

From Compactifying Lambda-Letrec Terms to Recognizing Regular-Expression Processes

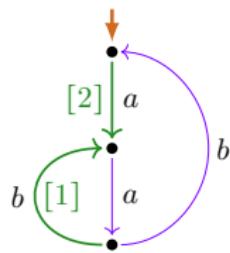
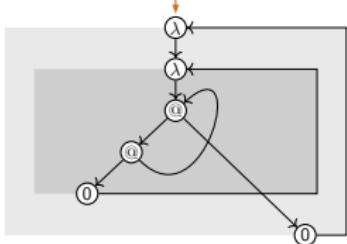
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<https://clegra.github.io>

Department of Computer Science



DCM'23
Sapienza Università di Roma
July 2, 2023



Overview

1. Compactifying λ -terms with letrec (maximal sharing of functional programs)

- ▶ higher-order λ -term graphs

2. Recognizing regular-expression processes

- ▶ **LEE-witnesses:** graph labelings based on a loop-condition LEE

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 - ▶ from terms in the λ -calculus with letrec to:
 - ▶ higher-order λ -term graphs
 - ▶ first-order λ -term graphs
 - ▶ λ -NFAs, and λ -DFAs
 - ▶ minimization / readback / efficiency / Haskell implementation
2. Recognizing regular-expression processes
 - ▶ LEE-witnesses: graph labelings based on a loop-condition LEE

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 - ▶ Milner's questions, known results
 - ▶ structure-constrained process graphs:
 - ▶ LEE-witnesses: graph labelings based on a loop-condition LEE
 - ▶ preservation under bisimulation collapse
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- ▶ Comparison results

Comparison original desiderata

λ -calculus with letrec under the unfolding semantics

Well-known: graph representations implemented by compilers

- ▶ but were **not intended** for use under \leftrightarrow

Not well-known: term graph interpretation that is studied under \leftrightarrow

Regular expressions under process semantics (bisimilarity \leftrightarrow)

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Regular expressions under process semantics (bisimilarity \leftrightarrow)

Given: process graph interpretation $P(\cdot)$, studied under \leftrightarrow

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Desired: reason with graphs that are $P(\cdot)$ -expressible modulo \leftrightarrow
 (at least with 'sufficiently many')

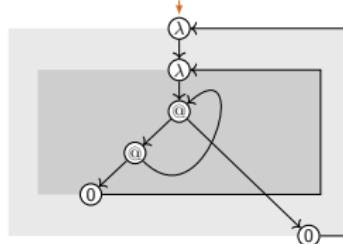
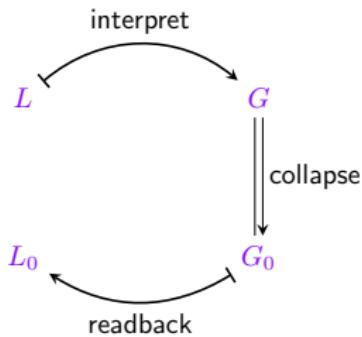
understand incompleteness by a structural graph property

structure constraints (L'Aquila)

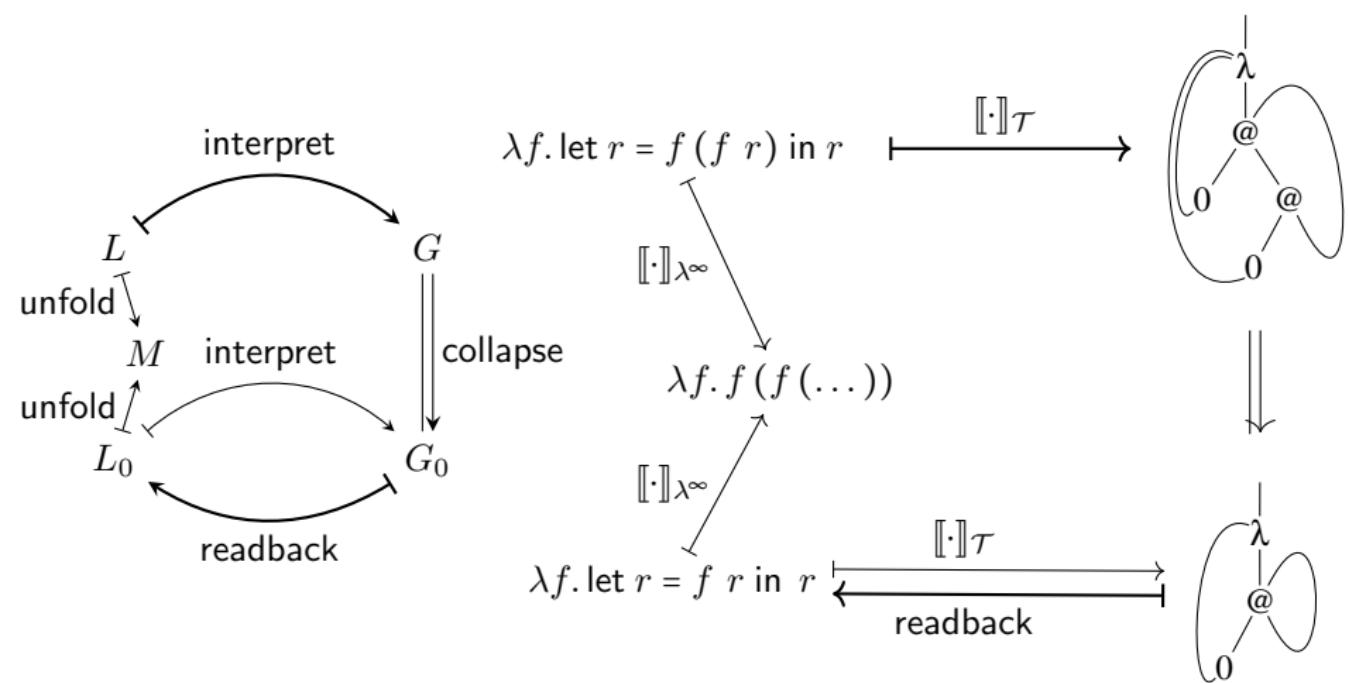


Maximal sharing of functional programs

(joint work with Jan Rochel)



Maximal sharing: example (fix)



Maximal sharing: the method

$$L \xrightarrow{[\cdot]_{\mathcal{H}}} \mathcal{G}$$

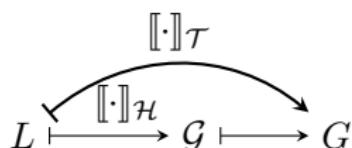
1. term graph interpretation $[\cdot]$.
of λ_{letrec} -term L as:
 - a. higher-order term graph
 $\mathcal{G} = [L]_{\mathcal{H}}$

Maximal sharing: the method

$$L \xrightarrow{[\cdot]_{\mathcal{H}}} \mathcal{G} \longmapsto G$$

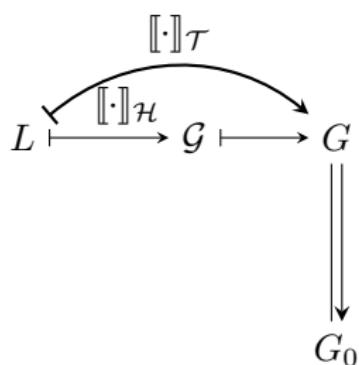
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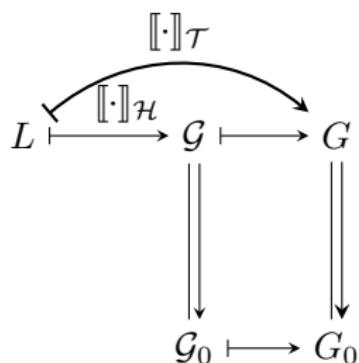
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of f-o term graph G into G_0

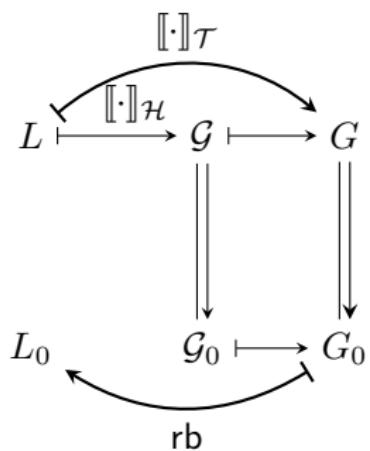
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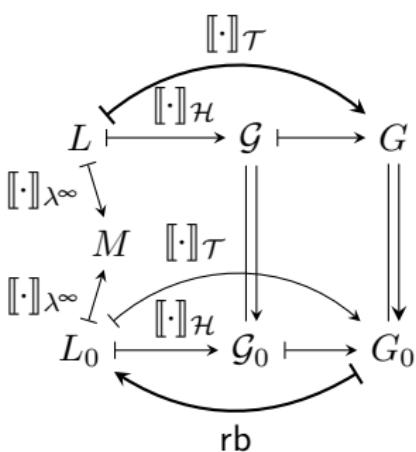
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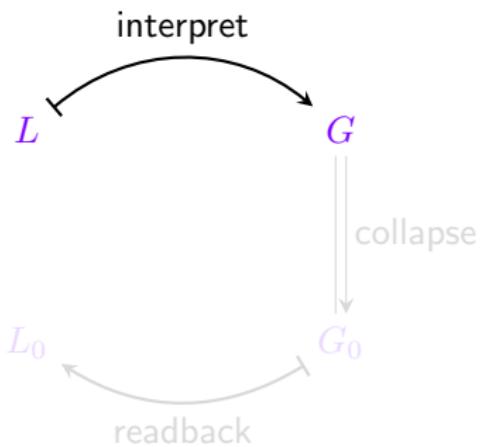
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of f-o term graph G_0
yielding program $L_0 = \text{rb}(G_0)$.

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Interpretation



Running example

instead of:

$$\lambda f. \text{let } r = f(f r) \text{ in } r \xrightarrow{\text{max-sharing}} \lambda f. \text{let } r = f r \text{ in } r$$

we use:

$$\lambda x. \lambda f. \text{let } r = f(f r x) x \text{ in } r \xrightarrow{\text{max-sharing}} \lambda x. \lambda f. \text{let } r = f r x \text{ in } r$$

L

$\xrightarrow{\text{max-sharing}}$

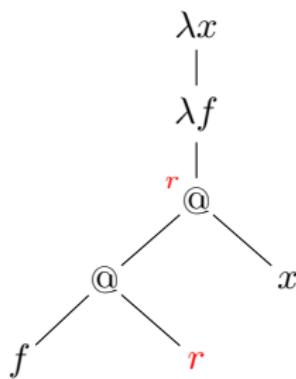
L_0

Graph interpretation (example 1)

$L_0 = \lambda x. \lambda f. \text{let } r = f\ r\ x \text{ in } r$

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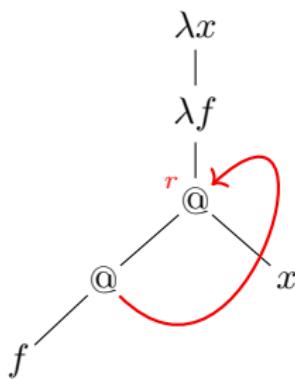
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syntax tree

Graph interpretation (example 1)

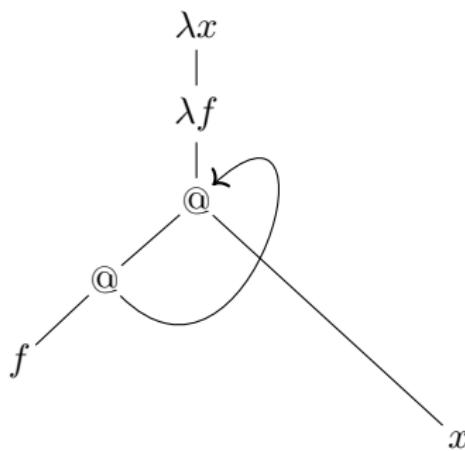
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syntax tree (+ recursive backlink)

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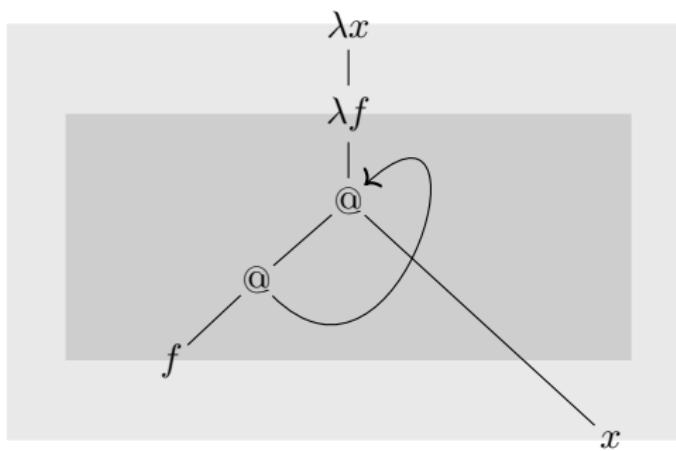
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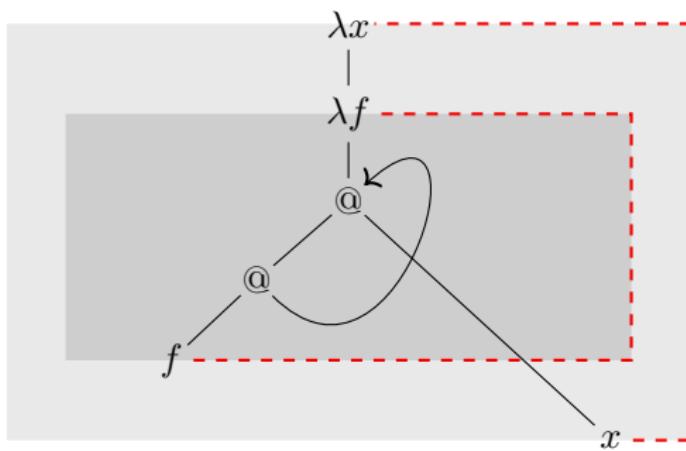
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syntax tree (+ recursive backlink, + scopes)

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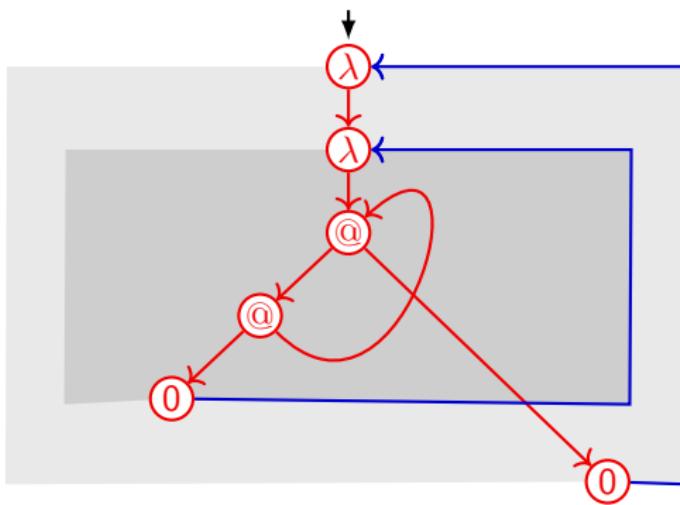
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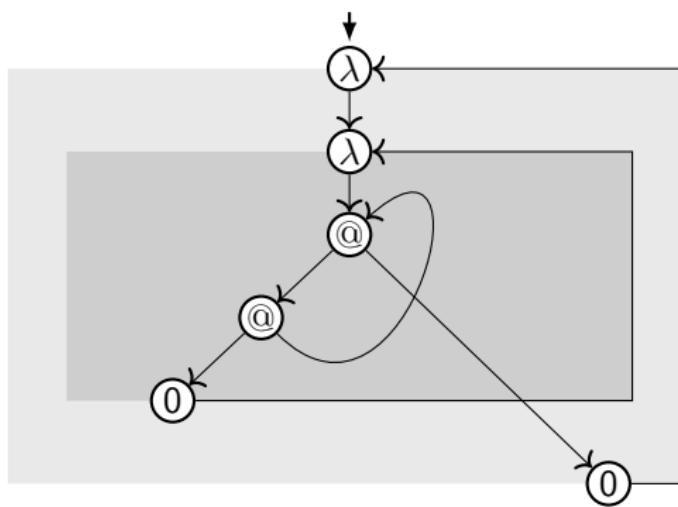
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first-order term graph with binding backlinks (+ scope sets)

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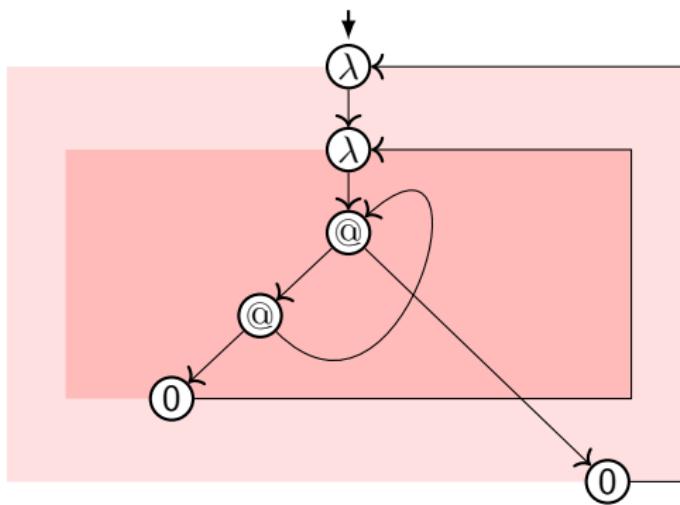
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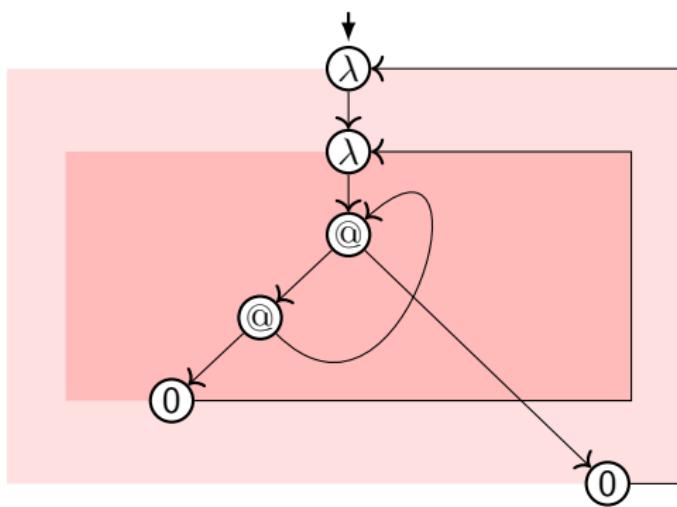
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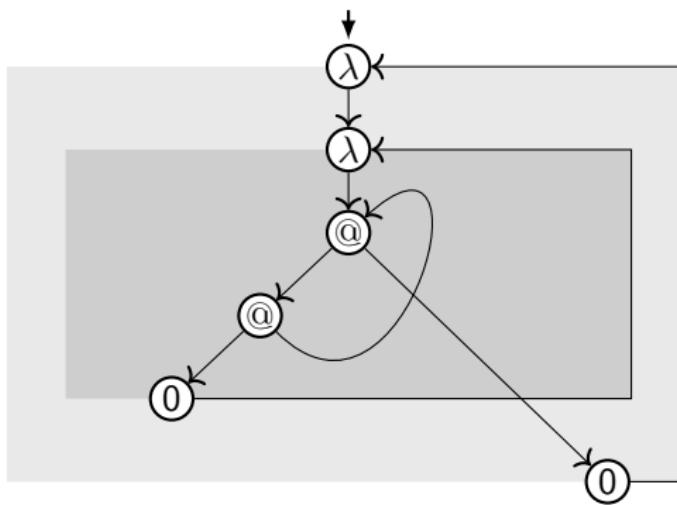
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higher-order term graph (with scope sets, Blom [2003])

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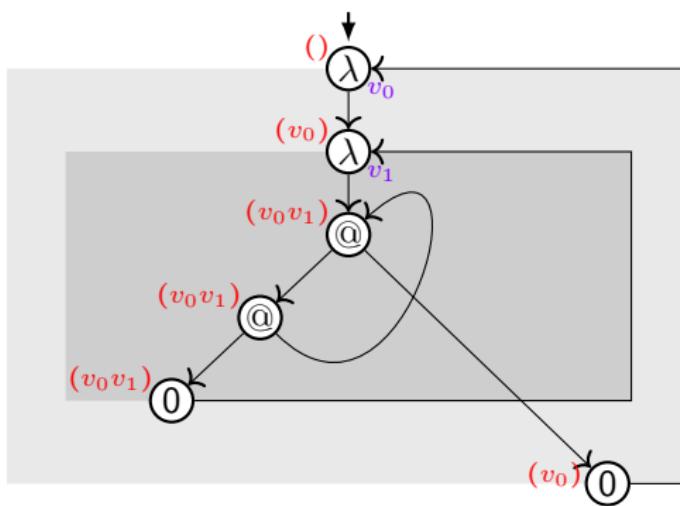
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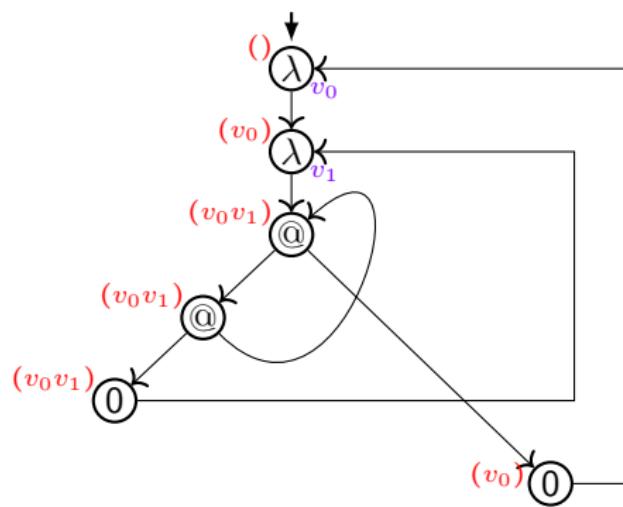
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higher-order term graph (with scope sets, + abstraction-prefix function)

Graph interpretation (example 1)

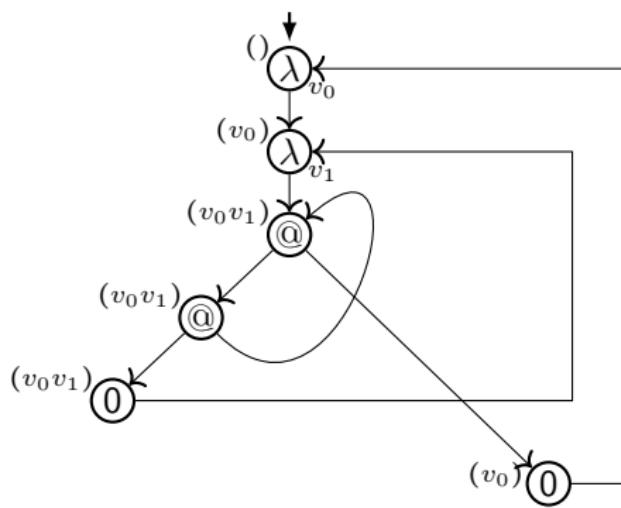
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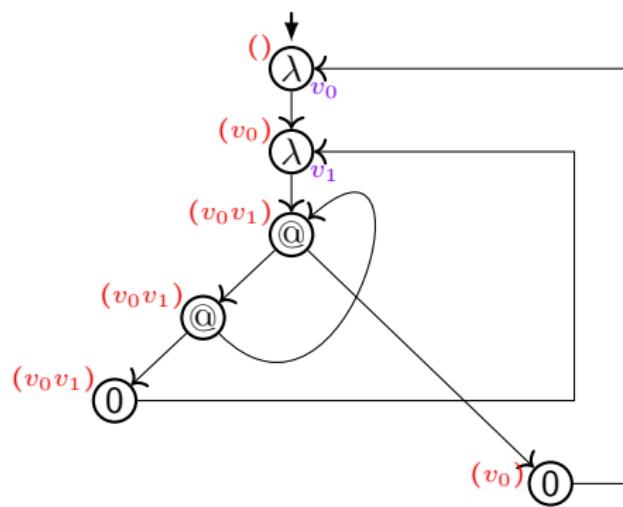
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λ -higher-order-term-graph $\llbracket L_0 \rrbracket_{\mathcal{H}}$

Graph interpretation (example 1)

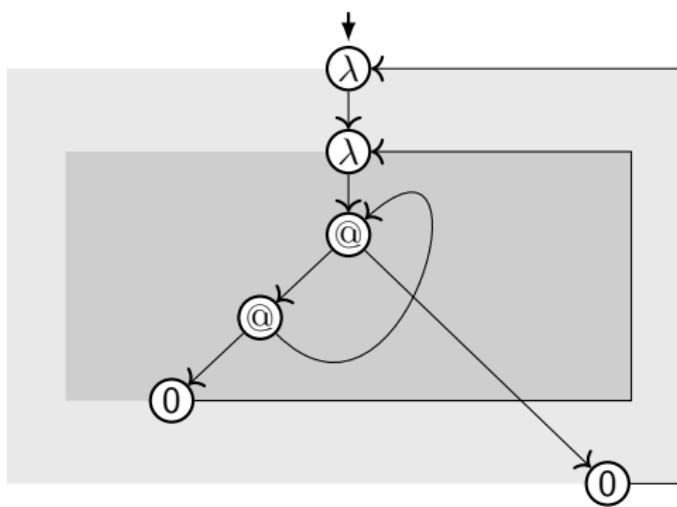
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first-order term graph (+ abstraction-prefix function)

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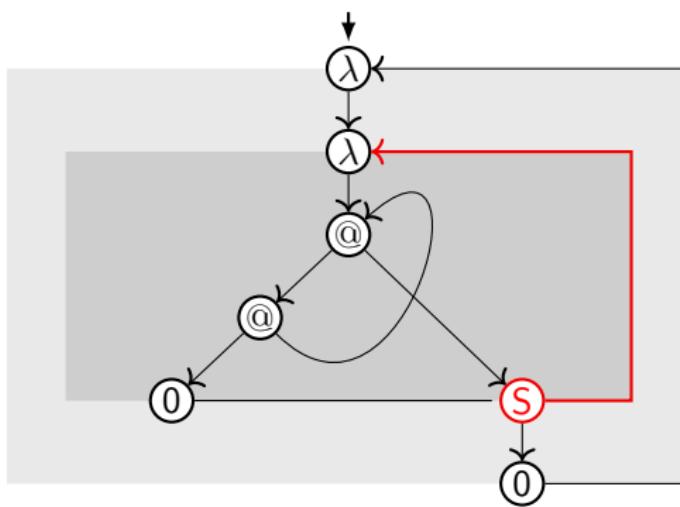
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first-order term graph with binding backlinks (+ scope sets)

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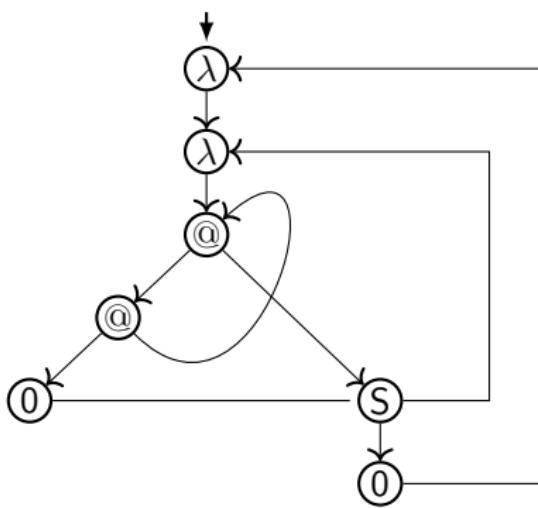
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first-order term graph with scope vertices with backlinks (+ scope sets)

Graph interpretation (example 1)

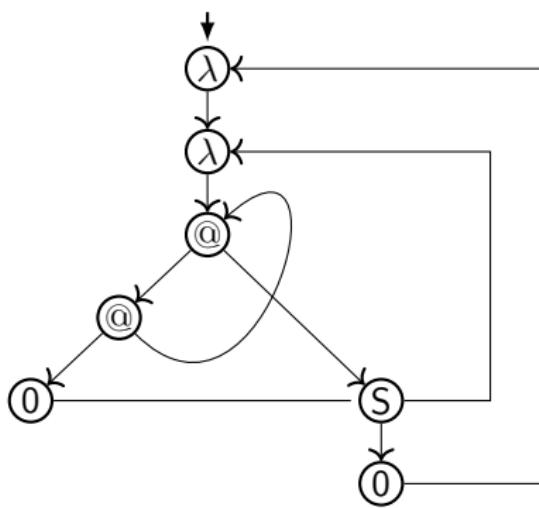
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first-order term graph with scope vertices with backlinks

