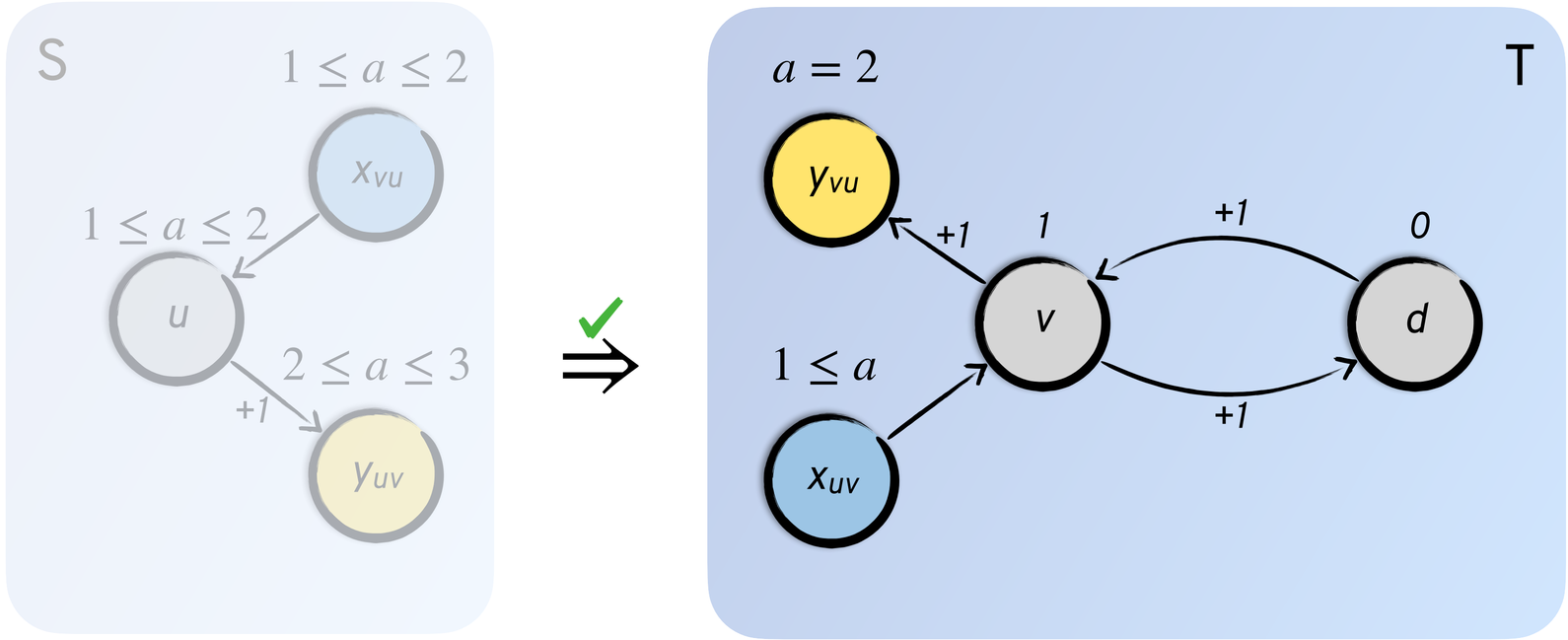
$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$



Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

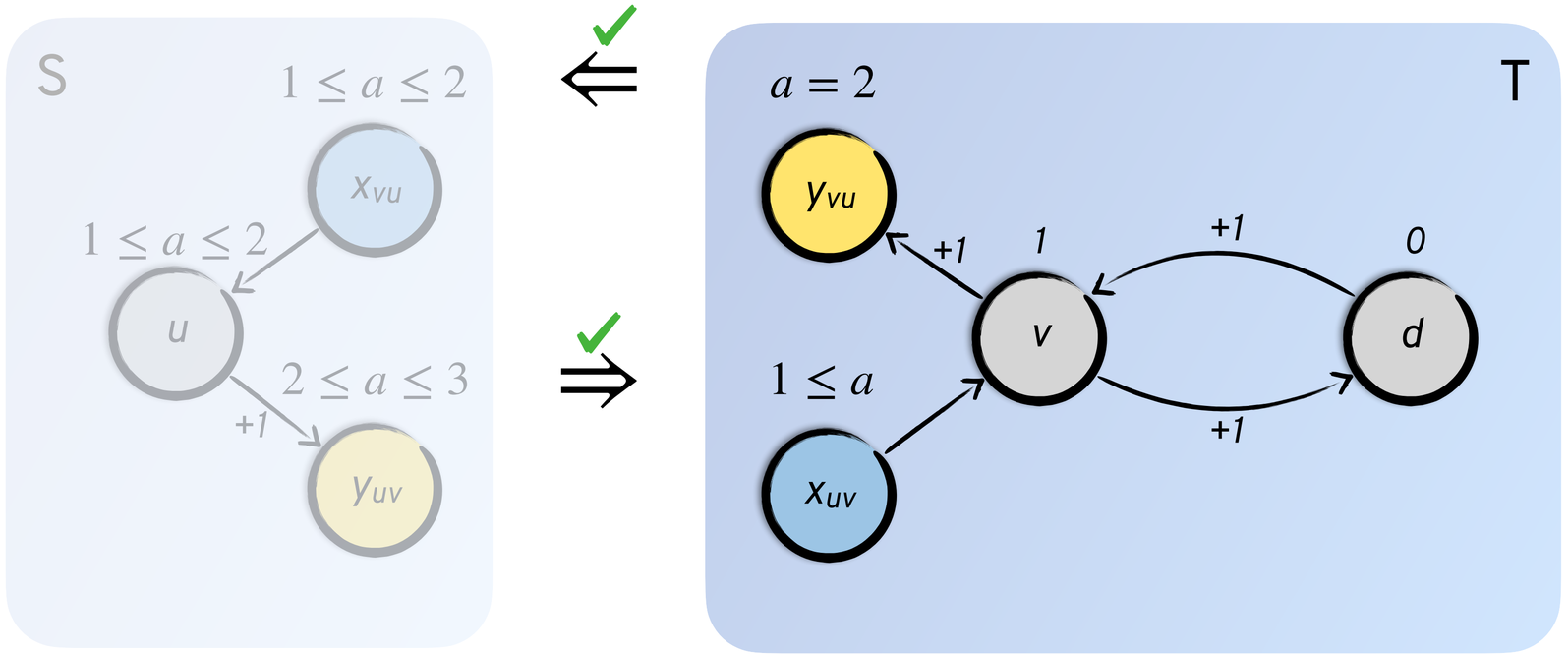
$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$



Checking an Interface

A: Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$

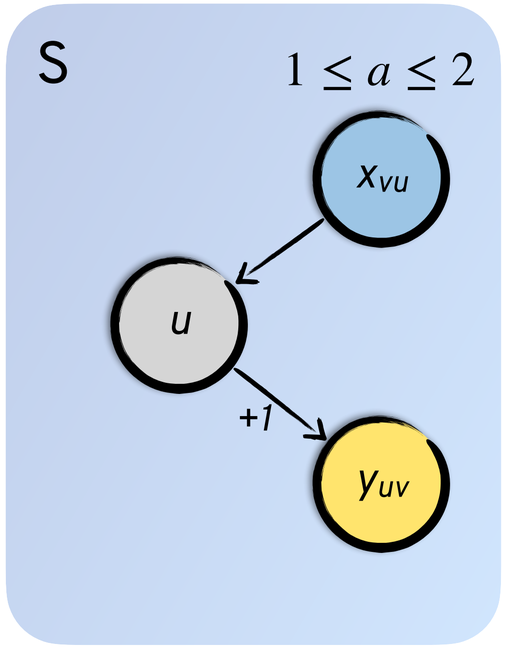


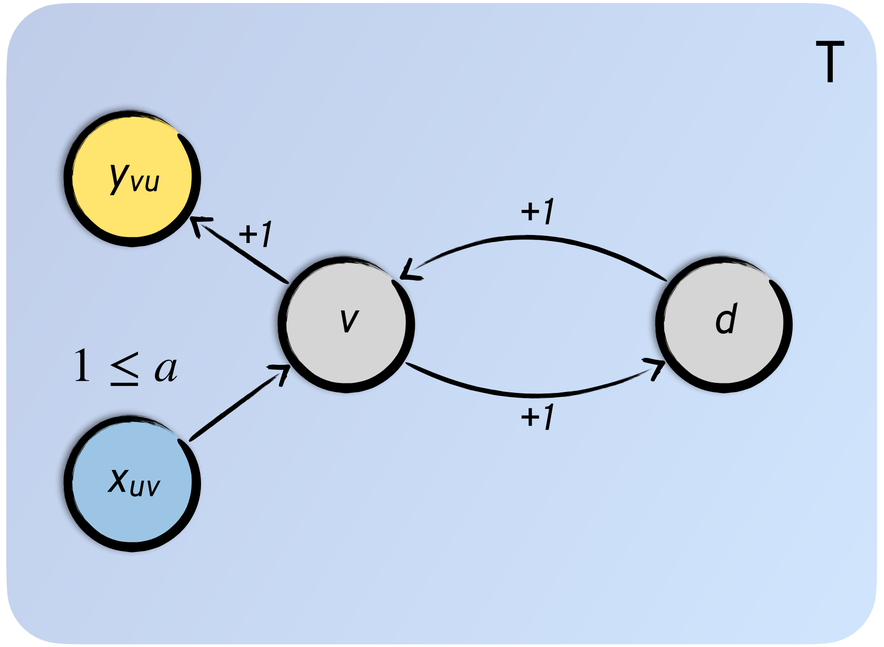
Checking an Interface

B: Safety: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle P_S \rangle$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle P_T \rangle$

$(v, u, 1 \leq a \leq 2)$

$(u, v, 1 \leq a)$





$P_S = \mathscr{L}(u) < 10$

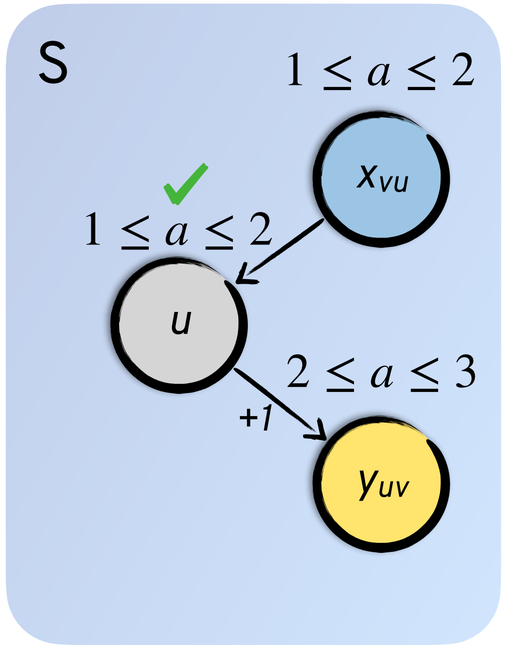
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

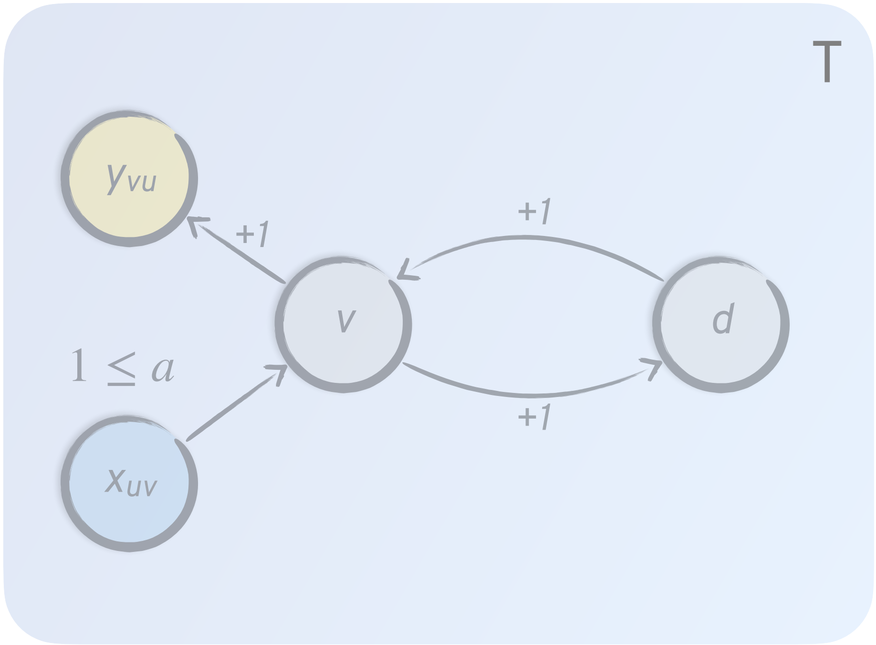
Checking an Interface

B: Safety: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle P_S \rangle$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle P_T \rangle$

$(v, u, 1 \leq a \leq 2)$

$(u, v, 1 \leq a)$





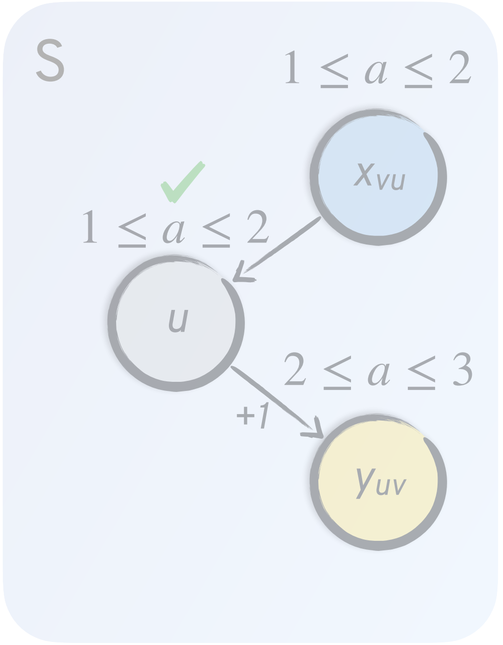
$P_S = \mathscr{L}(u) < 10$

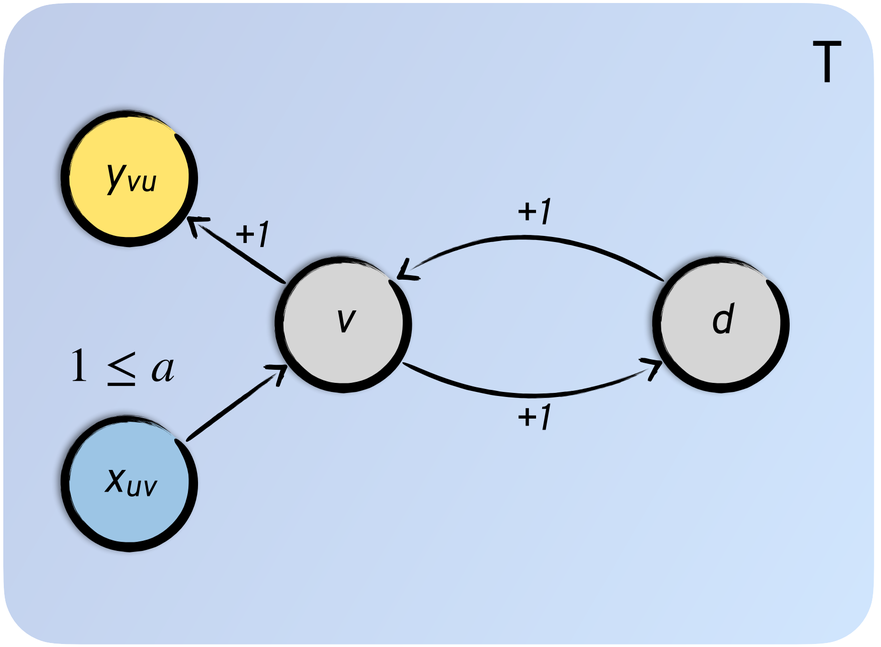
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

Checking an Interface

B: Safety: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle P_S \rangle$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle P_T \rangle$

$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$





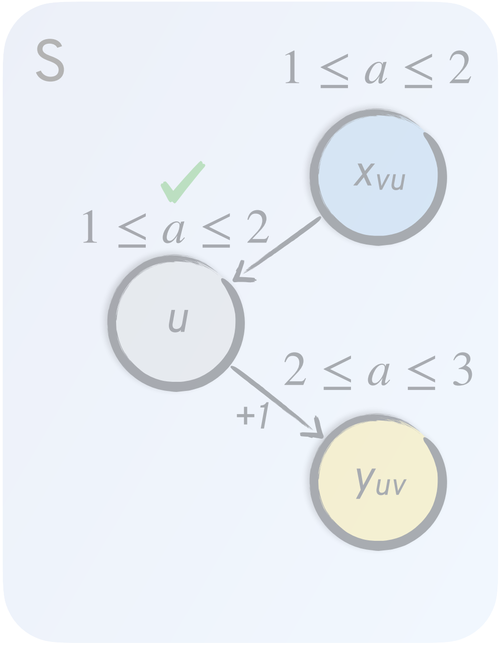
$P_S = \mathscr{L}(u) < 10$

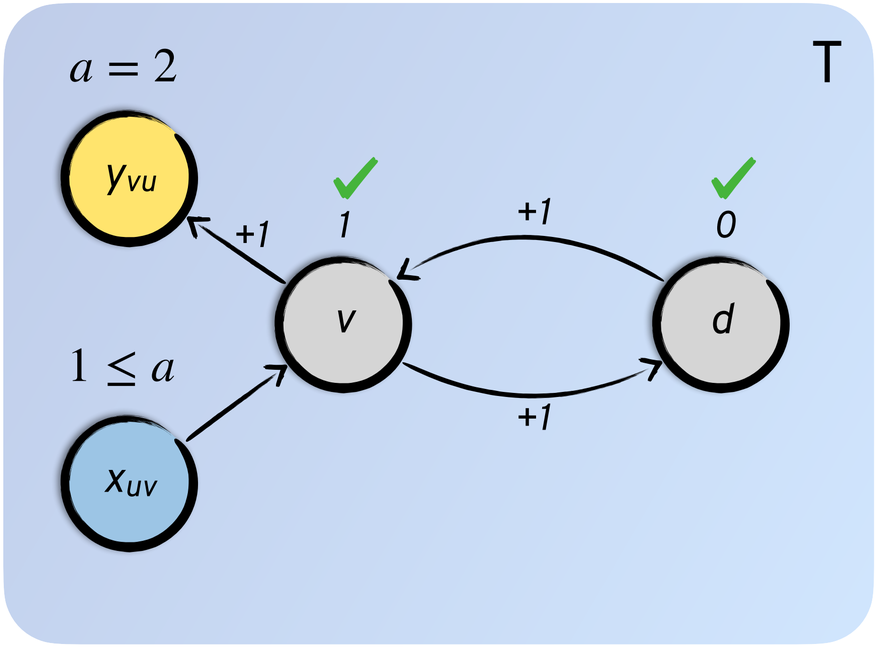
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

Checking an Interface

B: Safety: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle P_S \rangle$, $\langle \mathbf{H}_T \rangle \mathscr{M}_T \langle P_T \rangle$

$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$





$P_S = \mathscr{L}(u) < 10$

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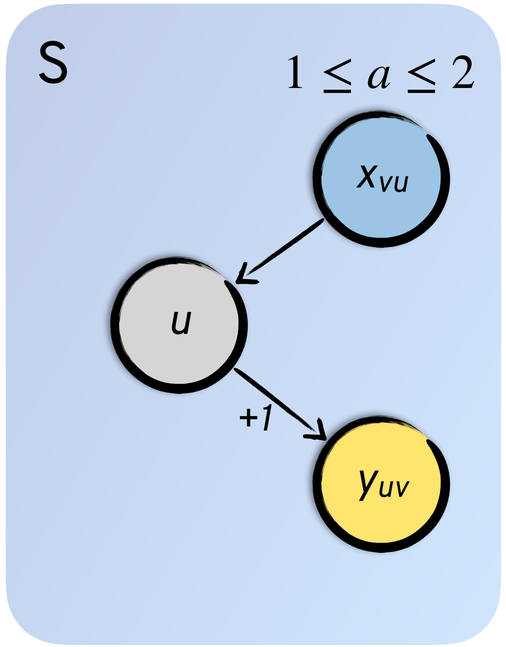
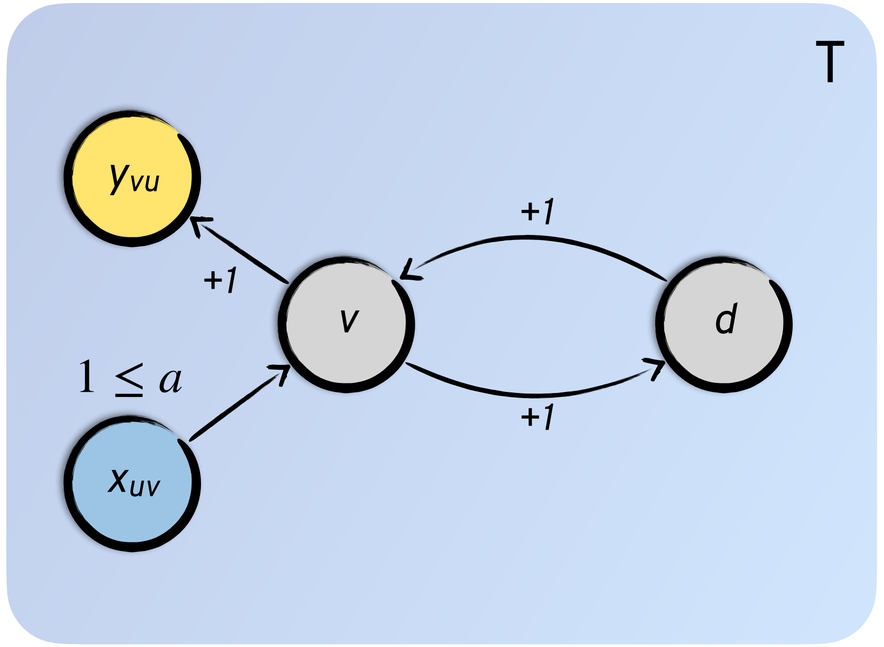
Checking an Interface

C: Initial: $\langle \text{true} \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \text{true} \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

$(v, u, 1 \leq a \leq 2)$
$(u, v, 1 \leq a)$



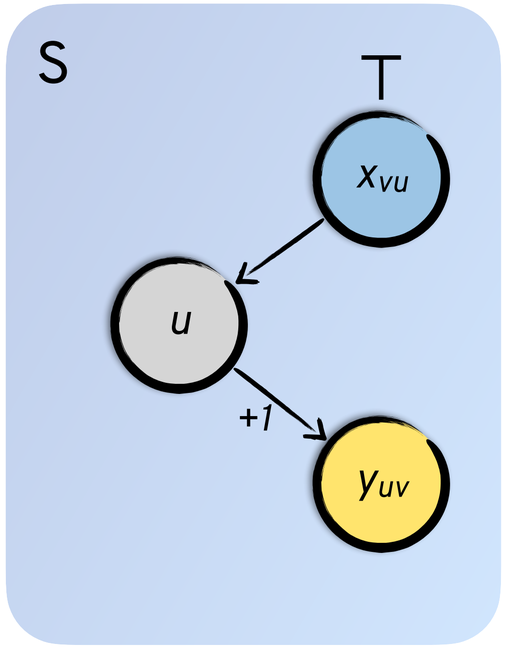


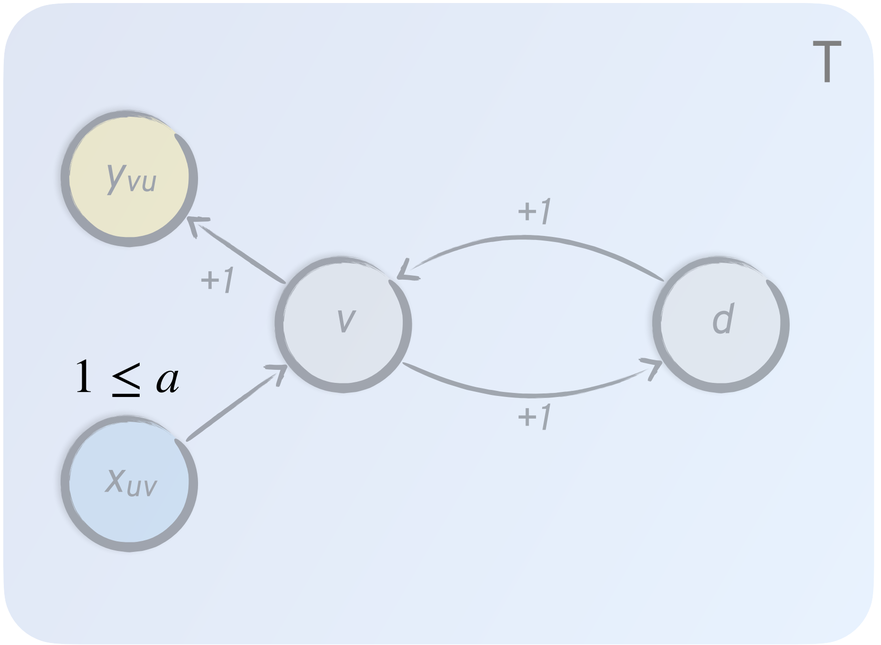
Checking an Interface

C: Initial: $\langle \text{true} \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$, $\langle \text{true} \rangle \mathscr{M}_T \langle G_T \rangle \wedge G_T \Rightarrow \mathbf{H}_S$

$(v, u, 1 \leq a \leq 2)$

$(u, v, 1 \leq a)$





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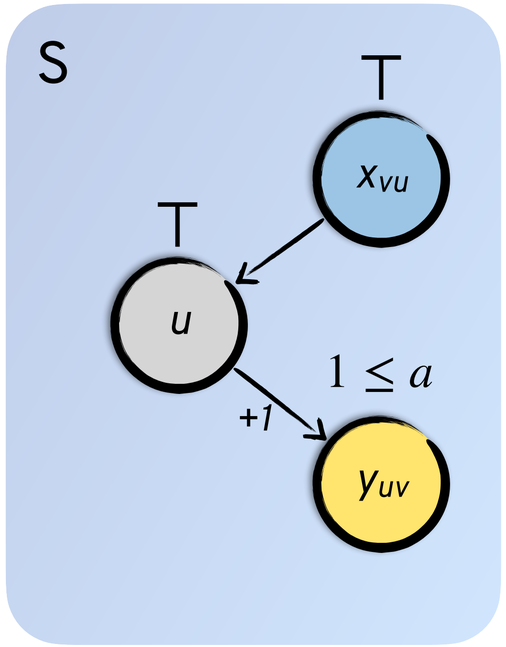

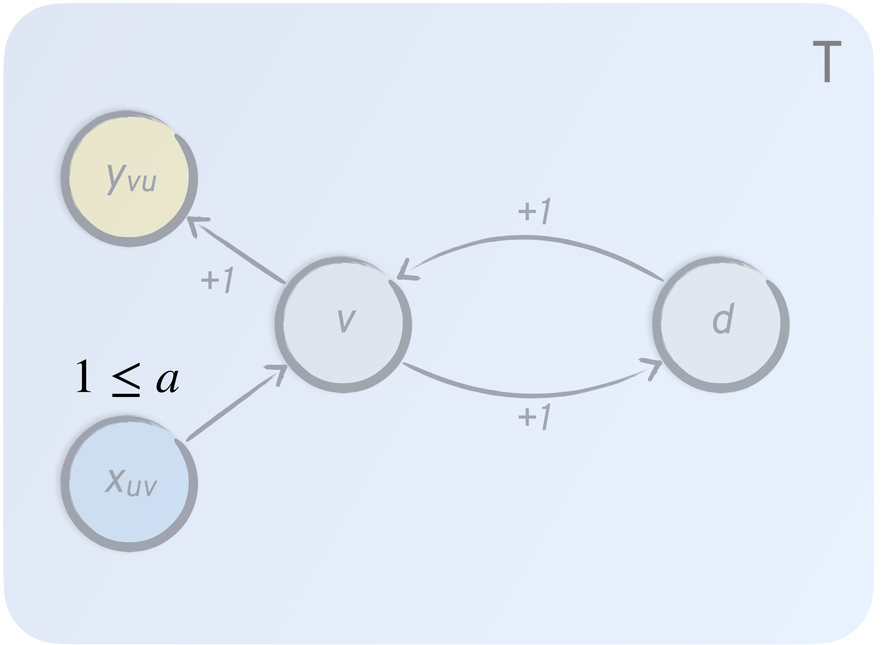

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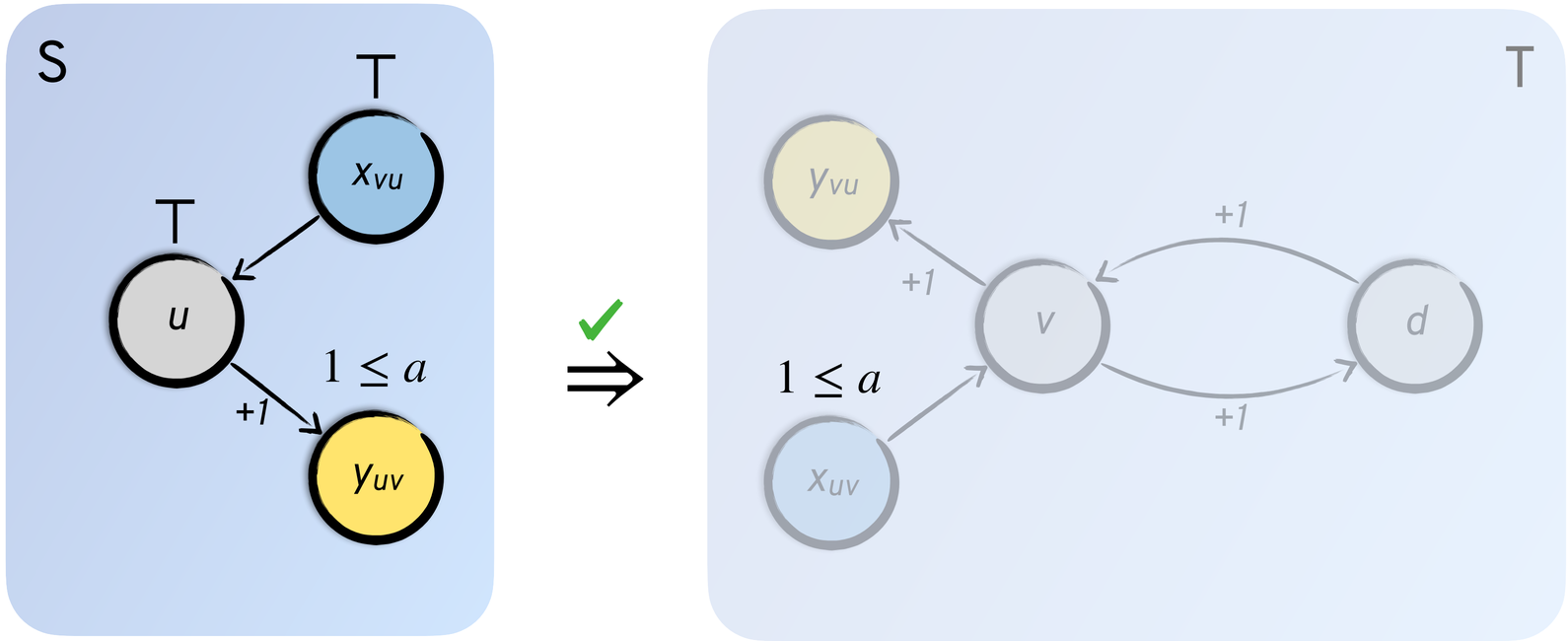

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$(v, u, 1 \leq a \leq 2)$
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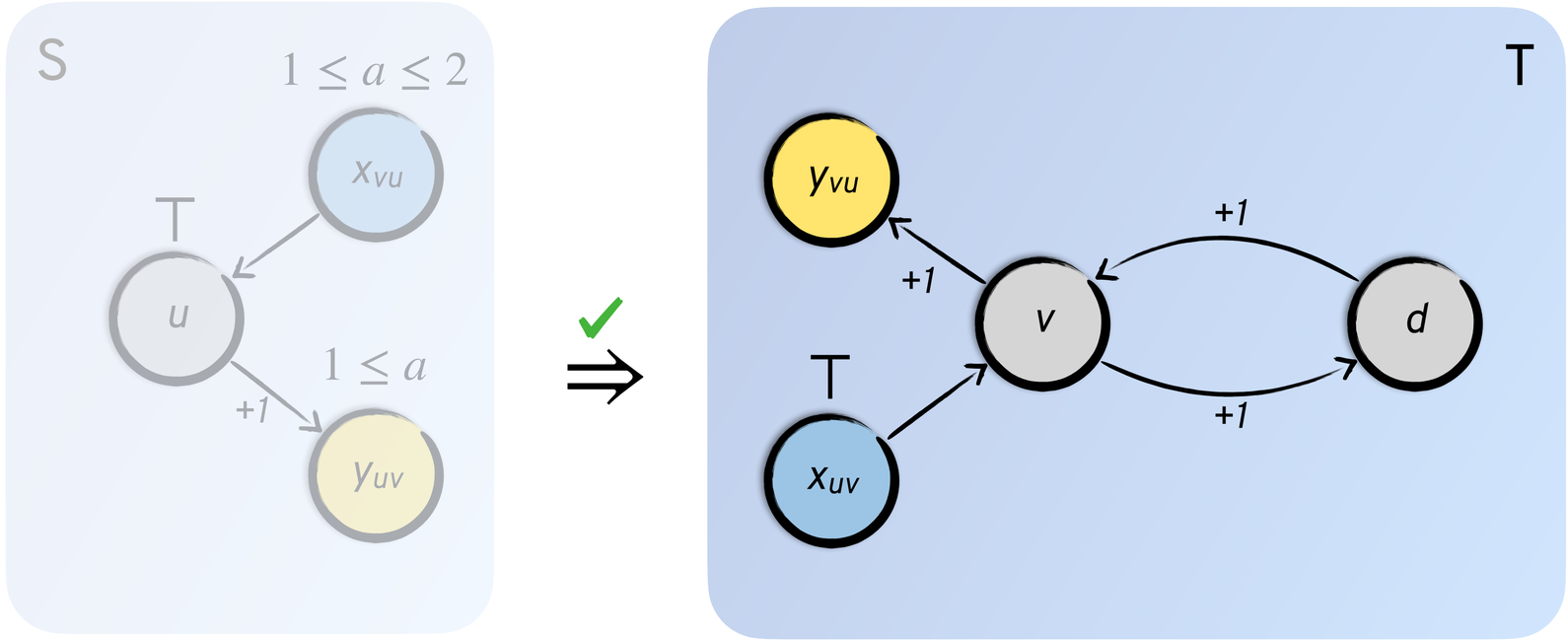

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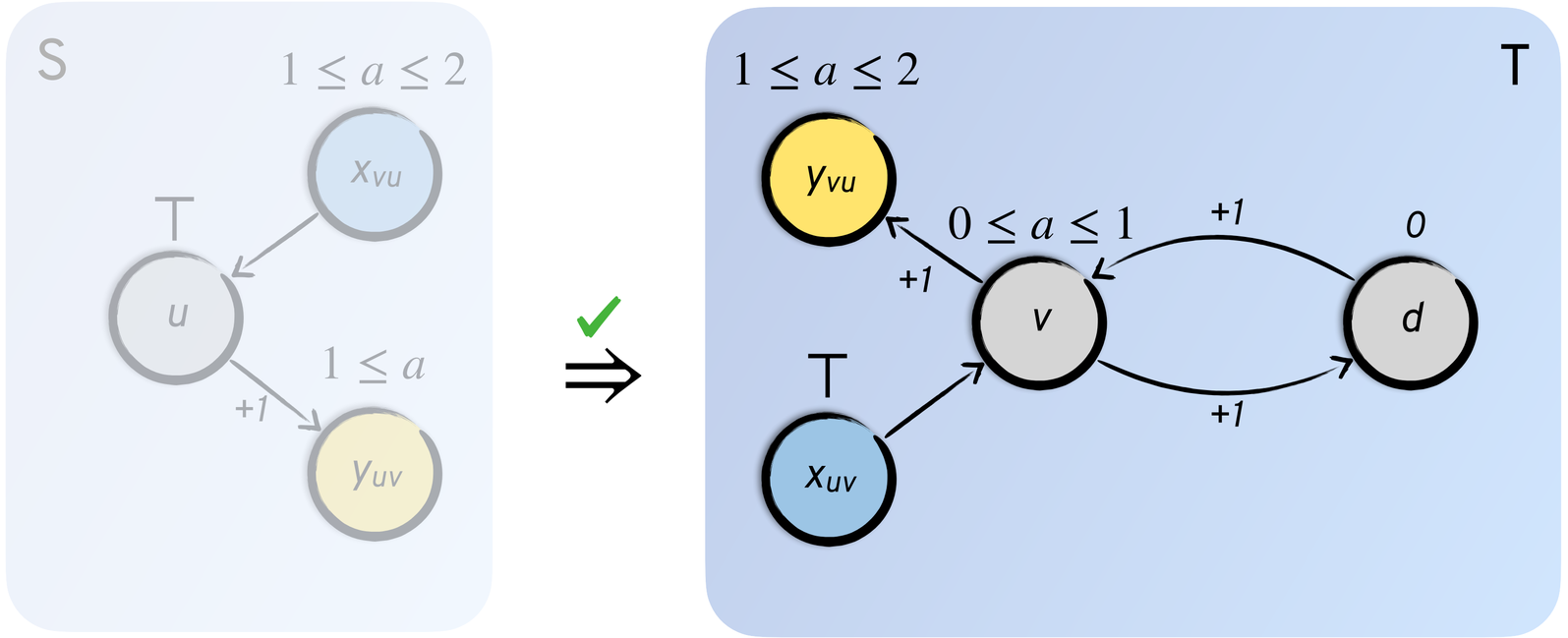

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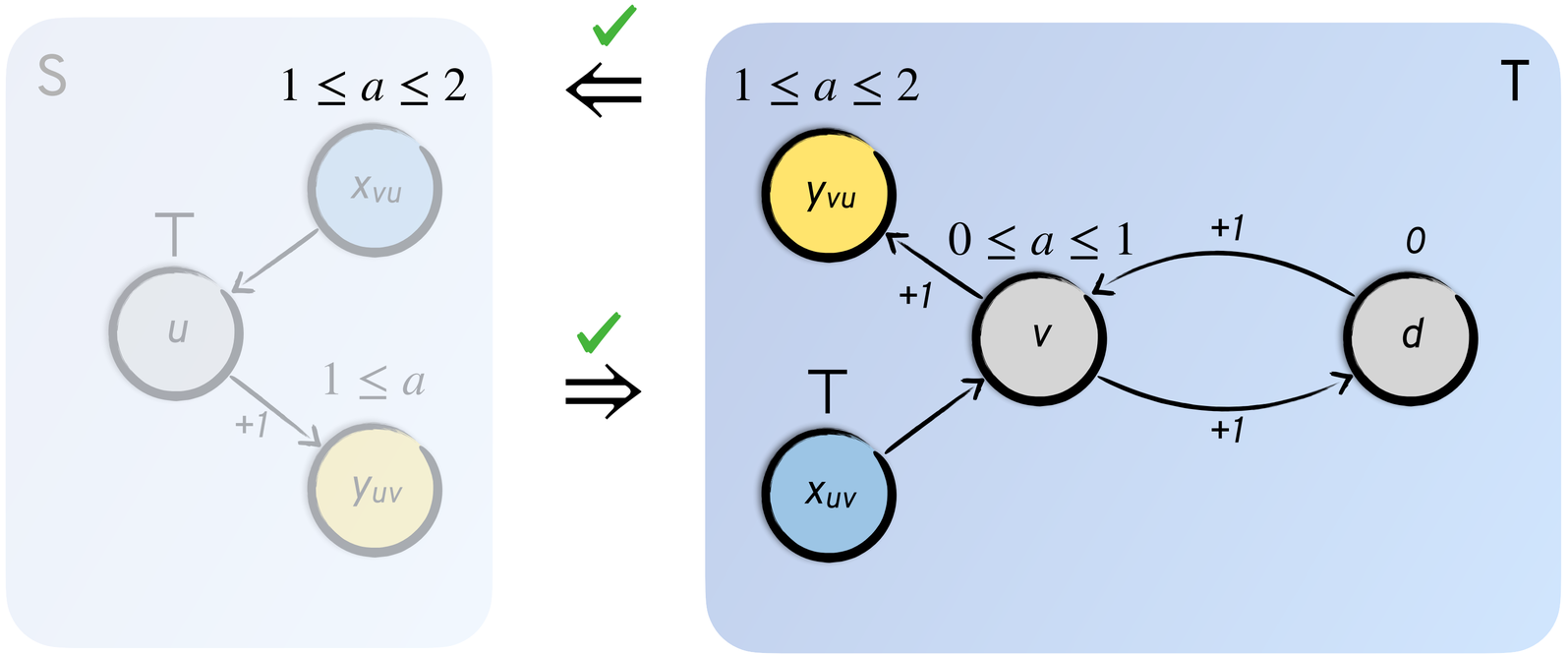
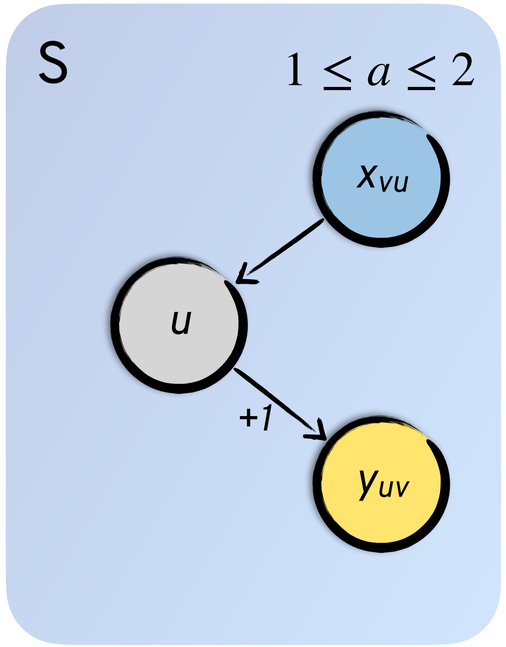
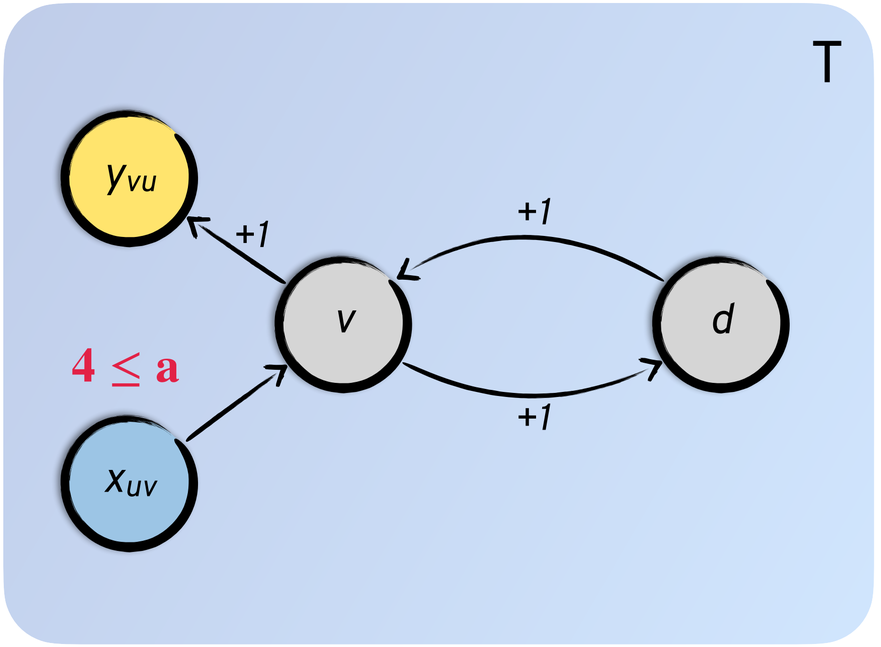


Checking an Interface

Inductiveness VC?



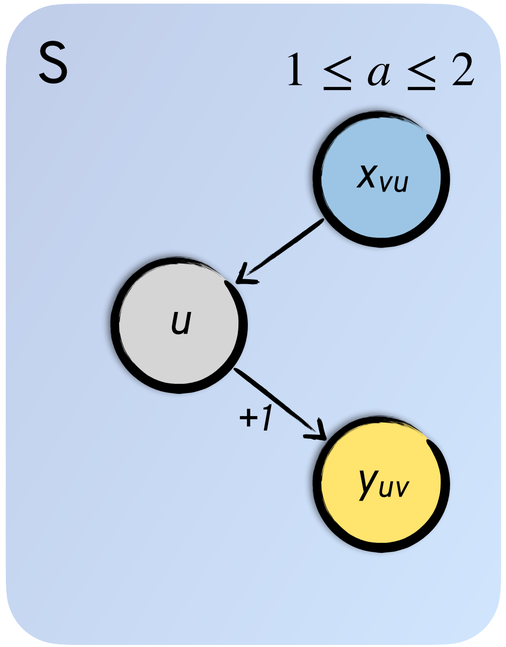


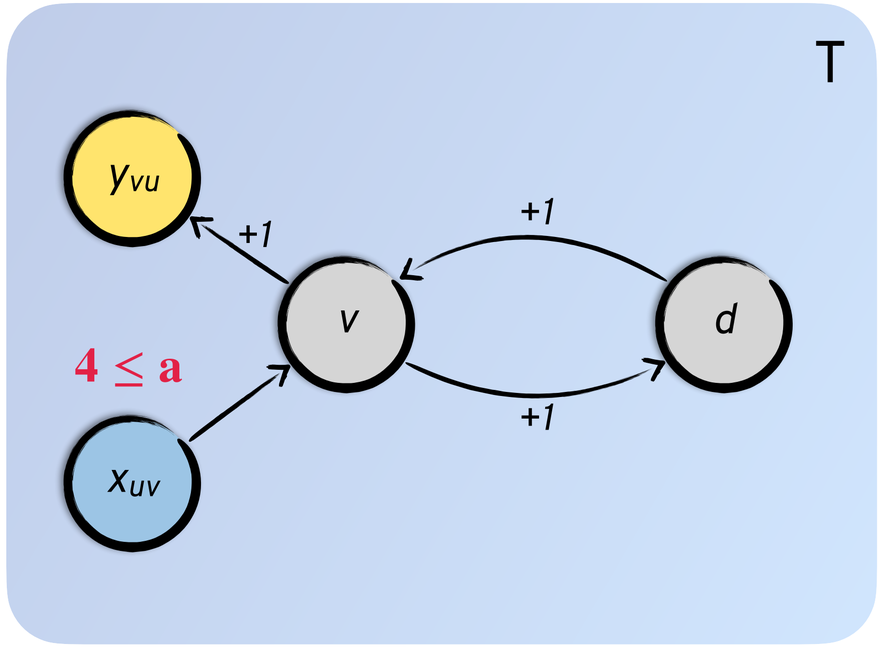
Checking an Interface

Inductiveness VC?

$(v, u, 1 \leq a \leq 2)$

$(u, v, \mathbf{4 \leq a})$





$P_S = \mathscr{L}(u) < 10$

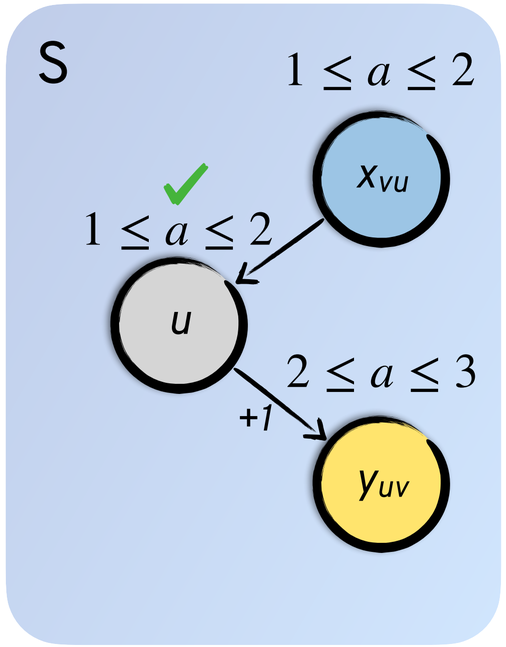
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

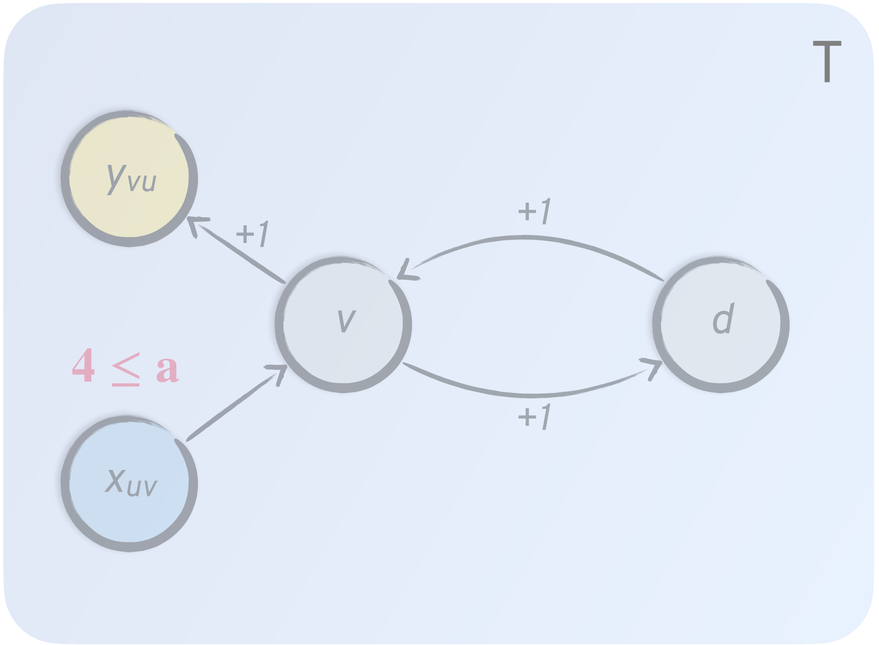
Checking an Interface

Inductiveness VC?

$(v, u, 1 \leq a \leq 2)$

$(u, v, \mathbf{4 \leq a})$





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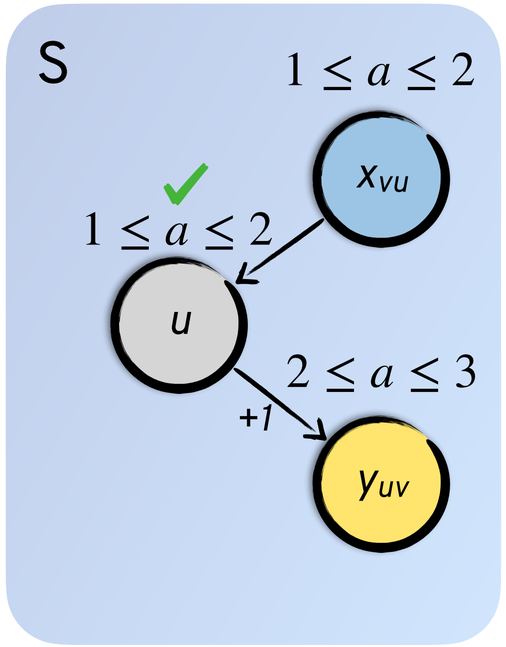
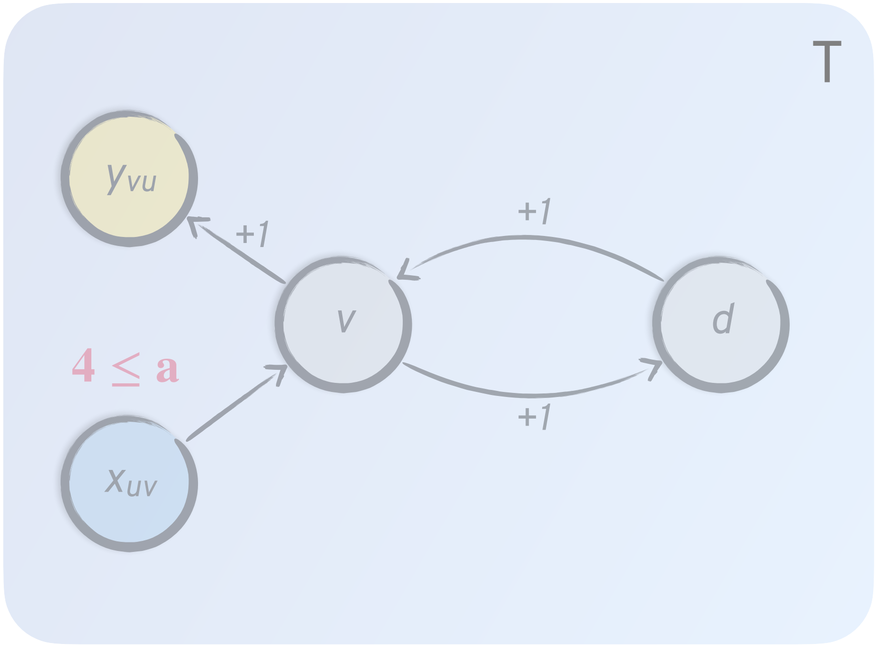
Checking an Interface

Inductiveness VC?

$(v, u, 1 \leq a \leq 2)$

$(u, v, \mathbf{4 \leq a})$





$P_S = \mathscr{L}(u) < 10$

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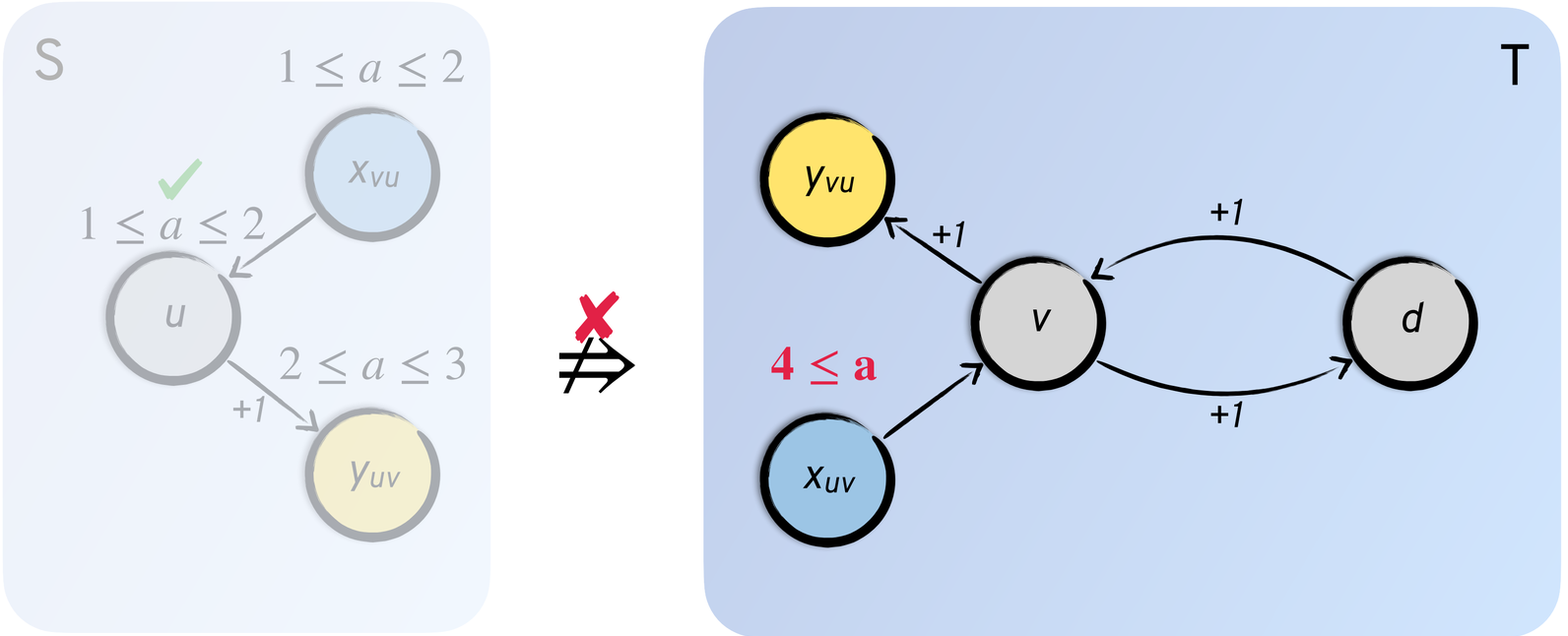
Checking an Interface

Inductiveness VC?