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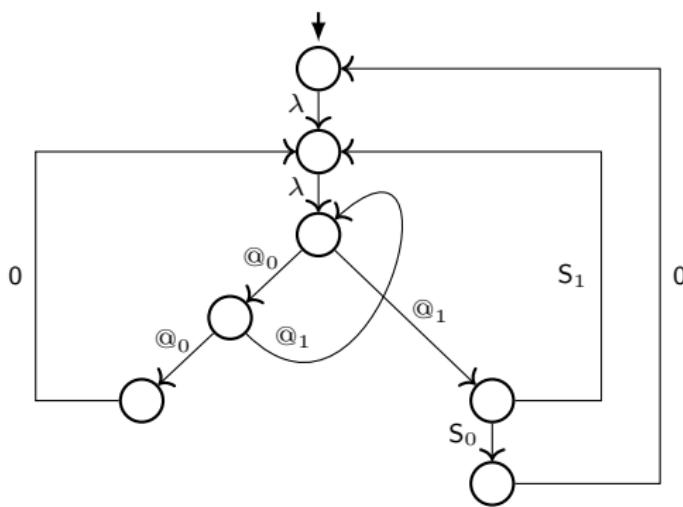
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λ -term-graph $\llbracket L_0 \rrbracket_{\mathcal{T}}$

Graph interpretation (example 1)

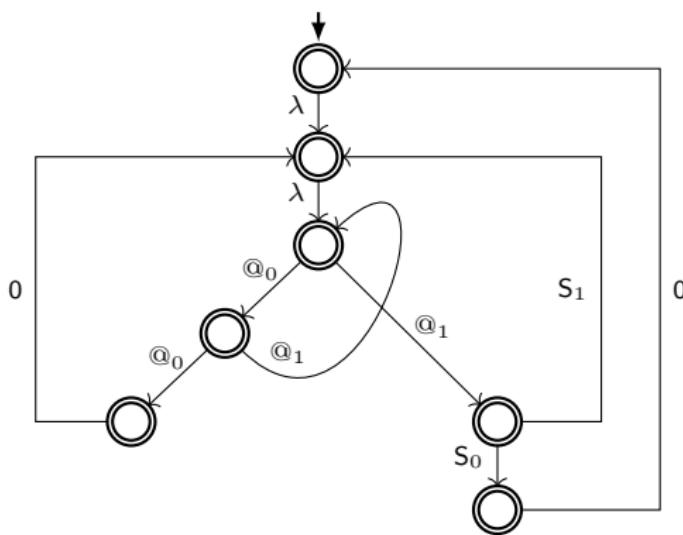
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incomplete DFA

Graph interpretation (example 1)

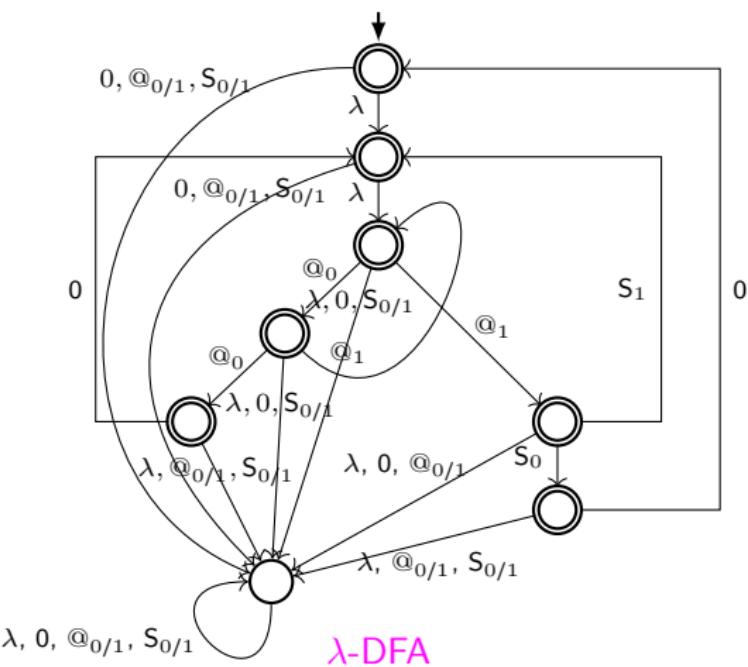
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incomplete λ -DFA

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$L_0 = \lambda x. \lambda f. \text{let } r = f\,r\,x \text{ in } r$

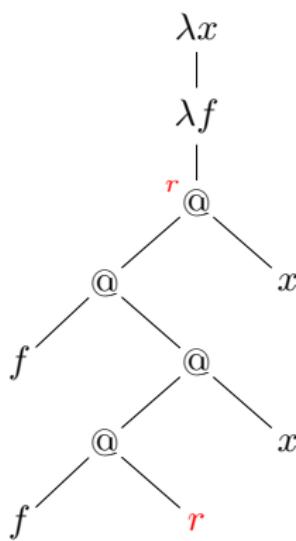


Graph interpretation (example 2)

$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$

Graph interpretation (example 2)

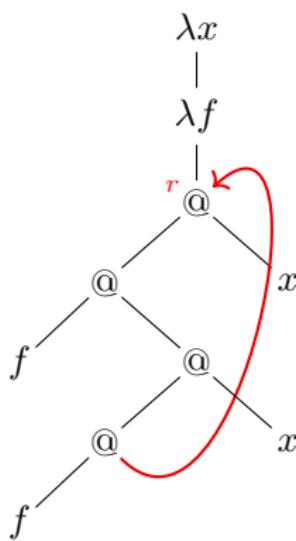
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syntax tree

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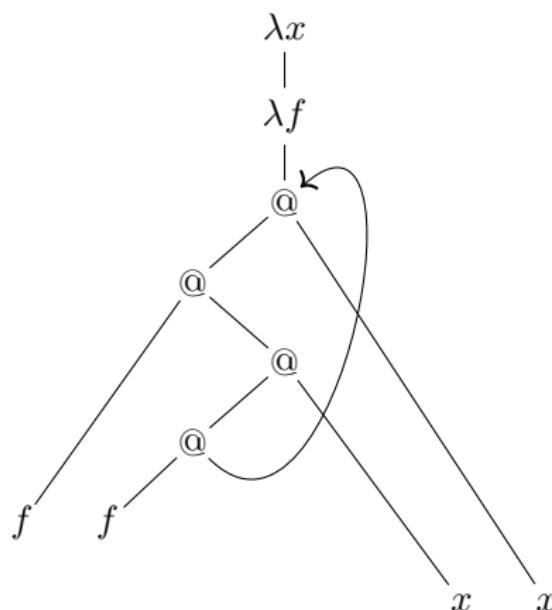
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syntax tree (+ recursive backlink)

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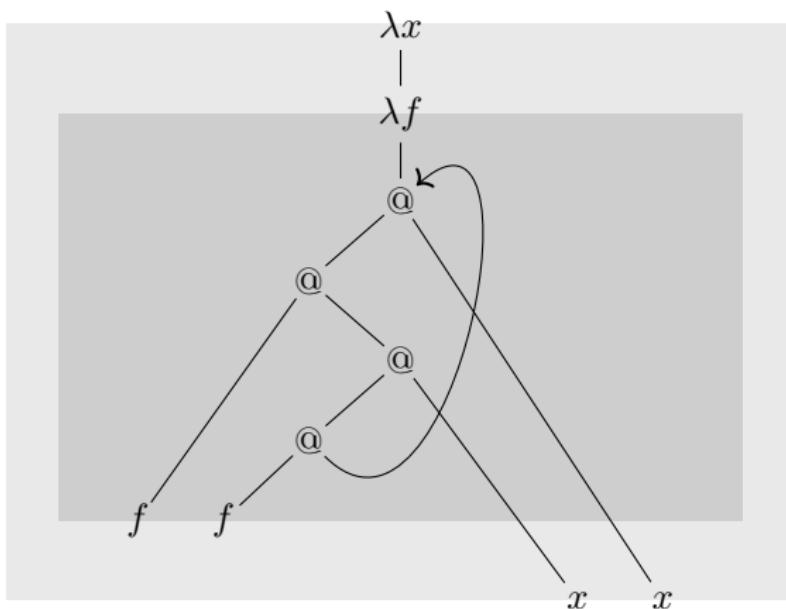
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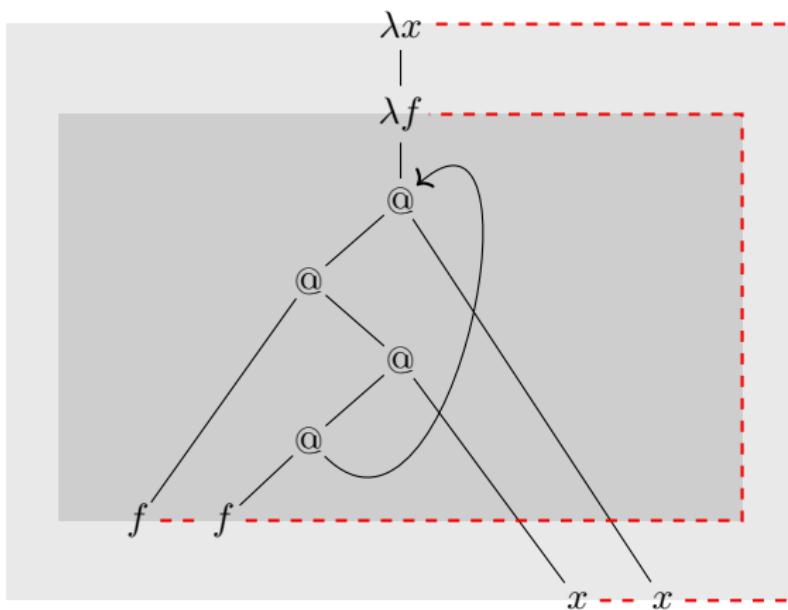
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syntax tree (+ recursive backlink, + scopes)

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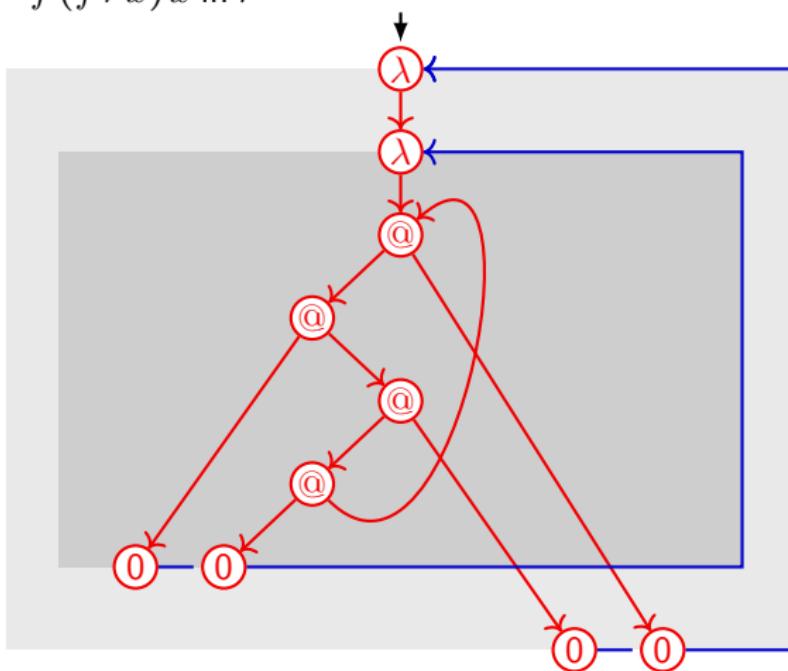
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syntax tree (+ recursive backlink, + scopes, + binding links)

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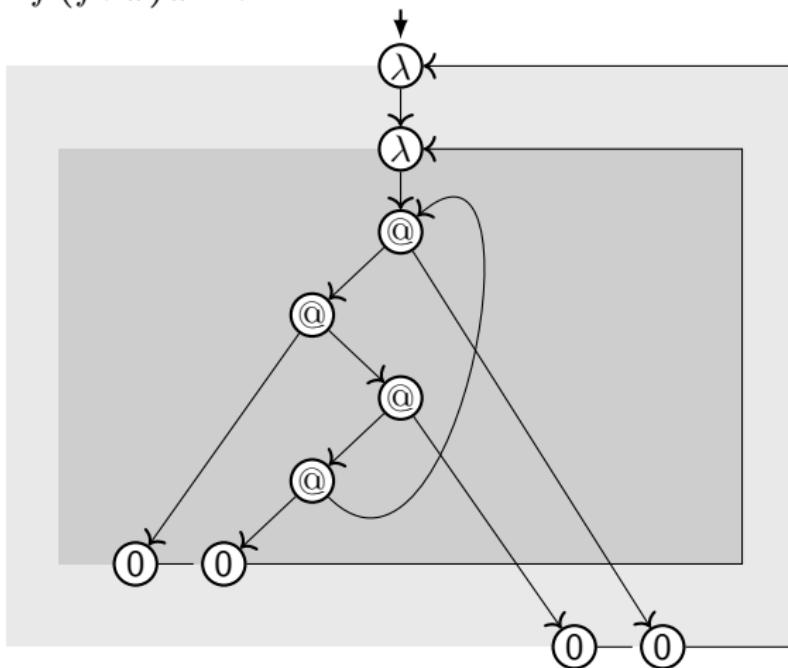
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first-order term graph with binding backlinks (+ scope sets)

Graph interpretation (example 2)

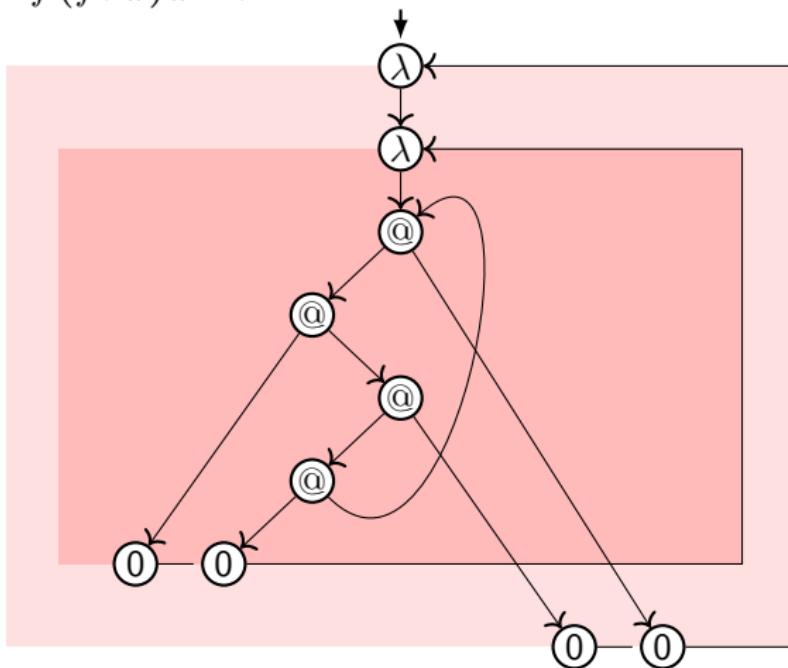
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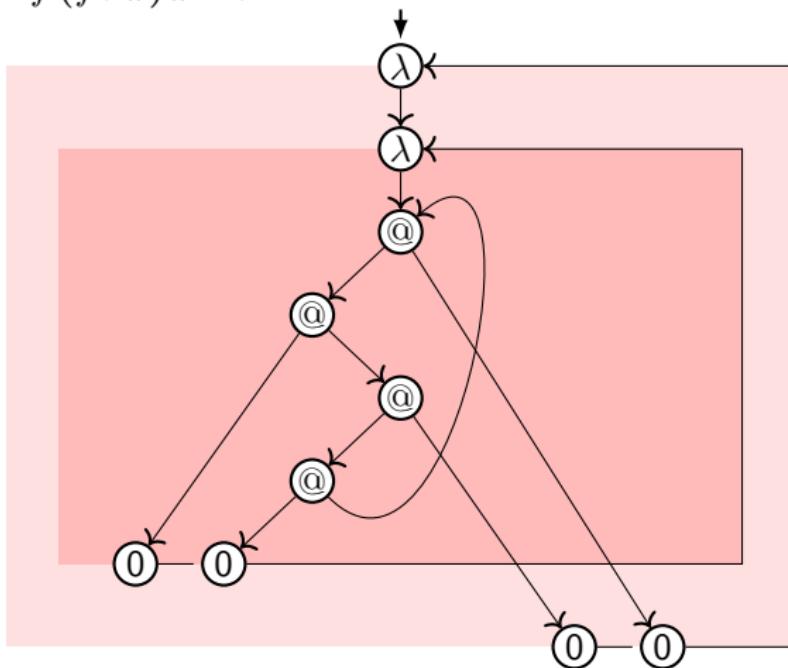
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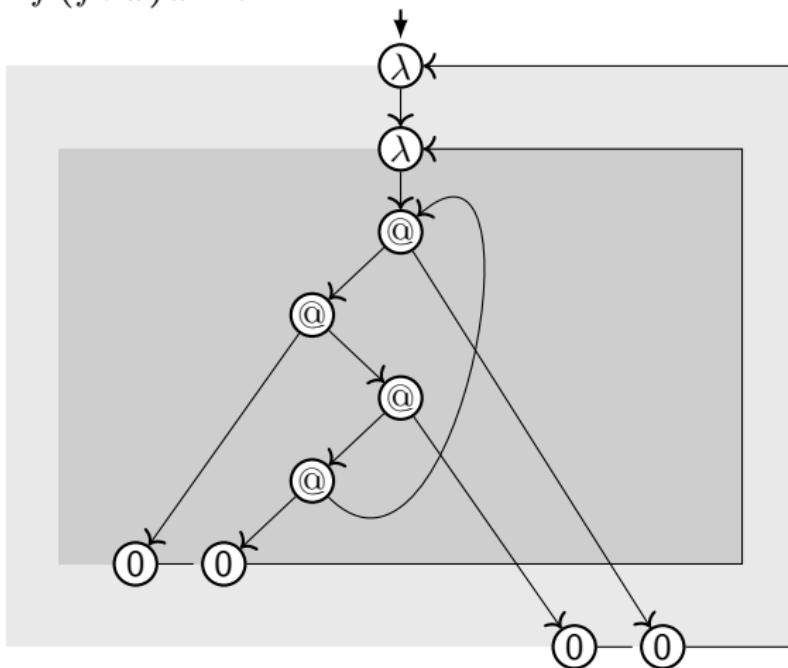
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higher-order term graph (with scope sets, Blom [2003])

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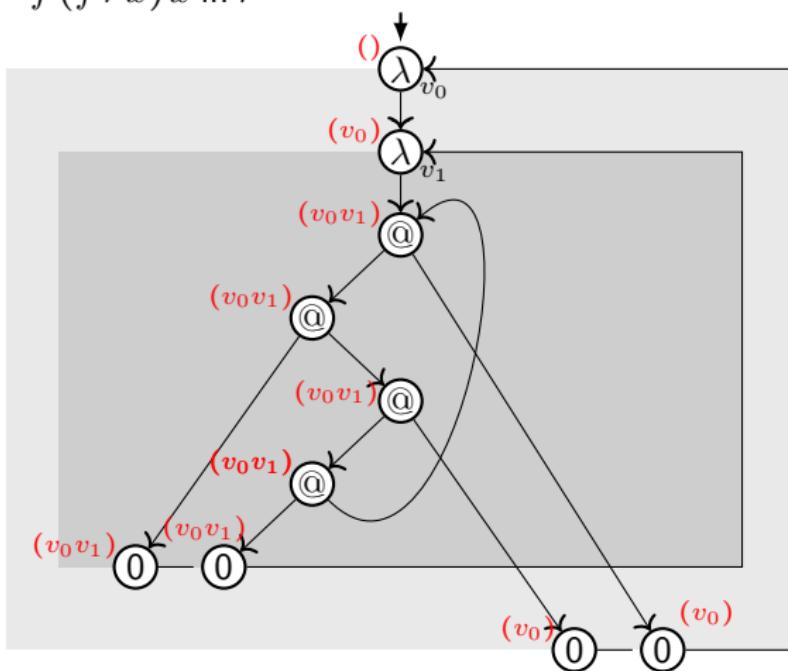
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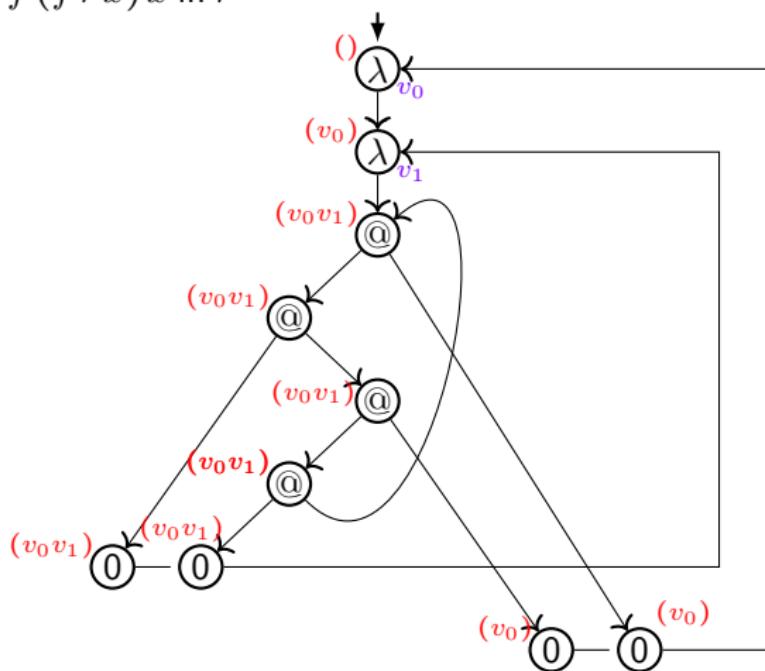
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higher-order term graph (with scope sets, + abstraction-prefix function)

Graph interpretation (example 2)

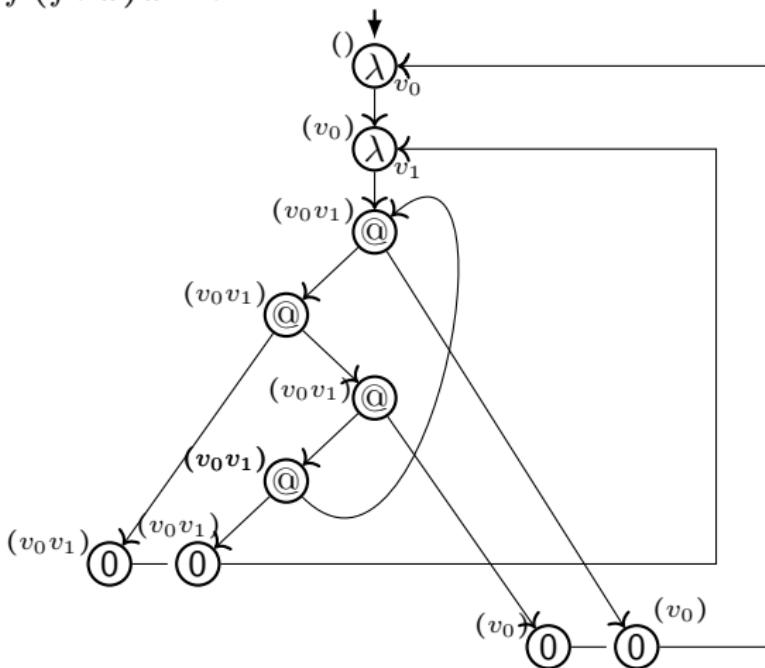
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higher-order term graph (with abstraction-prefix function)

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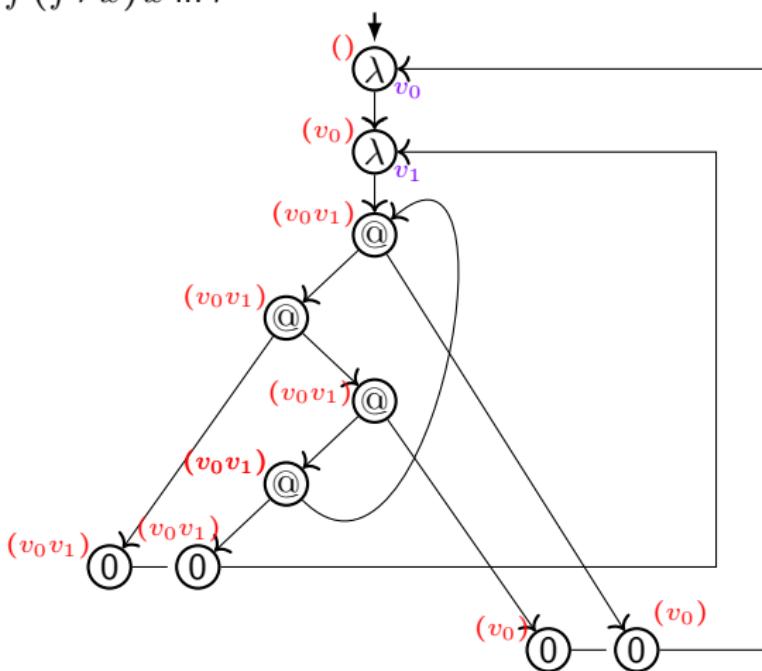
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λ -higher-order-term-graph $\llbracket L \rrbracket_{\mathcal{H}}$

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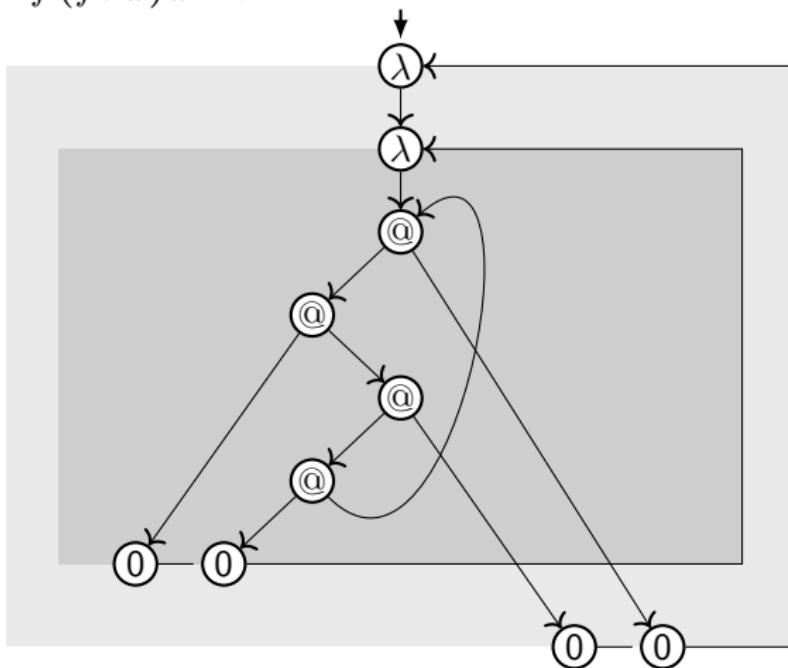
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first-order term graph (+ abstraction-prefix function)

Graph interpretation (example 2)

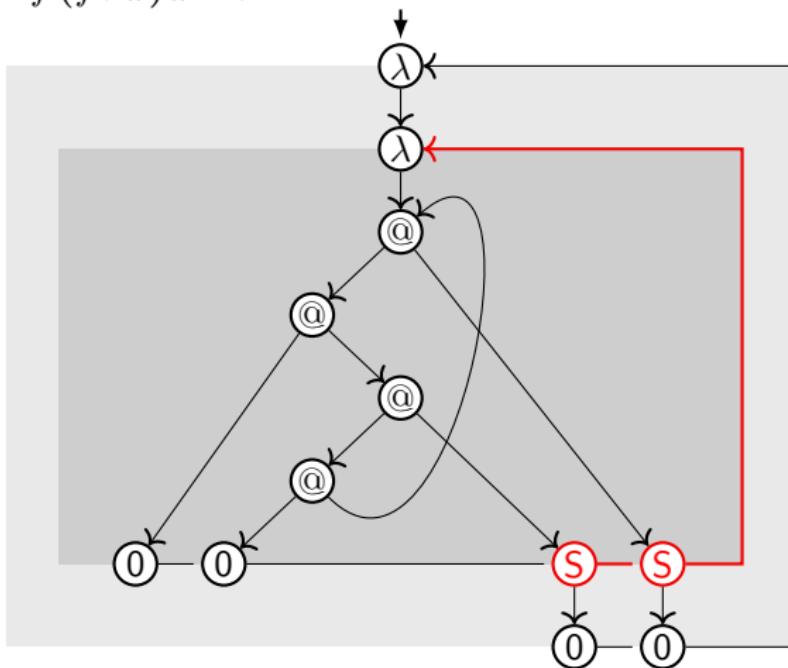
$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$



first-order term graph with binding backlinks (+ scope sets)