$(v, u, 1 \leq a \leq 2)$

$(u, v, \mathbf{4 \leq a})$



$P_S = \mathscr{L}(u) < 10$

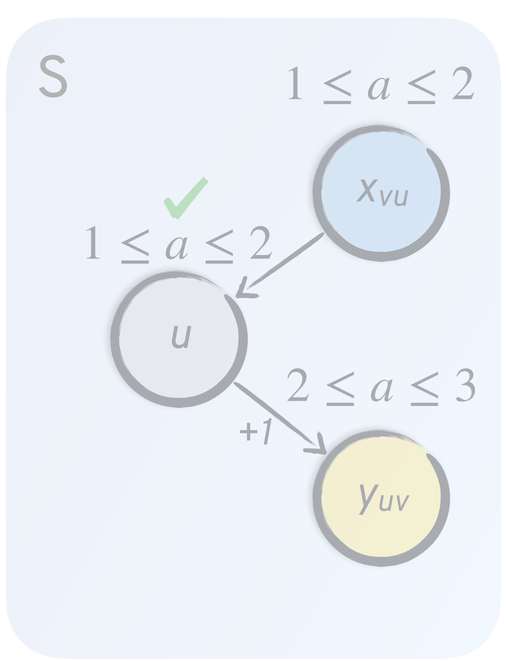
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

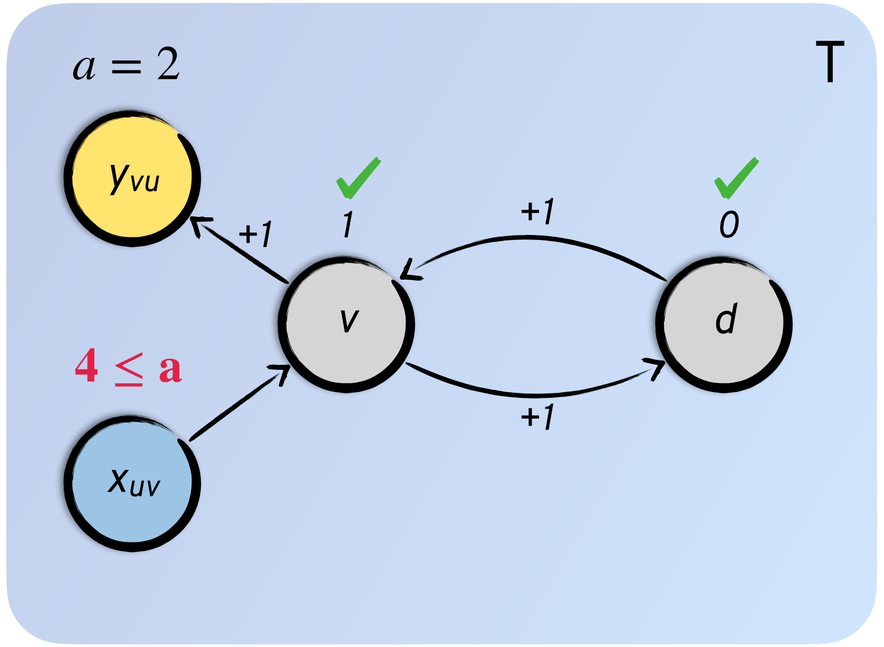
Checking an Interface

Inductiveness VC?

$(v, u, 1 \leq a \leq 2)$

$(u, v, \mathbf{4 \leq a})$





$P_S = \mathscr{L}(u) < 10$

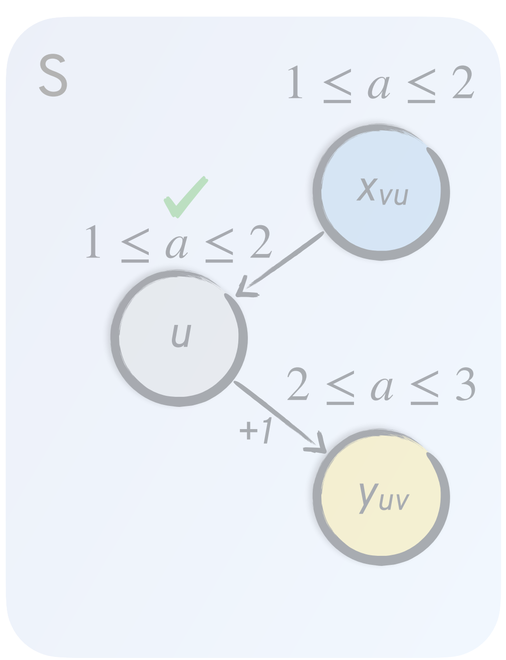
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

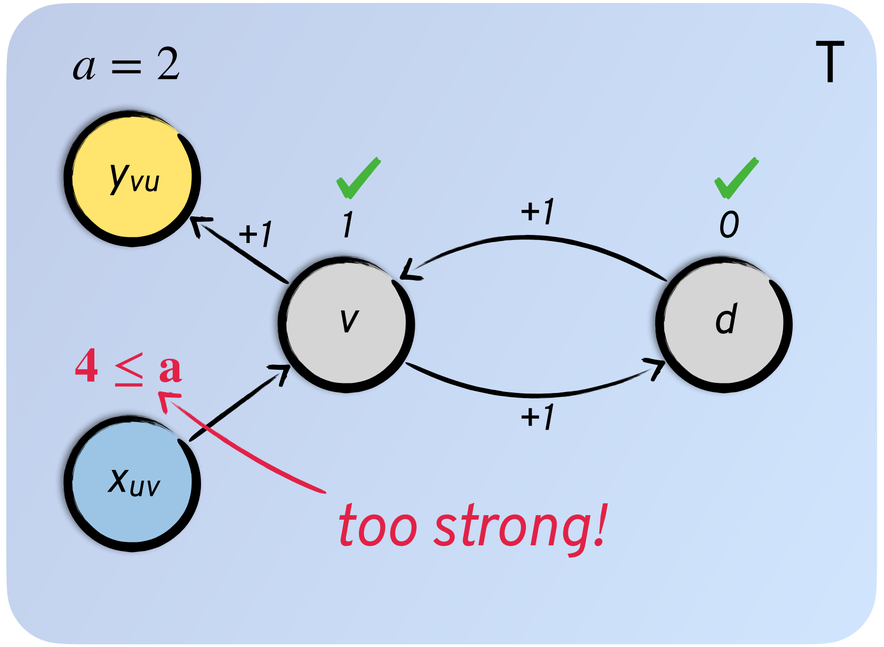
Checking an Interface

Inductiveness VC?

$(v, u, 1 \leq a \leq 2)$

$(u, v, \mathbf{4 \leq a})$





$P_S = \mathscr{L}(u) < 10$

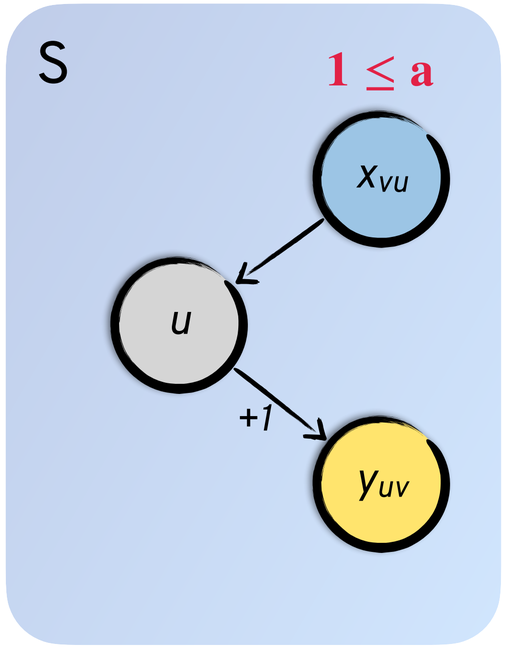
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

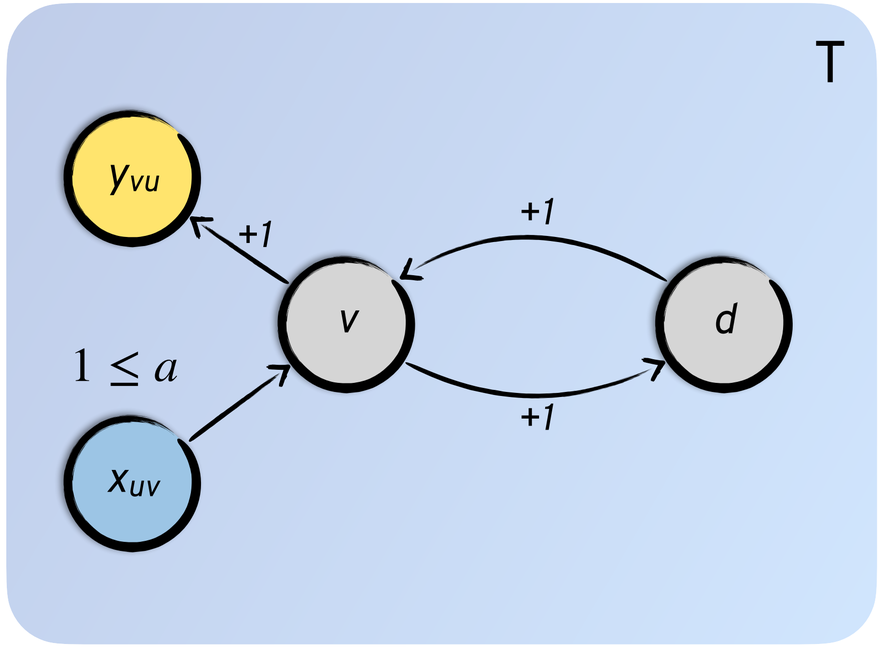
Checking an Interface

Safety VC?

$(v, u, \mathbf{1 \leq a})$

$(u, v, 1 \leq a)$





$P_S = \mathscr{L}(u) < 10$

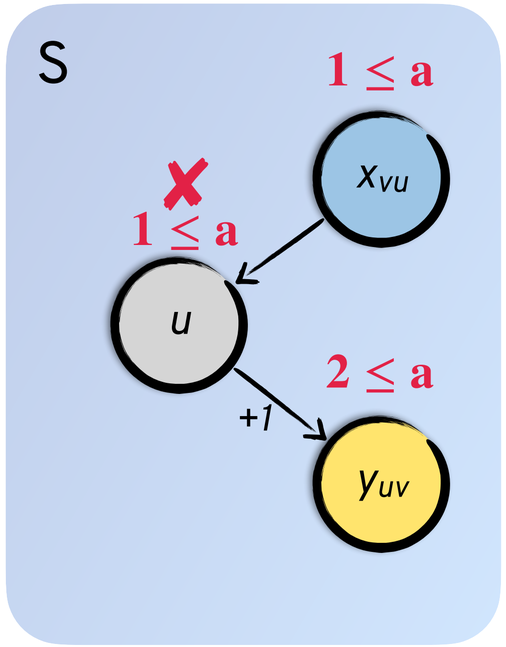
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

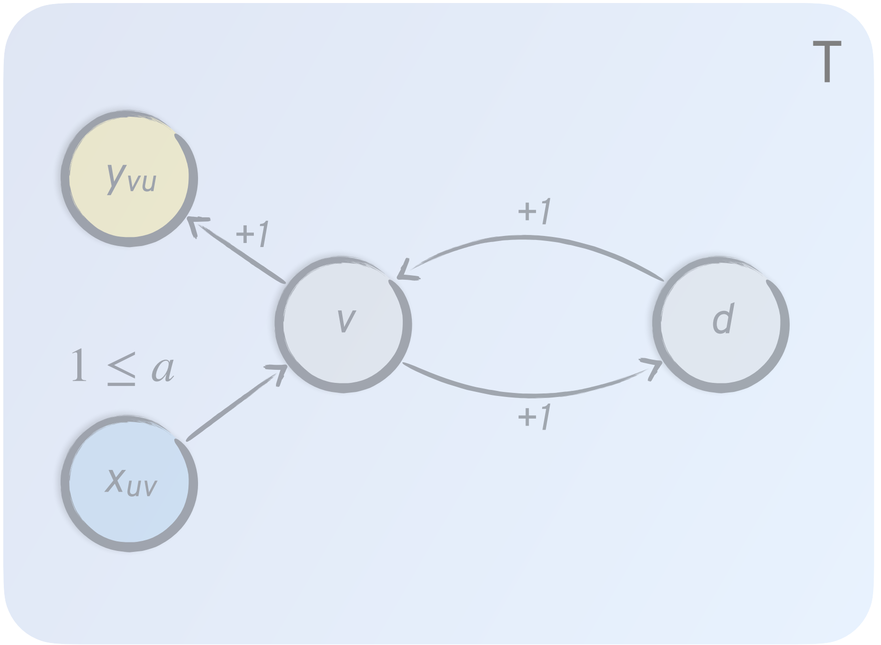
Checking an Interface

Safety VC?

$(v, u, \mathbf{1 \leq a})$

$(u, v, 1 \leq a)$





$P_S = \mathscr{L}(u) < 10$

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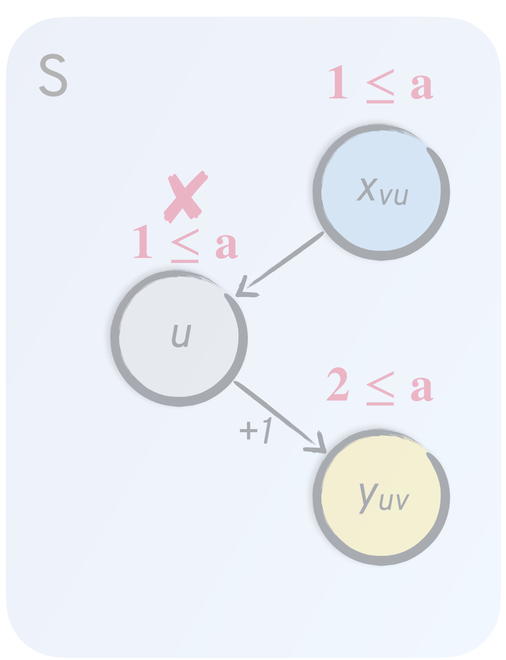
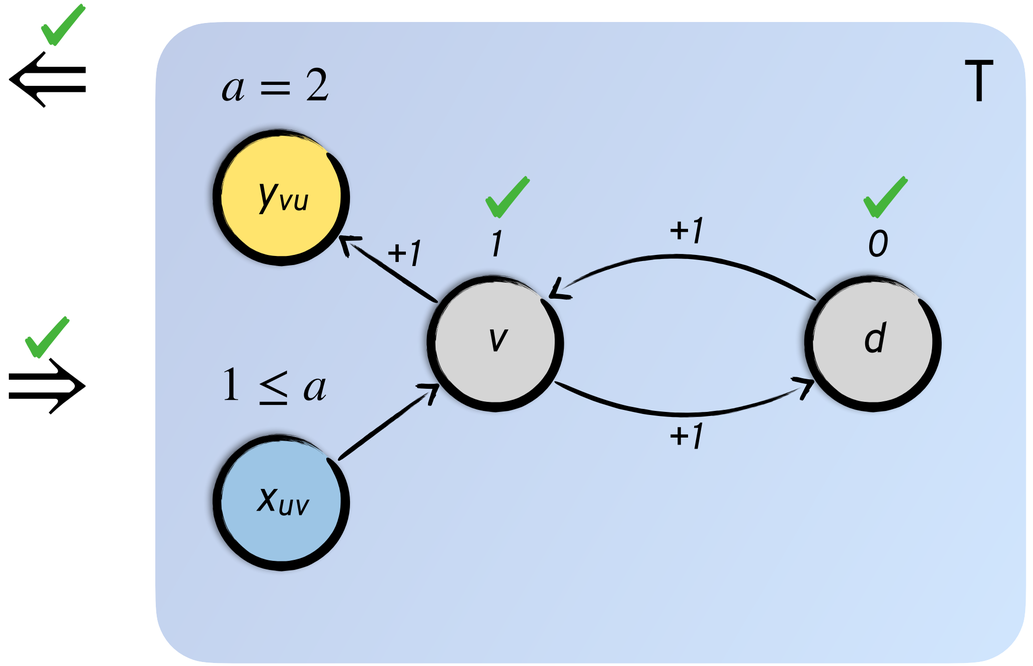
Checking an Interface

Safety VC?

$(v, u, \mathbf{1 \leq a})$

$(u, v, 1 \leq a)$





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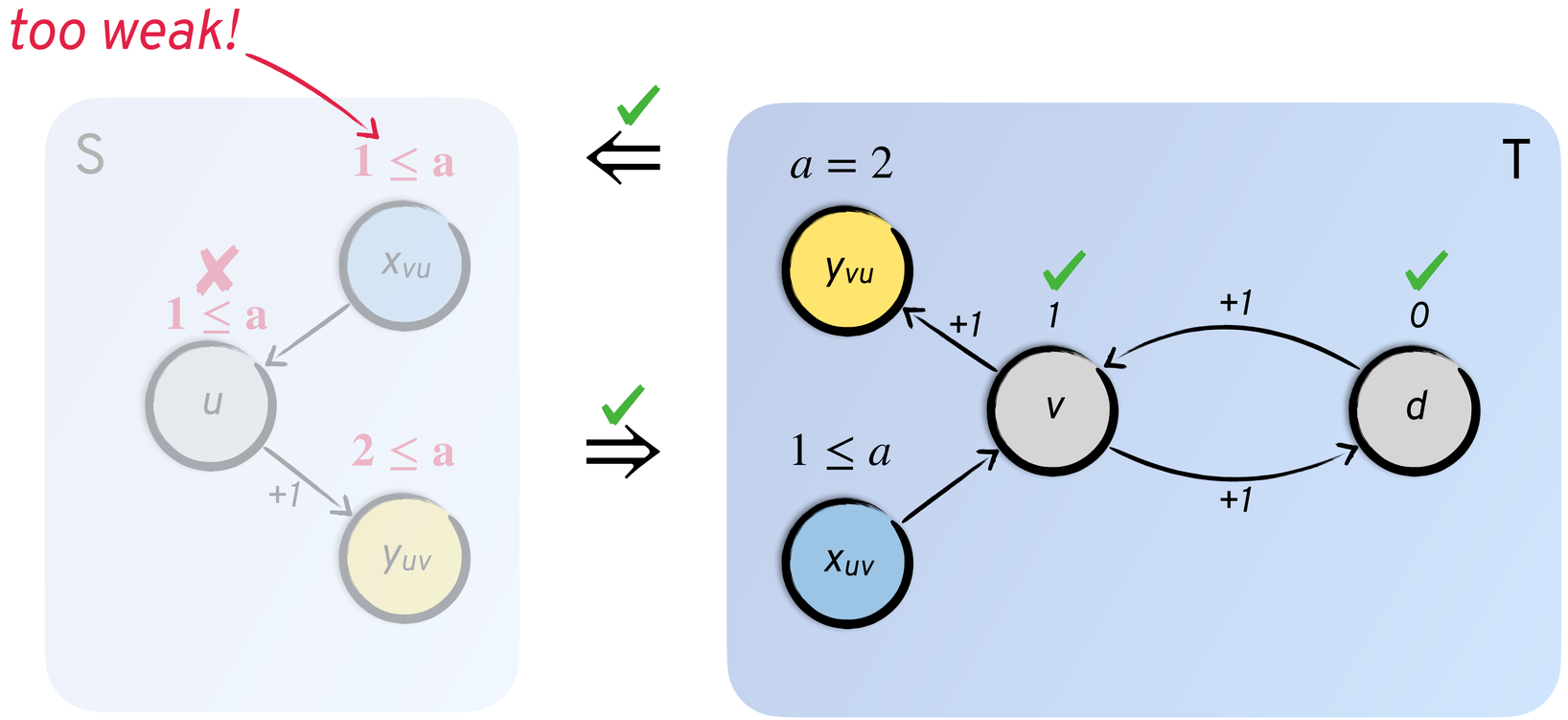
Checking an Interface

Safety VC?

$(v, u, \mathbf{1 \leq a})$

$(u, v, 1 \leq a)$



$P_S = \mathscr{L}(u) < 10$

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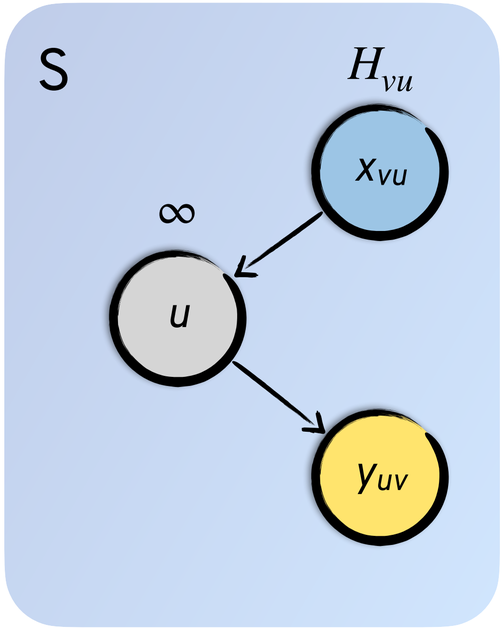
Checking an Interface

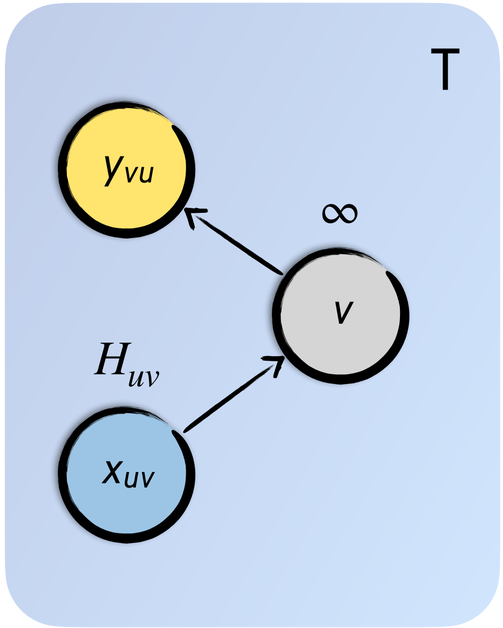
Networks with Multiple Solutions

$(v, u, a = \infty)$

$(u, v, a = \infty)$



$P_S = true$



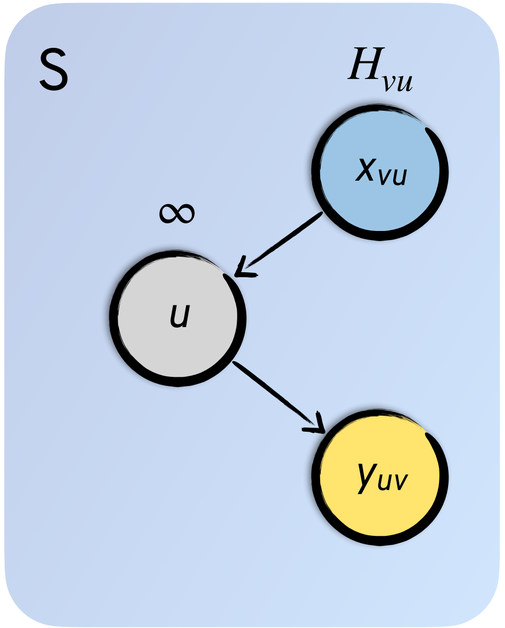
$P_T = true$

Checking an Interface

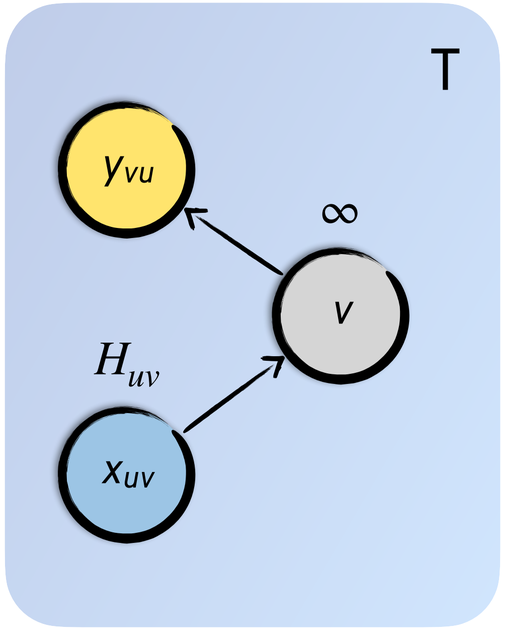
Networks with Multiple Solutions

$(v, u, a = \infty)$

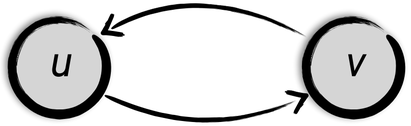
$(u, v, a = \infty)$



$P_S = true$



$P_T = true$

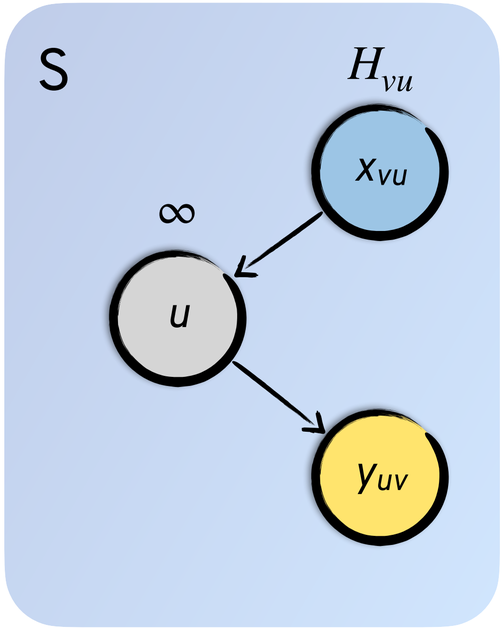


Checking an Interface

Networks with Multiple Solutions

$(v, u, a = \infty)$

$(u, v, a = \infty)$



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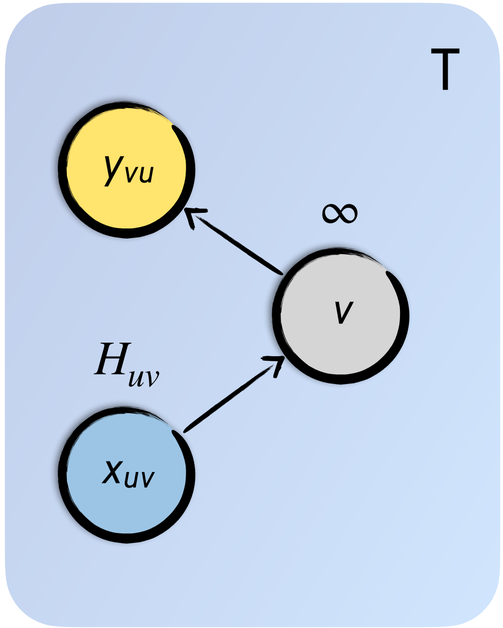
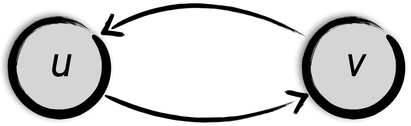


$P_T = true$



$$\mathscr{L}(u) = \mathscr{L}(v) = 0$$
$$= 1$$
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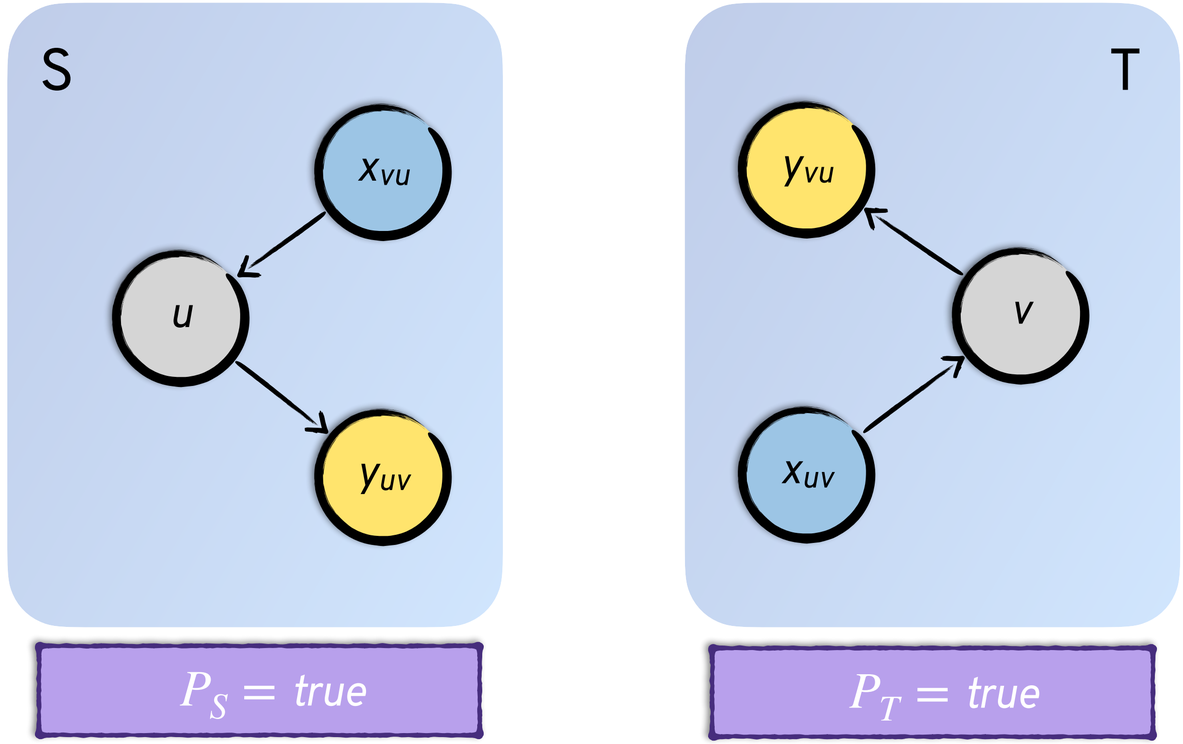
$$= \infty$$