Graph interpretation (example 2)

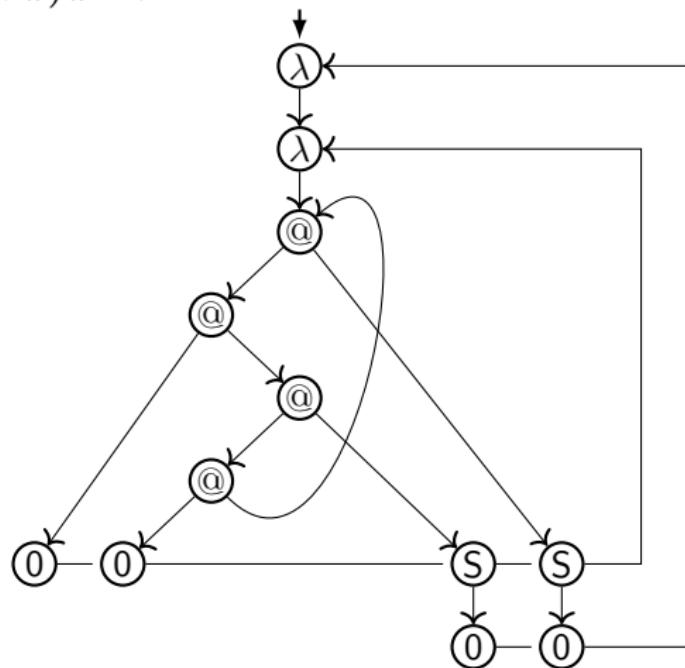
$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$



first-order term graph with scope vertices with backlinks (+ scope sets)

Graph interpretation (example 2)

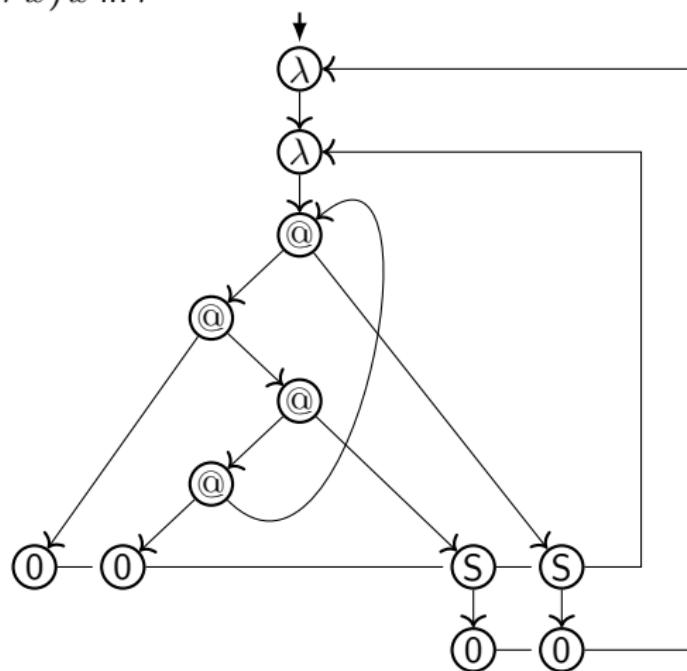
$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$



first-order term graph with scope vertices with backlinks

Graph interpretation (example 2)

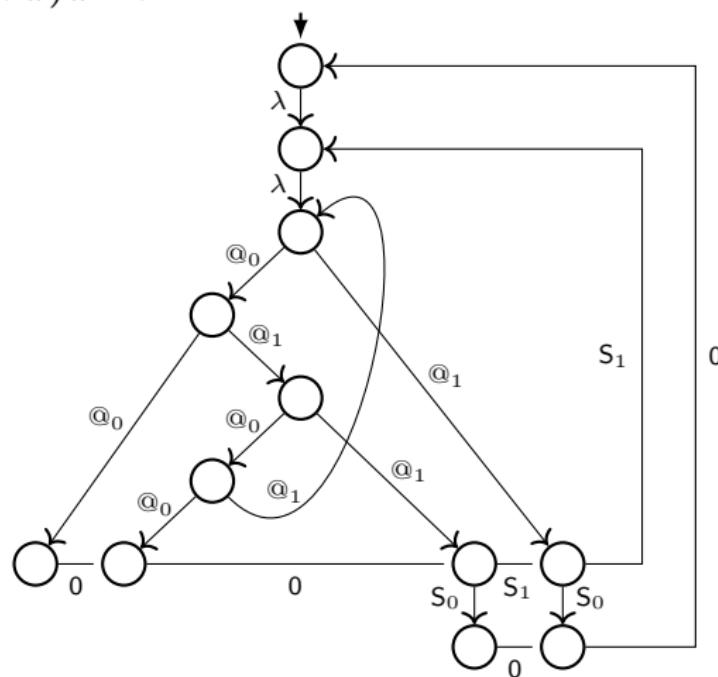
$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$



λ -term-graph $\llbracket L \rrbracket_{\mathcal{T}}$

Graph interpretation (example 2)

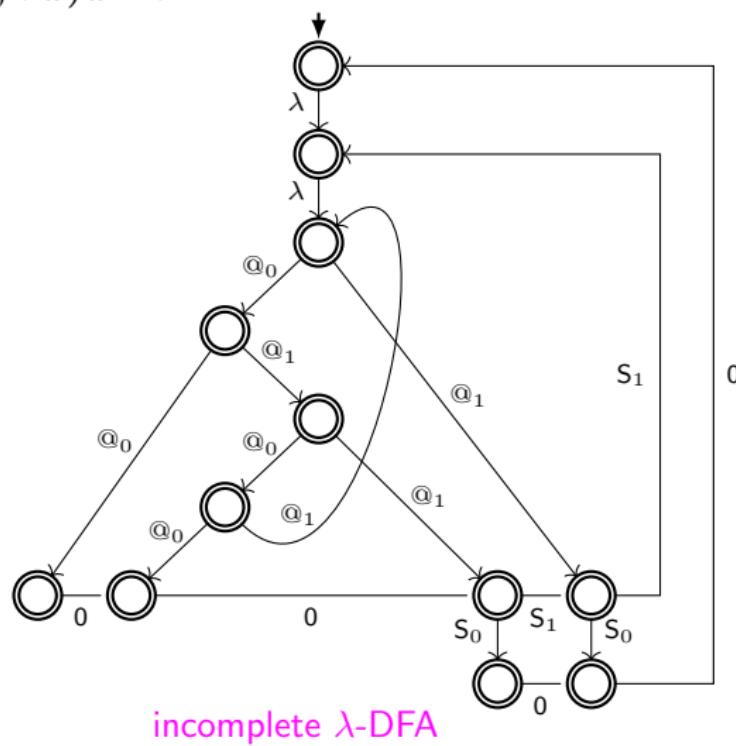
$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$



incomplete DFA

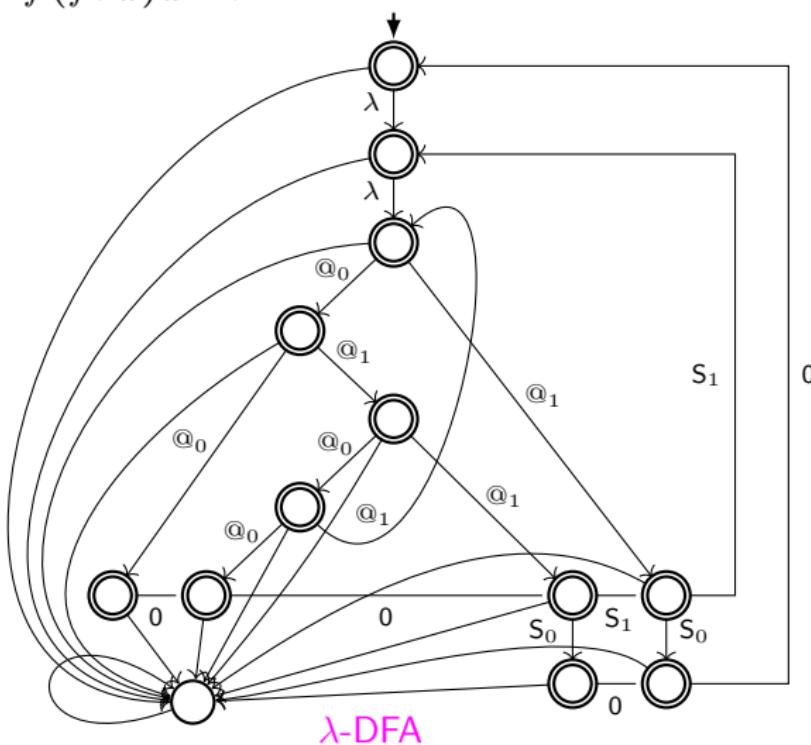
Graph interpretation (example 2)

$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$

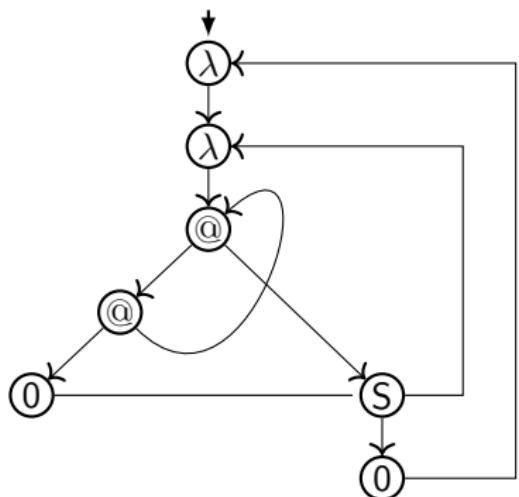
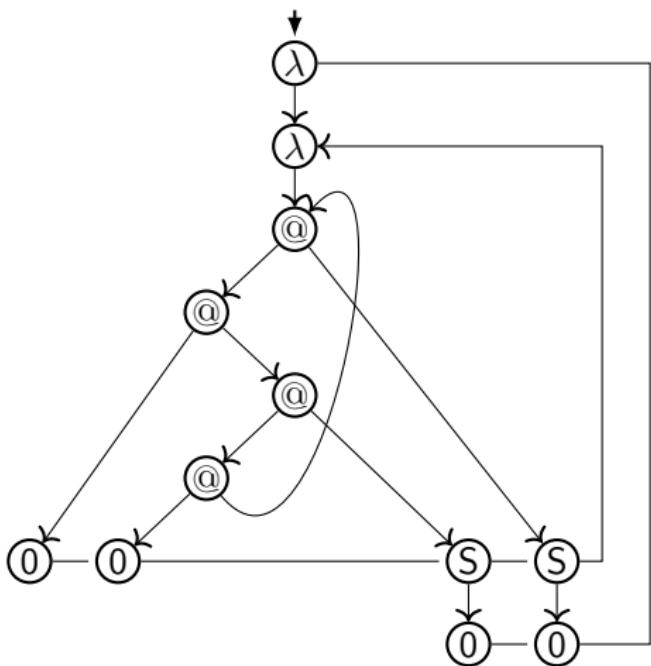


Graph interpretation (example 2)

$L = \lambda x. \lambda f. \text{let } r = f(f\,r\,x) \text{ in } r$



Graph interpretation (examples 1 and 2)


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$

 $\llbracket L \rrbracket_{\mathcal{T}}$

Interpretation $\llbracket \cdot \rrbracket_{\mathcal{T}}$: properties (cont.)

interpretation λ_{letrec} -term $L \mapsto \lambda\text{-term-graph } \llbracket L \rrbracket_{\mathcal{T}}$

- ▶ defined by induction on structure of L
- ▶ similar analysis as fully-lazy lambda-lifting
- ▶ yields **eager-scope λ -term-graphs**: \sim minimal scopes

Theorem

For λ_{letrec} -terms L_1 and L_2 it holds: Equality of infinite unfolding coincides with bisimilarity of λ -term-graph interpretations:

$$\llbracket L_1 \rrbracket_{\lambda^\infty} = \llbracket L_2 \rrbracket_{\lambda^\infty} \iff \llbracket L_1 \rrbracket_{\mathcal{T}} \simeq \llbracket L_2 \rrbracket_{\mathcal{T}}$$

Interpretation $\llbracket \cdot \rrbracket_{\mathcal{T}}$: properties (cont.)

interpretation λ_{letrec} -term L \mapsto λ -term-graph $\llbracket L \rrbracket_{\mathcal{T}}$

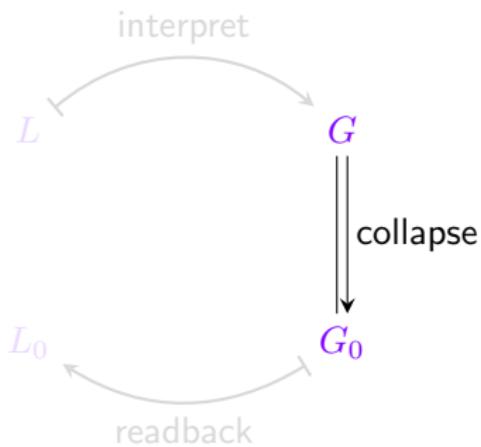
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Theorem

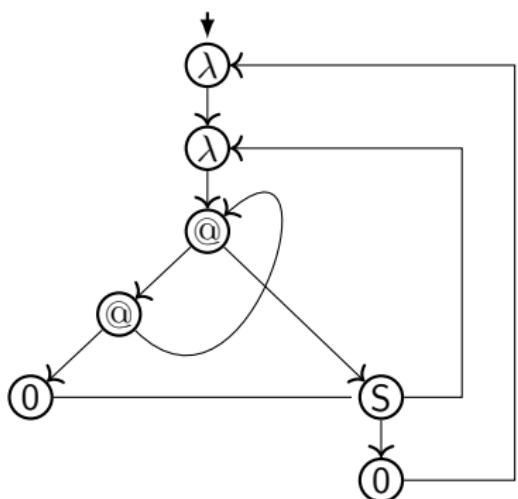
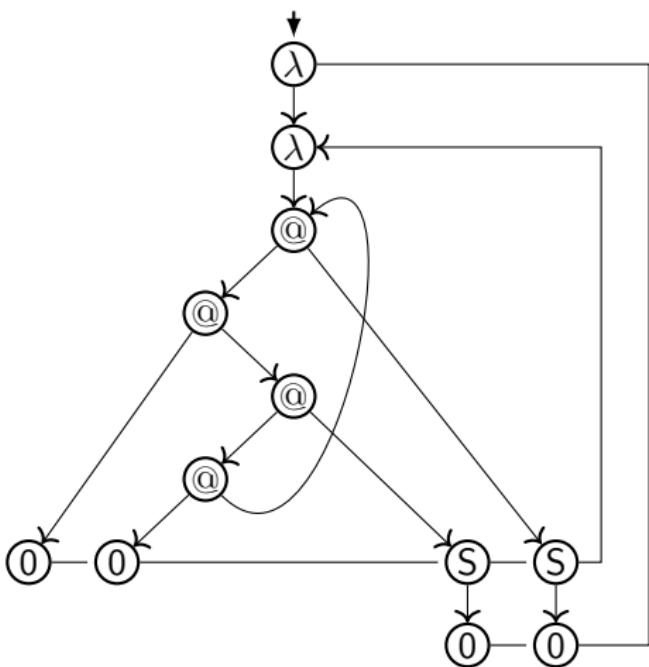
For λ_{letrec} -terms L_1 and L_2 it holds: Equality of infinite unfolding coincides with **bisimilarity** of λ -term-graph interpretations:

$$\llbracket L_1 \rrbracket_{\lambda^\infty} = \llbracket L_2 \rrbracket_{\lambda^\infty} \iff \llbracket L_1 \rrbracket_{\mathcal{T}} \simeq \llbracket L_2 \rrbracket_{\mathcal{T}}$$

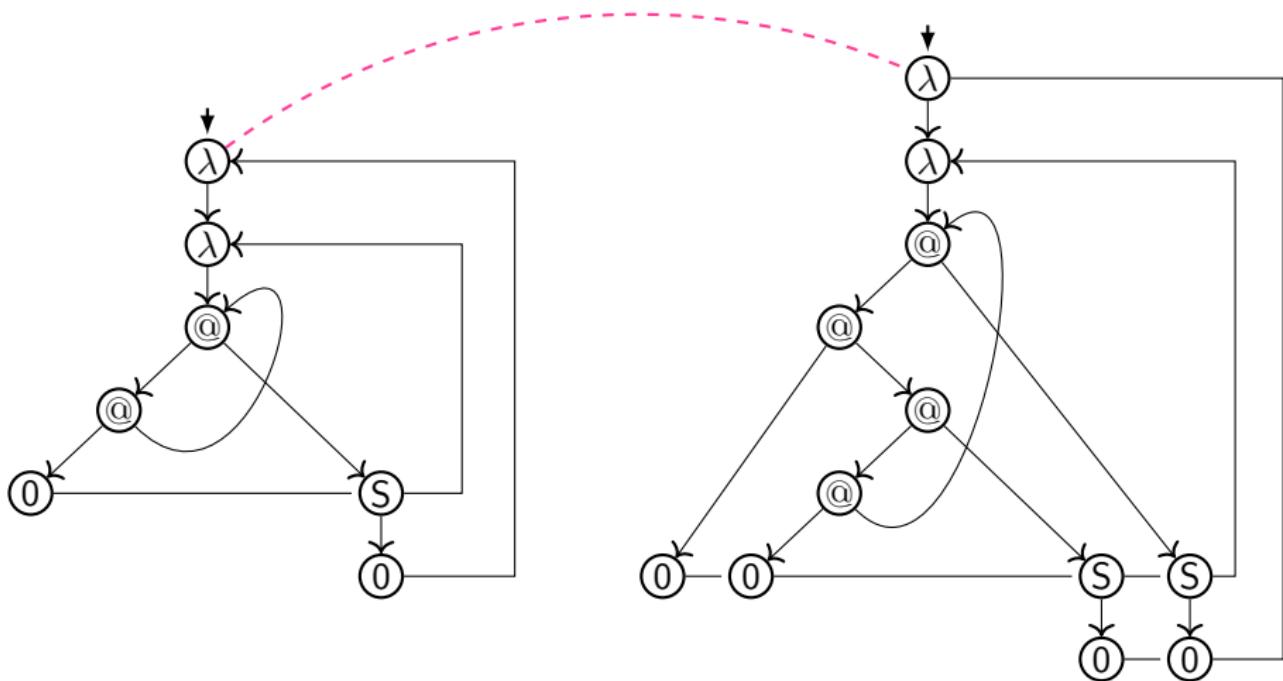
Collapse



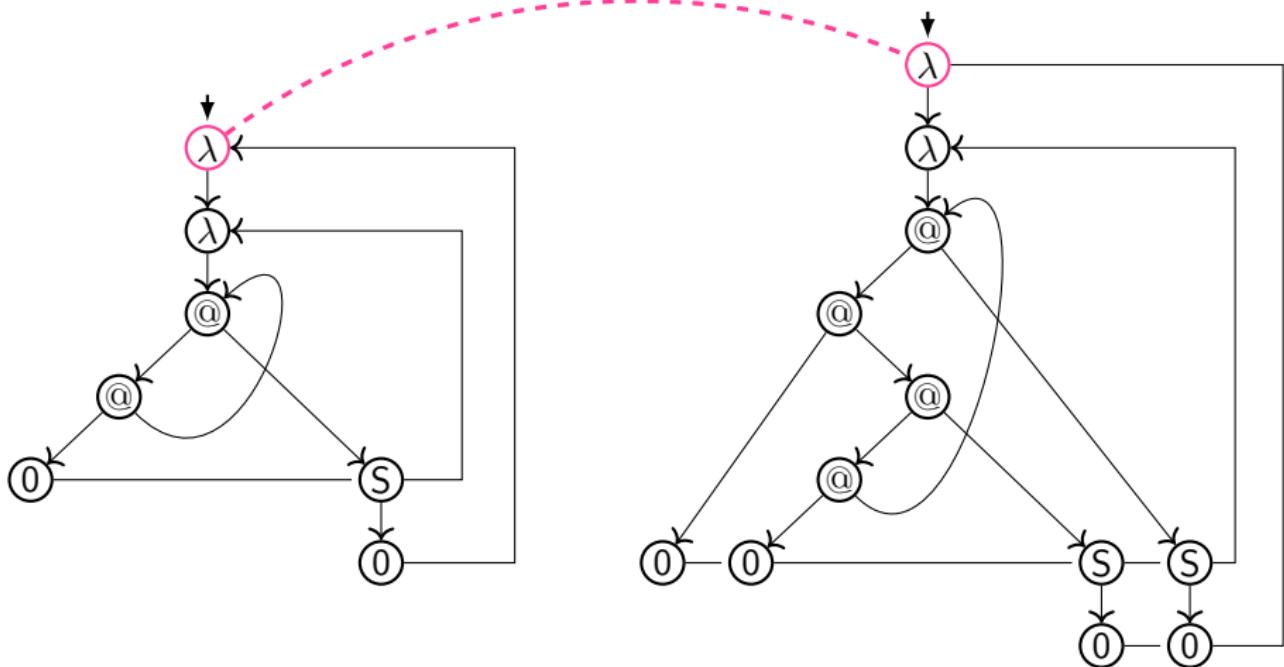
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$

 $\llbracket L \rrbracket_{\mathcal{T}}$

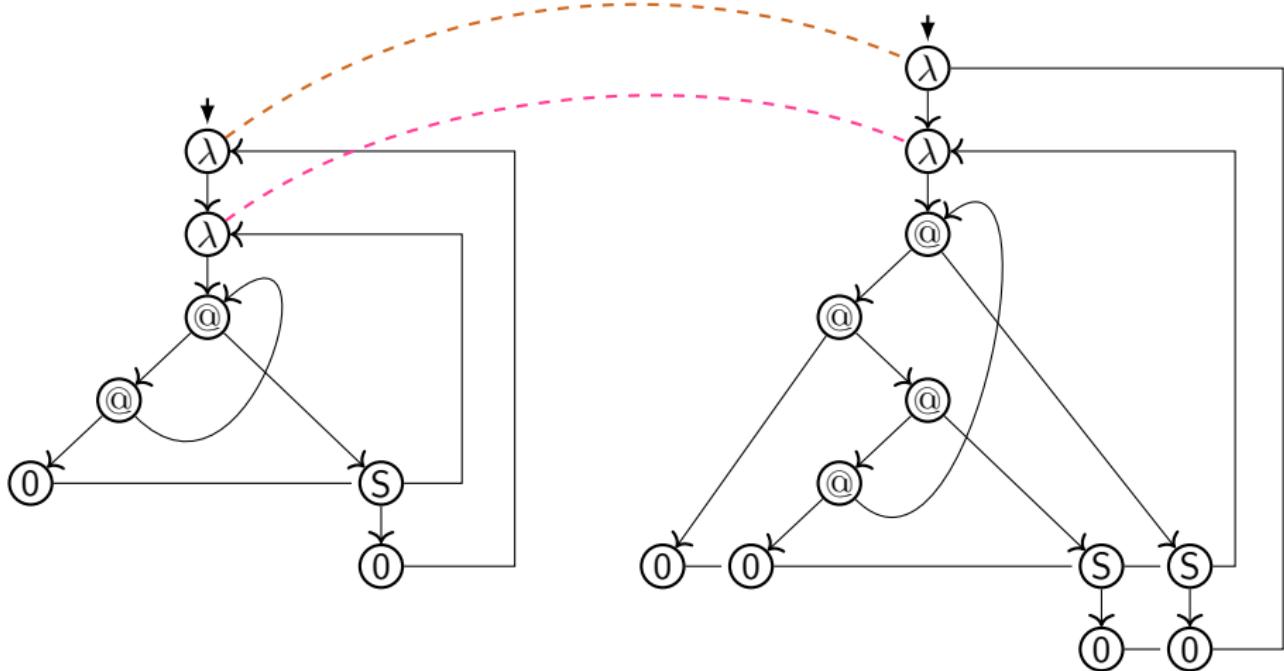
Bisimulation check between λ -term-graphs


 $[[L_0]]_\tau$
 $[[L]]_\tau$

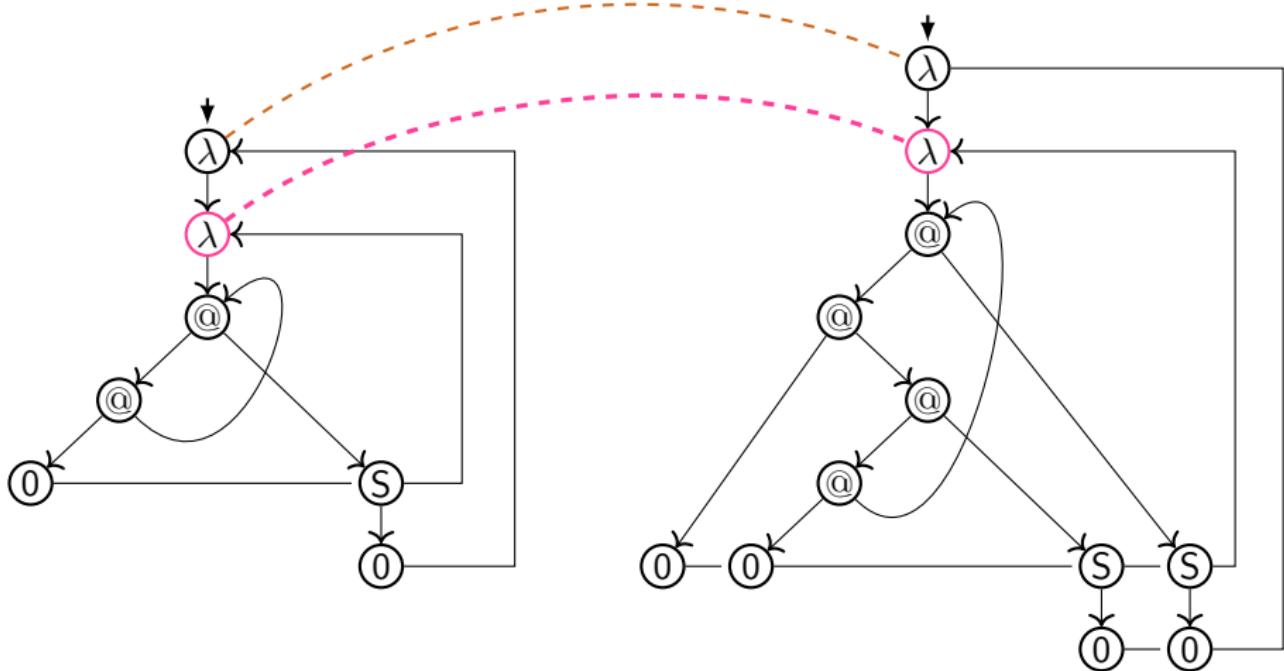
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_T$
 $\llbracket L \rrbracket_T$

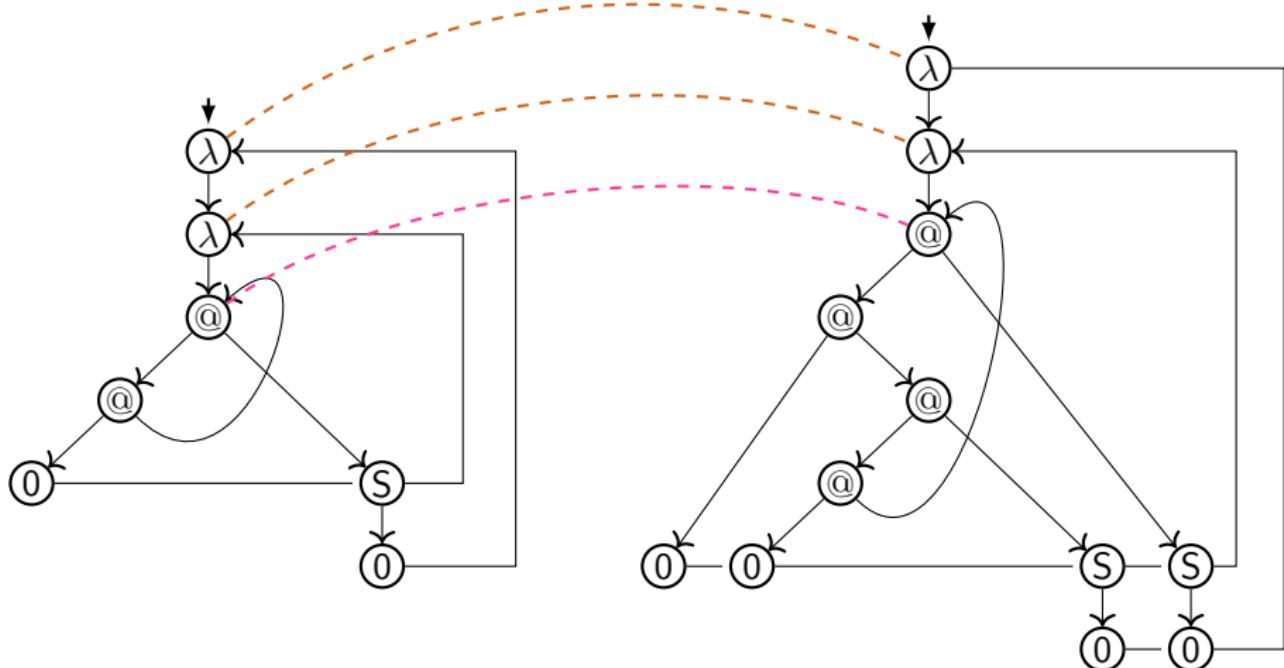
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

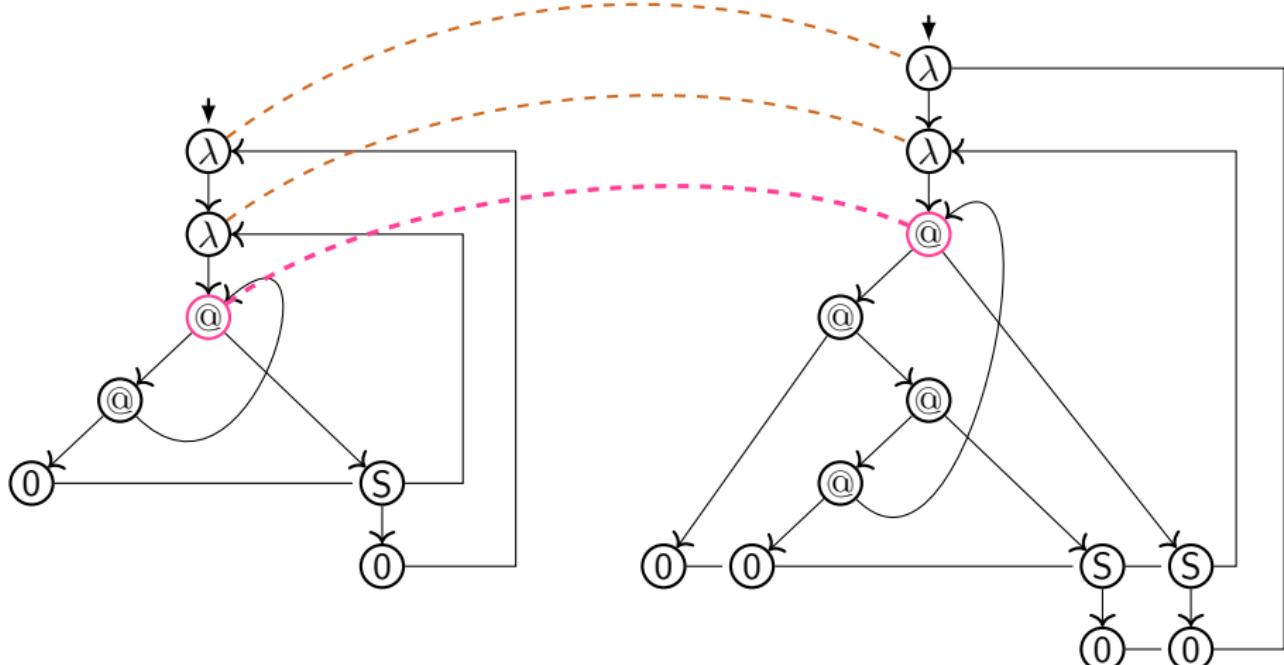
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

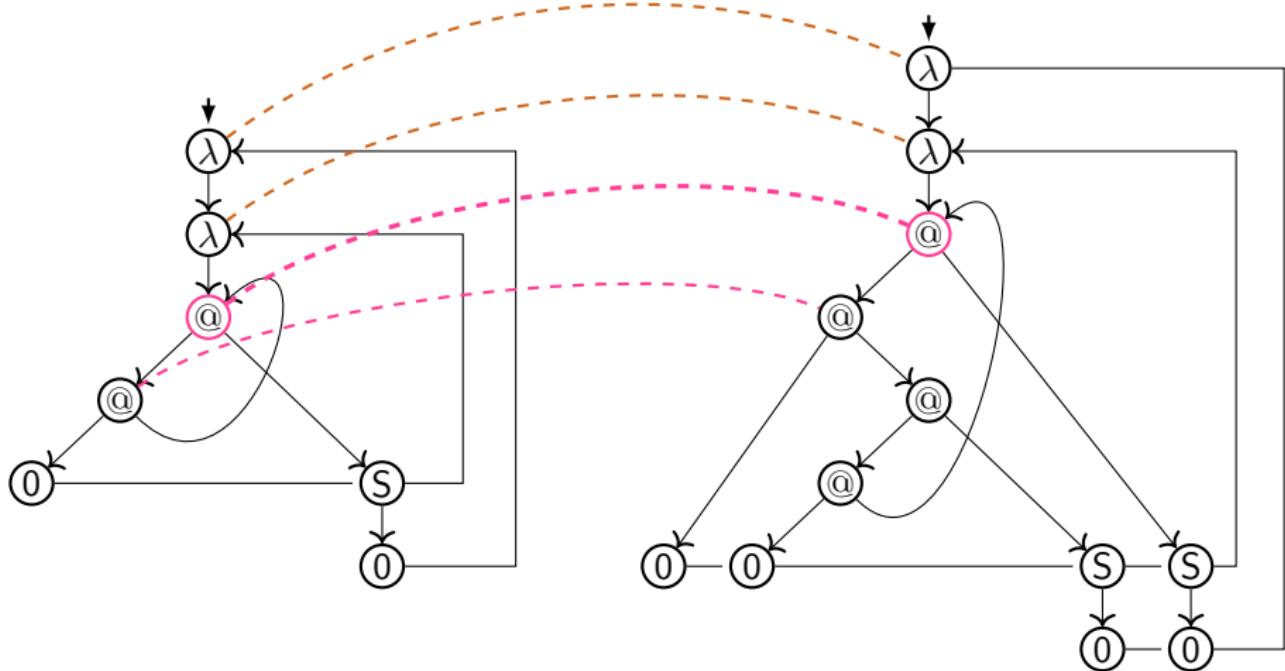
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_T$
 $\llbracket L \rrbracket_T$

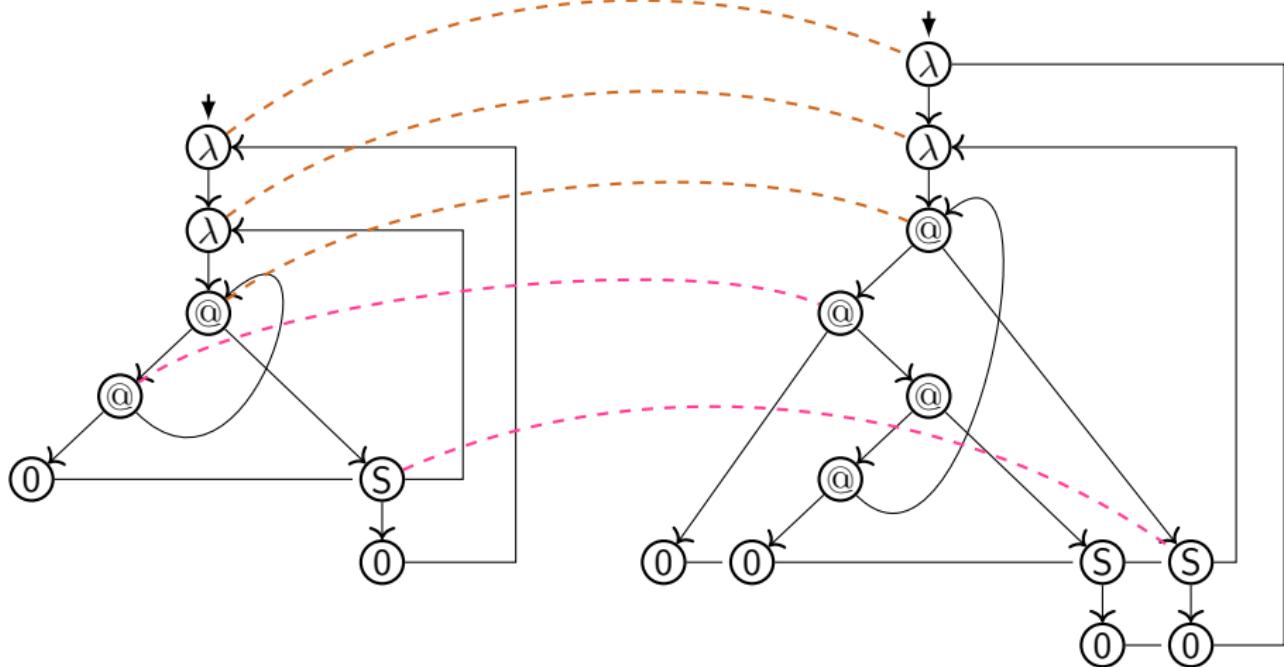
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_T$
 $\llbracket L \rrbracket_T$

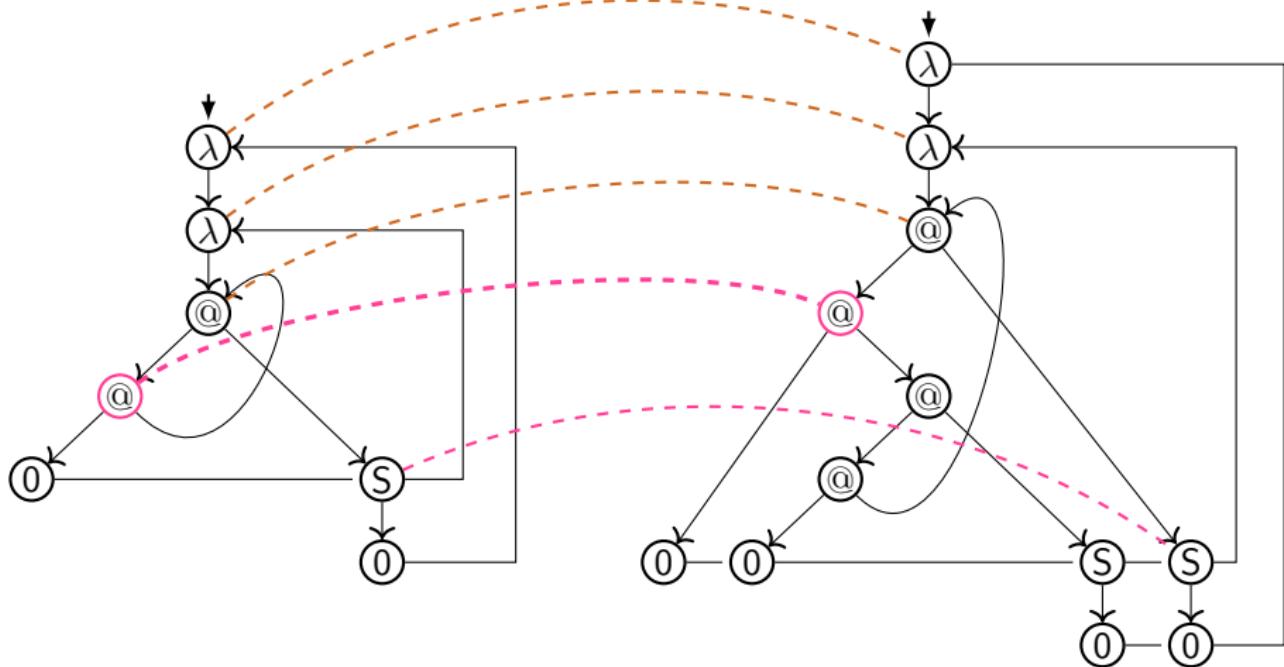
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

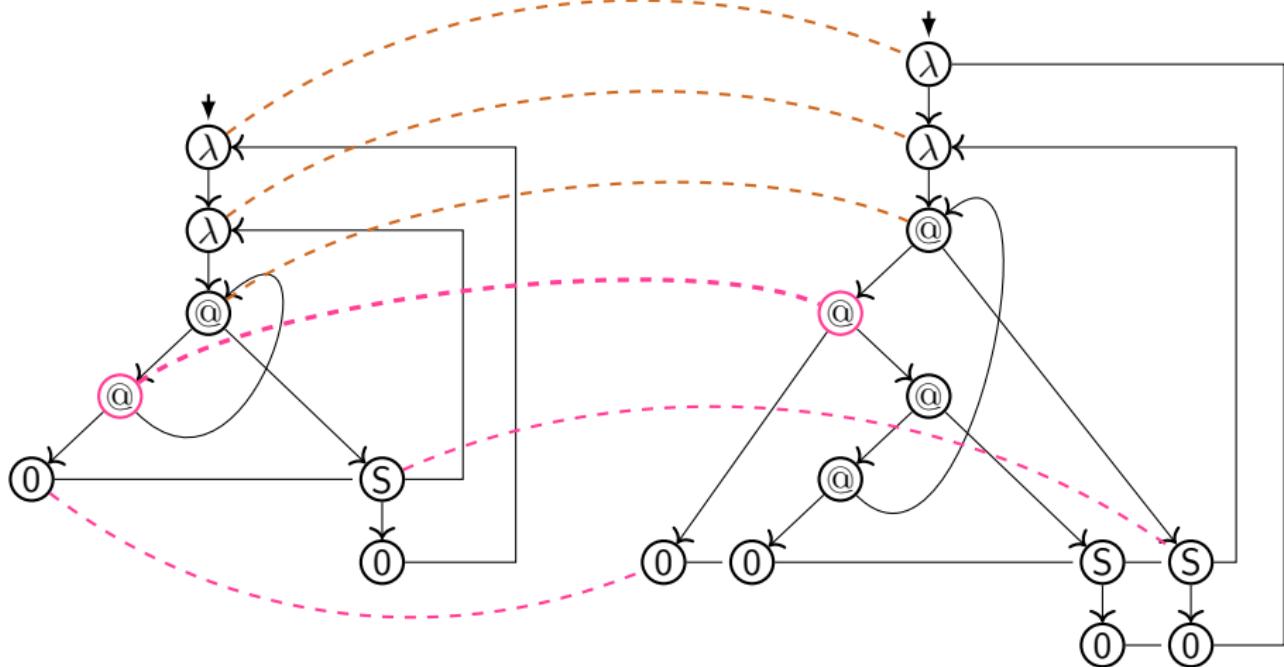
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

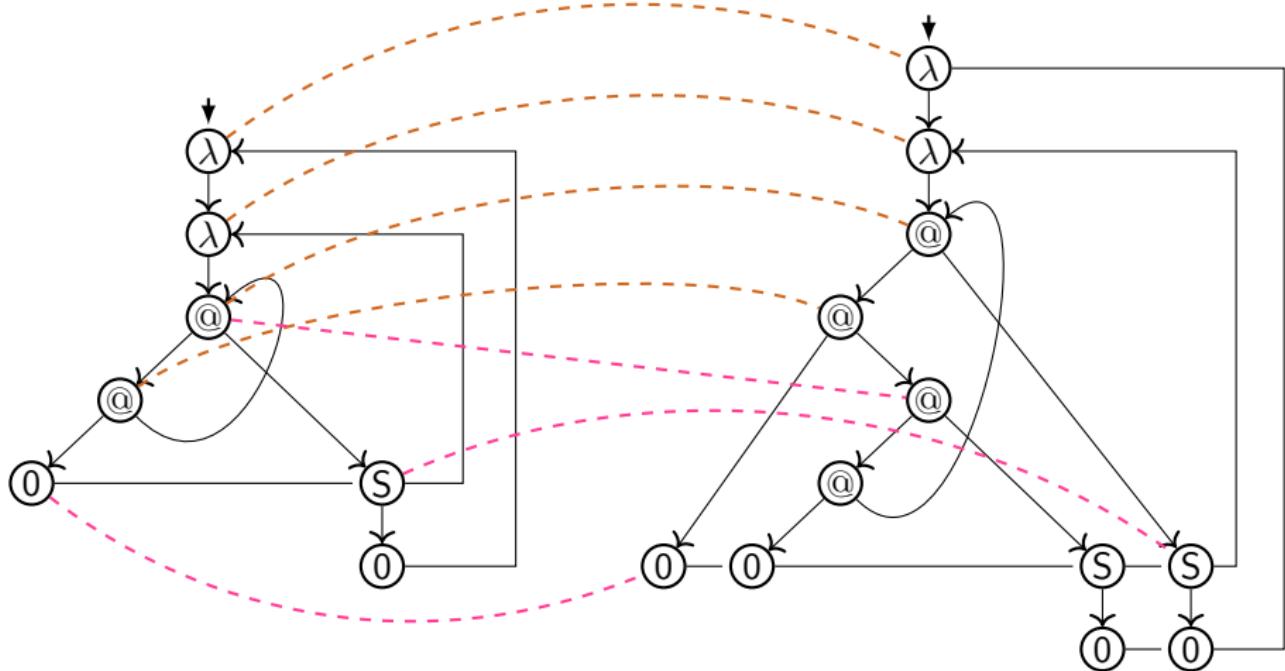
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 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

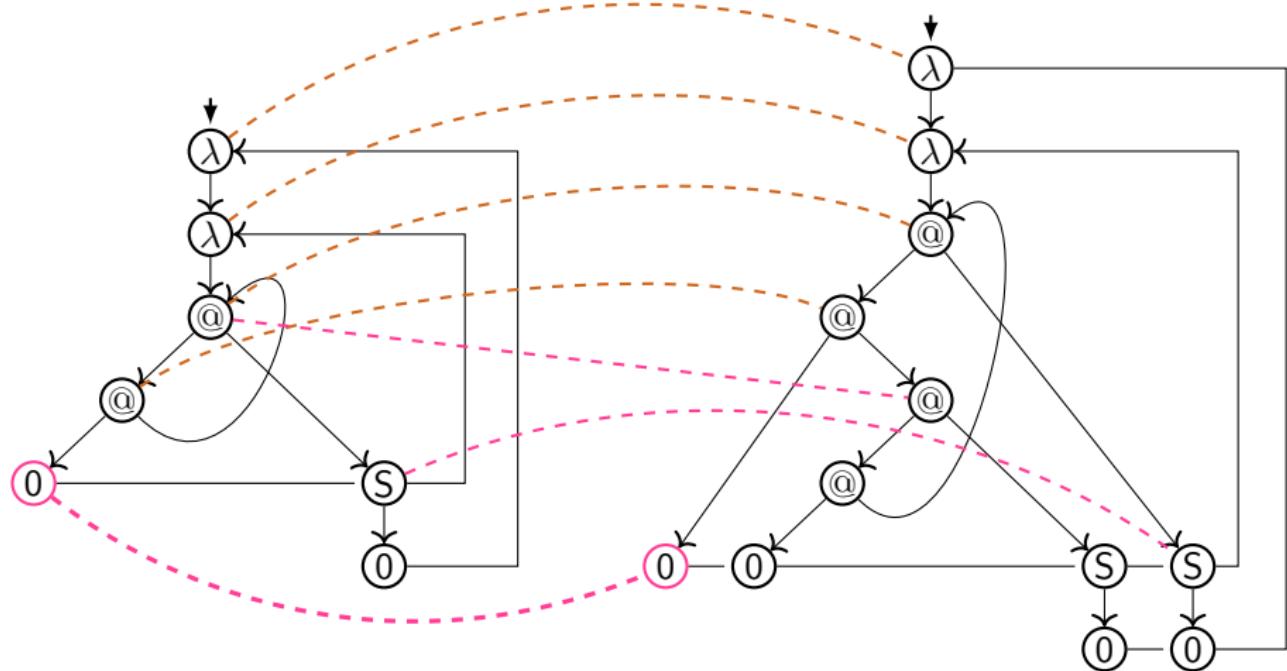
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

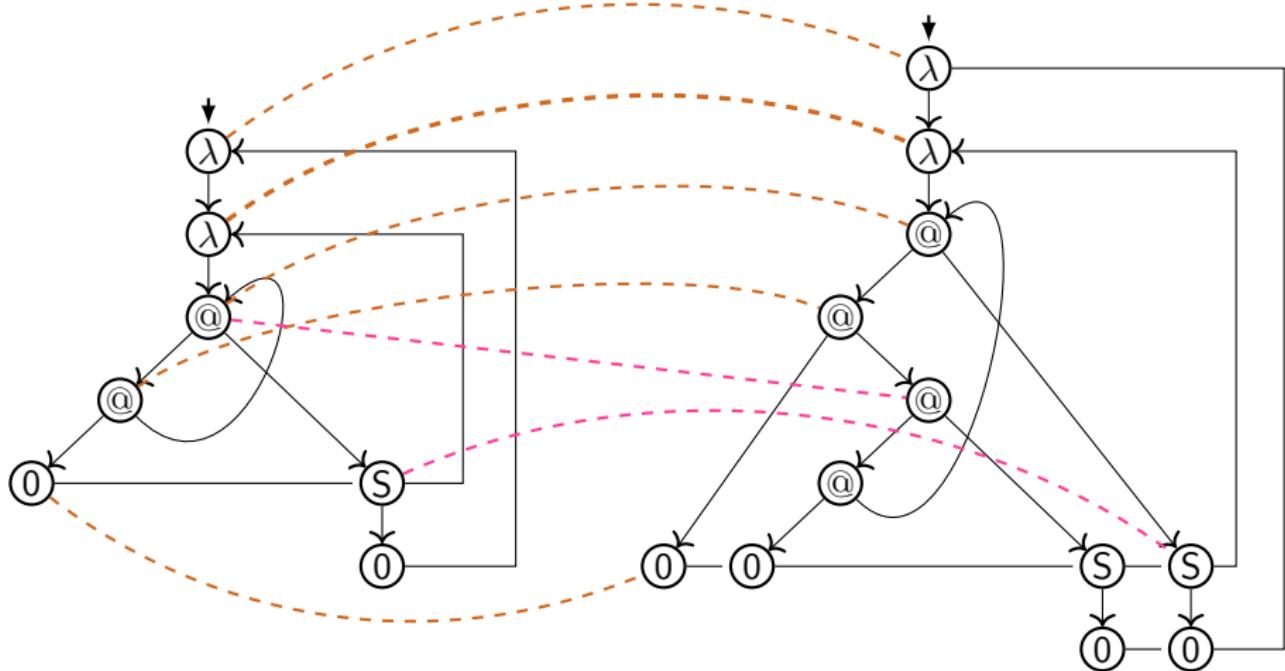
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 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

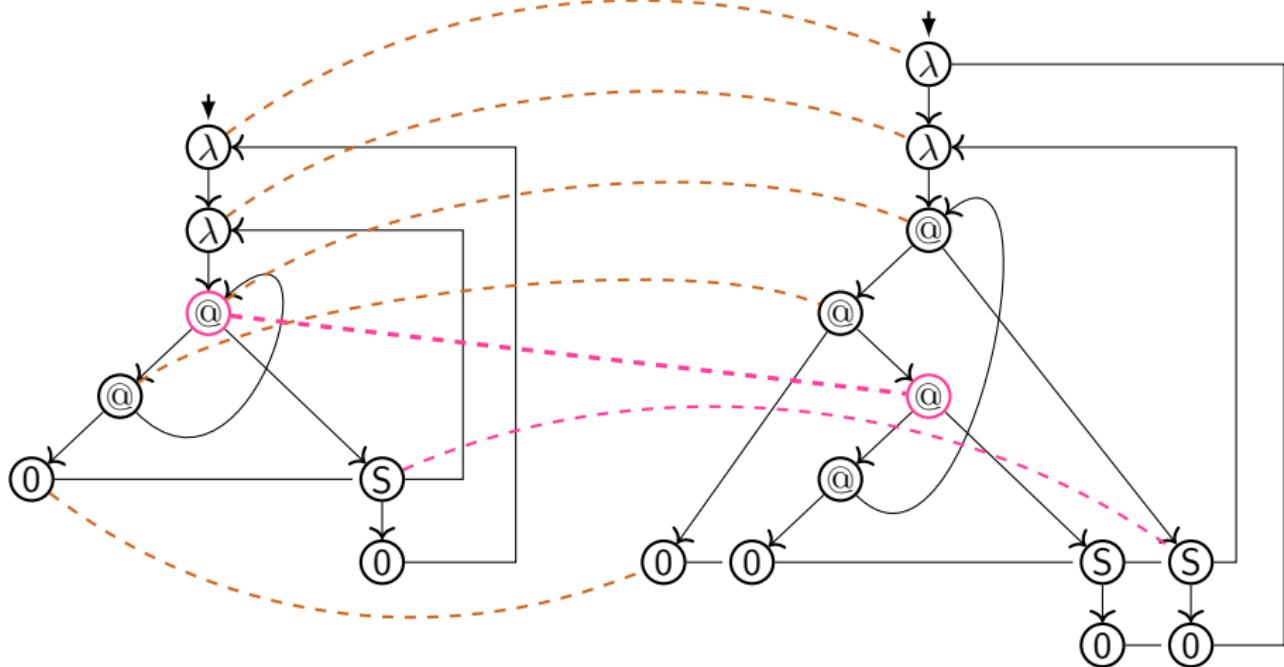
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

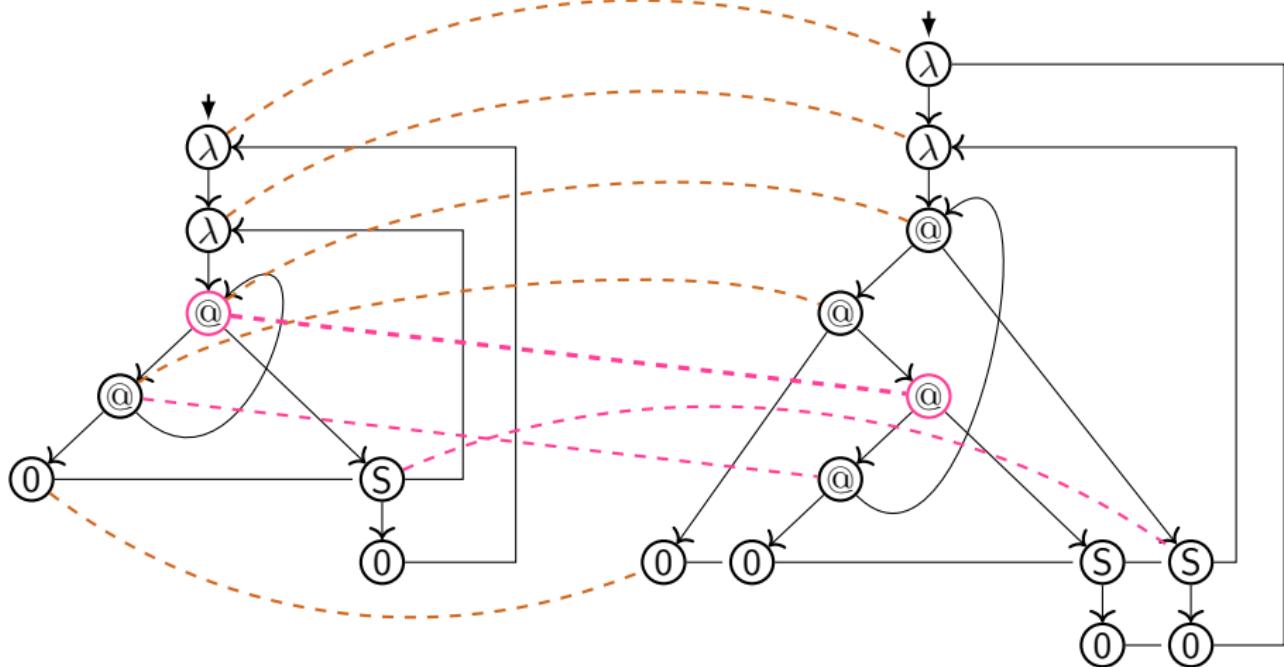
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 $\llbracket L \rrbracket_{\mathcal{T}}$