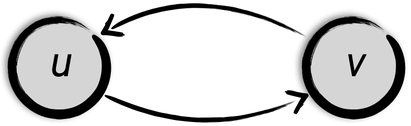
Checking an Interface

Networks with Multiple Solutions

$(v, u, a = \infty)$

$(u, v, a = \infty)$





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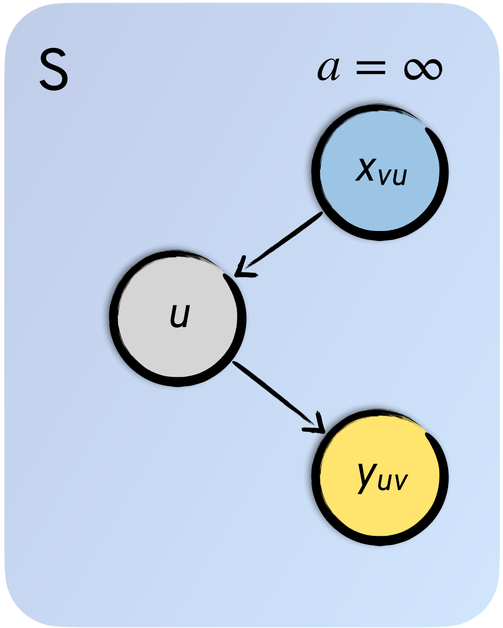
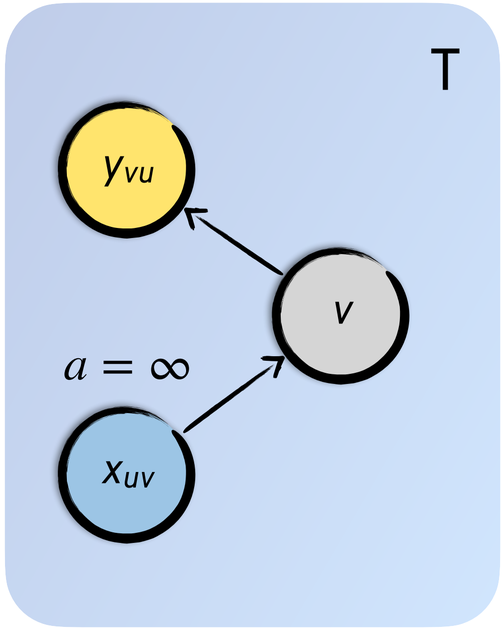
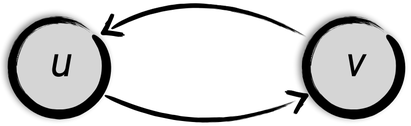




$P_S = true$

$P_T = true$



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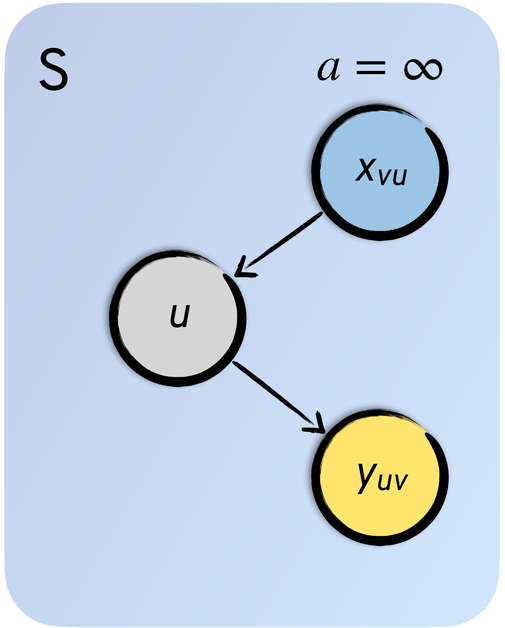
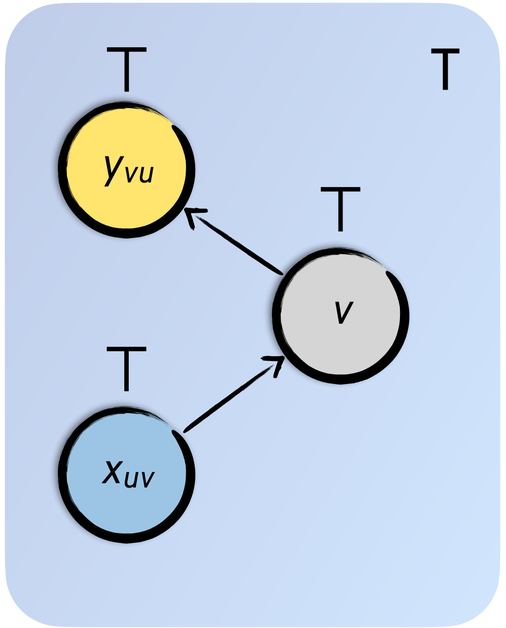
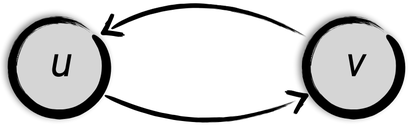


$P_S = true$



$P_T = true$



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Networks with Multiple Solutions

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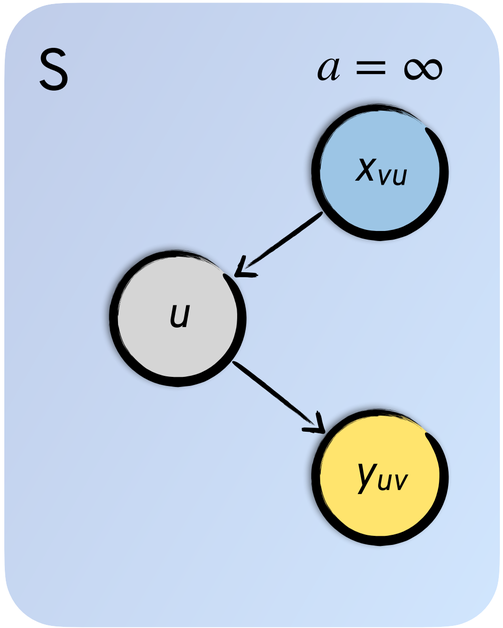

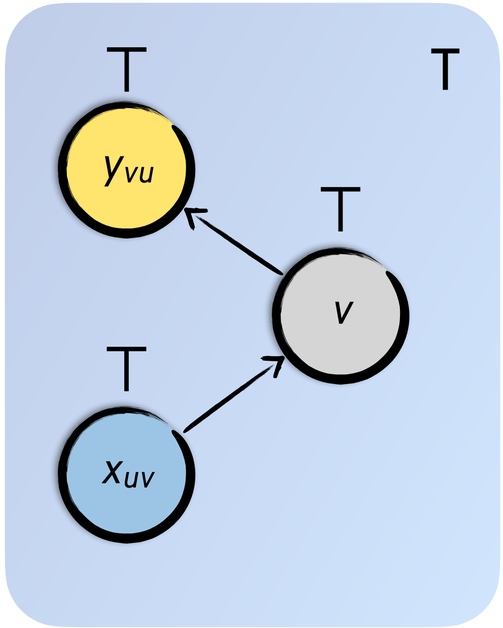

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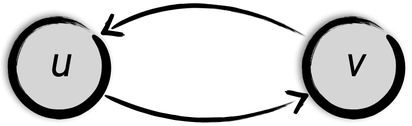

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Networks with Multiple Solutions

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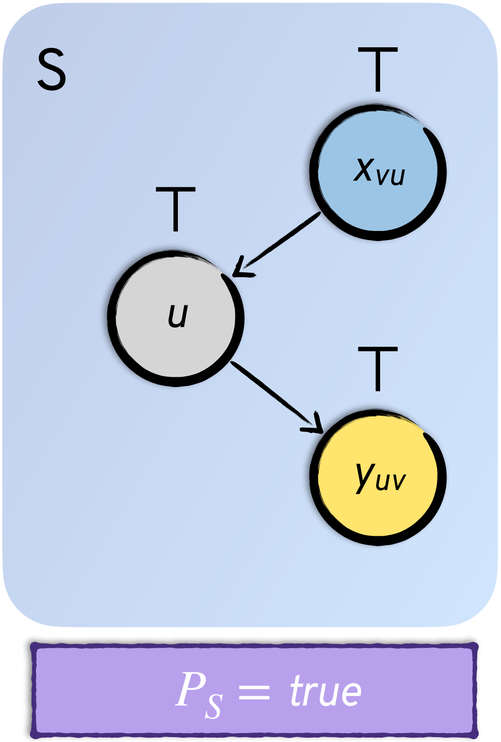
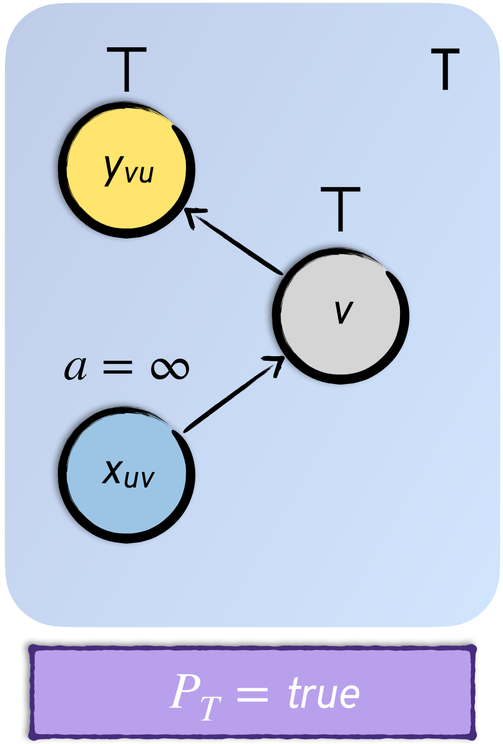
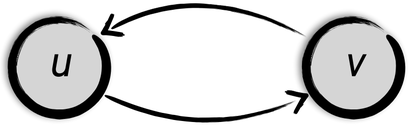


$P_S = true$



$P_T = true$



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Checking an Interface

Networks with Multiple Solutions

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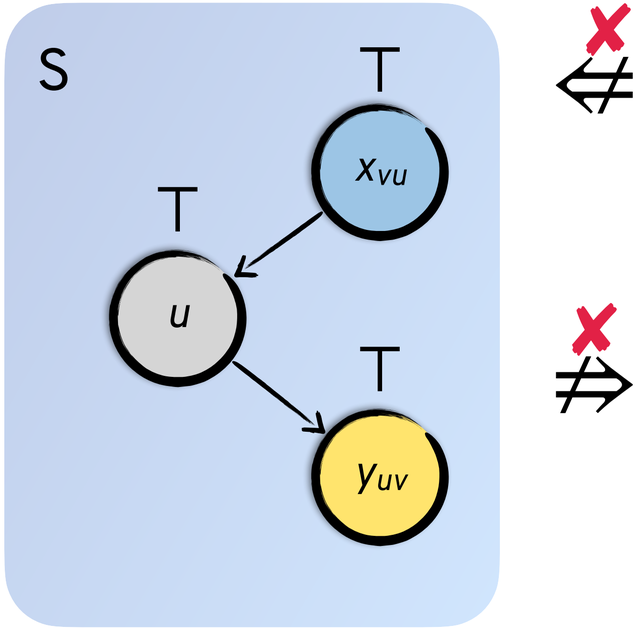

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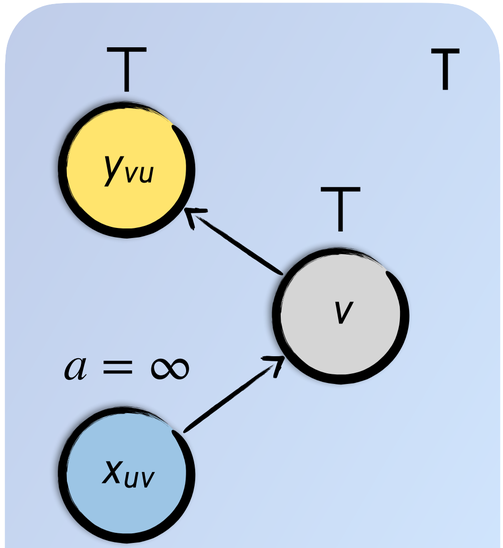
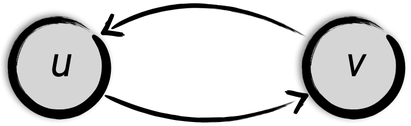


$P_T = true$



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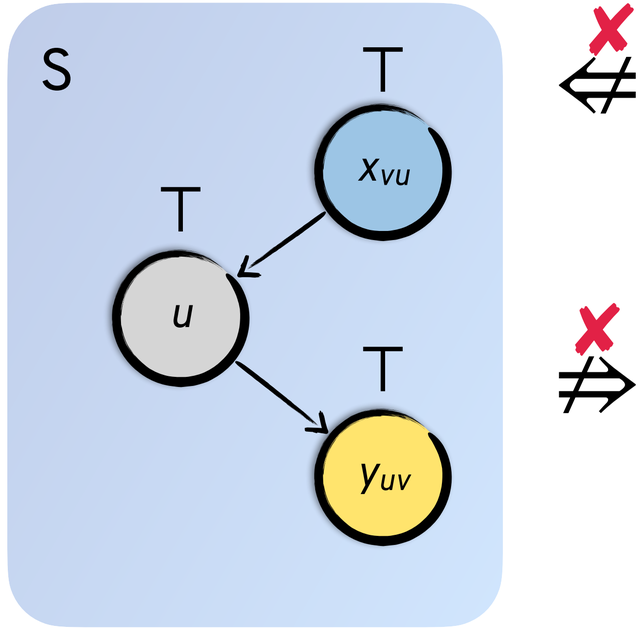
Checking an Interface

Networks with Multiple Solutions

$(v, u, true)$

$(u, v, true)$



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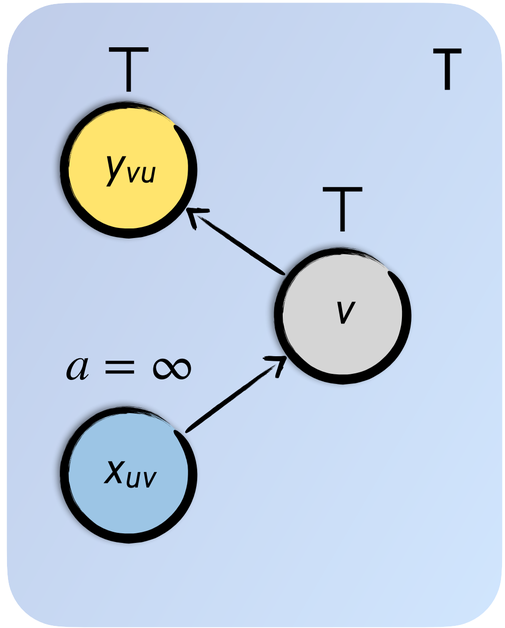

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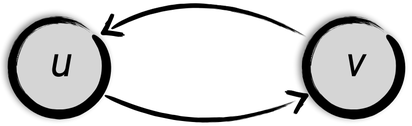

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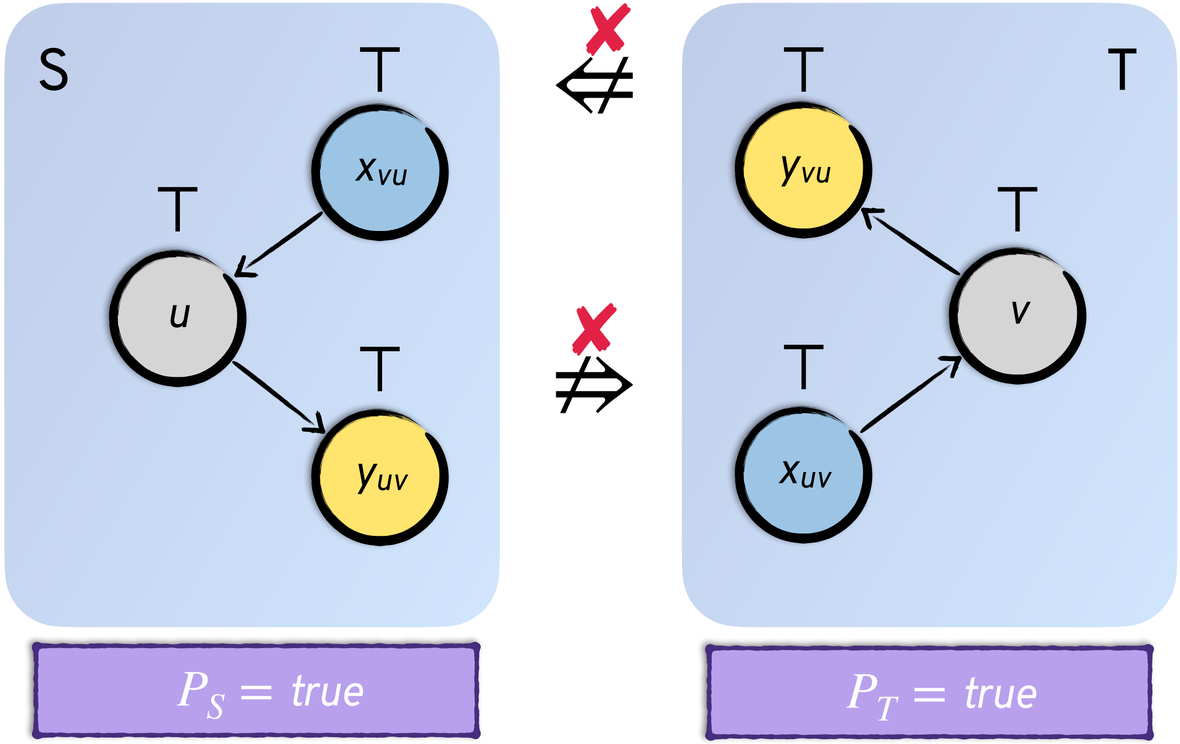
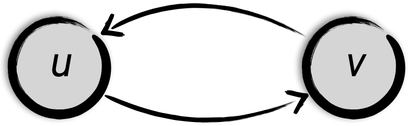
Checking an Interface

Networks with Multiple Solutions

$(v, u, true)$

$(u, v, true)$





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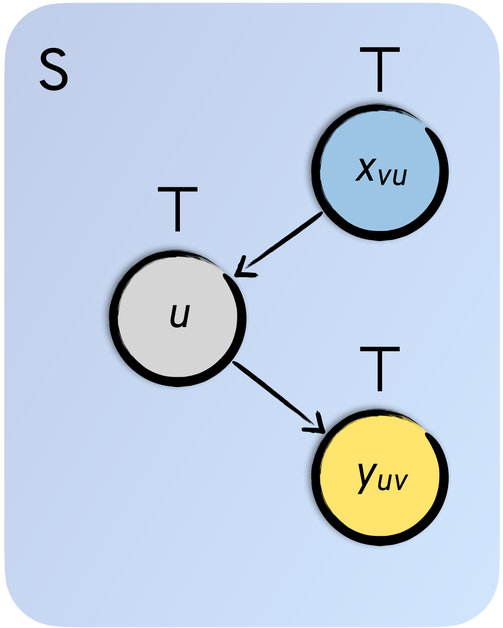
Checking an Interface

Networks with Multiple Solutions

$(v, u, true)$

$(u, v, true)$



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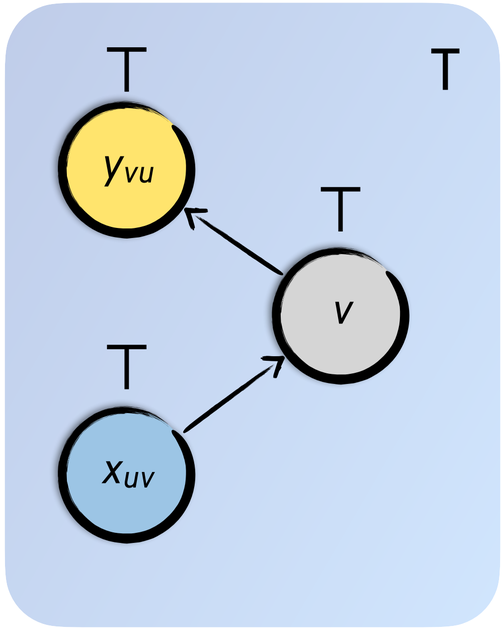

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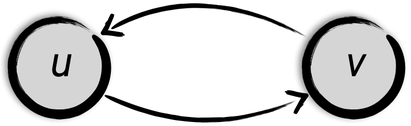

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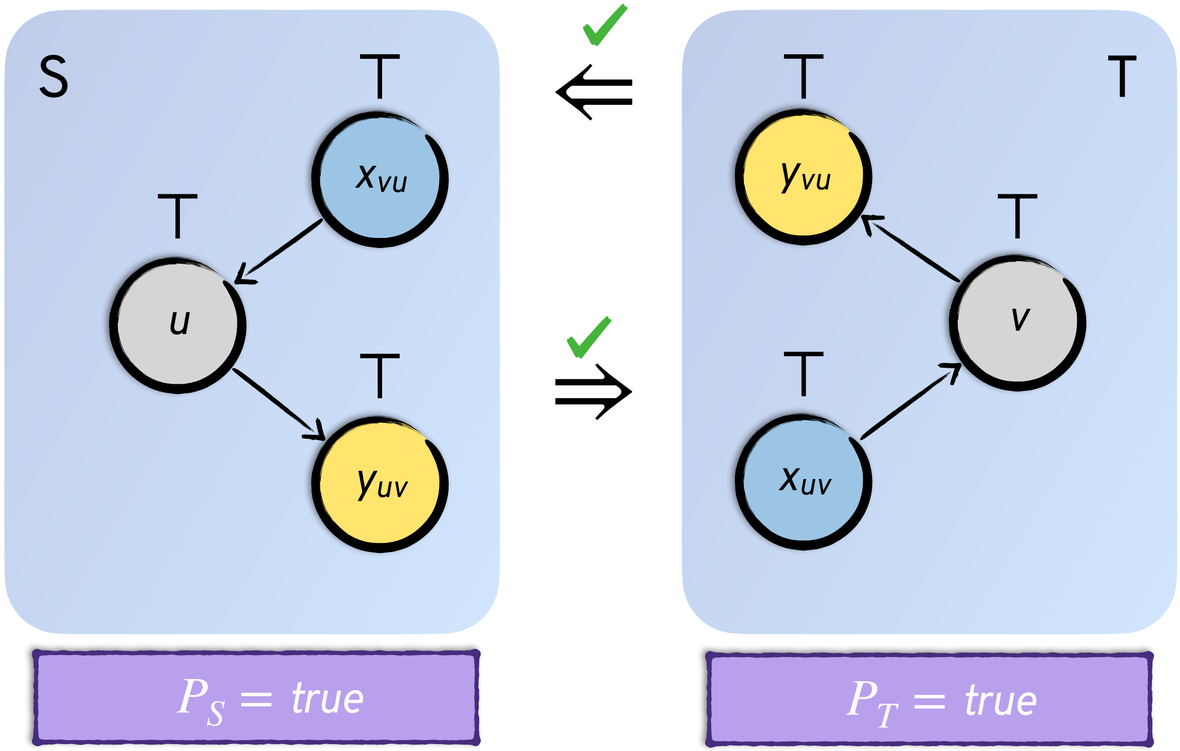
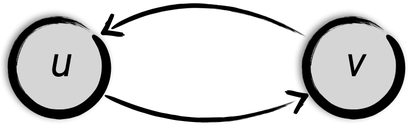
Networks with Multiple Solutions

$(v, u, true)$

$(u, v, true)$





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Kirigami Is Sound!

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Theorem: if Kirigami returns true, then property P holds for monolithic network R

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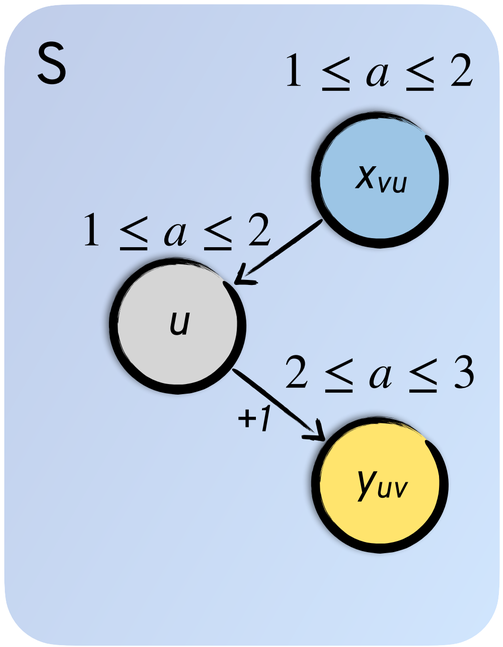

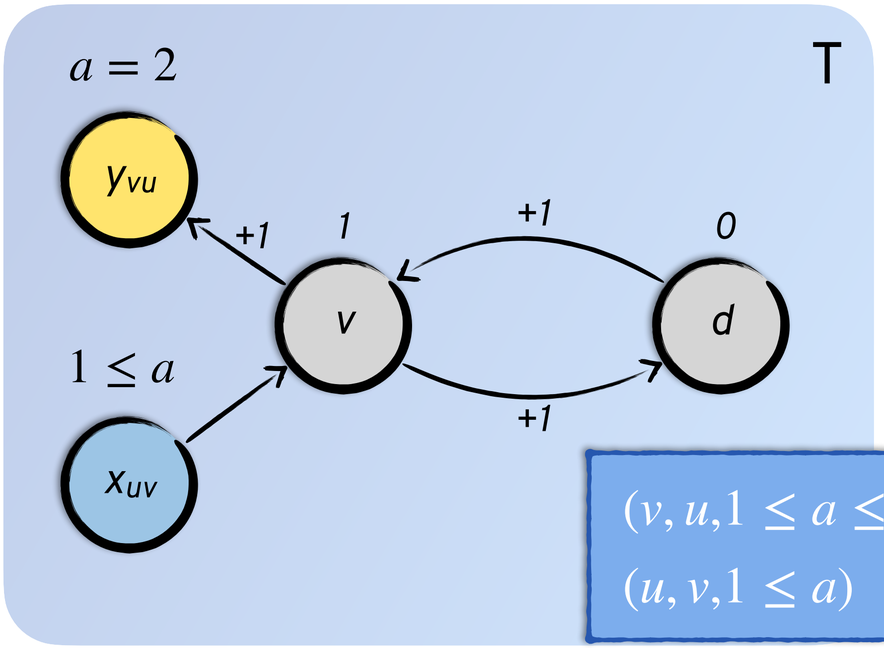

$(v, u, 1 \le a \le 2)$

$(u, v, 1 \le a)$

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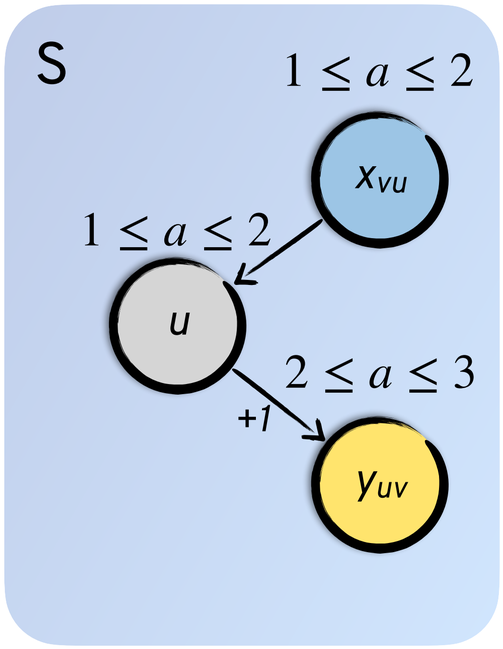

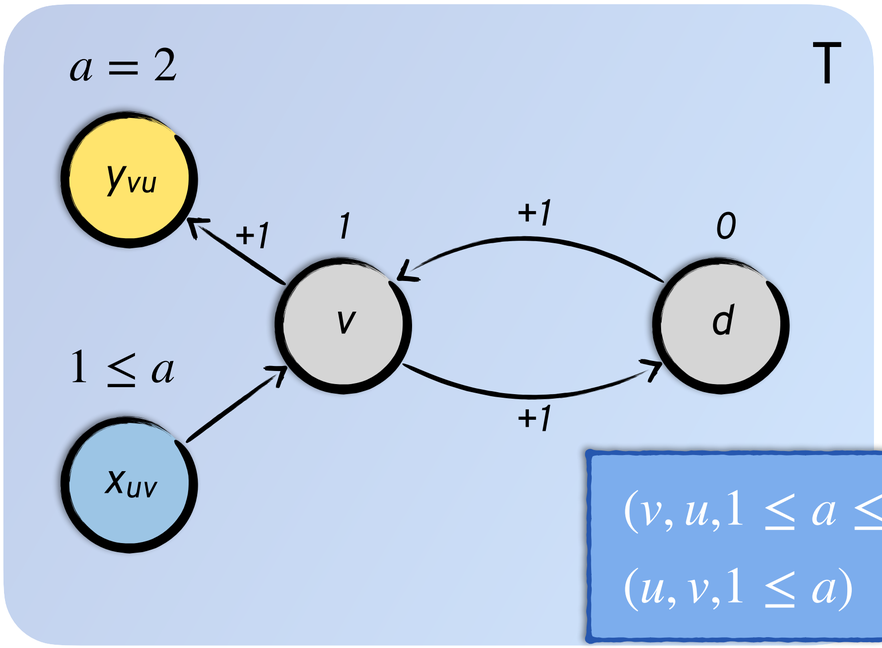

$(v, u, 1 \le a \le 2)$
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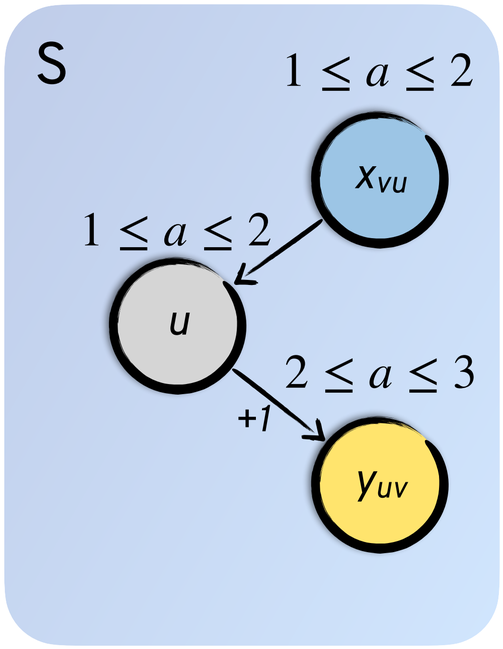
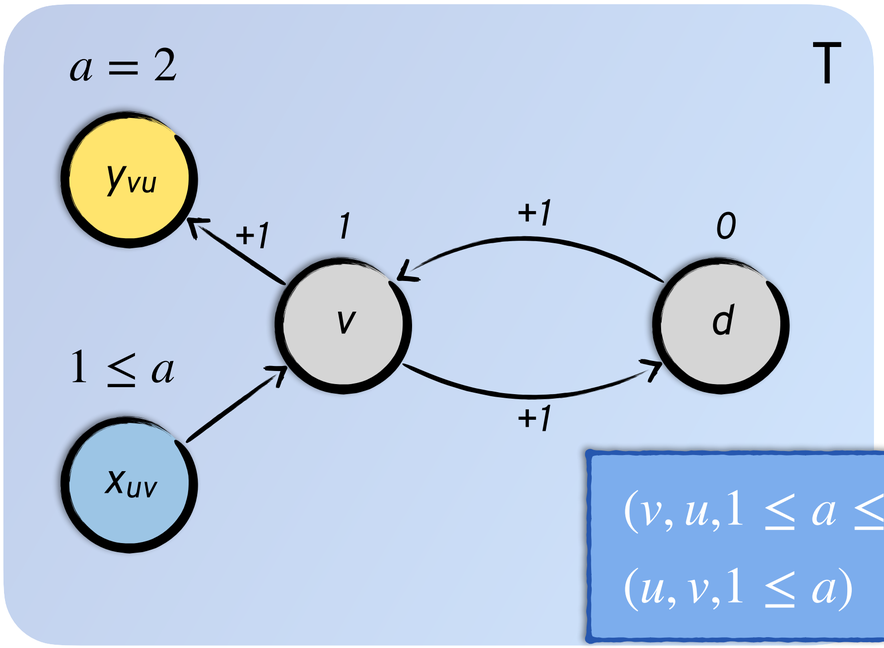
- To start, show that for all nodes v, $\mathscr{L}_R(v) \subseteq \mathscr{L}_T(v)$ (or S)

Kirigami Is Sound!

Theorem: if Kirigami returns true, then property P holds for monolithic network R





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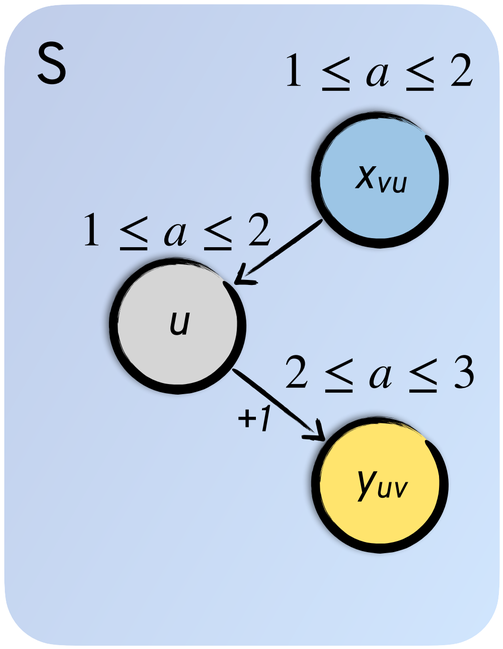
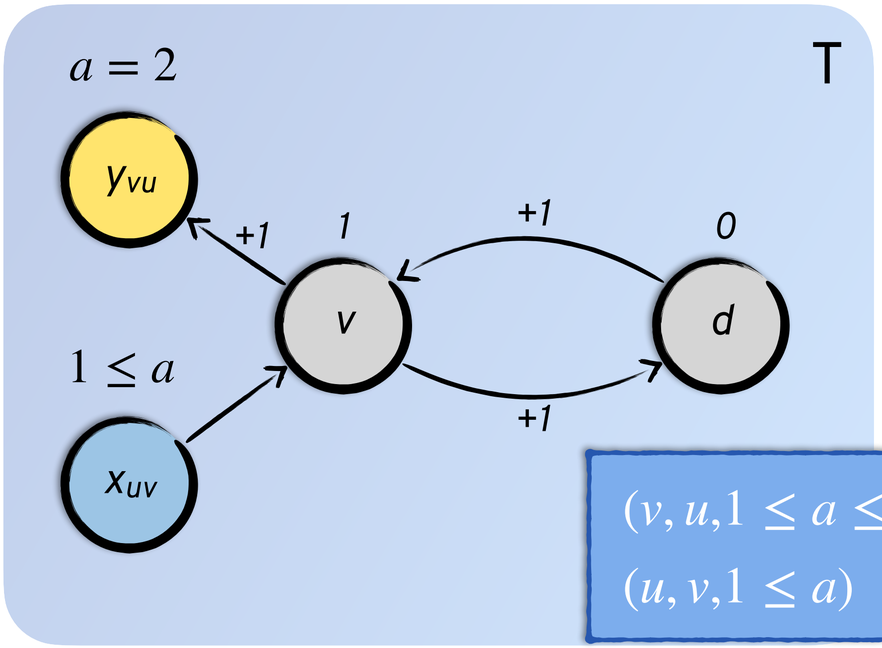
- To start, show that for all nodes v, $\mathscr{L}_R(v) \subseteq \mathscr{L}_T(v)$ (or S)
- Node's solution in terms of neighbors' transferred solutions trans$((u, v), \mathscr{L}(u))$

Kirigami Is Sound!

Theorem: if Kirigami returns true, then property P holds for monolithic network R





$P_S = \mathscr{L}(u) < 10$

$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

- To start, show that for all nodes v, $\mathscr{L}_R(v) \subseteq \mathscr{L}_T(v)$ (or S)
- Node's solution in terms of neighbors' transferred solutions $\text{trans}((u, v), \mathscr{L}(u))$
- Case analysis on the neighbors of v in T (or S)

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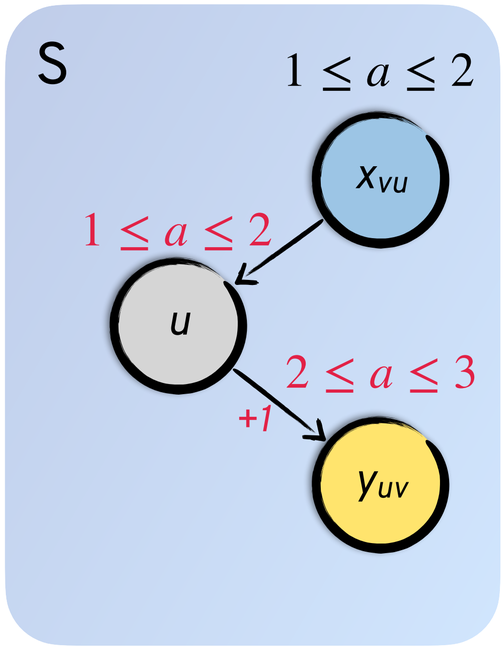

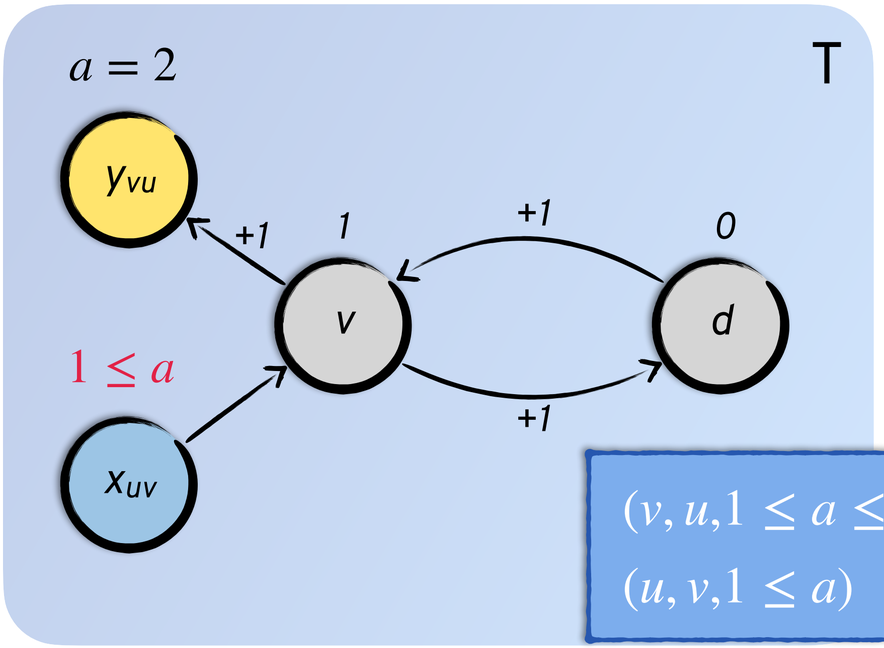

$(v, u, 1 \le a \le 2)$

$(u, v, 1 \le a)$

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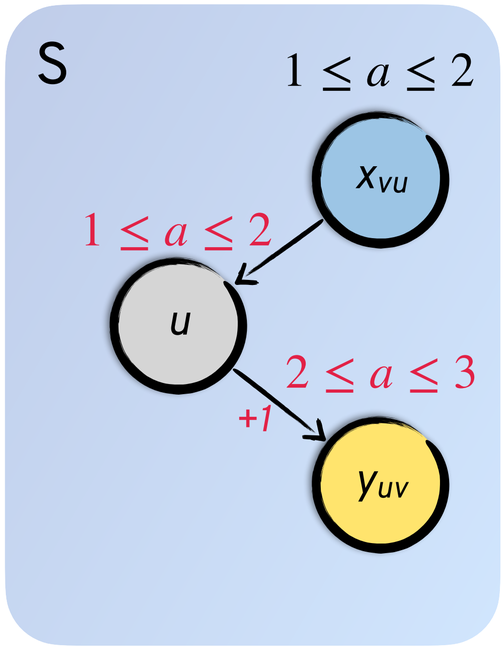

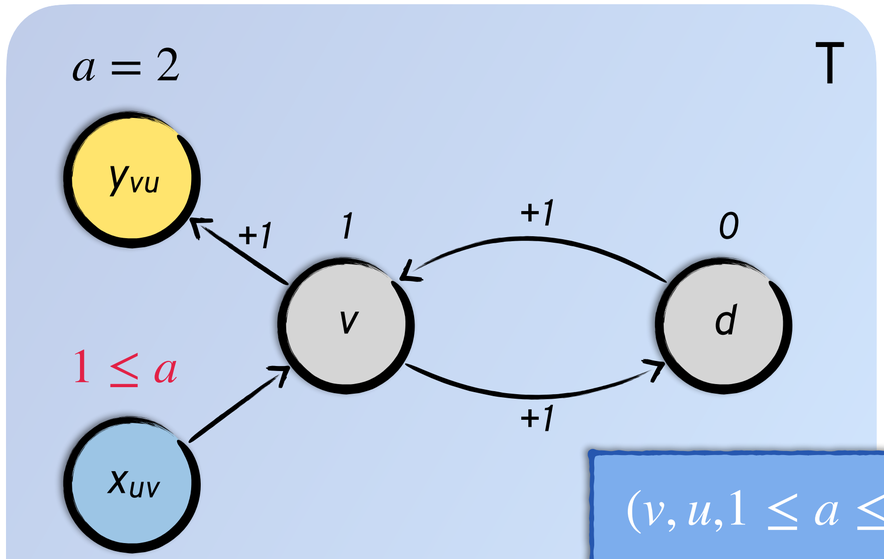

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Case 1: neighbor is input node

x_{uv}:

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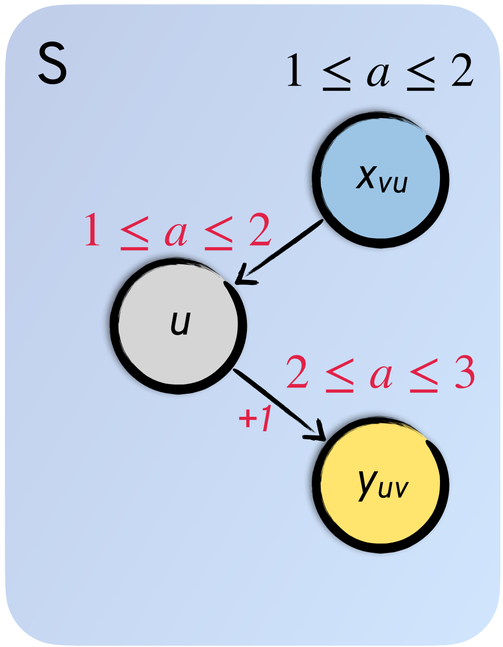

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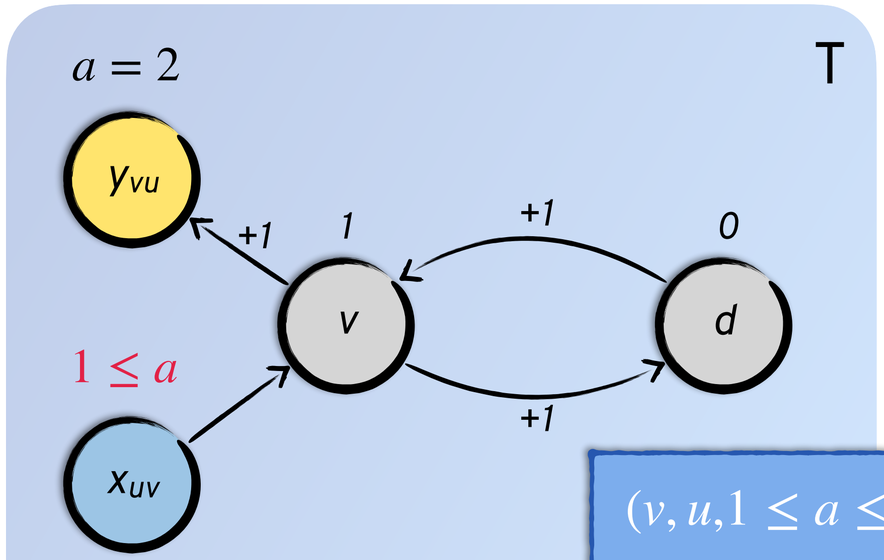

$(v, u, 1 \le a \le 2)$
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$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

Case 1: neighbor is input node x_{uv}:

- By inductiveness check, $\text{trans}((u, y_{uv}), \mathscr{L}_S(u)) \subseteq \text{trans}((x_{uv}, v), \mathscr{L}_T(x_{uv}))$

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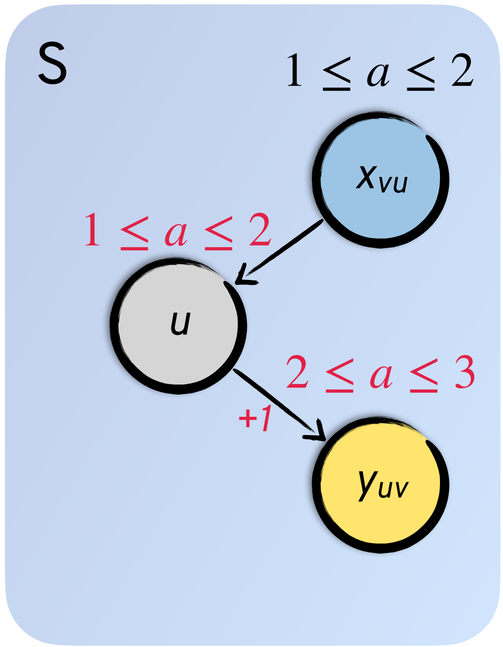

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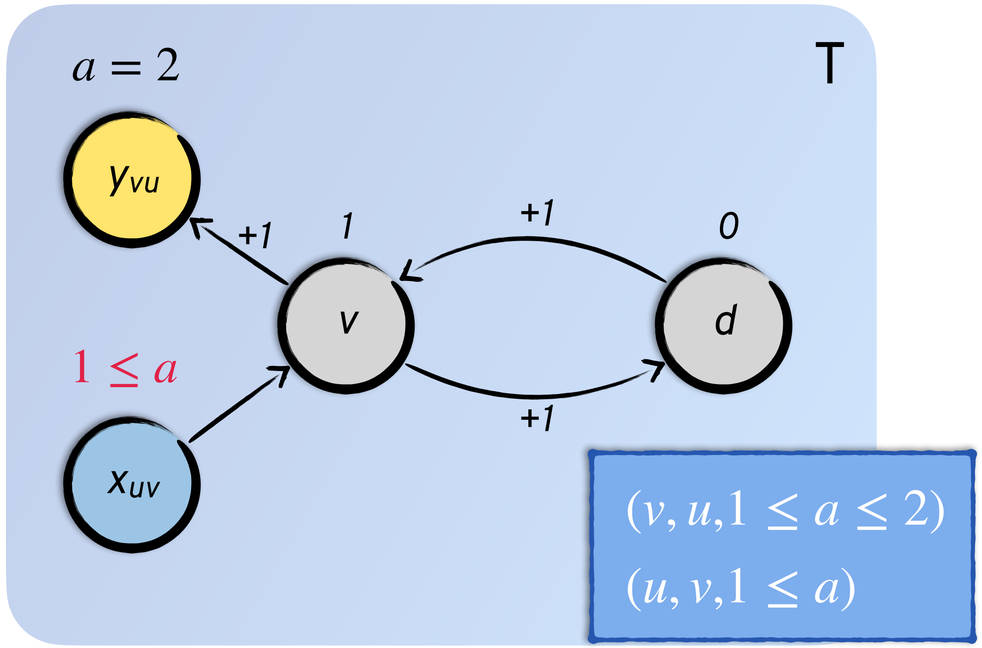

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Case 1: neighbor is input node x_{uv}:

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- By co-induction, $\mathscr{L}_R(u) \subseteq \mathscr{L}_S(u)$

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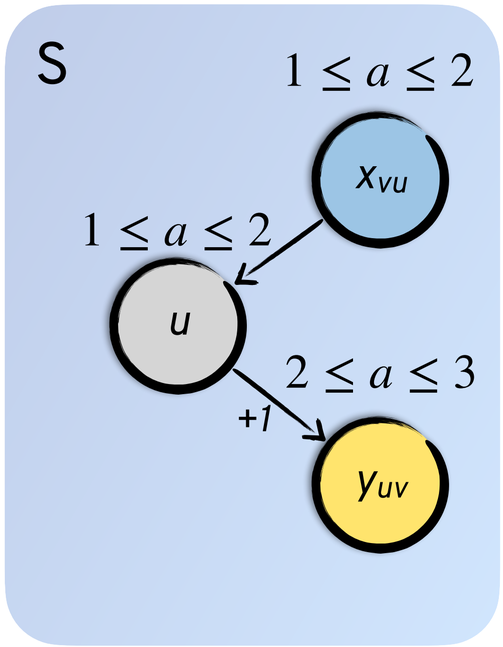

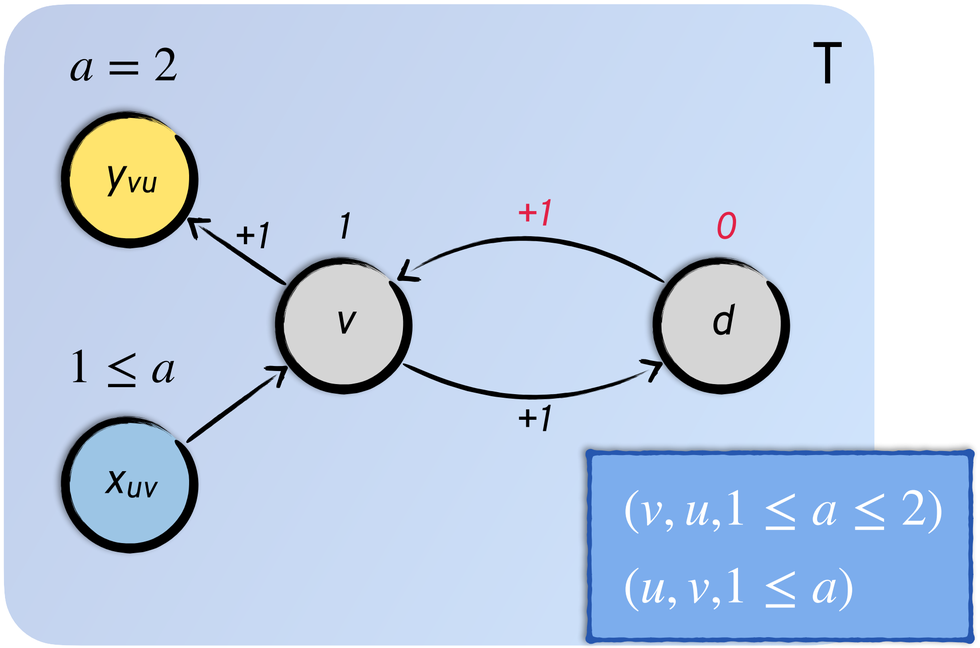

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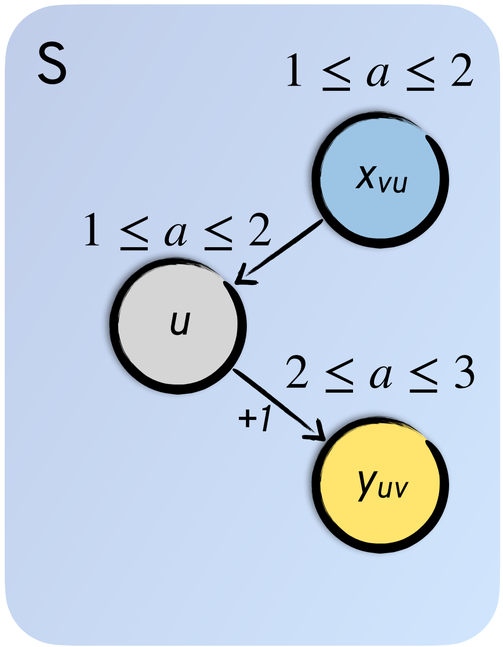

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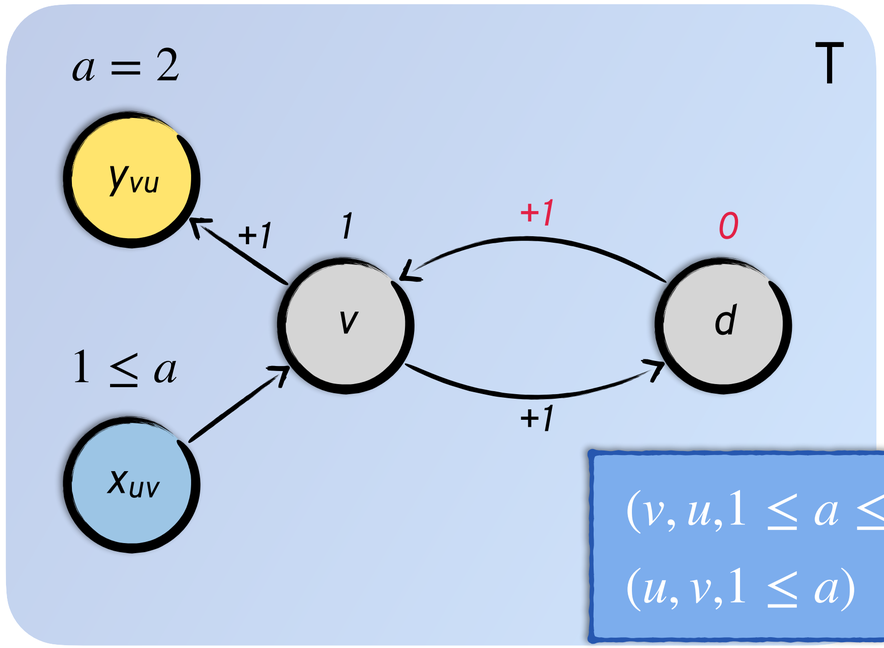

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Case 2: neighbor is a base node d:

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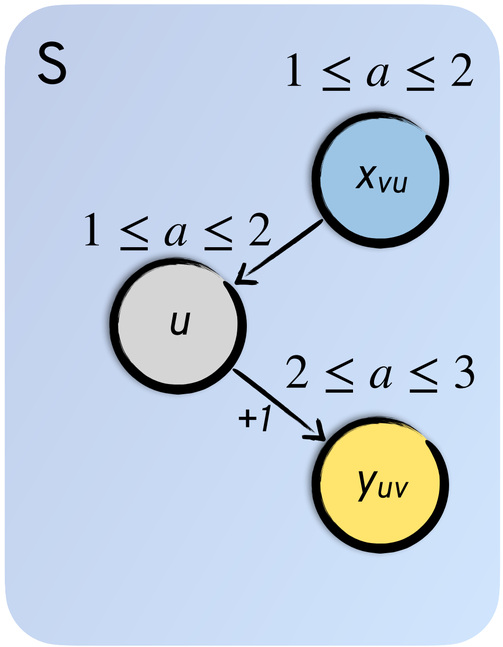

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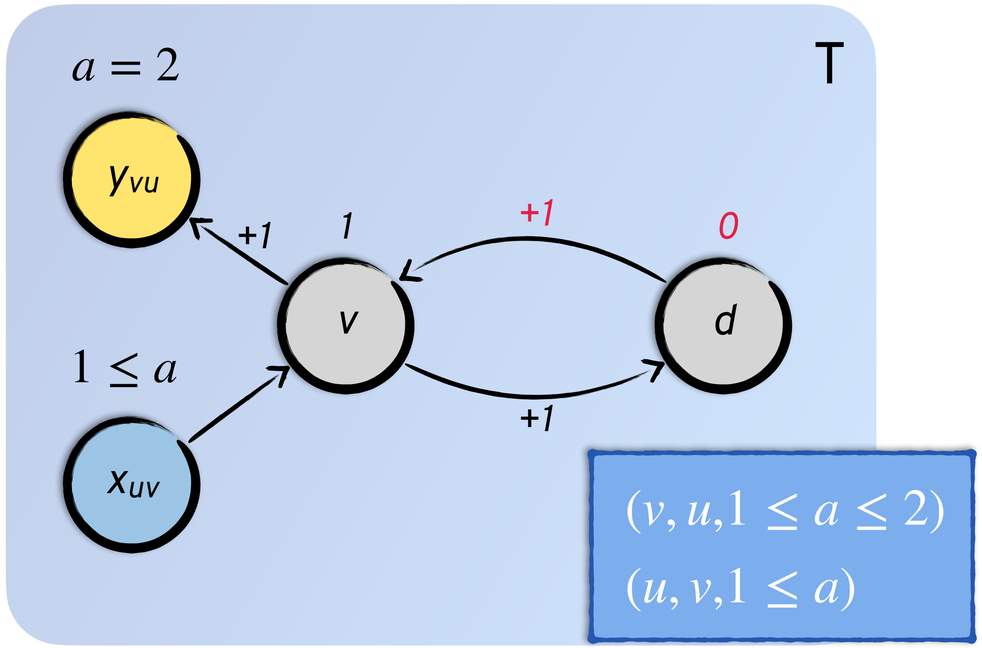

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$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

Case 2: neighbor is a base node d:

- By co-induction, $\mathscr{L}_R(d) \subseteq \mathscr{L}_T(d)$

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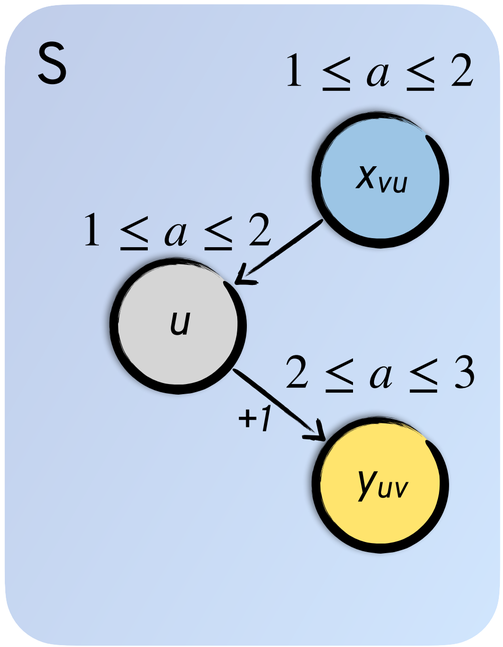