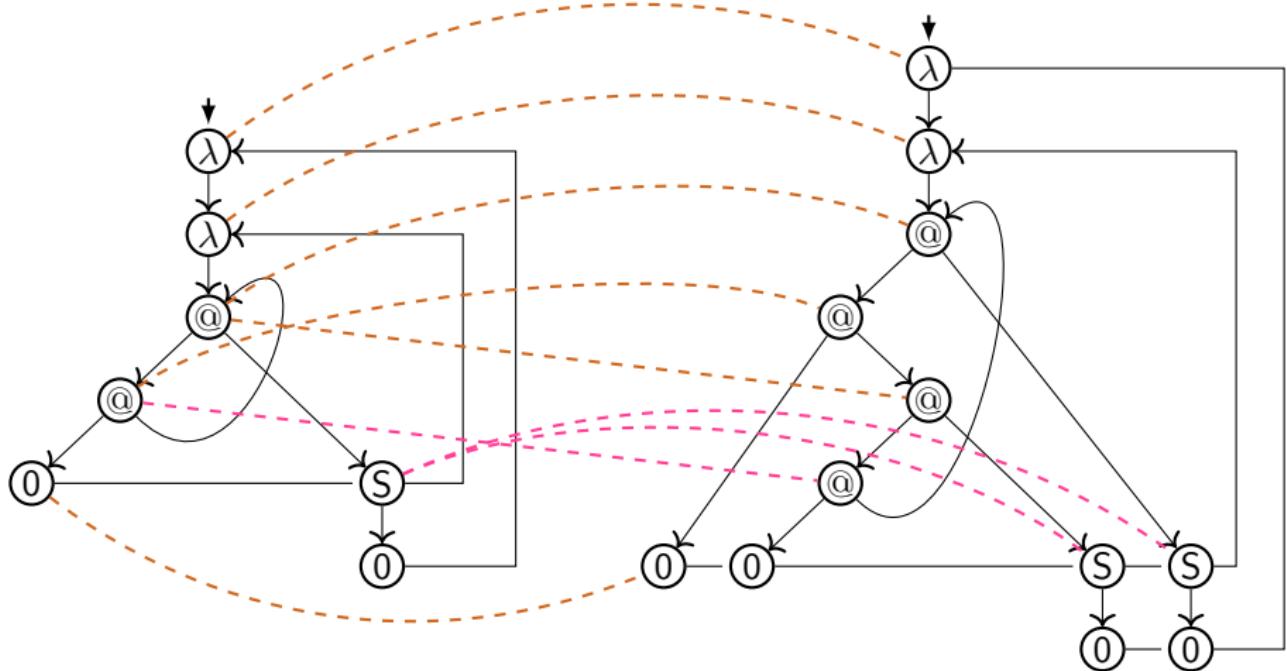
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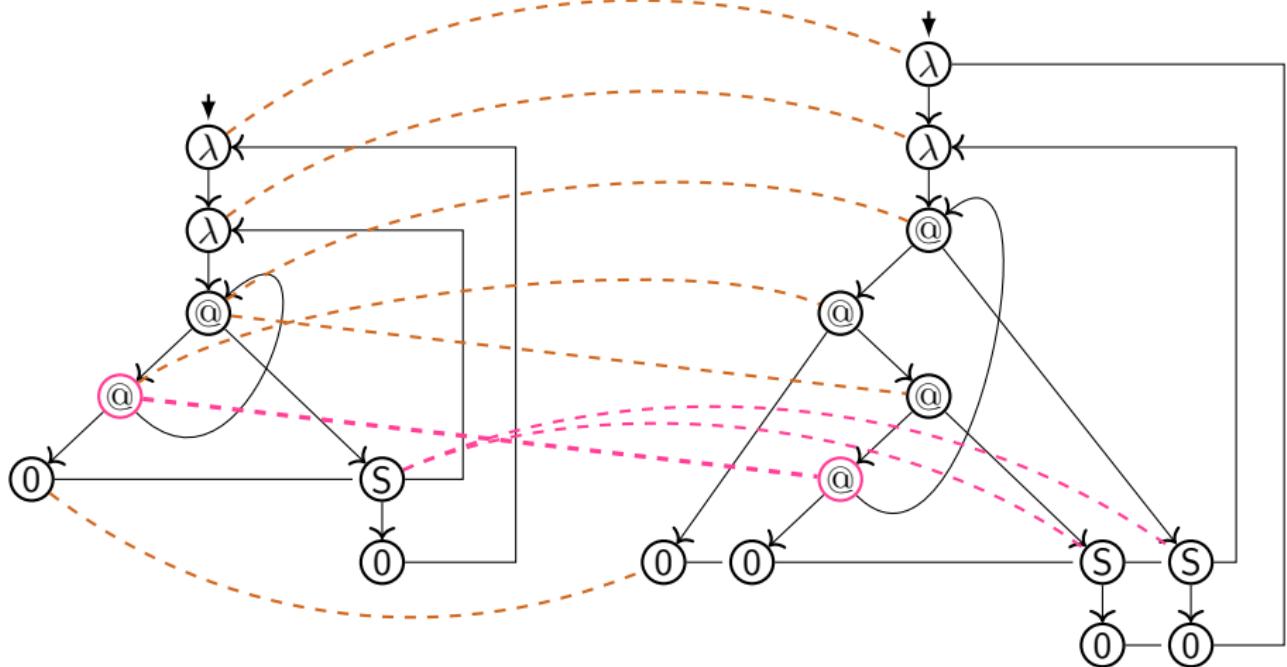
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
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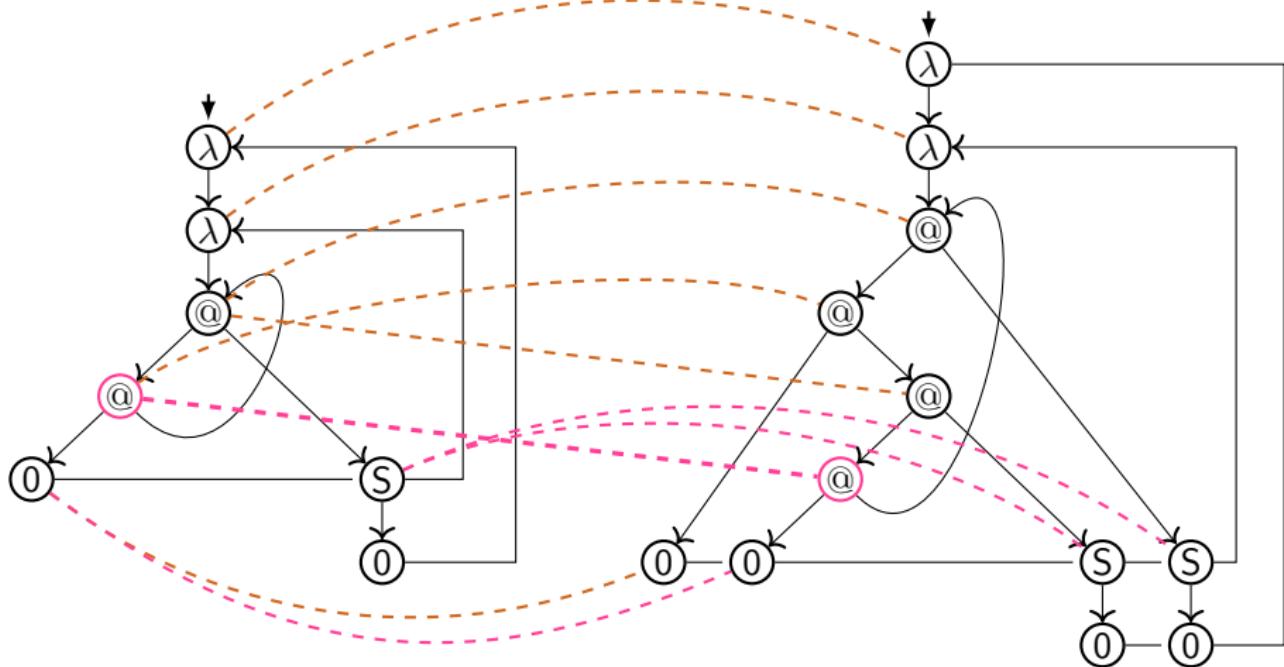
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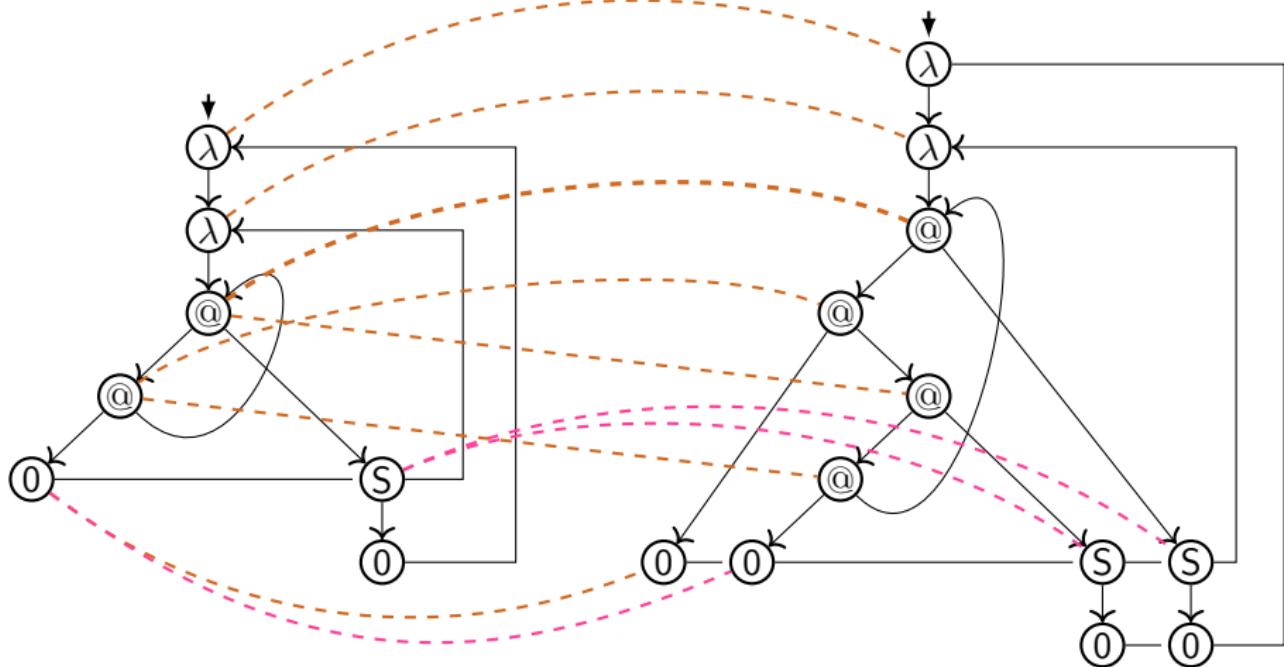
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
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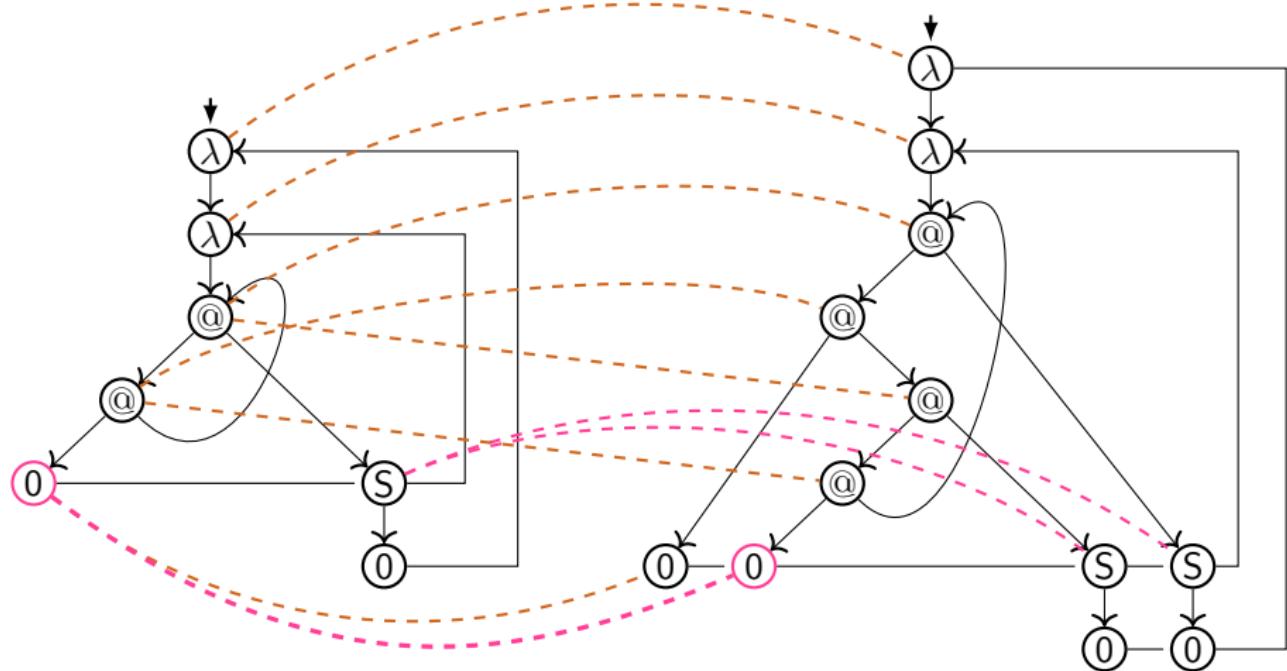
Bisimulation check between λ -term-graphs


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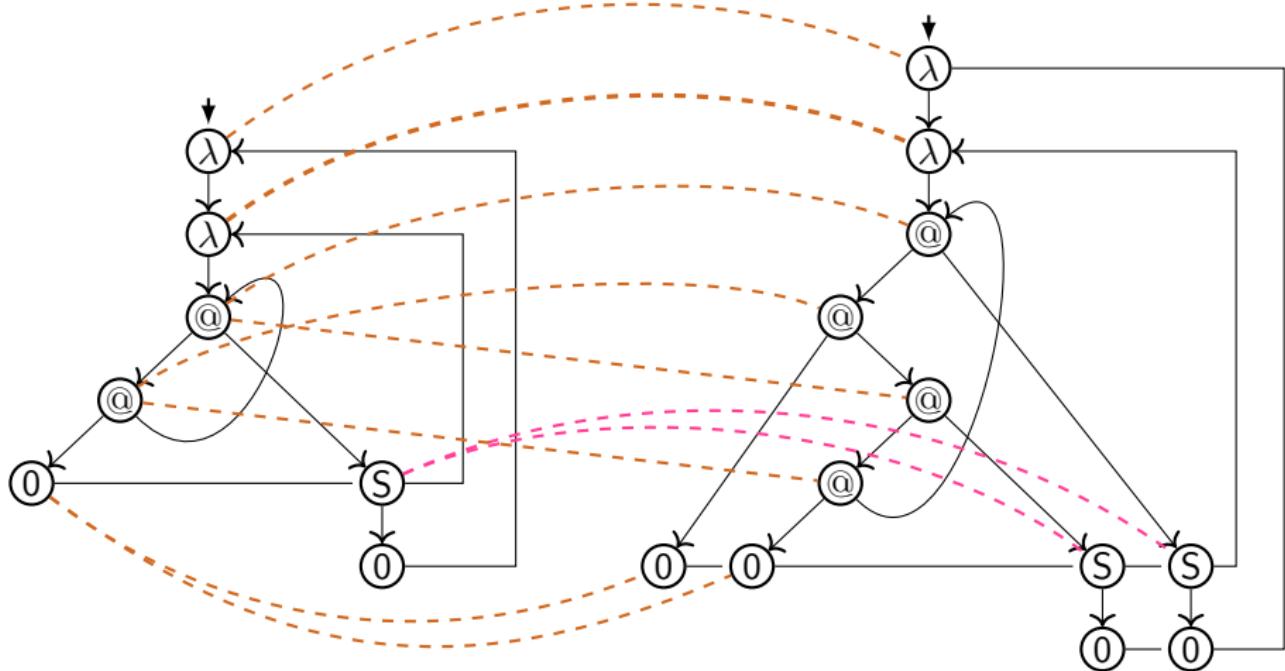
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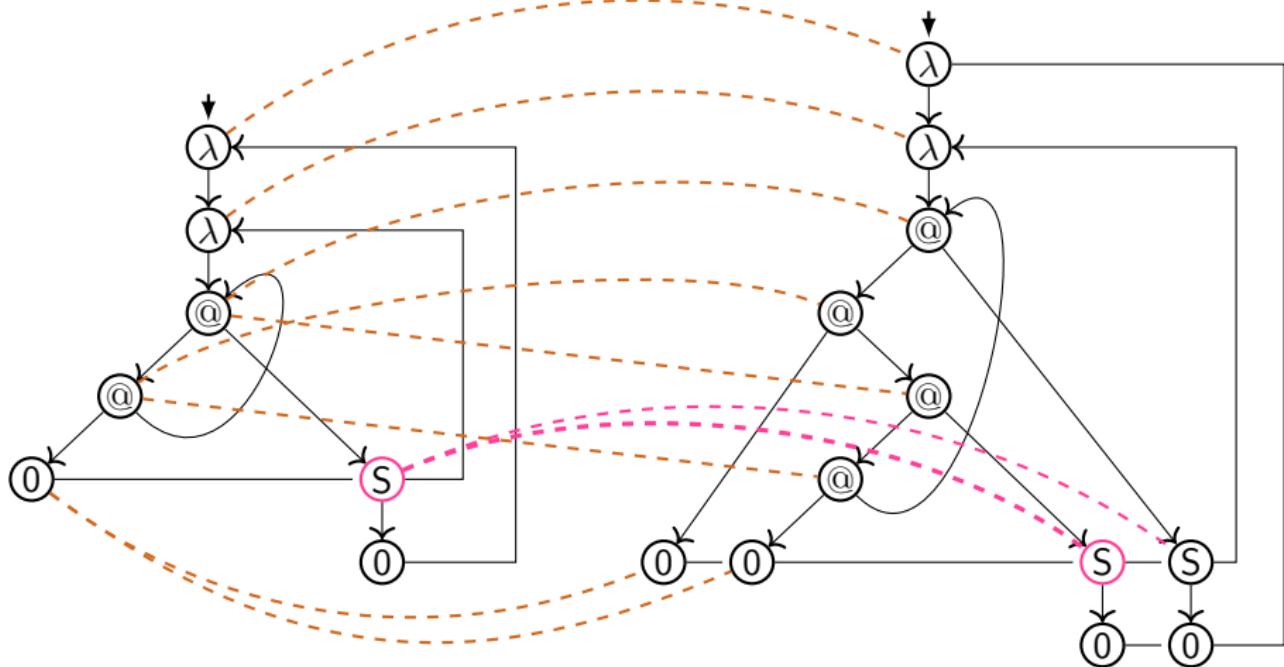
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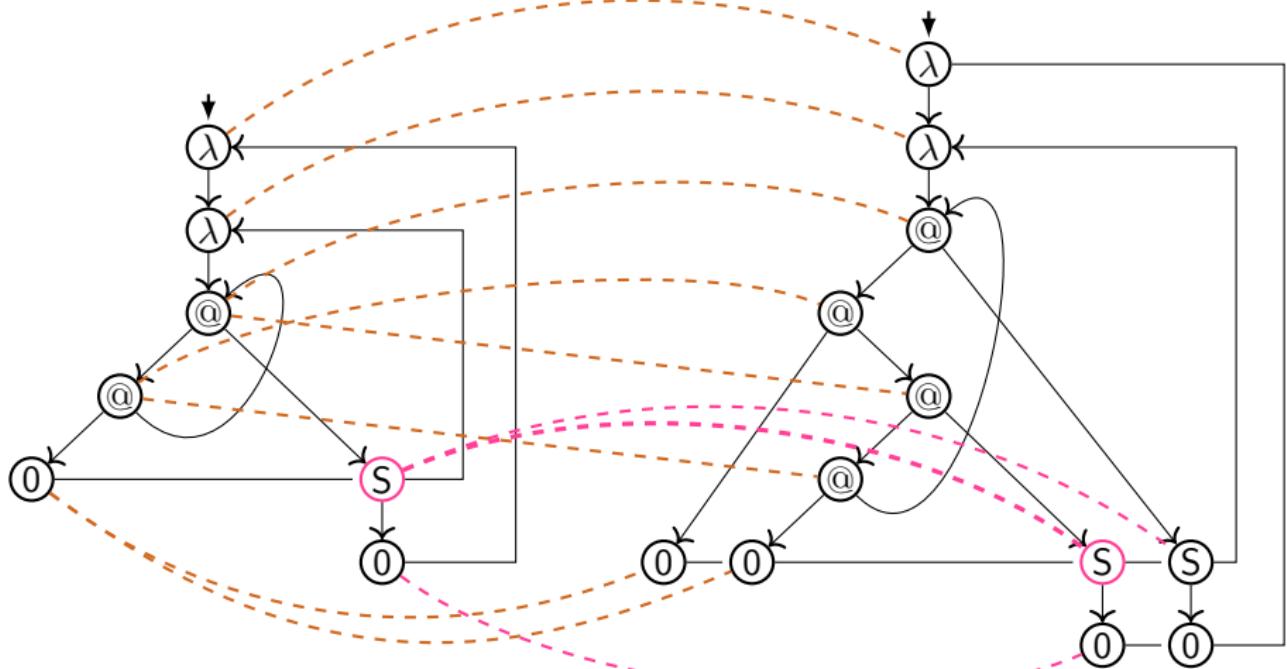
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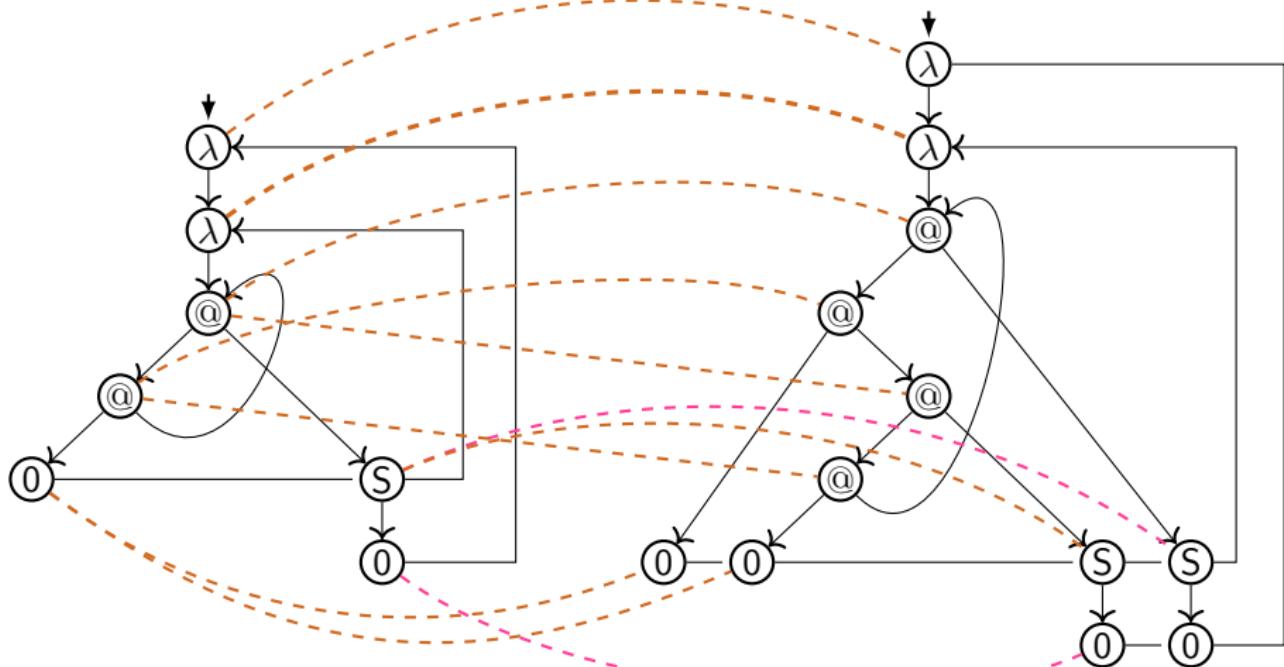
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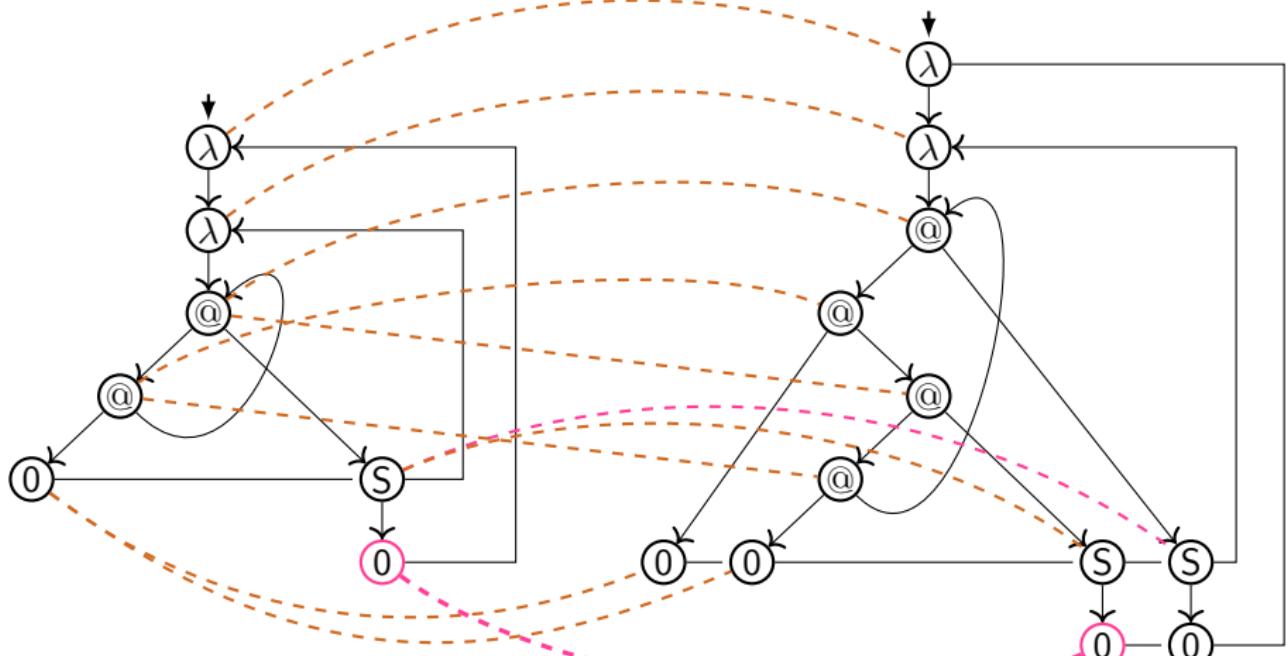
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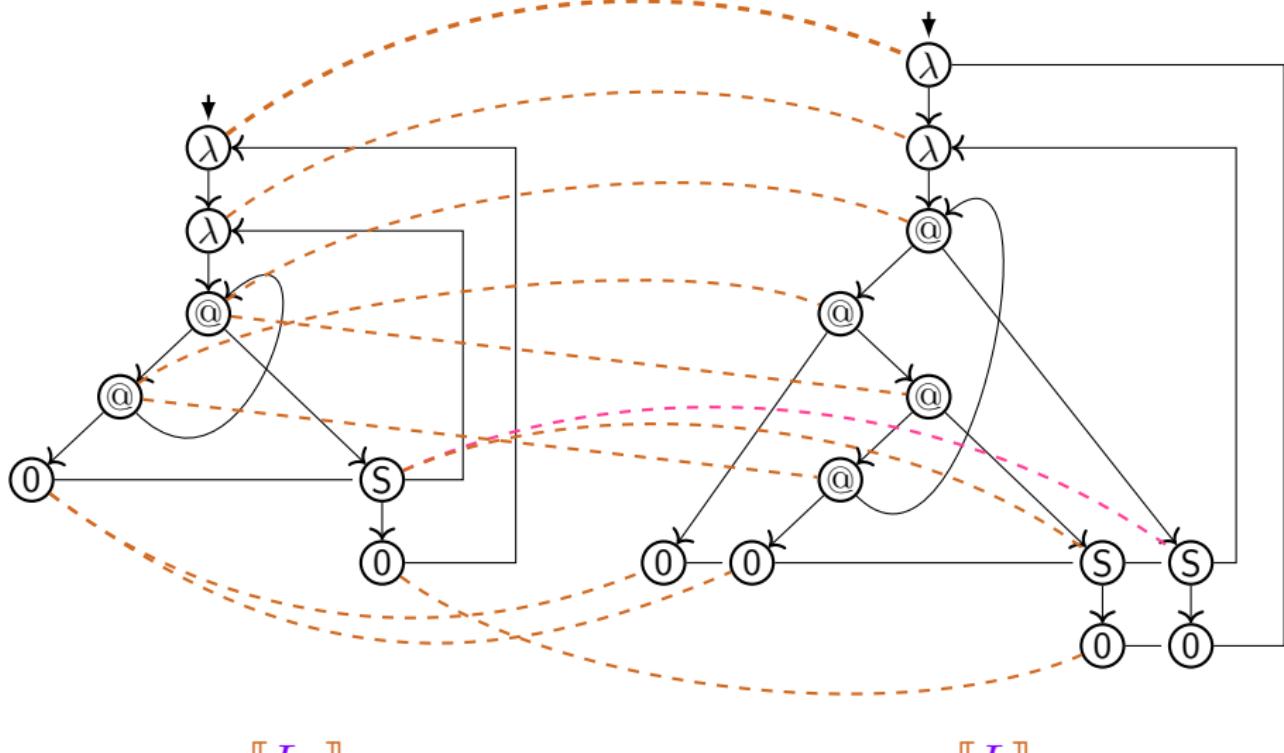
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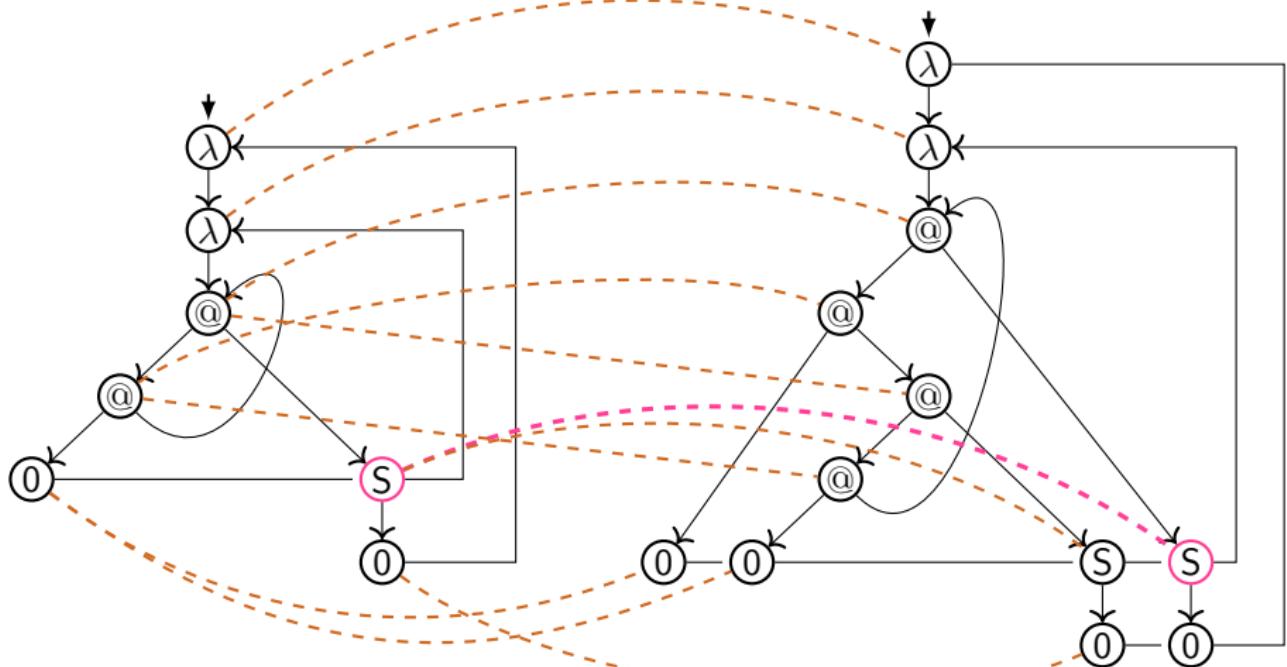
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
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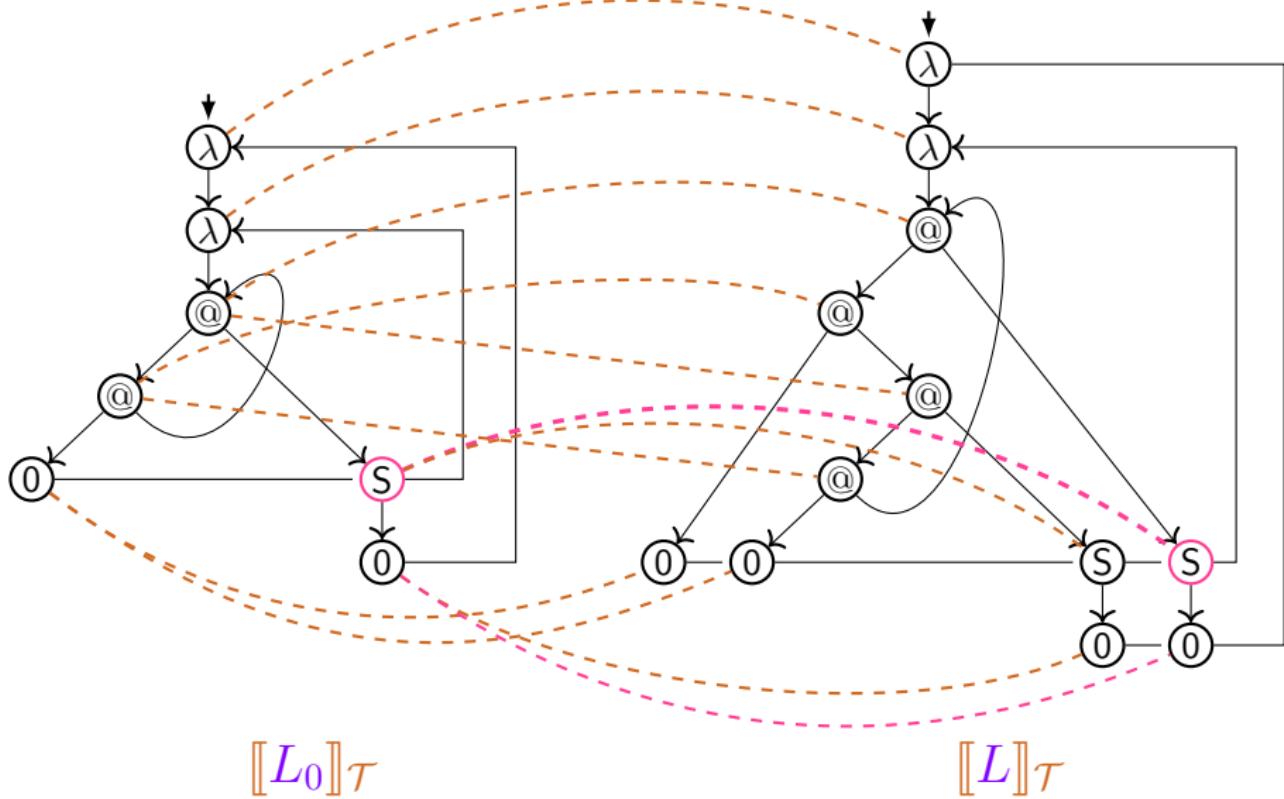
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
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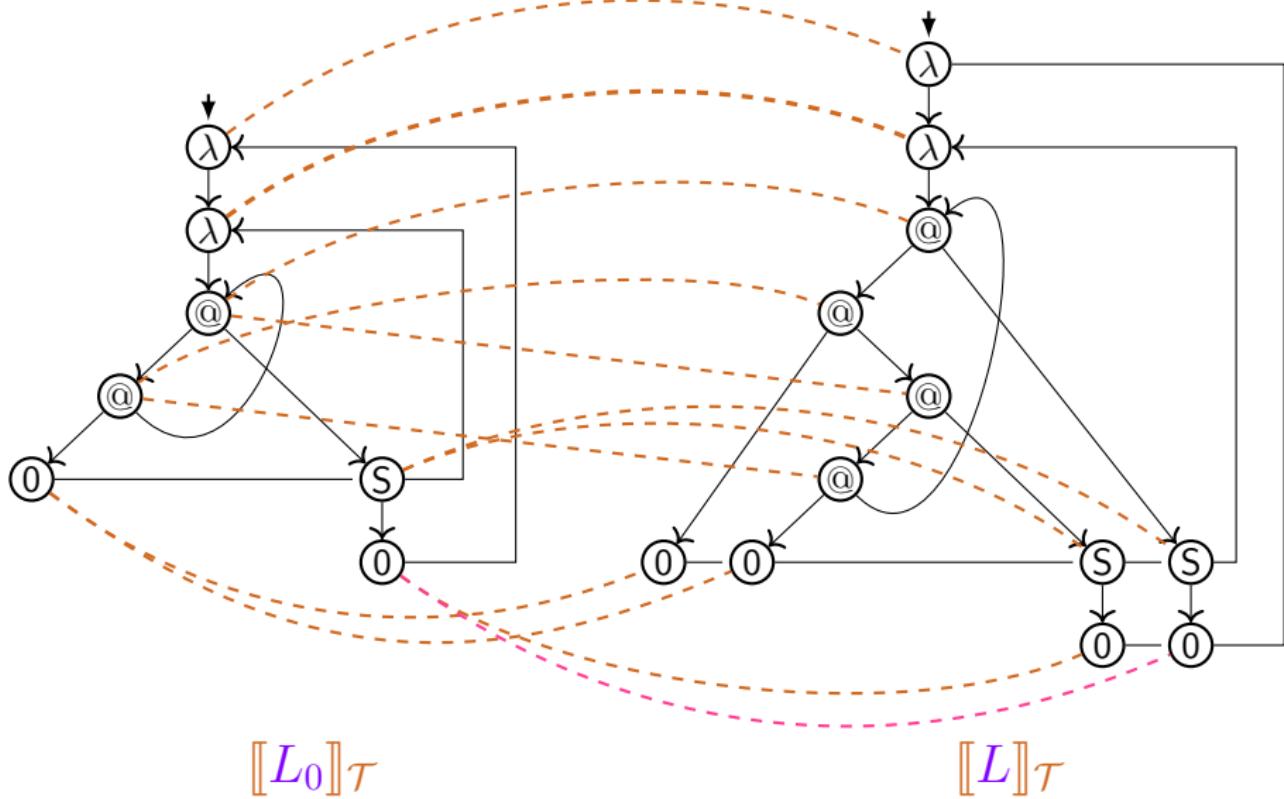
Bisimulation check between λ -term-graphs