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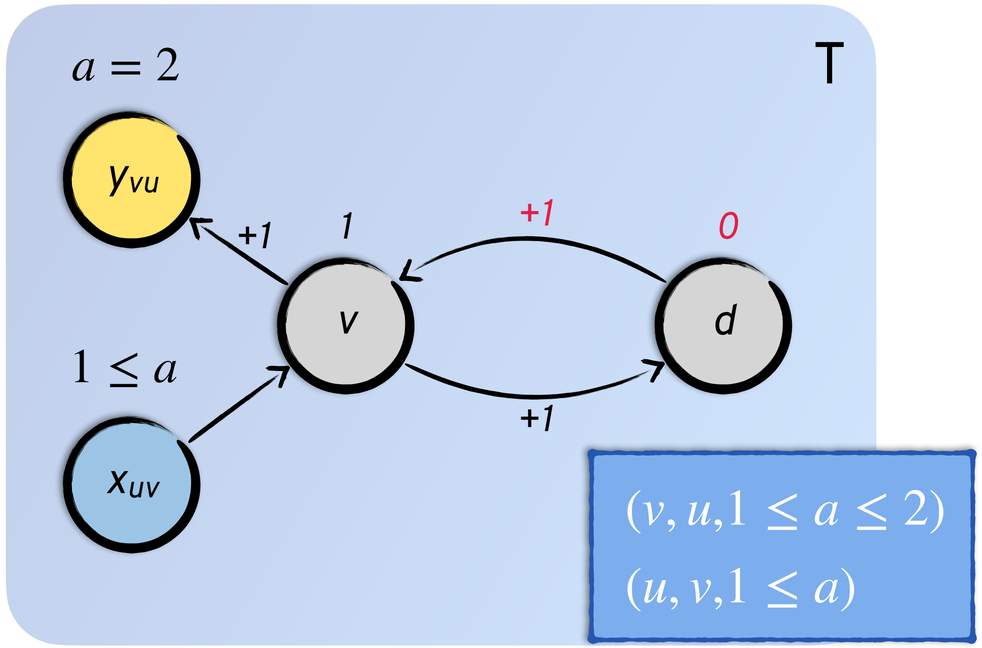

$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

Case 2: neighbor is a base node d:

- By co-induction, $\mathscr{L}_R(d) \subseteq \mathscr{L}_T(d)$
- trans in R is the same as trans in T

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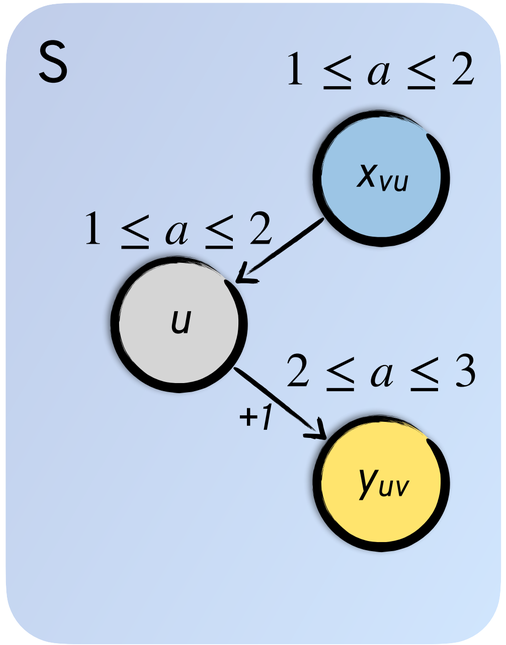

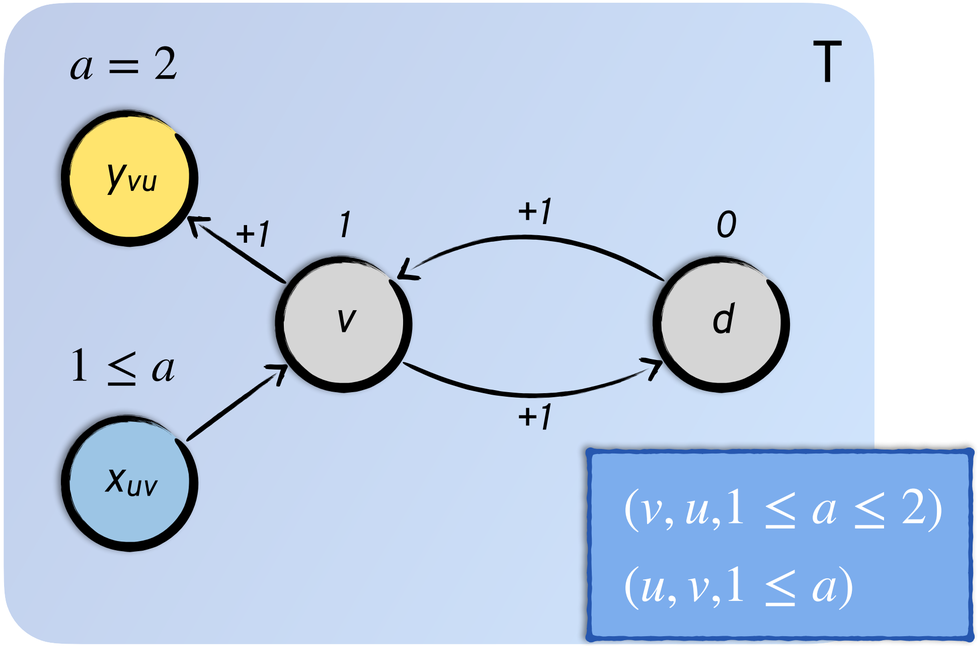

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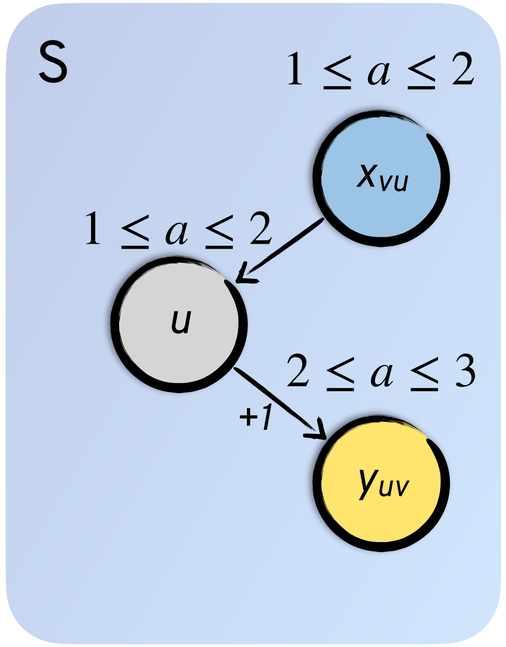

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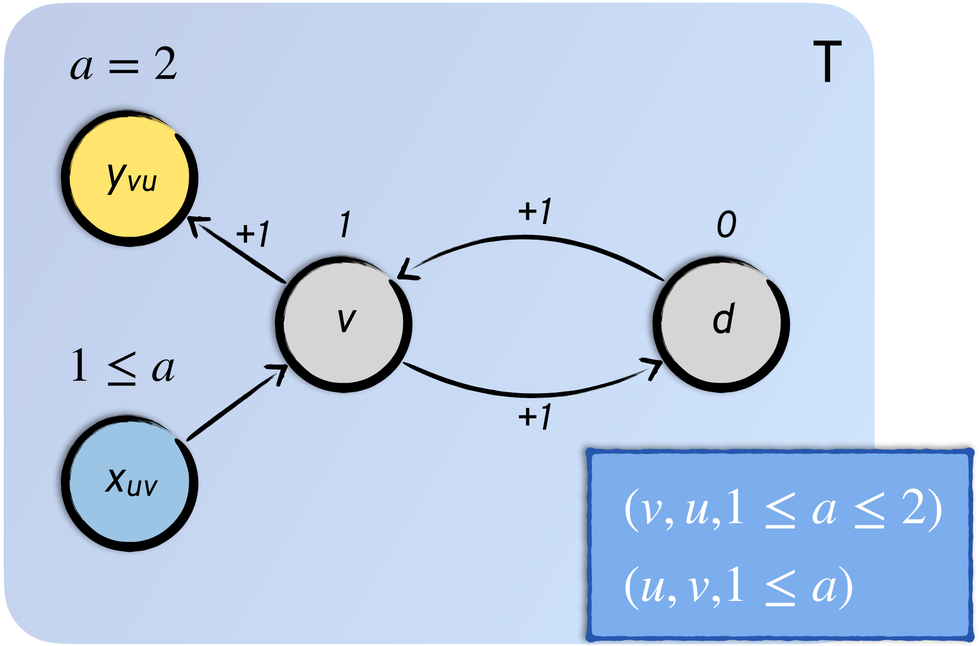

$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

- By the two cases, for all nodes v,
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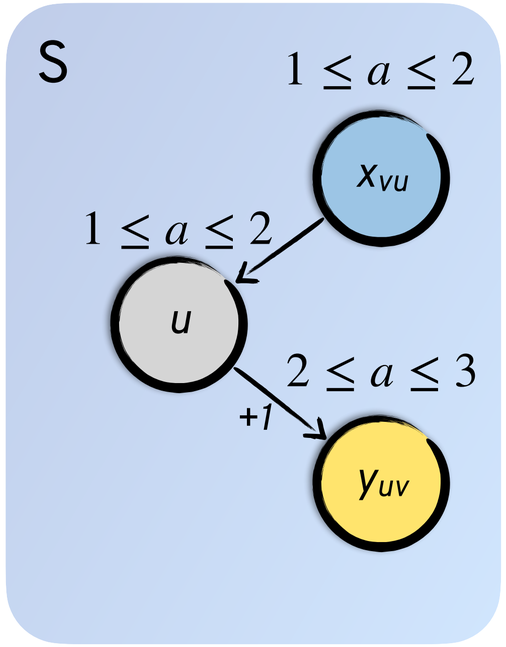

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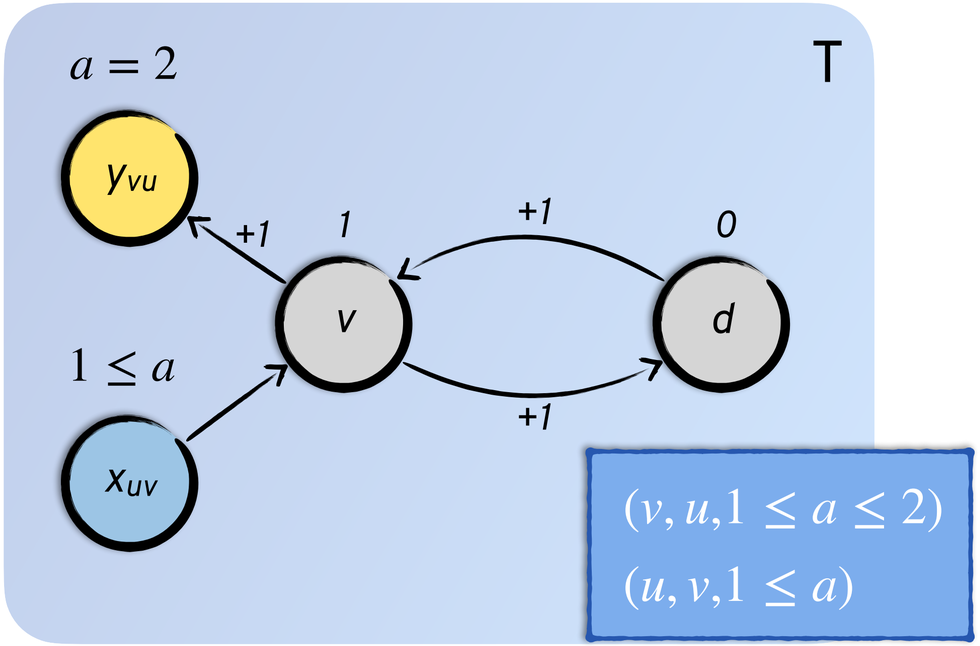


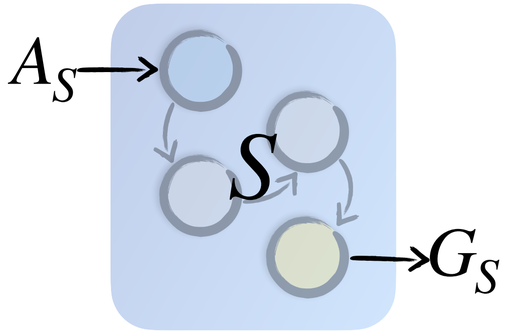
$P_T = \mathscr{L}(v) < 10 \wedge \mathscr{L}(d) < 10$

- By the two cases, for all nodes v,
  $\mathscr{L}_R(v) \subseteq \mathscr{L}_T(v)$ (or S)
- Then, since property P holds for S and T (by the safety check), it must also hold for R

An Assume-Guarantee Proof Rule

[Giannakopoulou et al., *Handbook of Model Checking.* 2018]

An Assume-Guarantee Proof Rule



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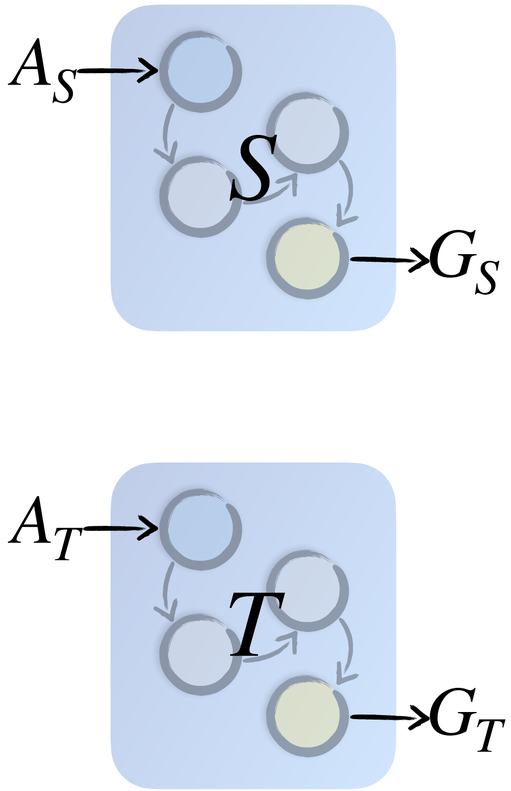

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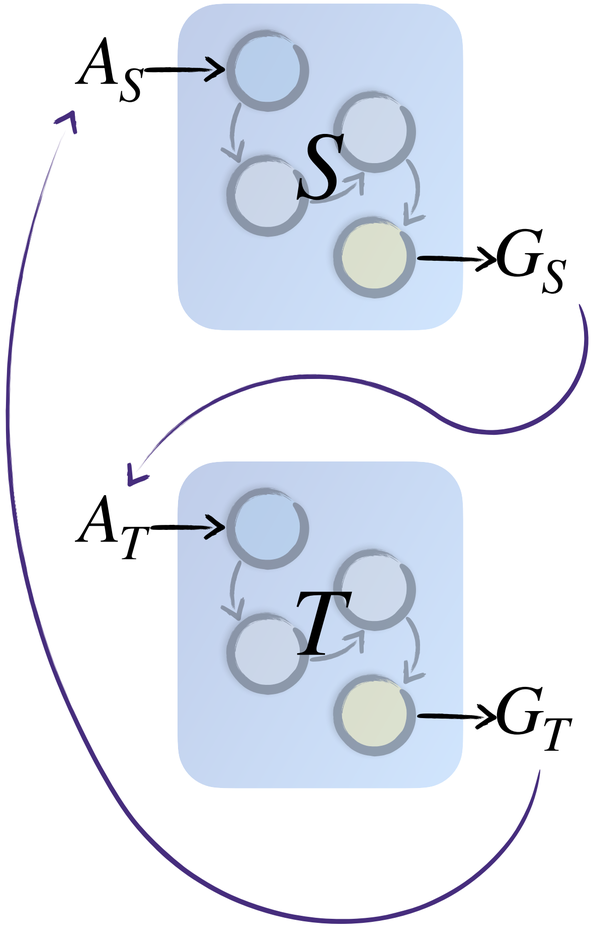

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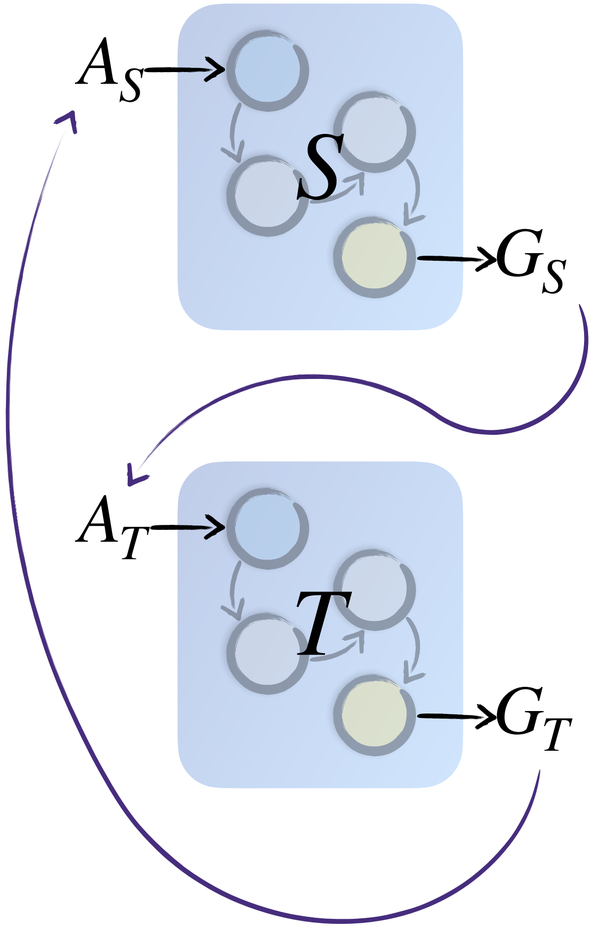

$$\frac{\begin{array}{c}\langle A_S\rangle\ S\ \langle G_S\rangle \\ \langle A_T\rangle\ T\ \langle G_T\rangle \\ G_T \Rightarrow A_S \\ G_S \Rightarrow A_T \\ \langle A_S\rangle\ S\ \langle P_S\rangle \\ \langle A_T\rangle\ T\ \langle P_T\rangle \\ \langle \mathsf{true}\rangle\ S\ \langle G_S\rangle \\ \langle \mathsf{true}\rangle\ T\ \langle G_T\rangle\end{array}}{\langle \mathsf{true}\rangle\ S \parallel T\ \langle P_S \wedge P_T\rangle}$$

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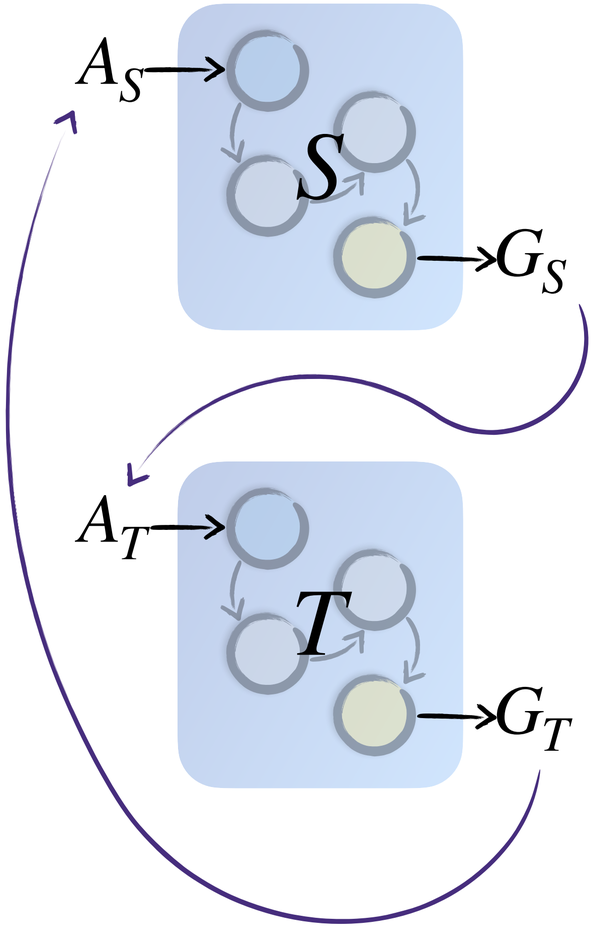

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Inductiveness check

[Giannakopoulou et al., *Handbook of Model Checking.* 2018]

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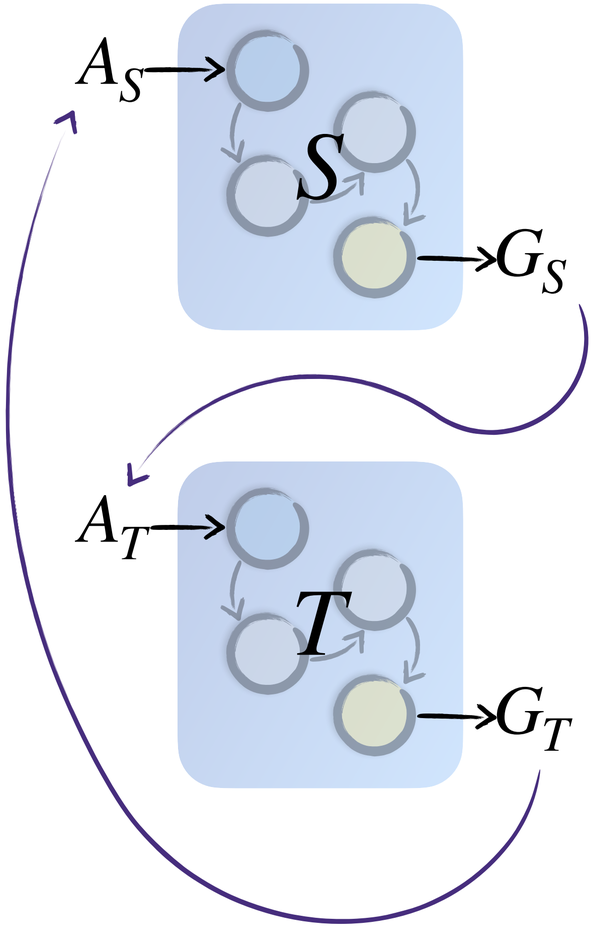

$$\frac{\begin{array}{rl} \langle A_S \rangle\ S\ \langle G_S \rangle & \left.\vphantom{\begin{array}{l}a\\a\\a\\a\end{array}}\right\} \text{Inductiveness check} \\ \langle A_T \rangle\ T\ \langle G_T \rangle & \\ G_T \Rightarrow A_S & \\ G_S \Rightarrow A_T & \\ \langle A_S \rangle\ S\ \langle P_S \rangle & \left.\vphantom{\begin{array}{l}a\\a\end{array}}\right\} \text{Safety check} \\ \langle A_T \rangle\ T\ \langle P_T \rangle & \\ \langle \text{true} \rangle\ S\ \langle G_S \rangle & \\ \langle \text{true} \rangle\ T\ \langle G_T \rangle & \end{array}}{\langle \text{true} \rangle\ S \parallel T\ \langle P_S \wedge P_T \rangle}$$

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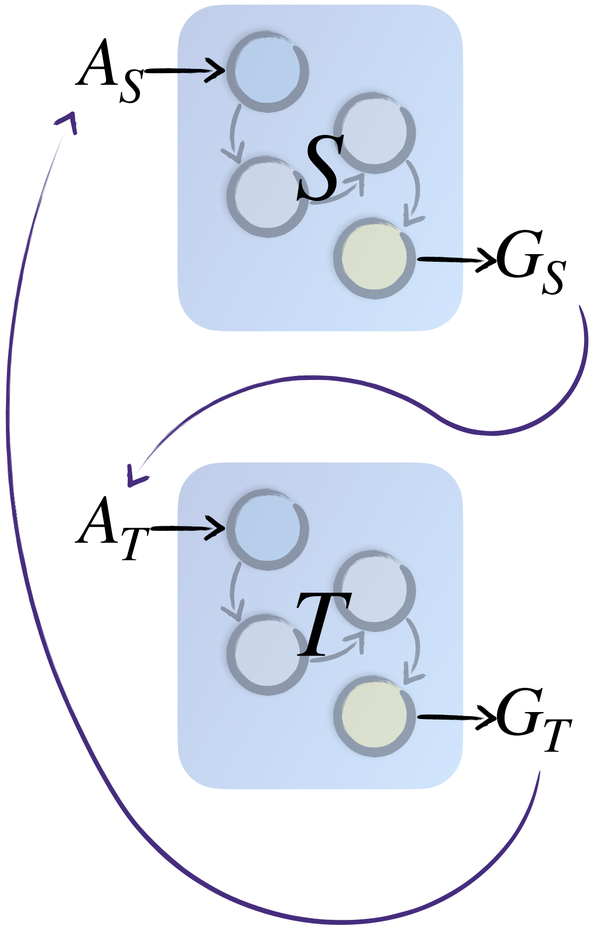

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[Giannakopoulou et al., *Handbook of Model Checking.* 2018]

Implementing Kirigami in NV

Implementing Kirigami in NV

[Beckett et al., NetPL 2019]

[Giannarakis et al., PLDI 2020]

Implementing Kirigami in NV

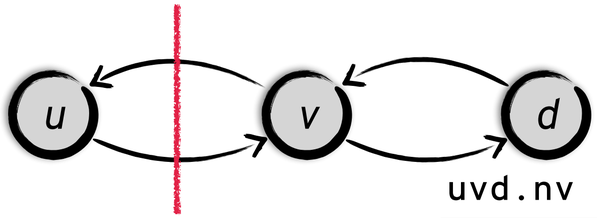
uvd.nv

```
type attribute = int

(* Number of nodes in network topology *)
(* 0 = d; 1 = v; 2 = u *)
let nodes = 3

(* List of edges in network topology *)
let edges = { 0=1; 1=2; }

(* The merge function for receiving attributes *)
let merge node x y =
  if x < y then x else y

(* The trans function for sending attributes *)
let trans edge x = x + 1

(* The initial state of the network *)
let init node =
  match node with
  | 0n -> 0
  | _ -> 10

(* The assertion on each node's solution *)
let assert node x = x < 10
```

[Beckett et al., NetPL 2019]

[Giannarakis et al., PLDI 2020]

Implementing Kirigami in NV



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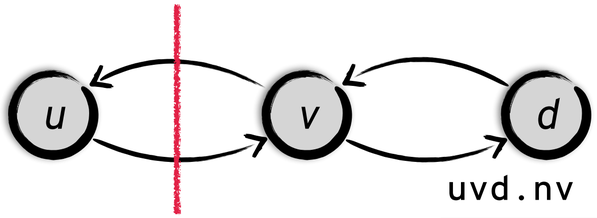
uvd-kirigami.nv

```
include "uvd.nv"
```

[Beckett et al., NetPL 2019]

[Giannarakis et al., PLDI 2020]

Implementing Kirigami in NV



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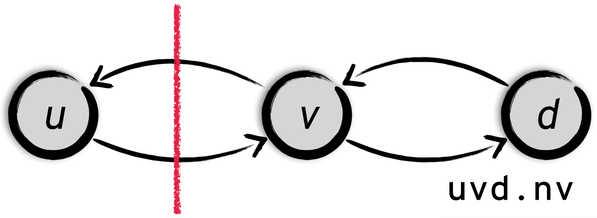
```

[Beckett et al., NetPL 2019]

[Giannarakis et al., PLDI 2020]

Implementing Kirigami in NV



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uvd-kirigami.nv

```
include "uvd.nv"

(* Associate each node with a partition *)
let partition node = match node with
  | 0n -> 0
  | 1n -> 0
  | 2n -> 1

(* Associate each edge with a hypothesis *)
let interface edge = match edge with
  | 1~2 -> Some (fun a -> a = 1 || a = 2)
  | 2~1 -> Some (fun a -> a >= 1)
  | _ -> None
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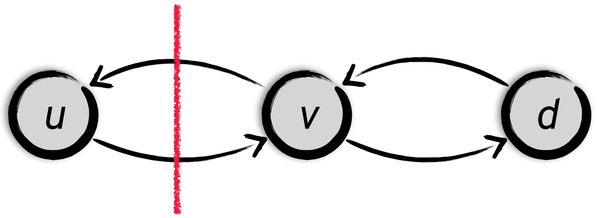
[Beckett et al., NetPL 2019]

[Giannarakis et al., PLDI 2020]

Implementing Kirigami in NV



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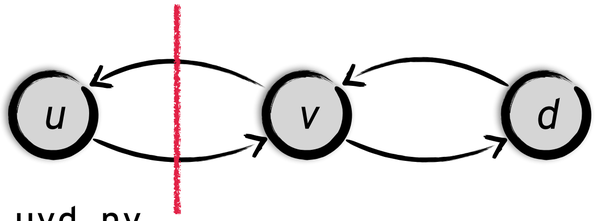


uvd.nv

```
type attribute = int

(* Number of nodes in network topology *)
(* 0 = d; 1 = v; 2 = u *)
let nodes = 3

(* List of edges in network topology *)
let edges = { 0=1; 1=2; }

(* The merge function for receiving attributes *)
let merge node x y =
  if x < y then x else y

(* The trans function for sending attributes *)
let trans edge x = x + 1

(* The initial state of the network *)
let init node =
  match node with
  | 0n -> 0
  | _ -> 10

(* The assertion on each node's solution *)
let assert node x = x < 10
```

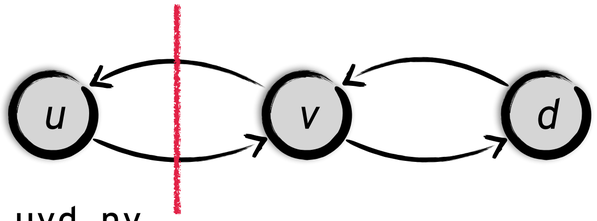
uvd-part.nv

```
include "uvd.nv"

(* Associate each node with a partition *)
let partition node = match node with
  | 0n -> 0
  | 1n -> 0
  | 2n -> 1

(* Associate each edge with a hypothesis *)
let interface edge = match edge with
  | 1~2 -> Some (fun a -> a = 1 || a = 2)
  | 2~1 -> Some (fun a -> a >= 1)
  | _ -> None
```

Implementing Kirigami in NV



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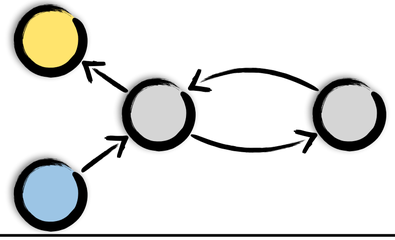
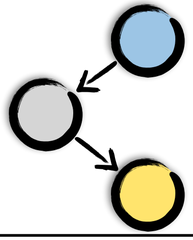




```
(* Partition 0 *)
(* Constraints over inputs *)
symbolic h_2_1 : int
require (fun a -> a >= 1) h_2_1

let nodes = (* updated nodes *)
let edges = (* updated edges *)

let merge node x y =
  if x < y then x else y

let trans edge x =
  match edge with
  | (* input edge *) -> x
  | _ -> x + 1

(* The initial state of the network *)
let init node =
  match node with
  | (* input of 2 *) -> h_2_1
  | (* ...as before... *)

(* The assertion on each node's solution *)
let assert node x =
   match node with
  | (* output of 1 *) -> (fun a -> a = 1 || a = 2) x
  | _ -> x < 10
```

```
(* Partition 1 *)
(* Constraints over inputs *)
symbolic h_1_2 : int
require (fun a -> a = 1 || a = 2) h_1_2

let nodes = (* updated nodes *)
let edges = (* updated edges *)

let merge node x y =
  if x < y then x else y

let trans edge x =
  match edge with
  | (* input edge *) -> x
  | _ -> x + 1

(* The initial state of the network *)
let init node =
  match node with
  | (* input of 1 *) -> h_1_2
  | (* ...as before... *)

(* The assertion on each node's solution *)
let assert node x =
   match node with
  | (* output of 2 *) -> (fun a -> a >= 1) x
  | _ -> x < 10
```

Internal representation

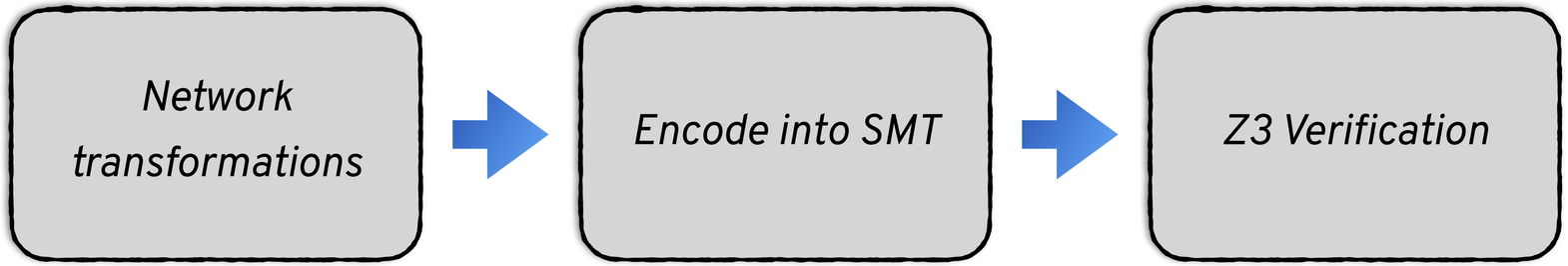
Running a Query in NV

[Beckett et al., NetPL 2019]

[Giannarakis et al., PLDI 2020]

[De Moura and Bjørner, TACAS 2008]

Running a Query in NV



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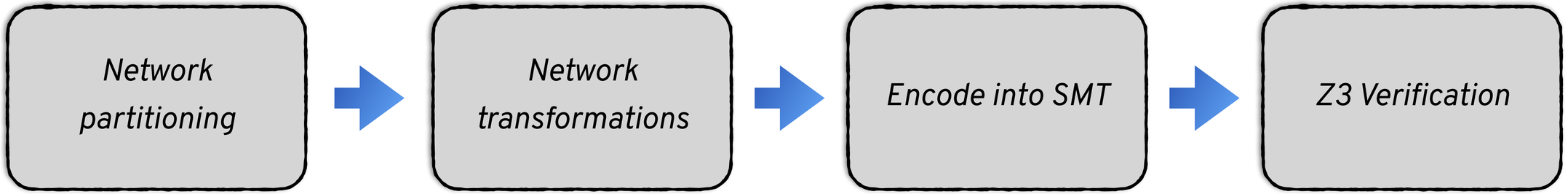

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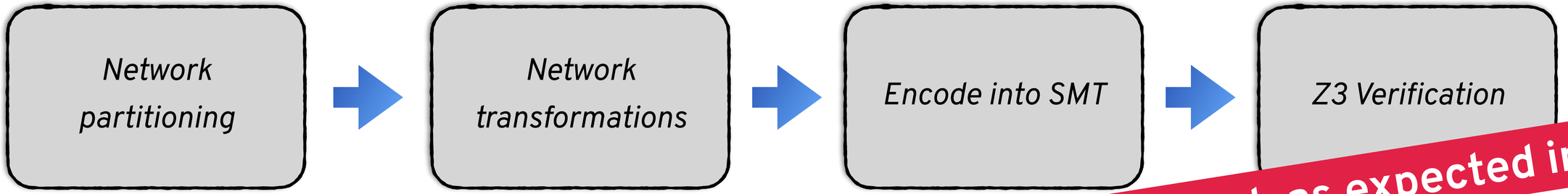

All the examples we've seen thus far have been verified and work as expected in NV!

[Beckett et al., NetPL 2019]
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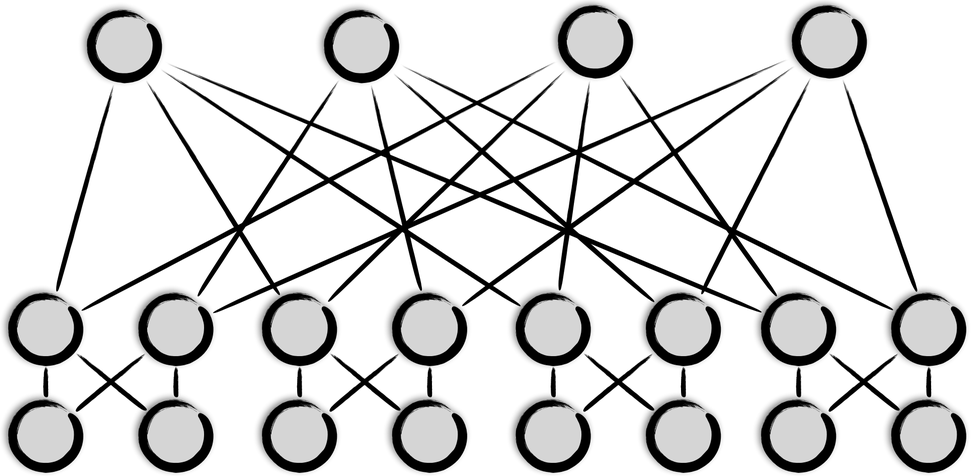
Results

Fattree Reachability

Case Study



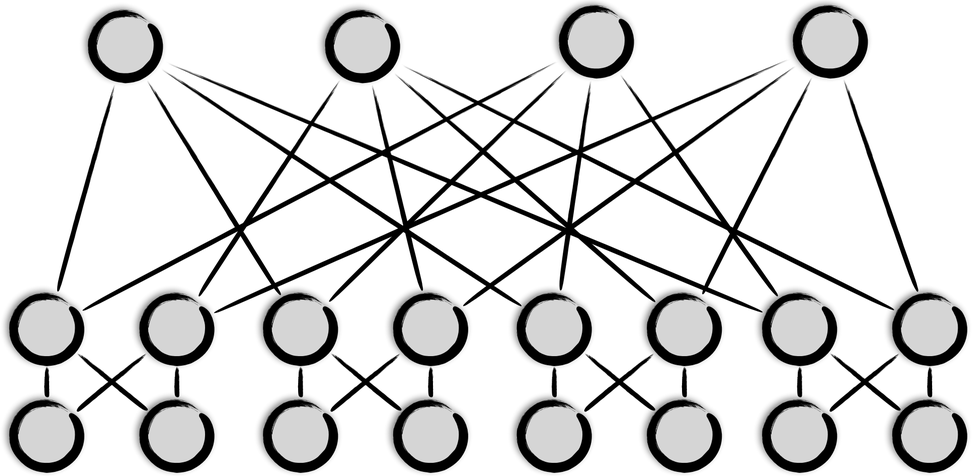
[Fogel et al., NSDI 2015]

[Leiserson, IEEE TC 1985]

Fattree Reachability

Case Study

- Common data centre network



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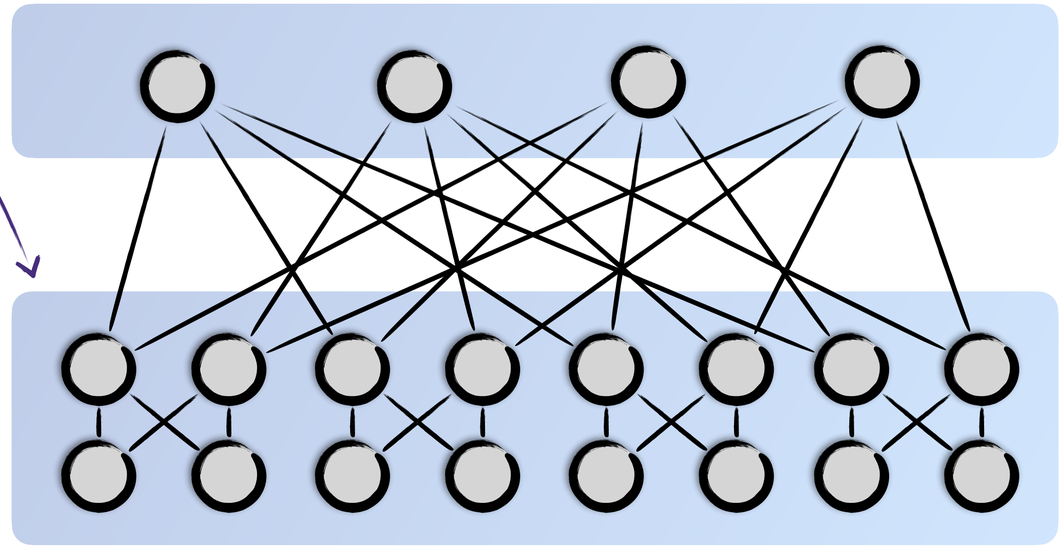
Fattree Reachability

Case Study

- Common data centre network
- Hierarchical design using *spines* and *pods*



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Fattree Reachability

Case Study

- Common data centre network
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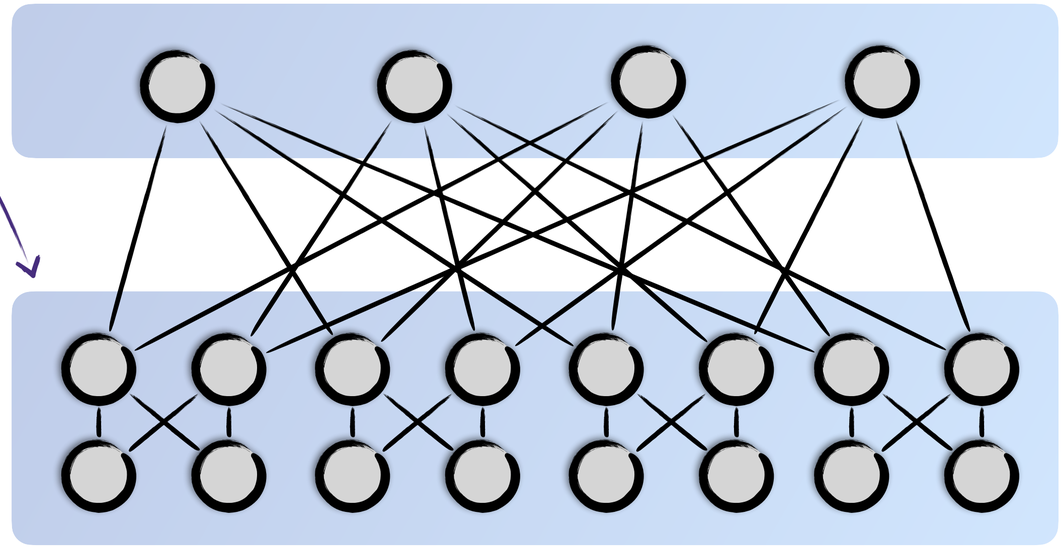
- Real-world infrastructures can have over 10,000 nodes



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Fattree Reachability

Case Study

- Common data centre network
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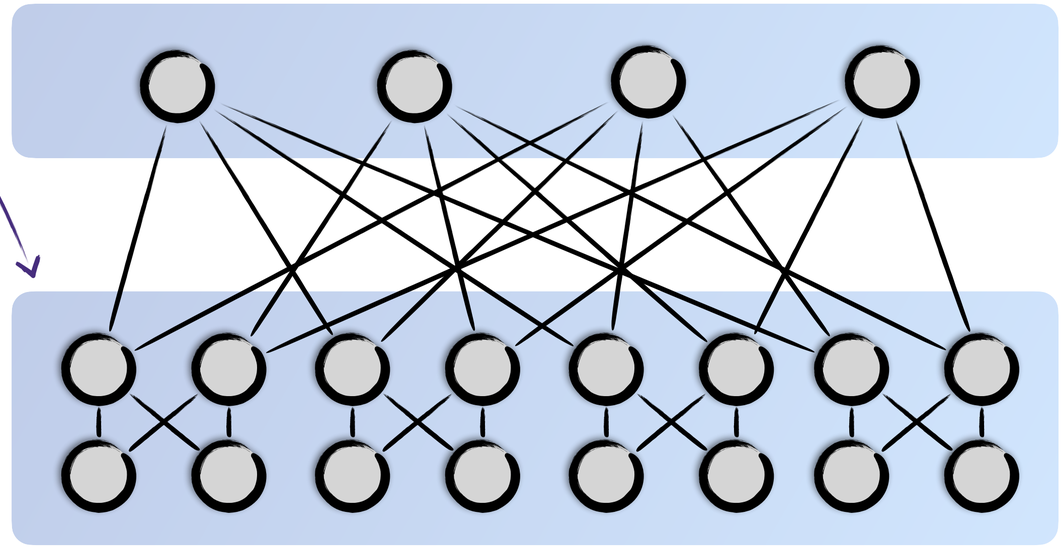
- Real-world infrastructures can have over 10,000 nodes
  - Synthetic networks ranged from 20 to 500 nodes



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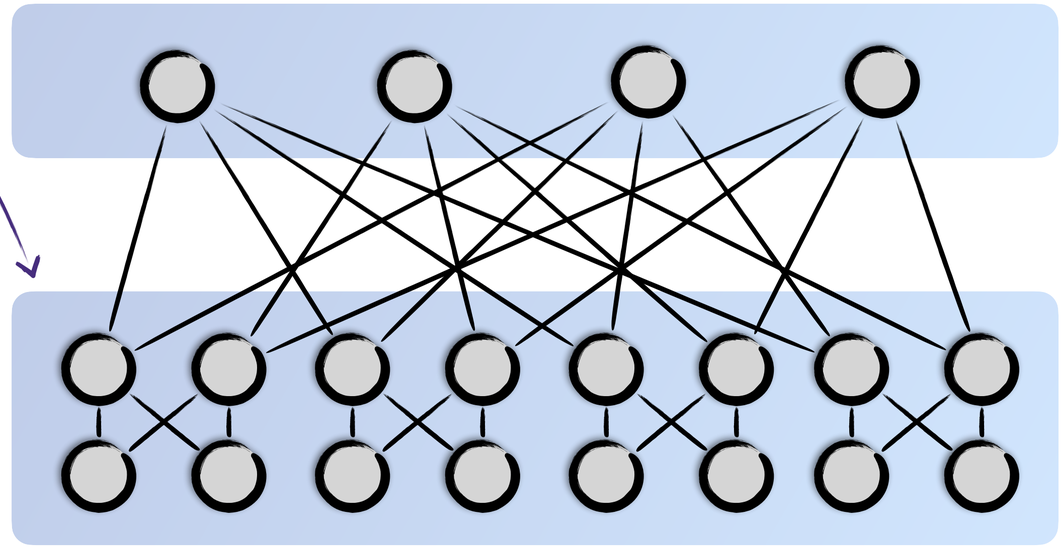

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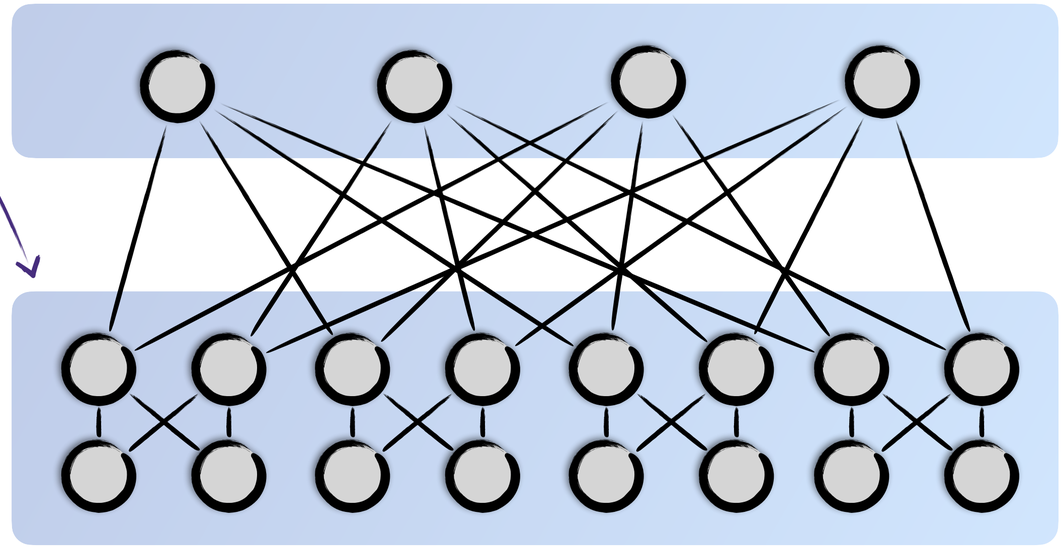
- Common data centre network
- Hierarchical design using *spines* and *pods*
- Real-world infrastructures can have over 10,000 nodes
  - Synthetic networks ranged from 20 to 500 nodes
- Modelled shortest-path routing
- Property: *reachability of a single destination*



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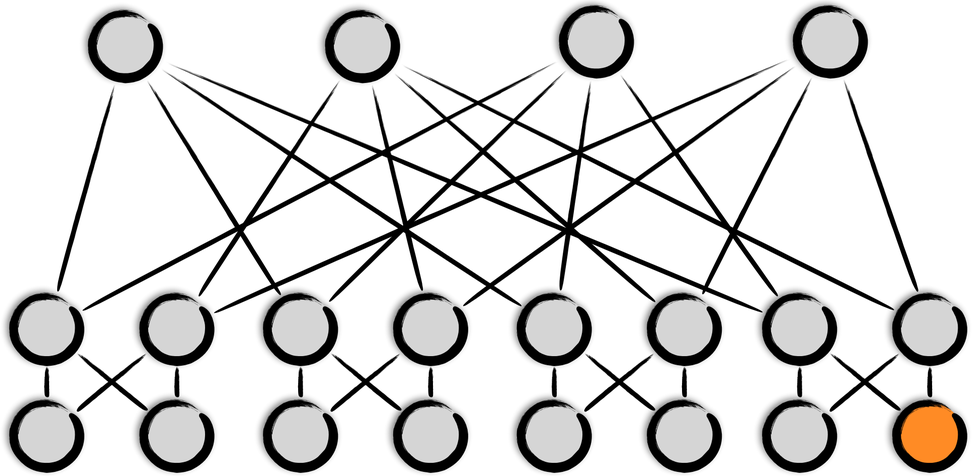
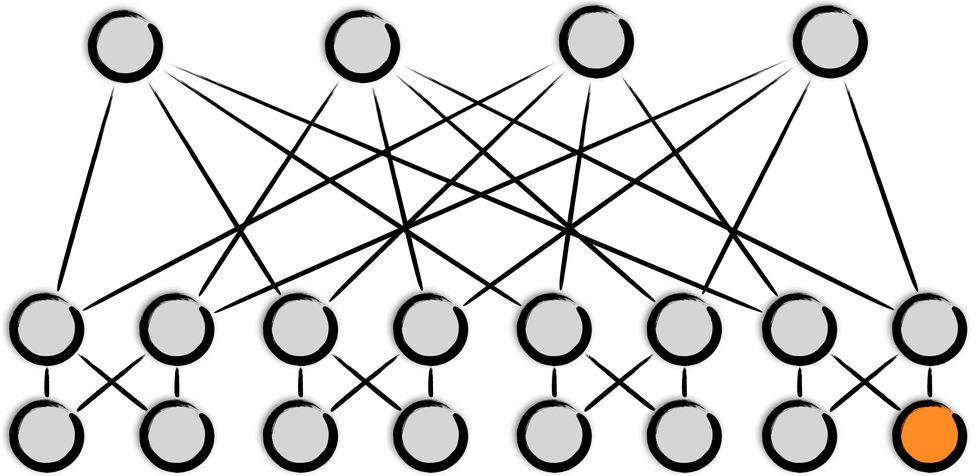


Fattree Reachability

Case Study

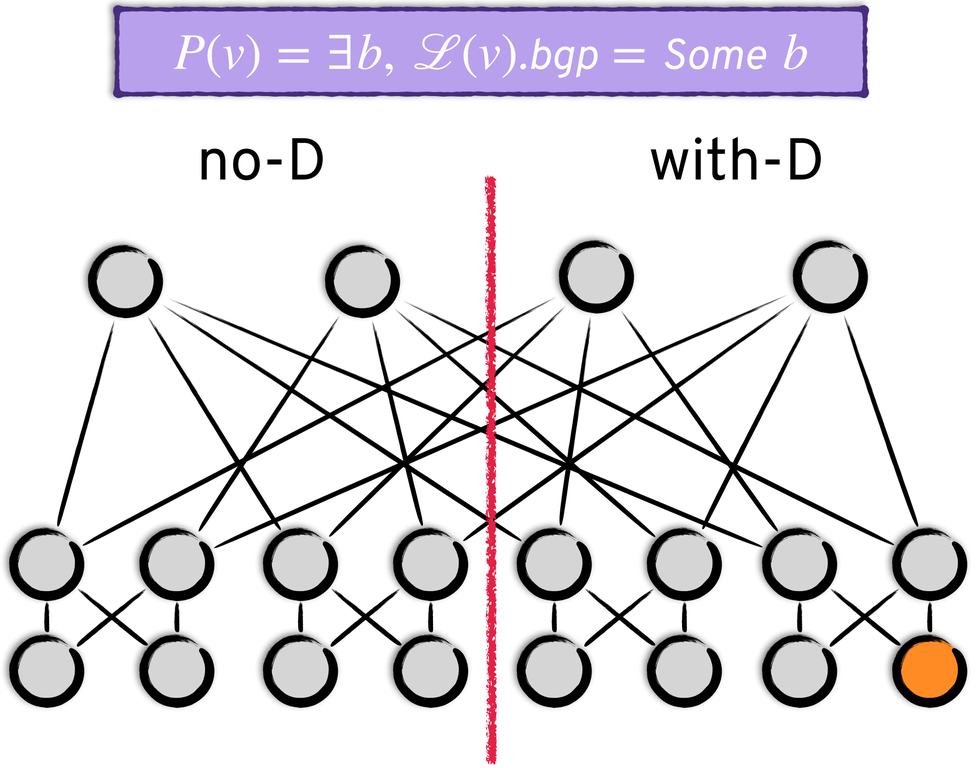
$$P(v) = \exists b,\ \mathscr{L}(v).bgp = Some\ b$$



Fattree Reachability

Case Study

- Partition vertically in half
  - Destination side (with-D)
  - Non-destination side (no-D)



Fattree Reachability

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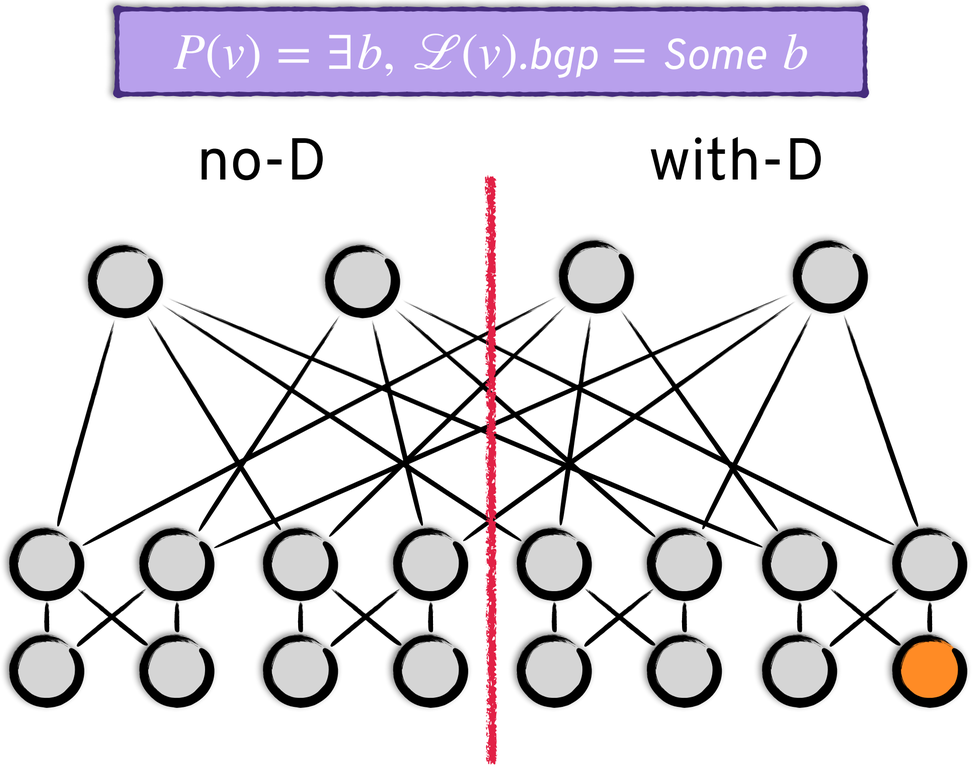
- Hypotheses needed are quite simple!