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 $\llbracket L \rrbracket_{\mathcal{T}}$

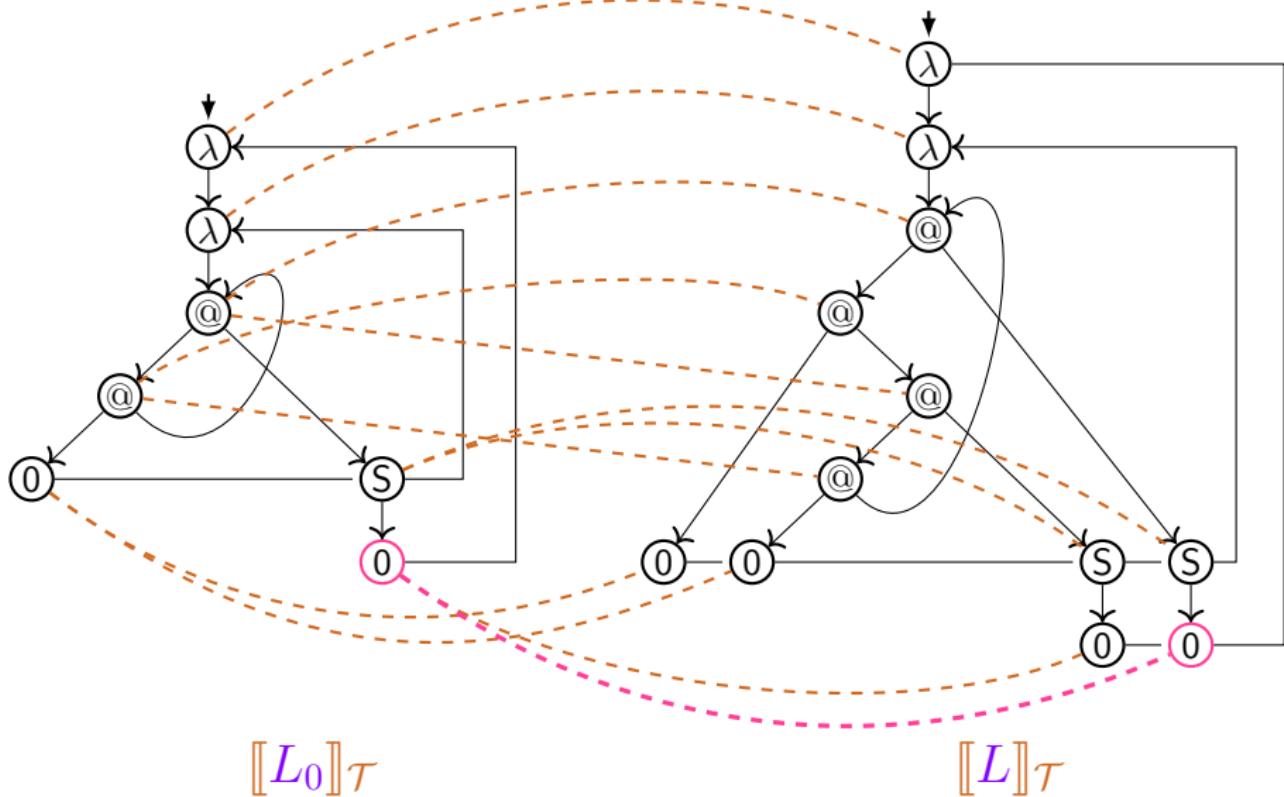
Bisimulation check between λ -term-graphs



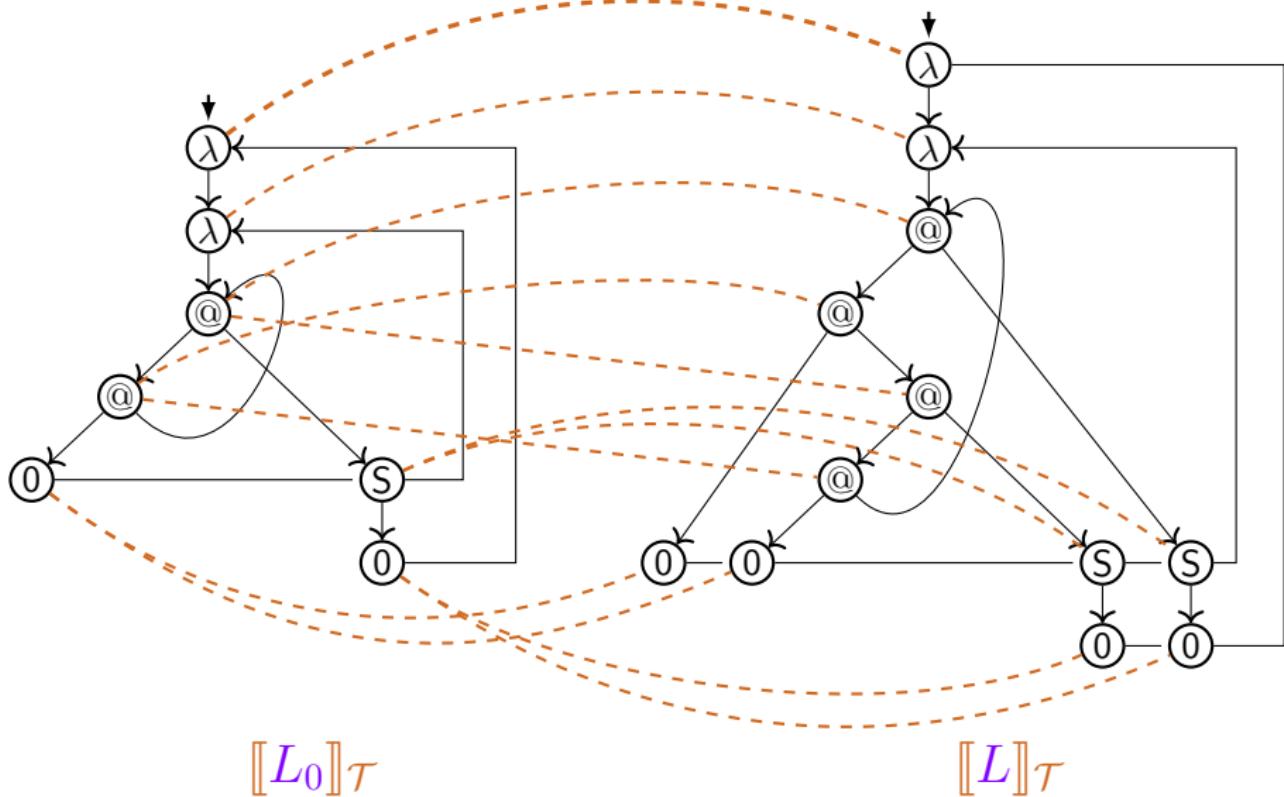
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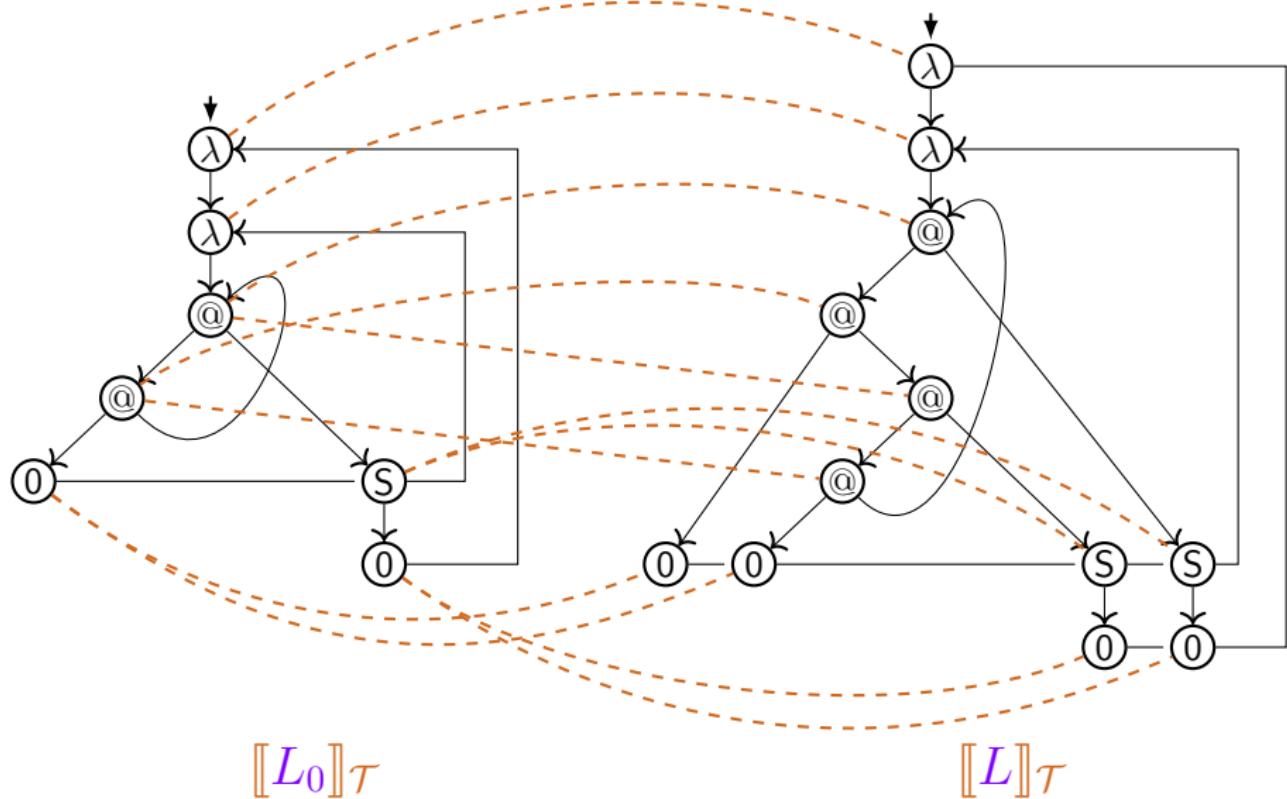
Bisimulation check between λ -term-graphs


 $\llbracket L_0 \rrbracket_\tau$
 $\llbracket L \rrbracket_\tau$

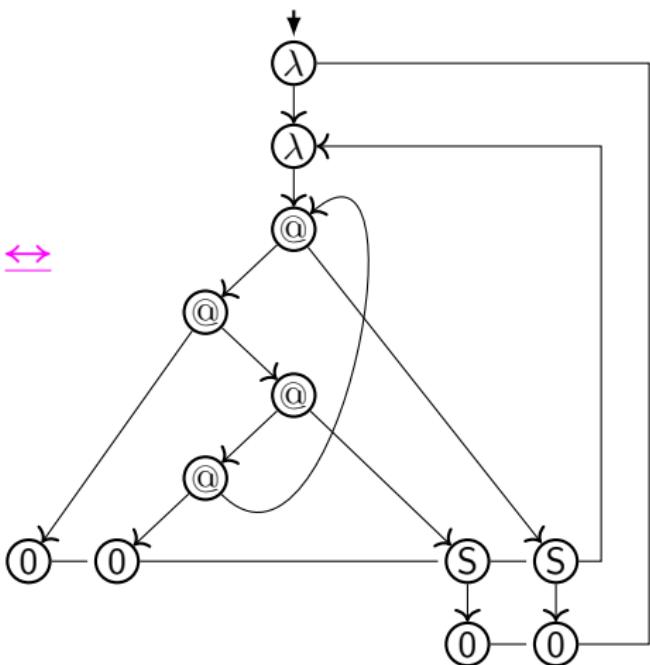
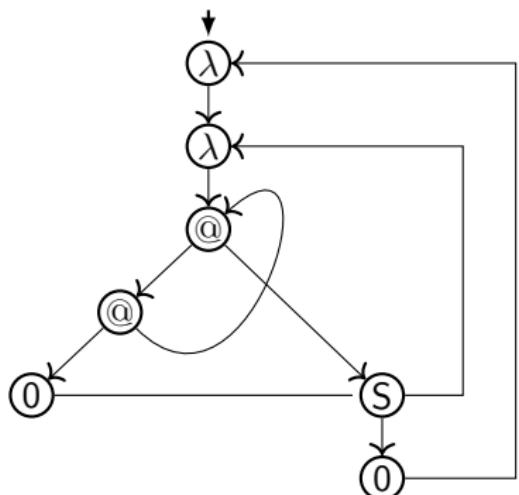
Bisimulation check between λ -term-graphs



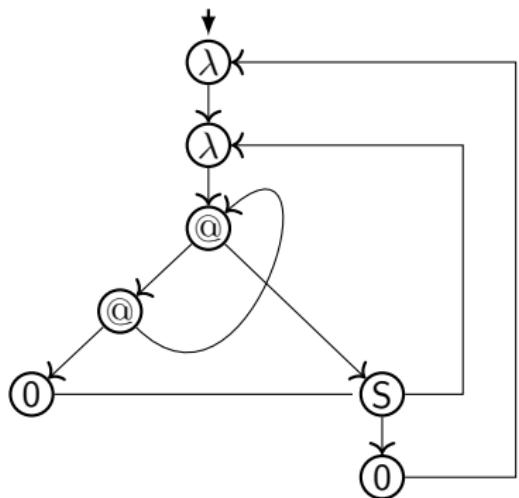
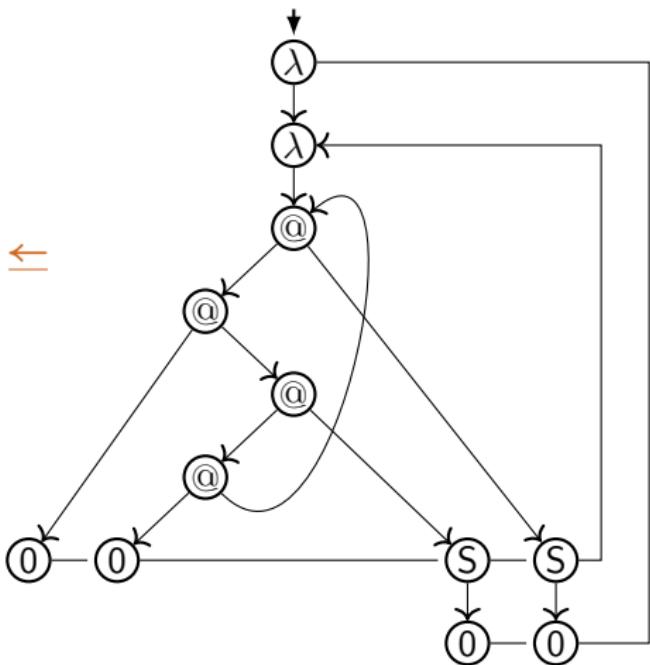
bisimulation between λ -term-graphs


 $\llbracket L_0 \rrbracket_\tau$
 $\llbracket L \rrbracket_\tau$

bisimilarity between λ -term-graphs


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 \Updownarrow
 $\llbracket L \rrbracket_{\mathcal{T}}$

functional bisimilarity and bisimulation collapse


 $\llbracket L_0 \rrbracket_{\mathcal{T}}$
 \Leftarrow
 $\llbracket L \rrbracket_{\mathcal{T}}$


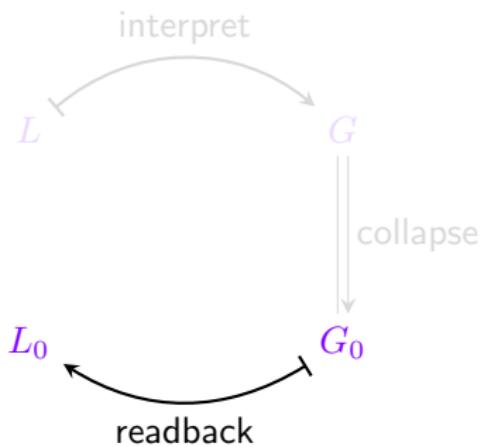
Bisimulation collapse: property

Theorem

*The class of eager-scope λ -term-graphs
is closed under functional bisimilarity Ξ .*

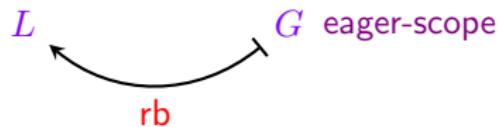
→ For a λ_{letrec} -term L
the bisimulation collapse of $\llbracket L \rrbracket_T$ is again an eager-scope λ -term-graph.

Readback



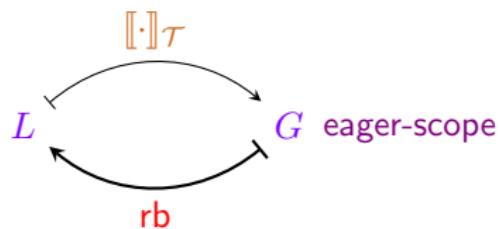
Readback

defined with property:



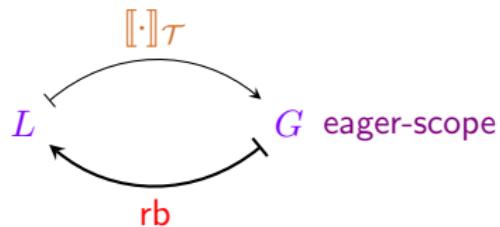
Readback

defined with property:



Readback

defined with property:



Theorem

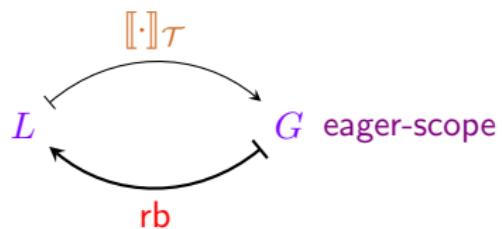
For all eager-scope λ -term-graphs G :

$$([\![\cdot]\!]_\tau \circ rb)(G) \simeq G$$

The readback rb is a right-inverse of $[\![\cdot]\!]_\tau$ modulo isomorphism \simeq .