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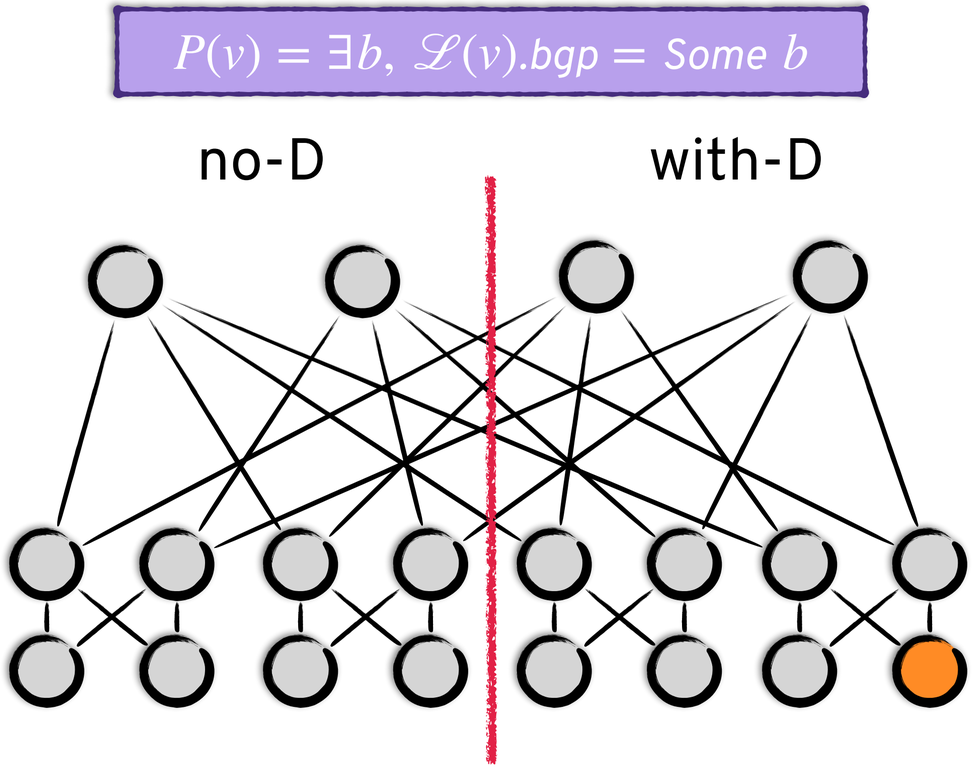

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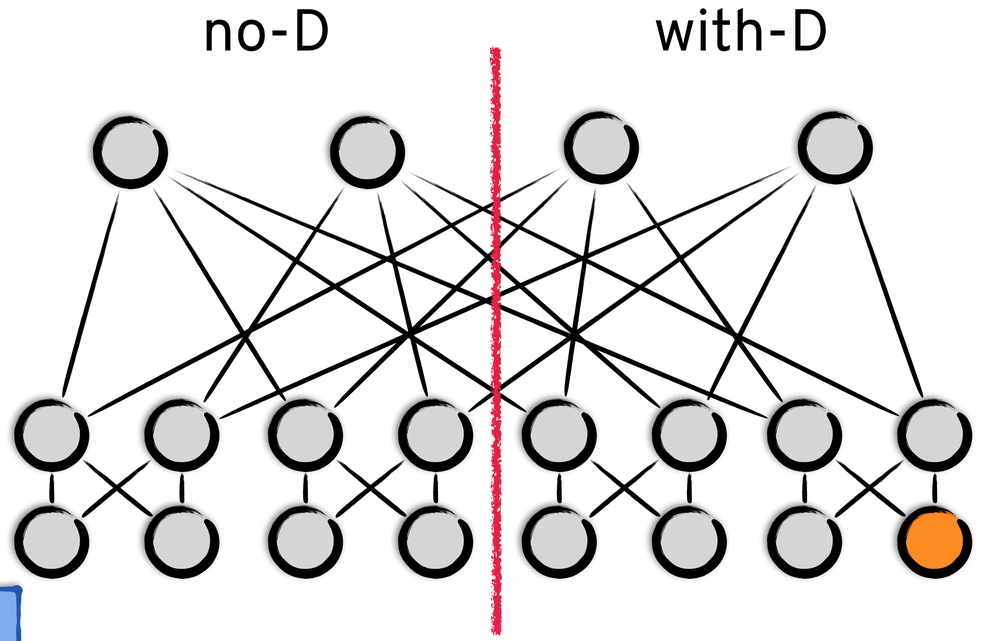
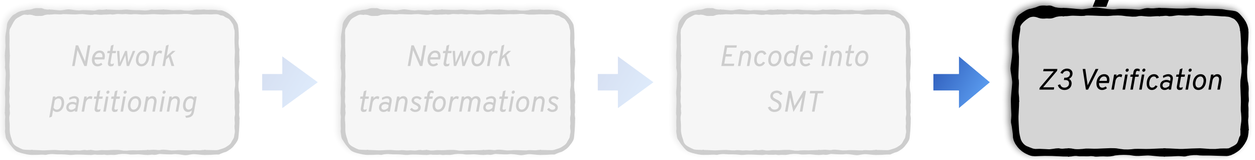
$P(v) = \exists b,\ \mathscr{L}(v).bgp = Some\ b$



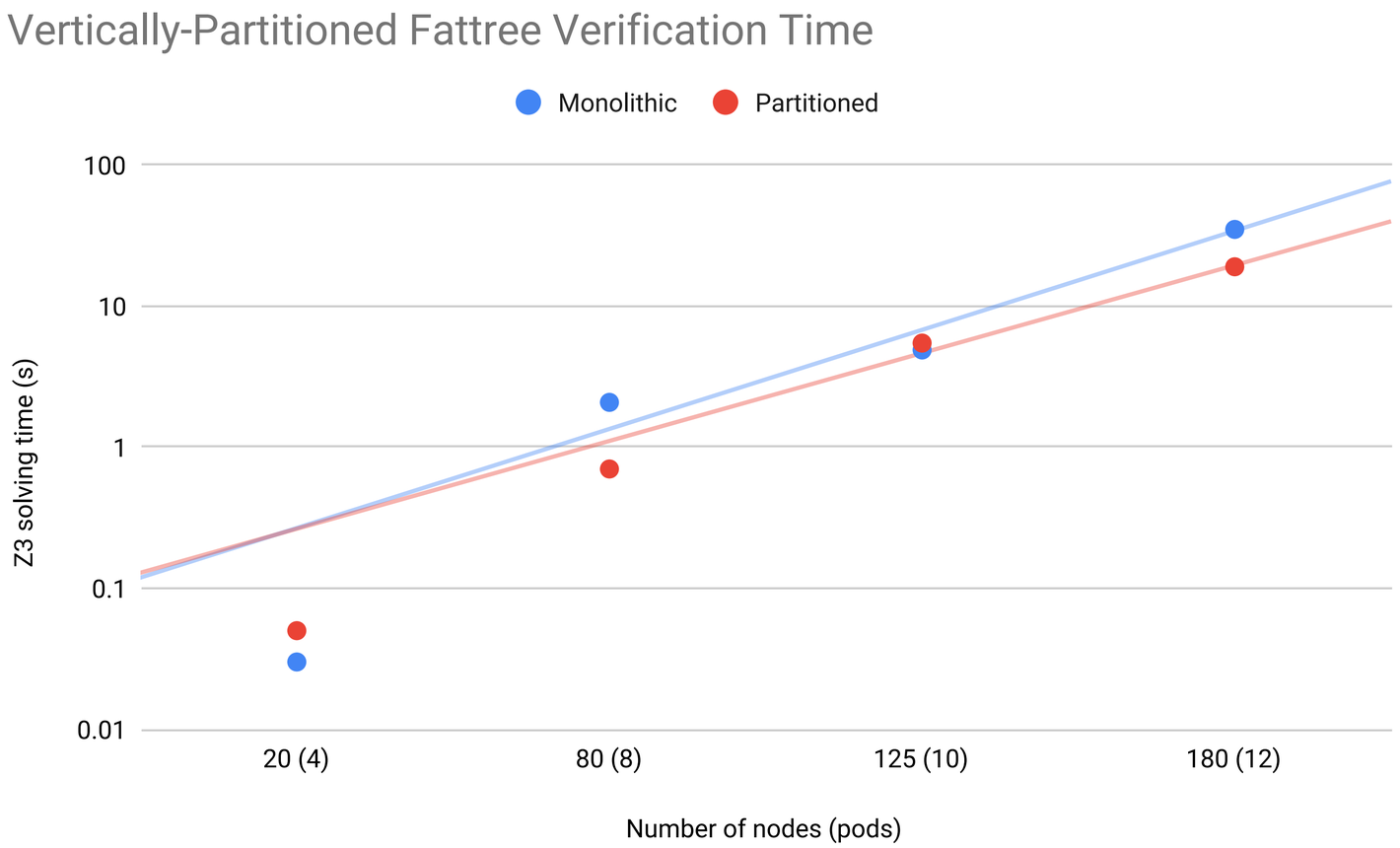
from no-D to with-D: $(\ldots, true)$

from with-D to no-D: $(\ldots, a = (\exists b, a.bgp = Some\ b))$

Fattree Reachability



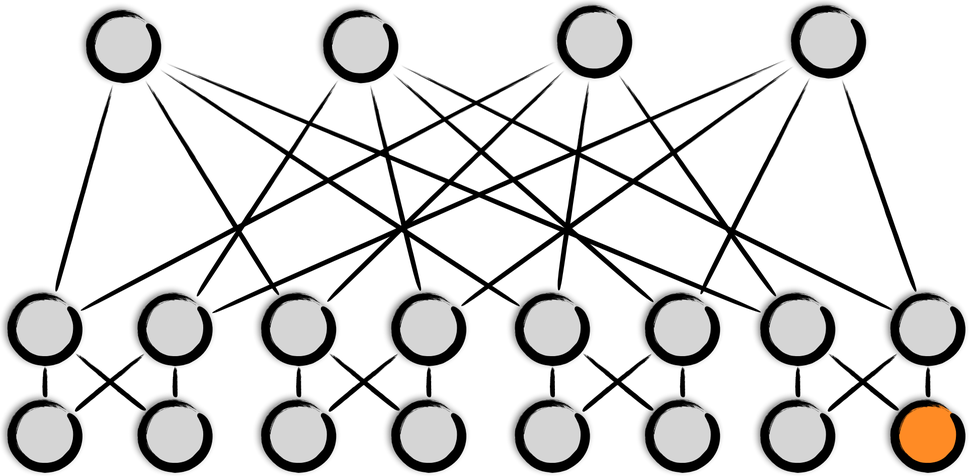
(lower is better)



Fattree Reachability

An alternative cut

$P(v) = \exists b,\ \mathscr{L}(v).bgp = Some\ b$

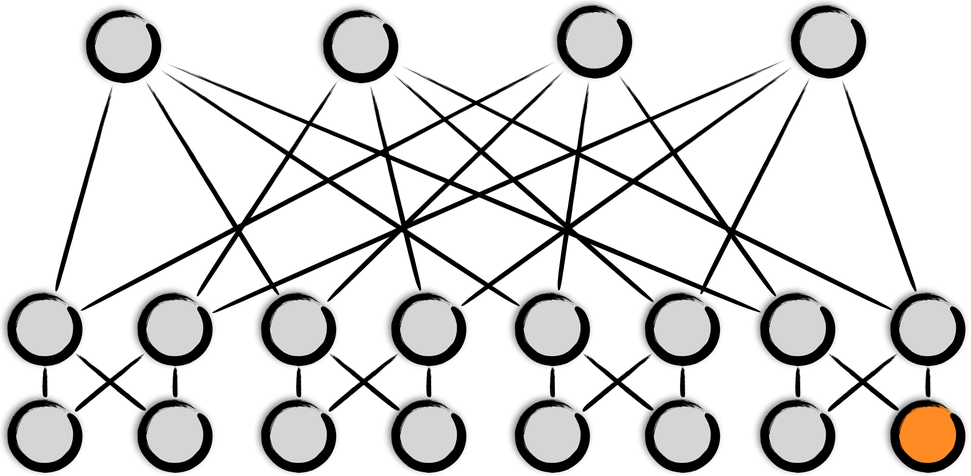


Fattree Reachability

An alternative cut

- Consider an alternative partition scheme

$$P(v) = \exists b,\ \mathscr{L}(v).bgp = Some\ b$$



Fattree Reachability

An alternative cut

- Consider an alternative partition scheme
  - Partition horizontally into spines and pods: pod with destination separate from others

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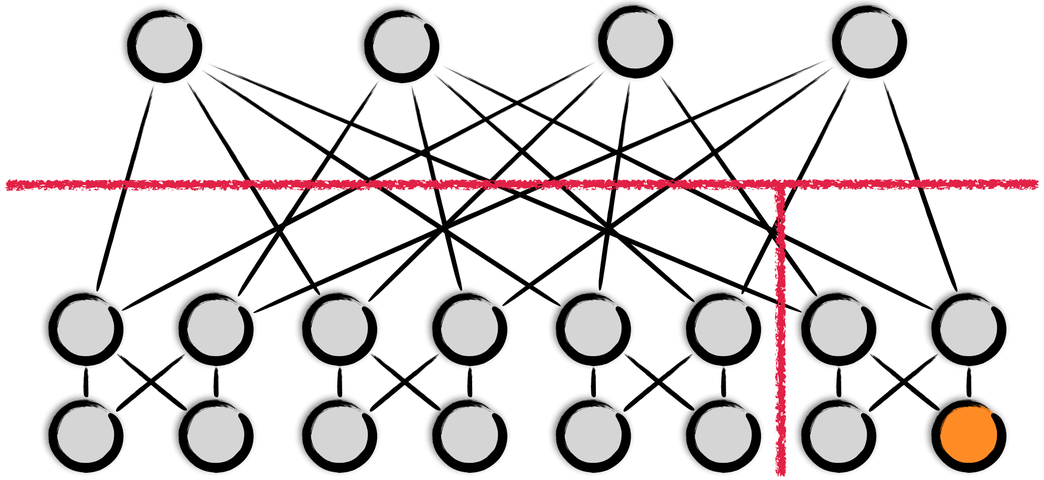

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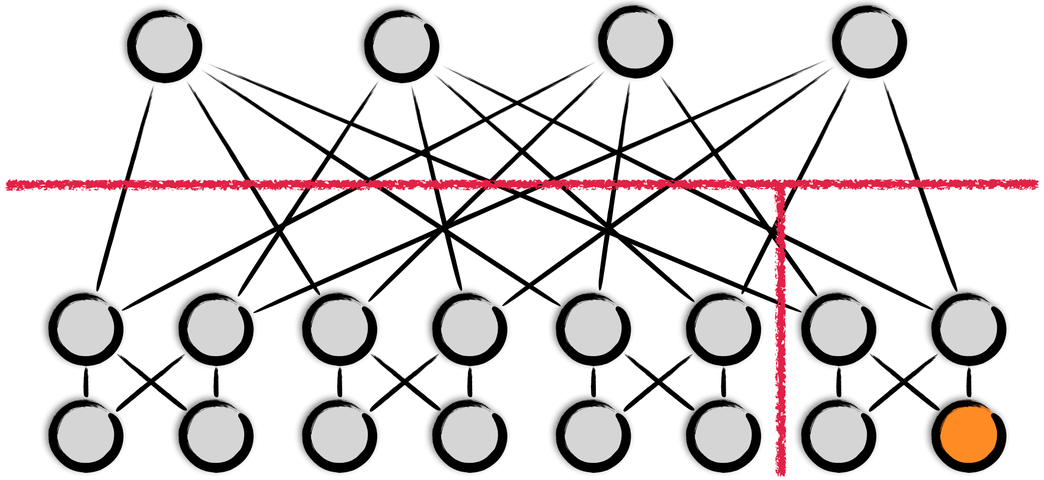


from pods-no-D to spines: $(\ldots, true)$; *from spines to pods-no-D:* $(\ldots, a = (\exists b, a.bgp = \text{Some } b))$

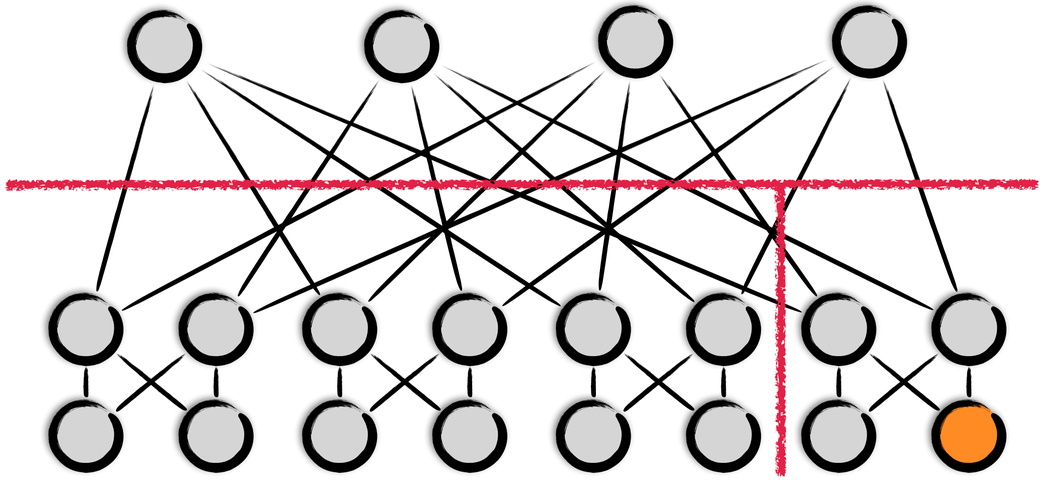
from spines to pod-with-D: $(\ldots, true)$; *from pod-with-D to spines:* $(\ldots, a = (\exists b, a.bgp = \text{Some } b))$

Fattree Reachability

An alternative cut

- Consider an alternative partition scheme
  - Partition horizontally into spines and pods: pod with destination separate from others
  - Should work just as before!
    - Unfortunately, initial check won't hold for spines to pods-no-D

$P(v) = \exists b,\ \mathscr{L}(v).bgp = \text{Some } b$



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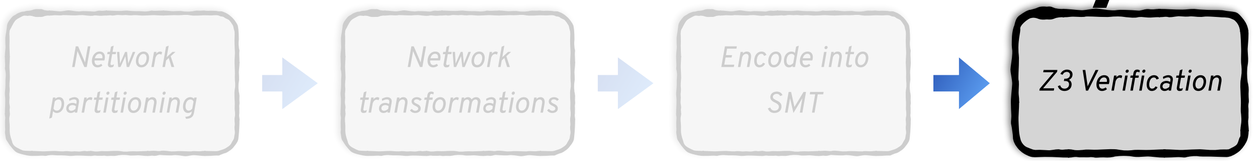

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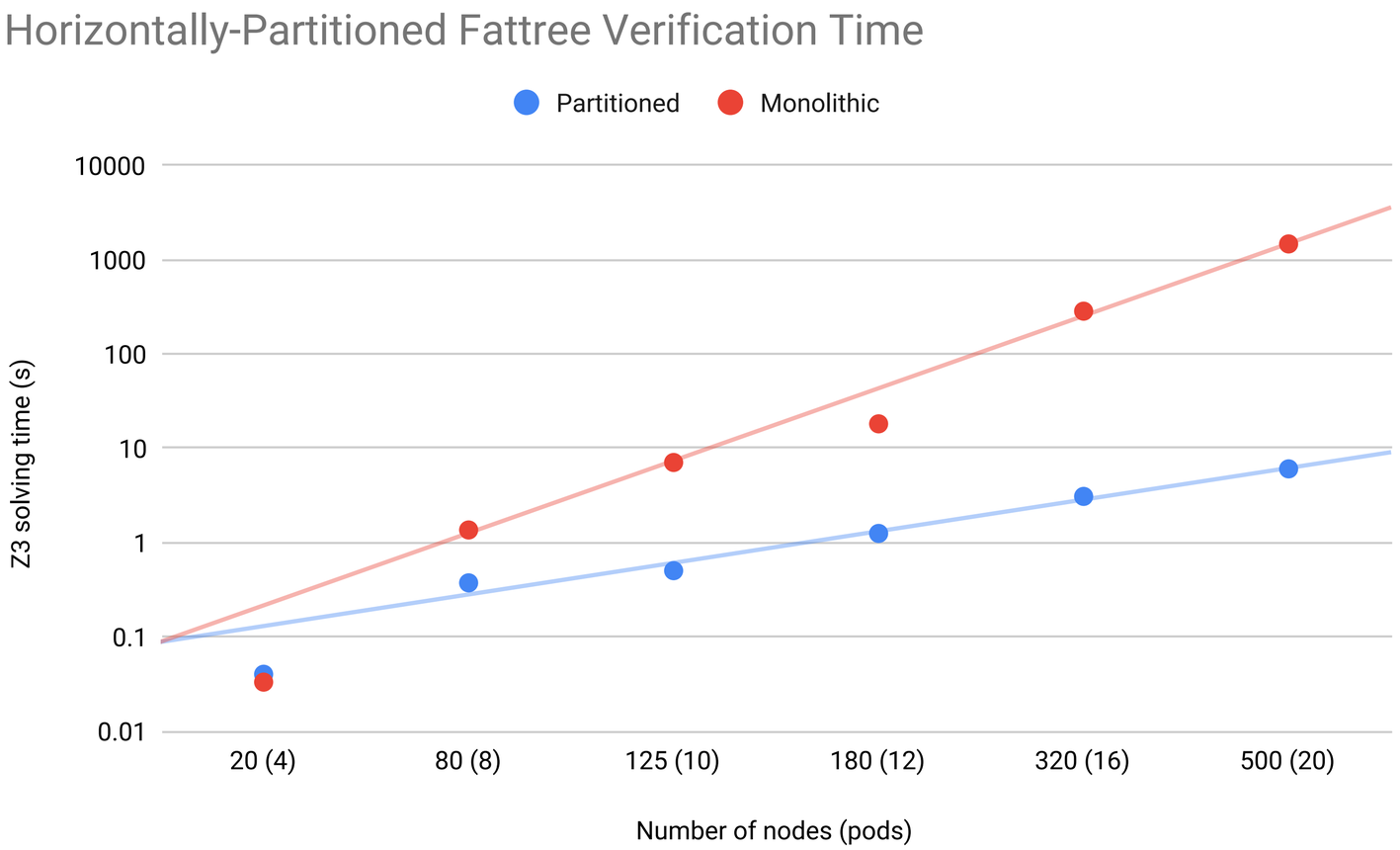

A New Assume-Guarantee Proof Rule?

[Giannakopoulou et al., *Handbook of Model Checking.* 2018]

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New Rule

$$\frac{\begin{array}{c}\langle A_S\rangle\ S\ \langle G_S\rangle \\ \langle A_T\rangle\ T\ \langle G_T\rangle \\ G_T \Rightarrow A_S \\ G_S \Rightarrow A_T \\ \langle A_S\rangle\ S\ \langle P_S\rangle \\ \langle A_T\rangle\ T\ \langle P_T\rangle \\ \langle \text{true}\rangle\ S\ \langle G_S\rangle\end{array}}{\langle \text{true}\rangle\ S \parallel T\ \langle P_S \wedge P_T\rangle}$$

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Rule CIRC

$$\frac{\begin{array}{c}\langle A_2\rangle\ M_2\ \langle A_1\rangle \\ \langle A_1\rangle\ M_1\ \langle P\rangle \\ \langle \text{true}\rangle\ M_1\ \langle A_2\rangle\end{array}}{\langle \text{true}\rangle\ M_1 \parallel M_2\ \langle P\rangle}$$

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Related Work and Future Directions

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- Network verification

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  - Control plane verification

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  - **Split invariants** [Cohen et al., CAV 2010]: uses *vector of assertions* defined over local state variables

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  - Consider graph properties, natural structure of topology


Thank you!

Appendix

Kirigami with an Alternate Initial Check

For partition S (resp. T), check validity of the following *verification conditions* (VCs) on $\mathscr{M}_S$ (resp. $\mathscr{M}_T$, swapping S and T):

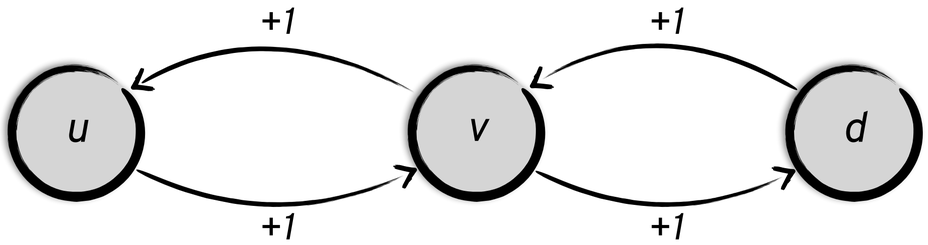
A. Inductiveness: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$

B. Safety: $\langle \mathbf{H}_S \rangle \mathscr{M}_S \langle P_S \rangle$

C. Initial: $\langle \text{true} \rangle \mathscr{M}_S \langle G_S \rangle \wedge G_S \Rightarrow \mathbf{H}_T$

If A and B hold for both S and T, and *C holds for* S *or* T, then return true

Drafts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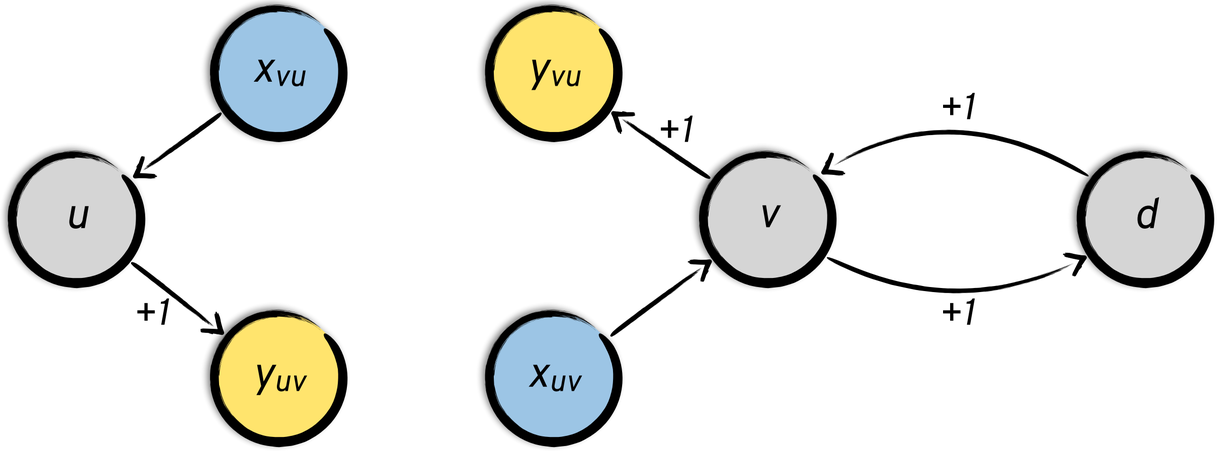
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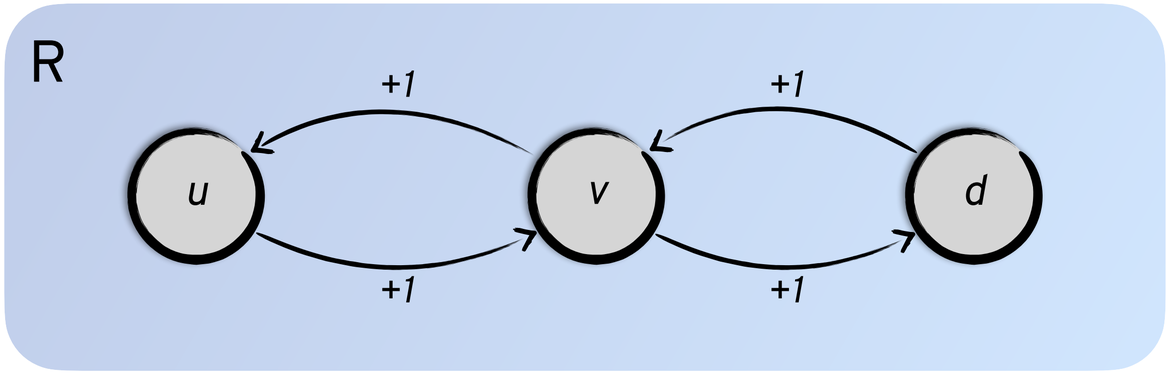
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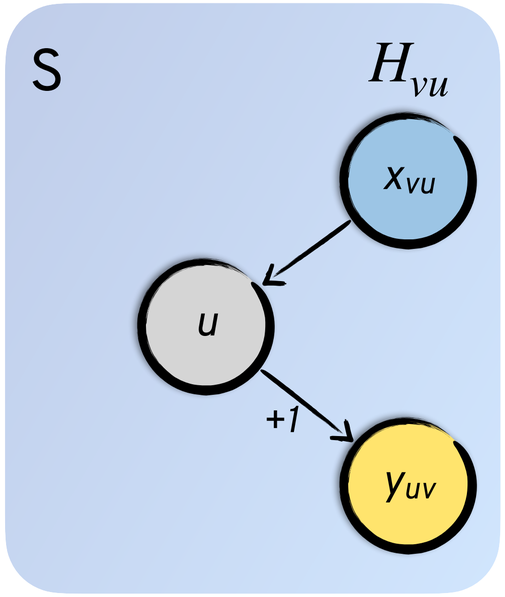
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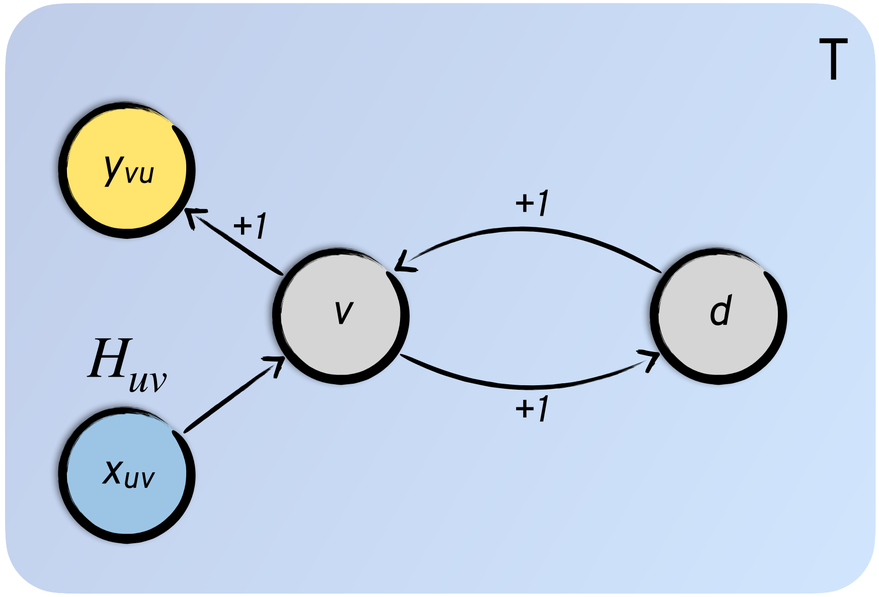
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