Readback

defined with property:



Theorem

For all eager-scope λ -term-graphs G :

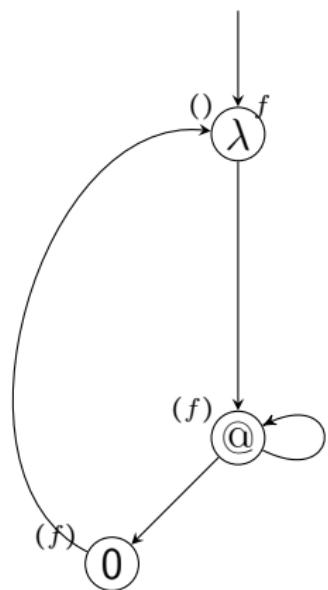
$$([\![\cdot]\!]_{\tau} \circ rb)(G) \simeq G$$

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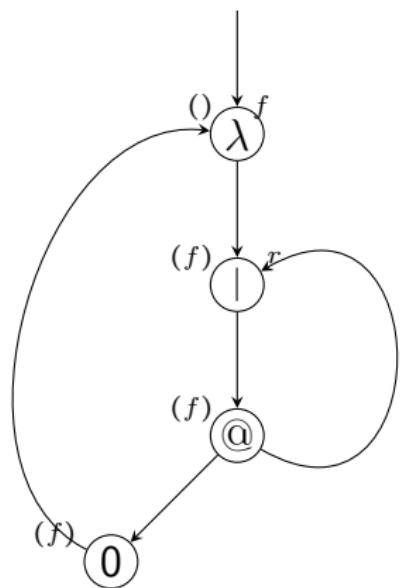
idea:

1. construct a spanning tree T of G
2. using local rules, in a bottom-up traversal of T synthesize $L = rb(G)$

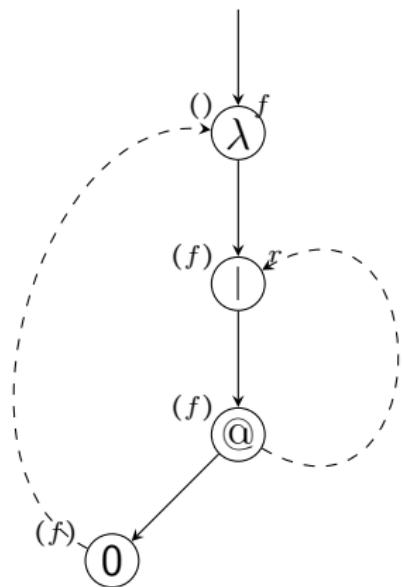
Readback: example (fix)



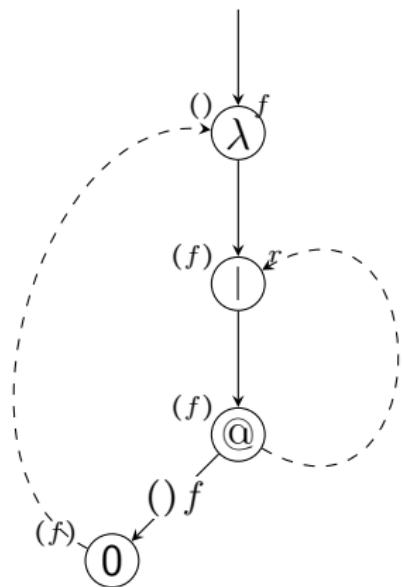
Readback: example (fix)



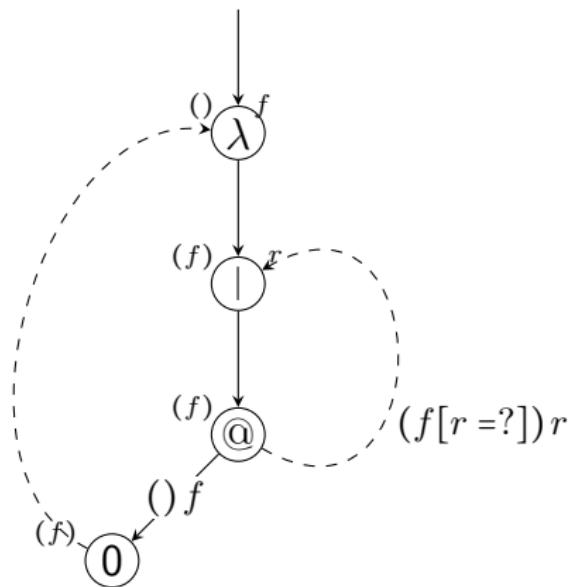
Readback: example (fix)



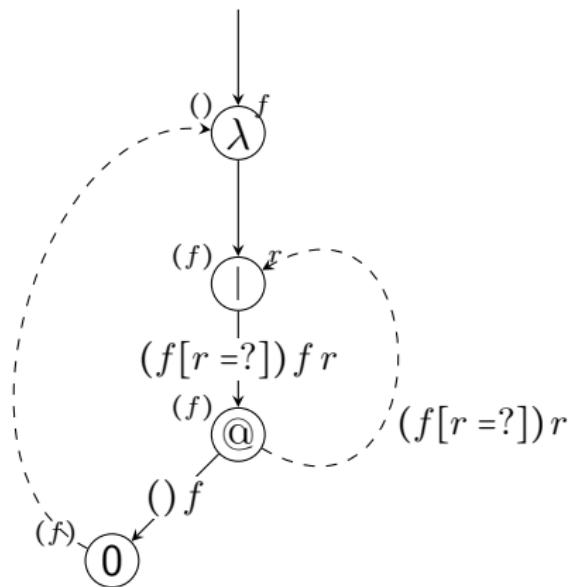
Readback: example (fix)



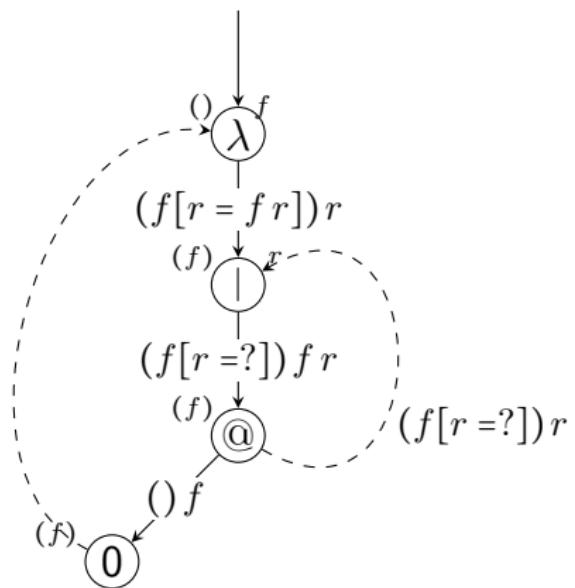
Readback: example (fix)



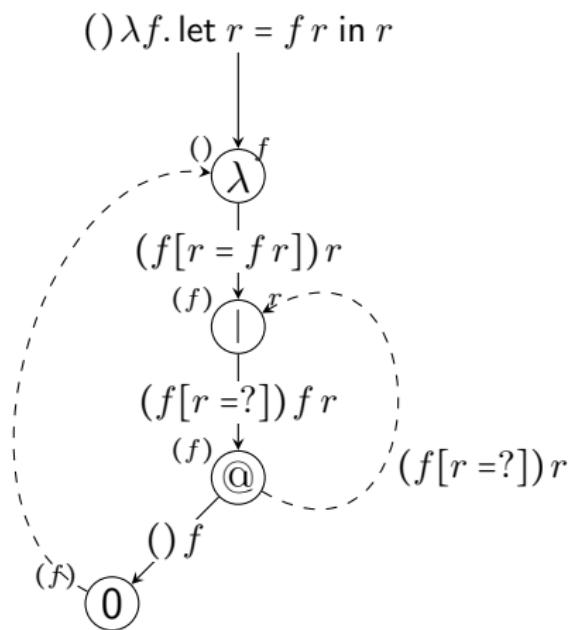
Readback: example (fix)



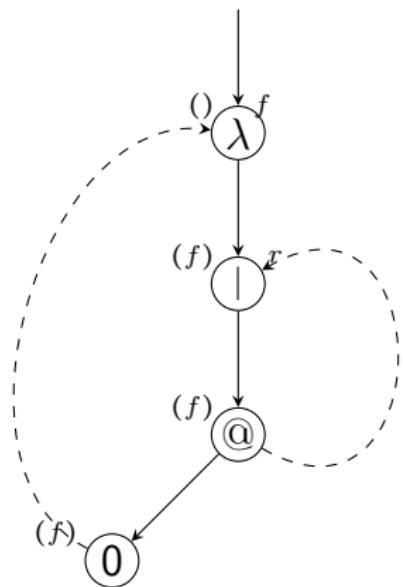
Readback: example (fix)



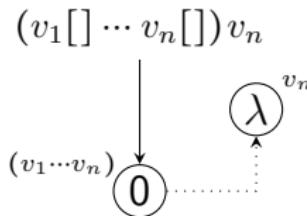
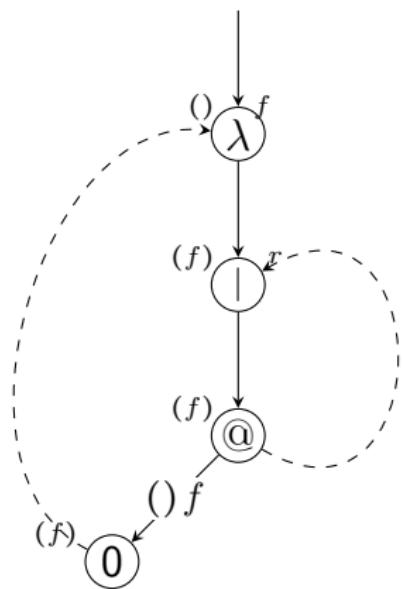
Readback: example (fix)



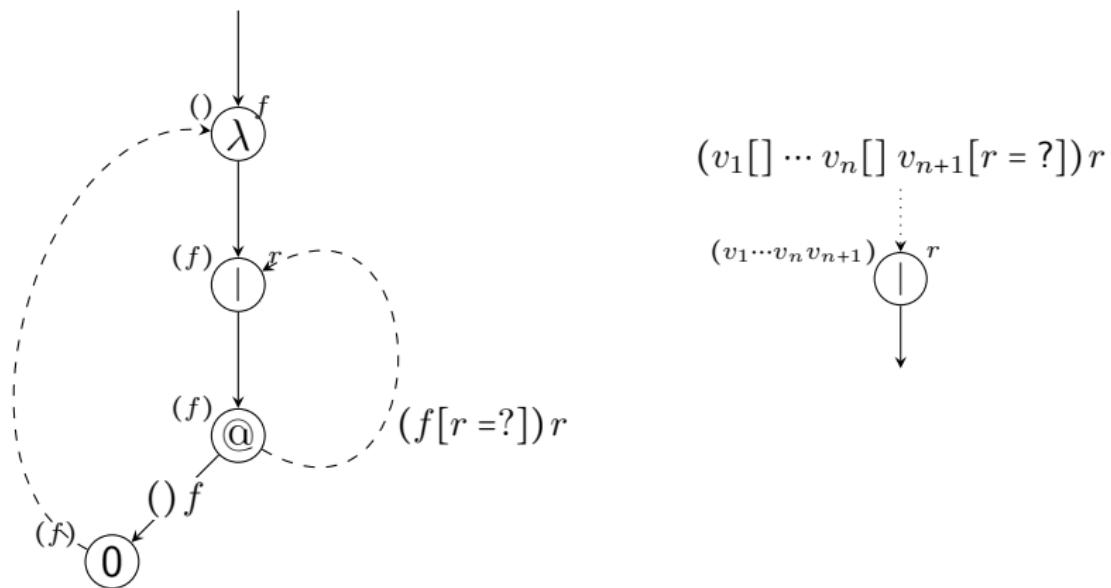
Readback: example (fix)



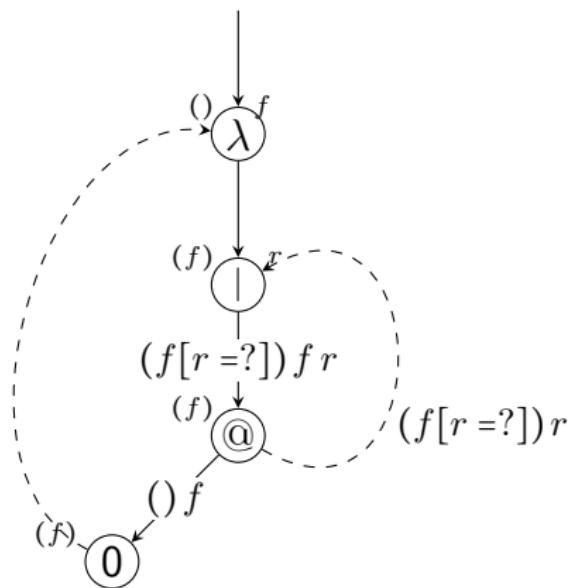
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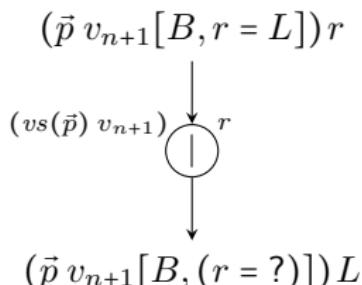
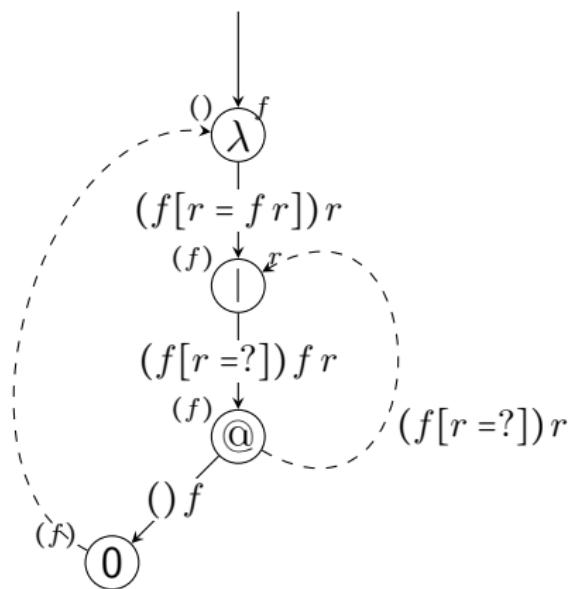


Readback: example (fix)

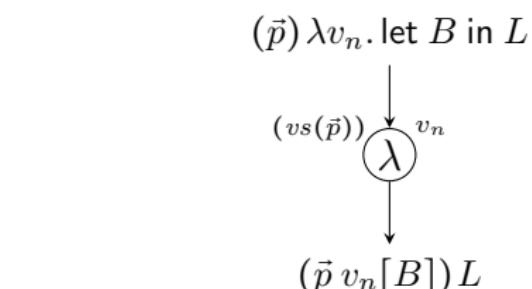
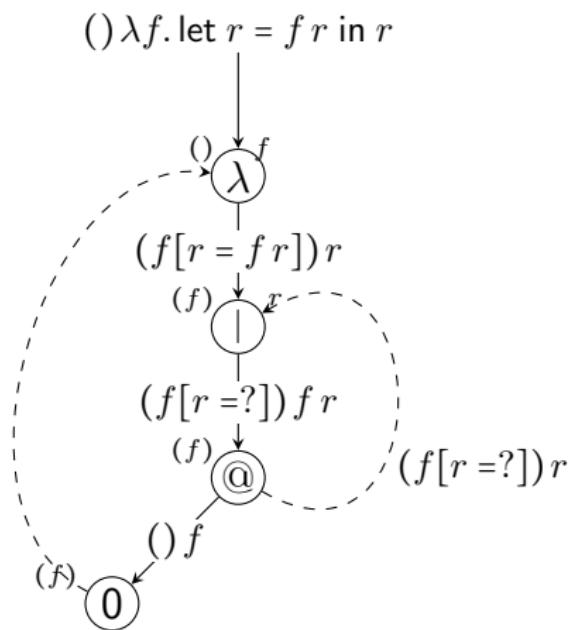


$$\begin{array}{c}
 (\vec{p}_0 \vec{\cup} \vec{p}_1) L_0 L_1 \\
 \downarrow (\vec{v}) \\
 @ \\
 \swarrow (\vec{p}_0) L_0 \quad \searrow (\vec{p}_1) L_1
 \end{array}$$

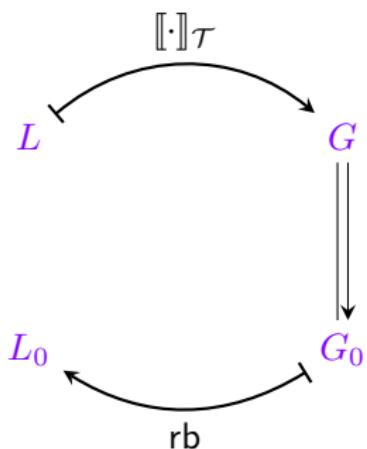
Readback: example (fix)



Readback: example (fix)



Maximal sharing: complexity



1. interpretation

of λ_{letrec} -term L with $|L| = n$

as λ -term-graph $G = \llbracket L \rrbracket_\tau$

- ▶ in time $O(n^2)$, size $|G| \in O(n^2)$.

2. bisimulation collapse \Downarrow

of f-o term graph G into G_0

- ▶ in time $O(|G| \log |G|) = O(n^2 \log n)$

3. readback rb

of f-o term graph G_0

yielding λ_{letrec} -term $L_0 = \text{rb}(G_0)$.

- ▶ in time $O(|G| \log |G|) = O(n^2 \log n)$

Theorem

Computing a maximally compact form $L_0 = (\text{rb} \circ \Downarrow \circ \llbracket \cdot \rrbracket_\tau)(L)$ of L for a λ_{letrec} -term L requires time $O(n^2 \log n)$, where $|L| = n$.

Demo: console output

jan:~/papers/maxsharing-ICFP/talks/ICFP-2014> maxsharing running.l

λ -letrec-term:

$\lambda x. \lambda f. \text{ let } r = f (f\ r\ x) \text{ x in } r$

derivation:

```

----- 0          ----- 0
(x f[r]) f      (x f[r]) r      (x) x
----- @ ----- S
(x f[r]) f r    (x f[r]) x
----- 0          ----- 0
(x f[r]) f      (x f[r]) f r x
----- @ ----- S
(x f[r]) f (f r x)      (x f[r]) x
----- @ ----- S
(x f[r]) f (f r x) x      (x f[r]) r
----- @ ----- let
(x f) let r = f (f r x) x in r
----- @ ----- λ
(x) λf. let r = f (f r x) x in r
----- @ ----- λ
() λx. λf. let r = f (f r x) x in r

```

writing DFA to file: running-dfa.pdf

readback of DFA:

$\lambda x. \lambda y. \text{ let } F = y (y\ F\ x) \text{ x in } F$

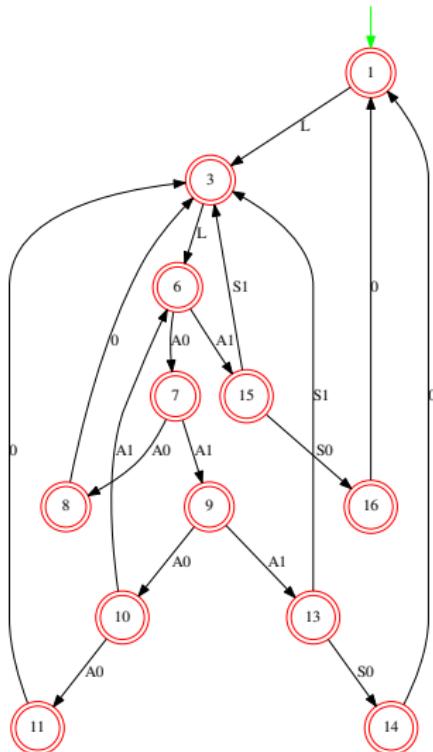
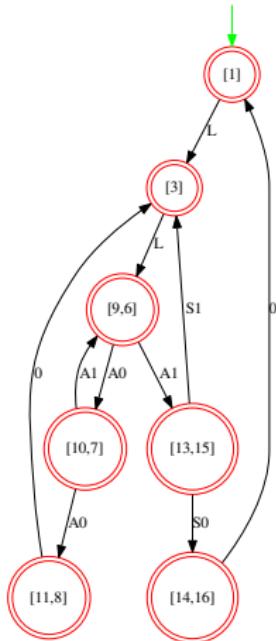
writing minimised DFA to file: running-mindfa.pdf

readback of minimised DFA:

$\lambda x. \lambda y. \text{ let } F = y\ F\ x \text{ in } F$

jan:~/papers/maxsharing-ICFP/talks/ICFP-2014> █

Demo: generated λ -NFAs

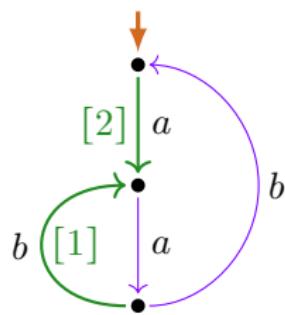


Resources (maximal sharing)

- ▶ tool **maxsharing** on hackage.haskell.org
- ▶ articles and reports
 - ▶ Maximal Sharing in the Lambda Calculus with Letrec
 - ▶ ICFP 2014 paper
 - ▶ accompanying report [arXiv:1401.1460](https://arxiv.org/abs/1401.1460)
 - ▶ Term Graph Representations for Cyclic Lambda Terms
 - ▶ TERMGRAPH 2013 proceedings
 - ▶ extended report [arXiv:1308.1034](https://arxiv.org/abs/1308.1034)
 - ▶ Vincent van Oostrom, CG: Nested Term Graphs
 - ▶ TERMGRAPH 2014 post-proceedings in [EPTCS 183](https://eptcs.net/eptcs/183)
- ▶ thesis Jan Rochel
 - ▶ Unfolding Semantics of the Untyped λ -Calculus with letrec
 - ▶ Ph.D. Thesis, Utrecht University, 2016

Process interpretation of regular expressions

(based on joint work with Wan Fokkink)



Regular expressions *(S.C. Kleene, 1951)*

Definition

The set $\text{Reg}(A)$ of **regular expressions** over alphabet A is defined by the grammar:

$$e, f ::= 0 \mid 1 \mid a \mid (e + f) \mid (e \cdot f) \mid (e^*) \quad (\text{for } a \in A).$$

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Note, here:

- ▶ symbol **0** instead of \emptyset
- ▶ symbol **1** used (often dropped, definable as 0^*)
- ▶ **no** complementation operation \bar{e}
 - ▶ which **is not expressible** under language interpretation

Language semantics $\llbracket \cdot \rrbracket_L$ of reg. expr's (Copi–Elgot–Wright, 1958)

0 \xrightarrow{L} empty language \emptyset

1 \xrightarrow{L} $\{\epsilon\}$ (ϵ the empty word)

a \xrightarrow{L} $\{a\}$

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$e + f$ \xrightarrow{L} union of $L(e)$ and $L(f)$

$e \cdot f$ \xrightarrow{L} element-wise concatenation of $L(e)$ and $L(f)$

e^* \xrightarrow{L} set of words formed by concatenating words in $L(e)$,
and adding the empty word ϵ

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and adding the empty word ϵ

$\llbracket e \rrbracket_L := L(e)$ (language defined by e)

Process semantics of regular expressions $\llbracket \cdot \rrbracket_P$ (Milner, 1984)

0 \xrightarrow{P} deadlock δ , no termination

1 \xrightarrow{P} empty-step process ϵ , then terminate

a \xrightarrow{P} atomic action a , then terminate

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$e + f \xrightarrow{P}$ (choice) execute $\llbracket e \rrbracket_P$ or $\llbracket f \rrbracket_P$

$e \cdot f \xrightarrow{P}$ (sequentialization) execute $\llbracket e \rrbracket_P$, then $\llbracket f \rrbracket_P$

$e^* \xrightarrow{P}$ (iteration) repeat (terminate or execute $\llbracket e \rrbracket_P$)

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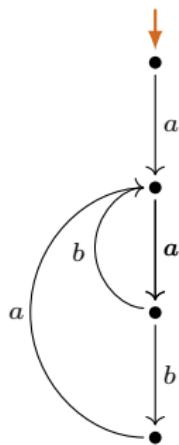
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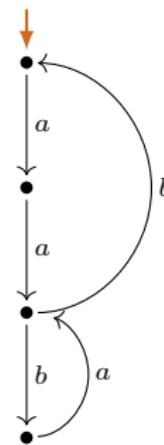
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$\llbracket e \rrbracket_P := [P(e)]_{\Leftarrow}$ (bisimilarity equivalence class of process $P(e)$)

Process interpretation of regular expressions

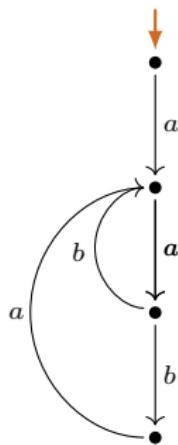


$P(a(a(b+ba))^*0)$

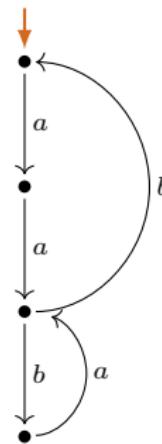


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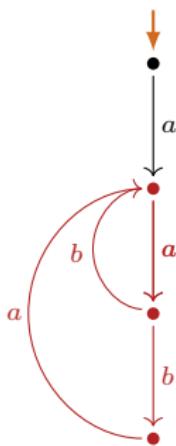


$$\textcolor{green}{P}(a \cdot (a \cdot (b + b \cdot a))^* \cdot 0)$$

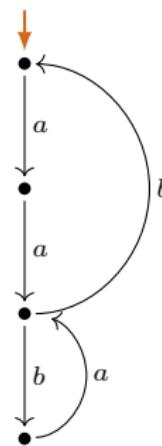


$$\textcolor{green}{P}((a \cdot a \cdot (b \cdot a))^* \cdot b)^* \cdot 0)$$

Process interpretation of regular expressions

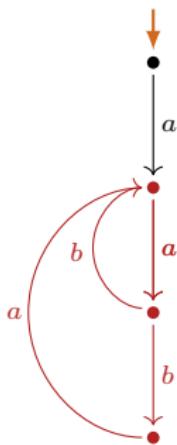


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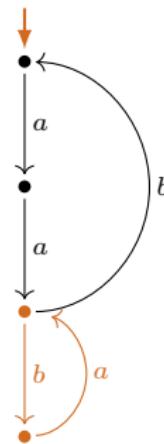


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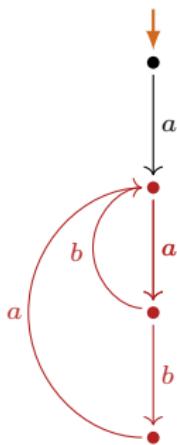


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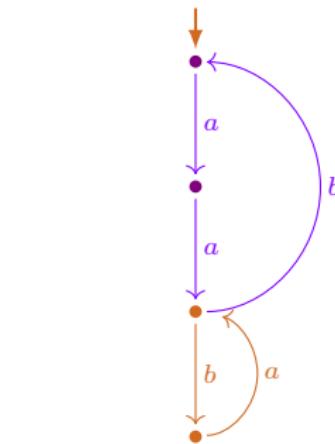


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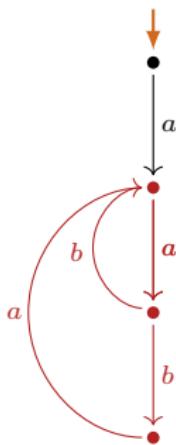


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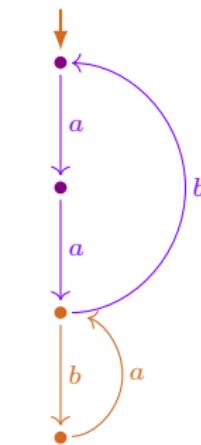


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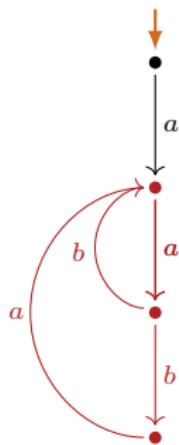
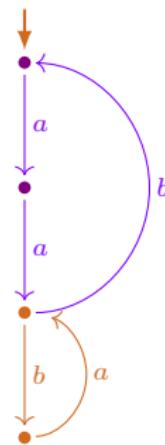


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Process interpretation of regular expressions


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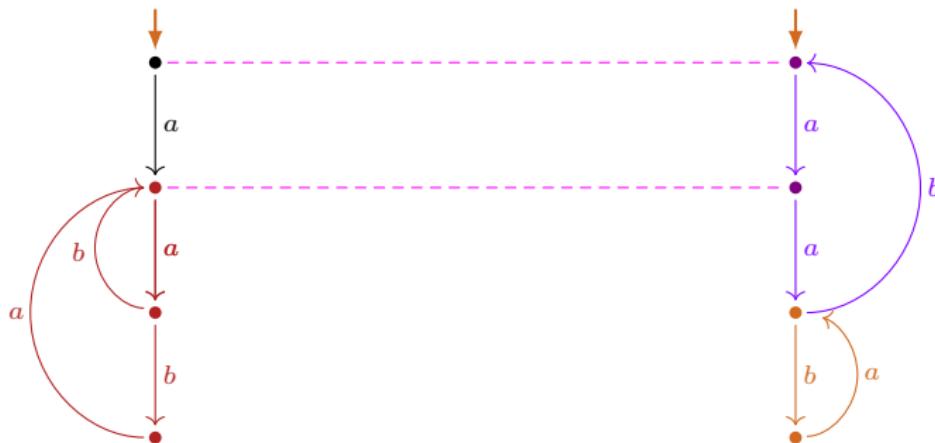
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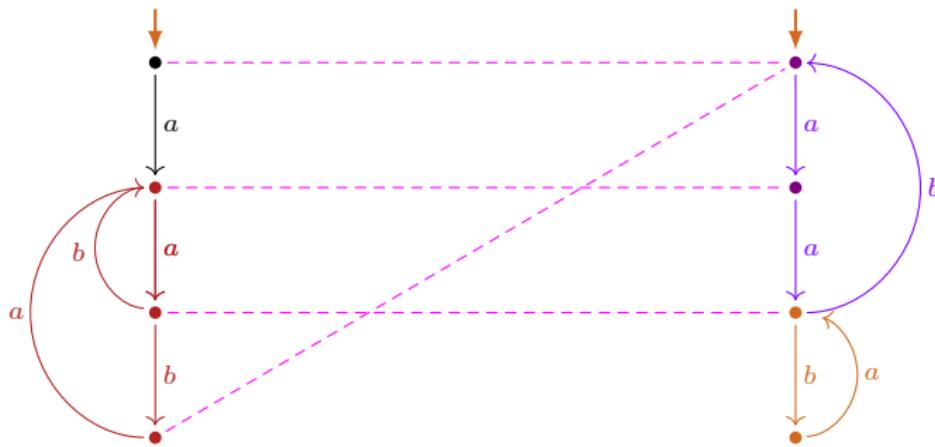
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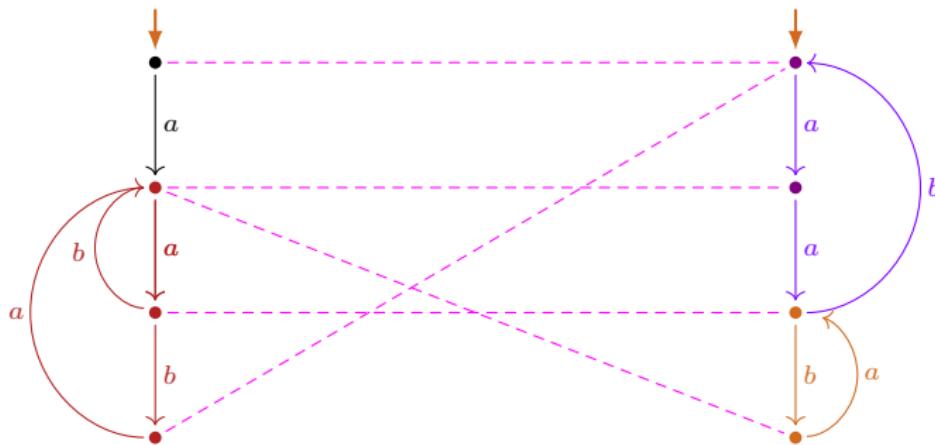
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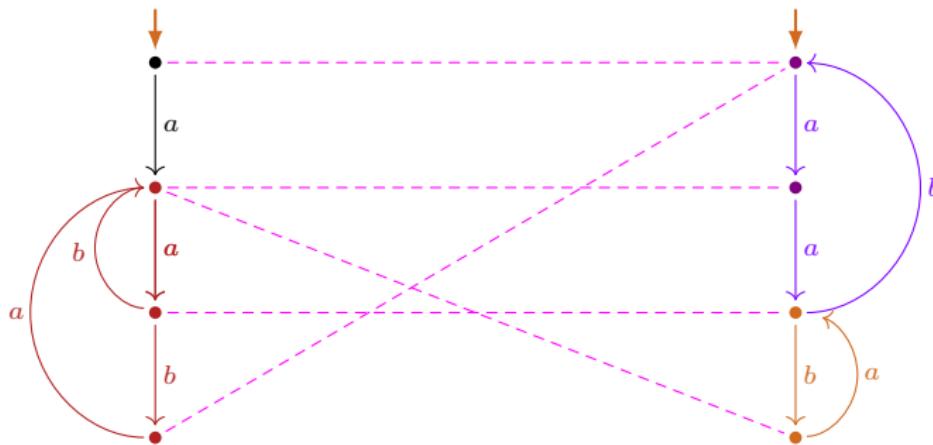
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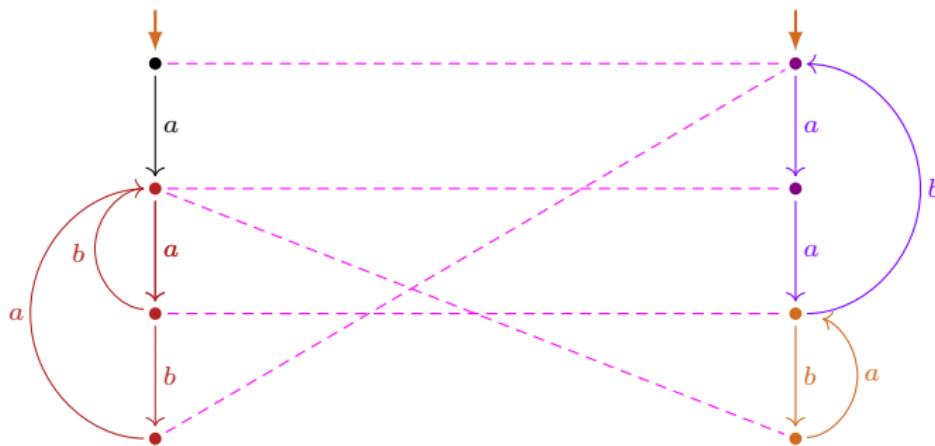
$$P((aa(ba)^*b)^*0)$$

Process interpretation of regular expressions



$$P(a(a(b+ba))^*0) \quad \leftrightarrow \quad P((aa(ba)^*b)^*0)$$

Process interpretation of regular expressions



$$a(a(b+ba))^* 0$$

$$\xleftrightarrow{P}$$

$$(aa(ba)^* b)^* 0$$

Process graphs and NFAs

Definition

A **process graph** over actions in A is a tuple $G = \langle V, v_s, T, E \rangle$ where:

- ▶ V is a set of *vertices*,
- ▶ $v_s \in V$ is the *start vertex*,
- ▶ $T \subseteq V \times A \times V$ the set of *transitions*,
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Correspondence with NFAs

With the finiteness restriction, process graphs can be viewed as:

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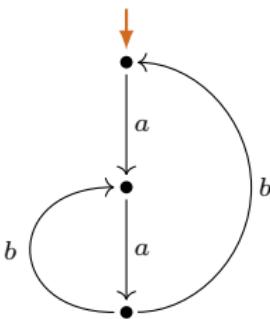
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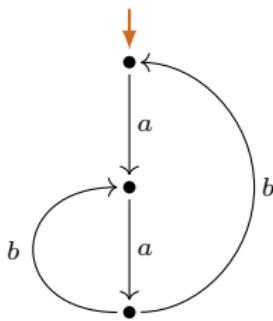
that are studied under bisimulation, not under language equivalence.

Antimirov (1996): NFA-definition of $P(\cdot)$ via partial derivatives.

Expressible process graphs (under bisimulation \leftrightarrow)

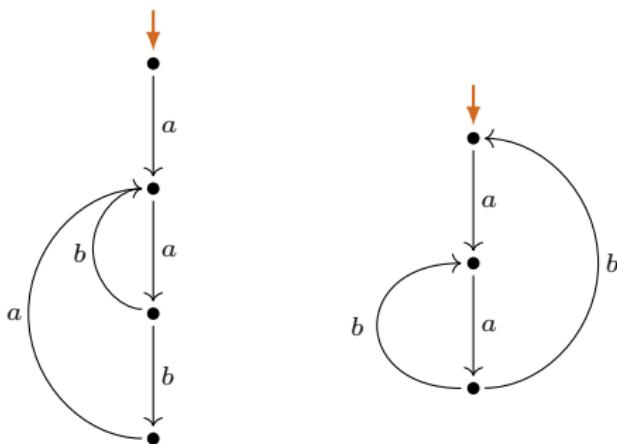


Expressible process graphs (under bisimulation \leftrightarrow)



? $\in im(\textcolor{green}{P}(\cdot))$?

Expressible process graphs (under bisimulation \leftrightarrow)

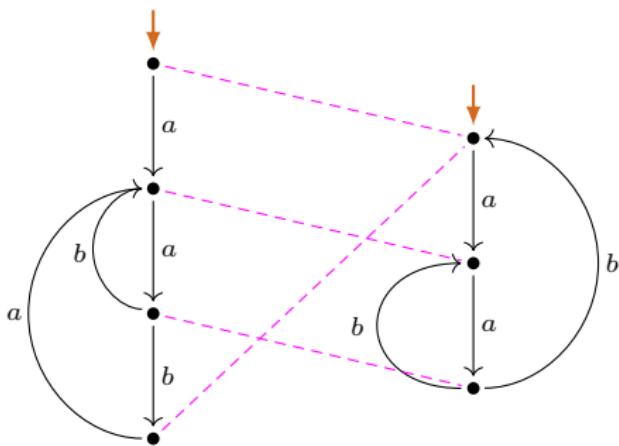


$\in im(\textcolor{violet}{P}(\cdot))$

$? \in im(\textcolor{violet}{P}(\cdot)) ?$

$\textcolor{violet}{P}(\cdot)$ -expressible

Expressible process graphs (under bisimulation \leftrightarrow)

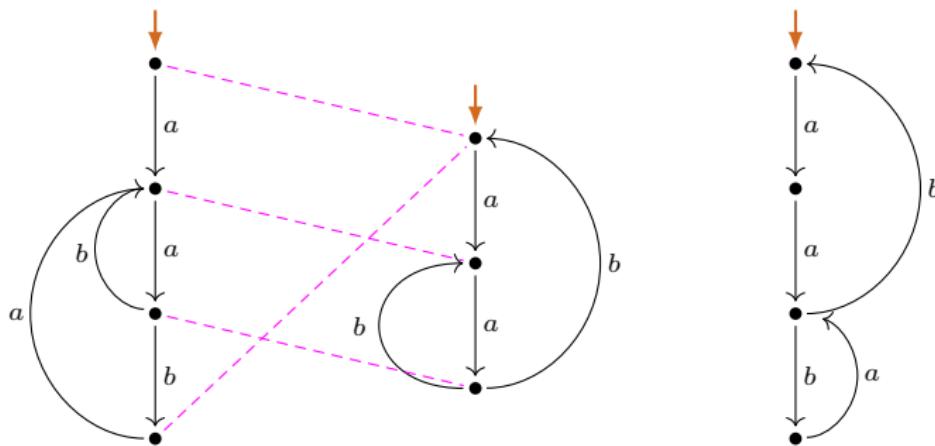


$\in im(\textcolor{violet}{P}(\cdot))$

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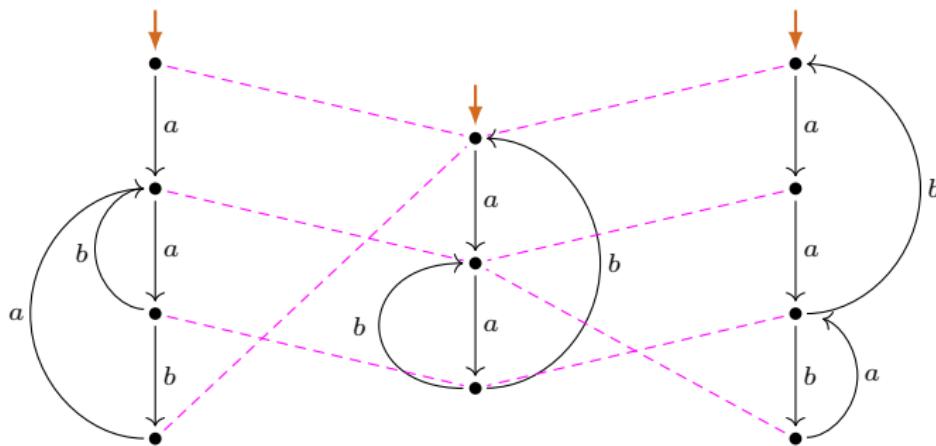
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Expressible process graphs (under bisimulation \leftrightarrow)


 $\in im(\textcolor{violet}{P}(\cdot))$
 $P(\cdot)$ -expressible

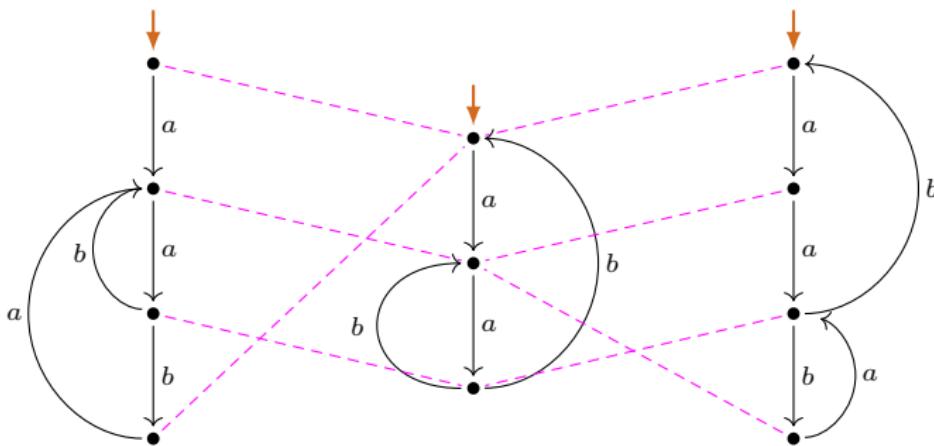
 $? \in im(\textcolor{violet}{P}(\cdot)) ?$
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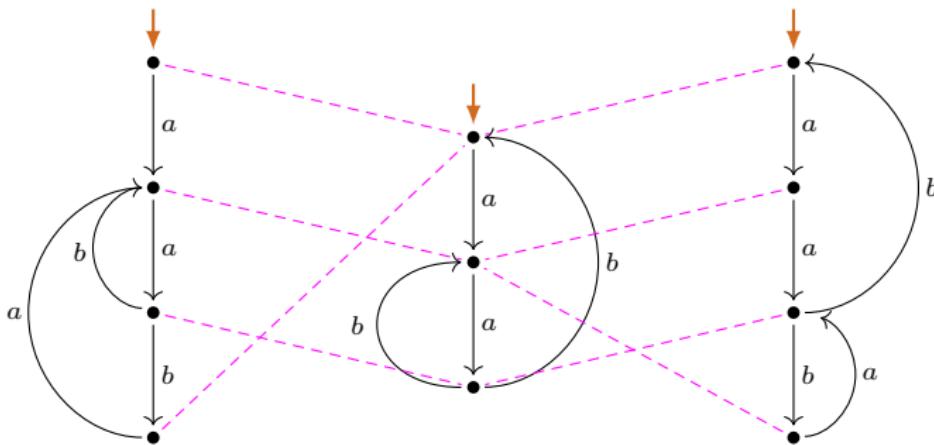
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Expressible process graphs (under bisimulation \Leftrightarrow)


 $\in im(P(\cdot))$
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 $? \in im(P(\cdot)) ?$
 $P(\cdot)$ -expressible
modulo \Leftrightarrow
 $\in im(P(\cdot))$
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Expressible process graphs (under bisimulation \Leftrightarrow)


 $\in im(P(\cdot))$
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 $\llbracket \cdot \rrbracket_P$ -expressible

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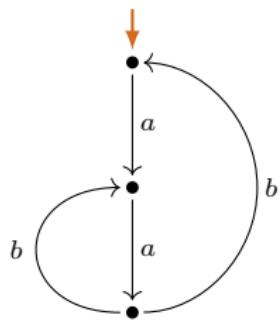
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 $\in im(P(\cdot))$
 $P(\cdot)$ -expressible

 $\llbracket \cdot \rrbracket_P$ -expressible

Properties of P and $\llbracket \cdot \rrbracket_P$

- ▶ Not every finite-state process is $P(\cdot)$ -expressible.

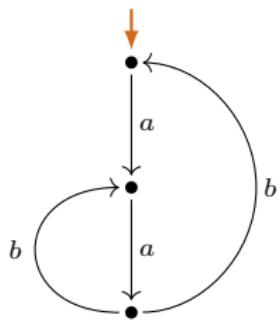


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$\llbracket \cdot \rrbracket_P$ -expressible

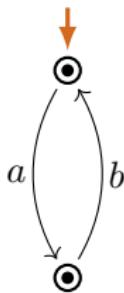
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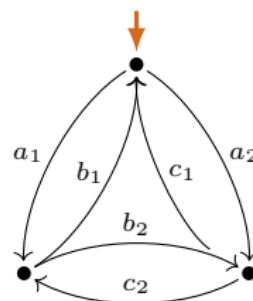


? $P(\cdot)$ -expressible ?

$\llbracket \cdot \rrbracket_P$ -expressible

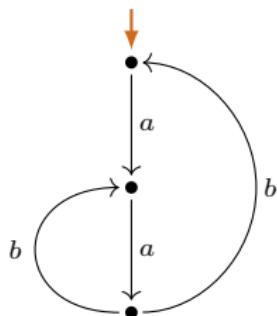


not $P(\cdot)$ -expressible



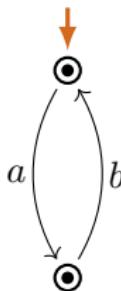
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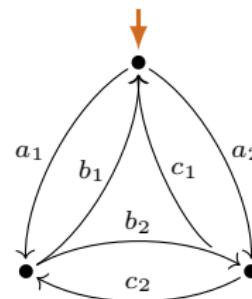
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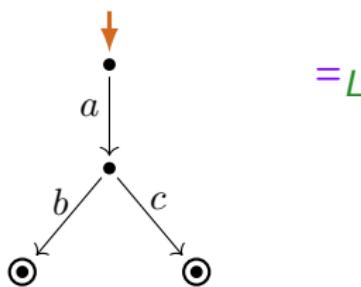


Properties of P and $\llbracket \cdot \rrbracket_P$

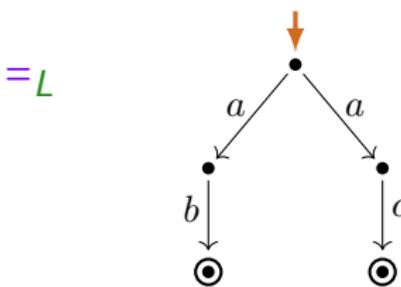
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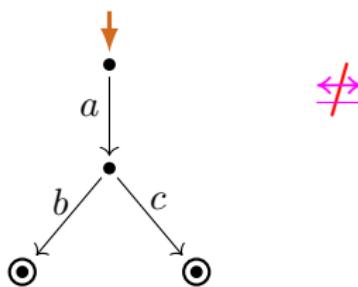


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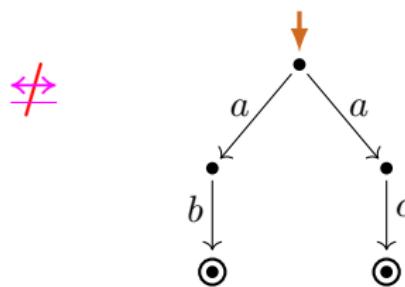
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$$\not\equiv_P$$

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Complete axiomatization of $=_L$ (Aanderaa/Salomaa, 1965/66)

Axioms:

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Inference rules: equational logic plus

$$\frac{e = f \cdot e + g}{e = f^* \cdot g} \text{ FIX } (\text{if } \underbrace{\{e\}}_{\text{non-empty-word}} \notin \text{L}(f))$$

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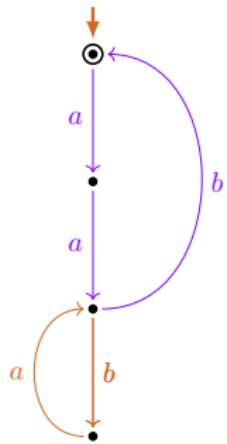
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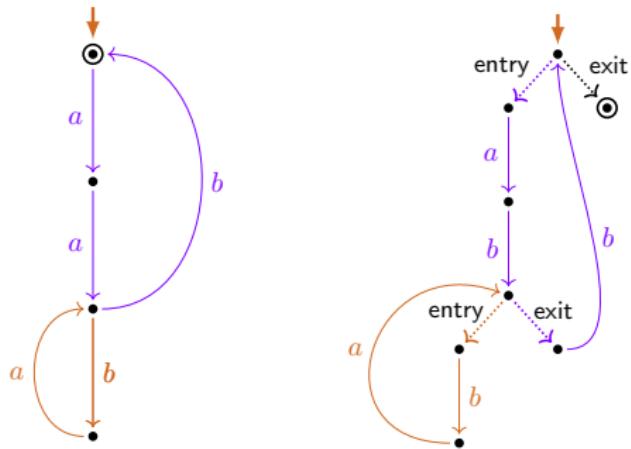
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Well-behaved form, looping palm trees



$P((aa(ba)^*b)^*)$

Well-behaved form, looping palm trees

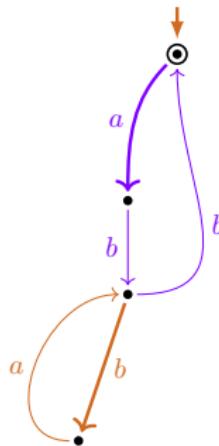
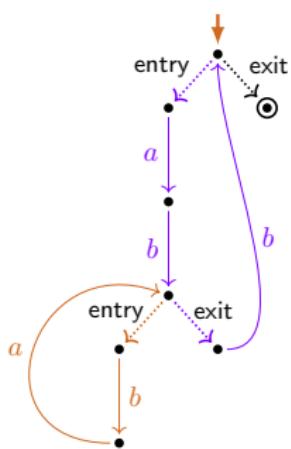
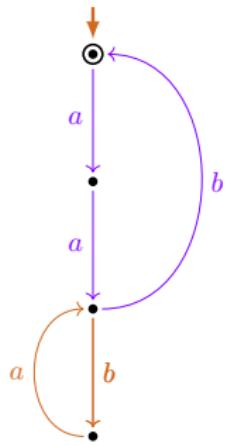


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Loop charts (interpretations of innermost iterations)

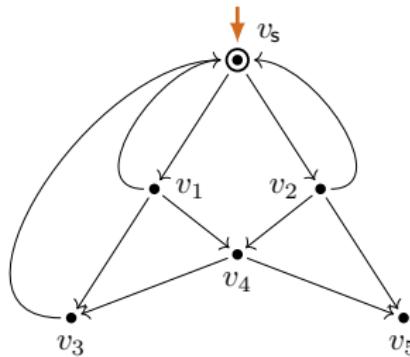
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L-1.

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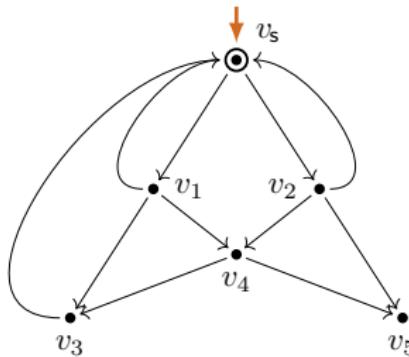


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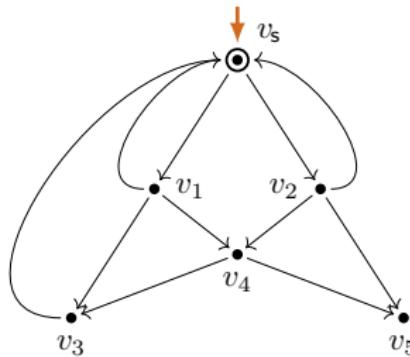


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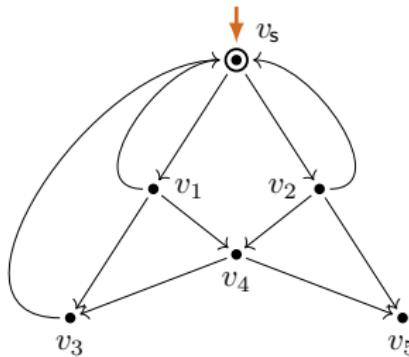


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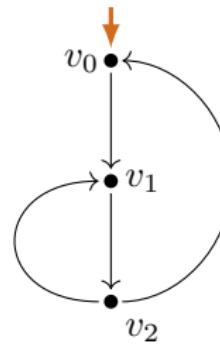
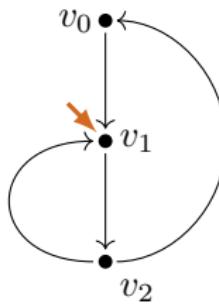
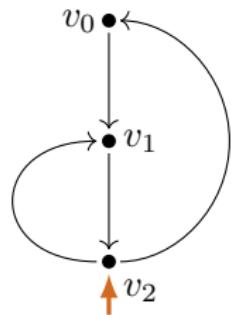


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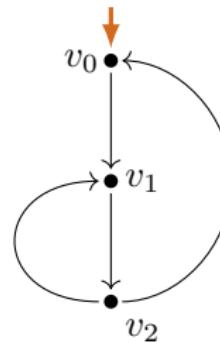
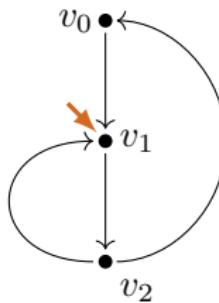
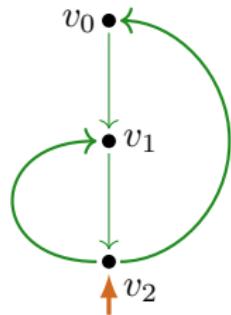


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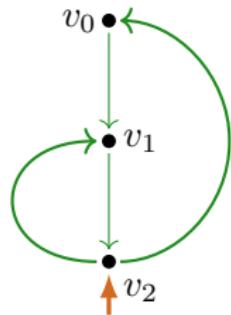


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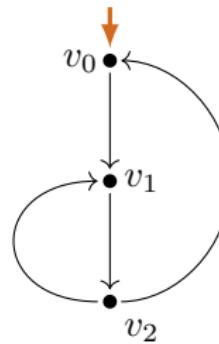
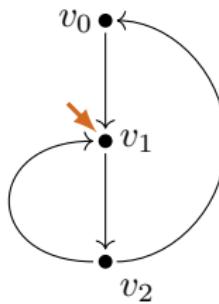
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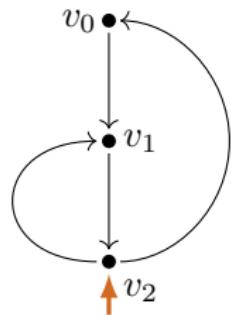


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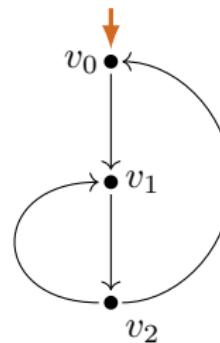
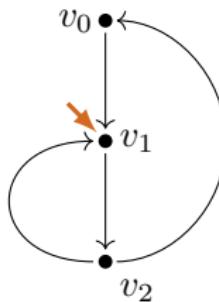
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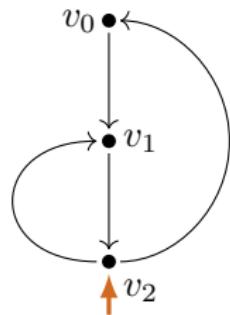


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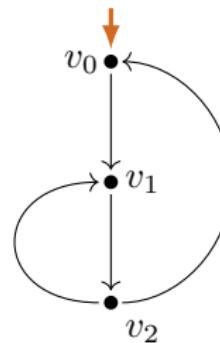
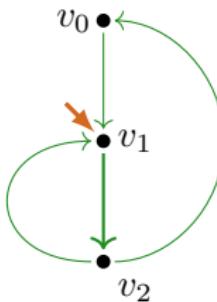
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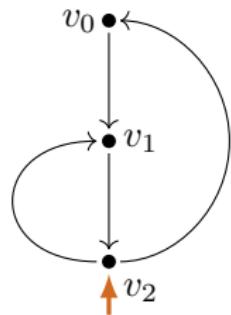


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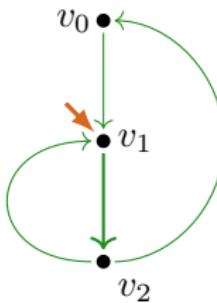
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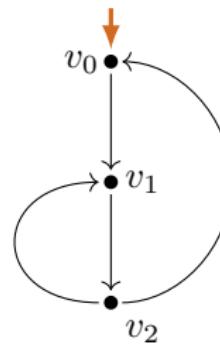
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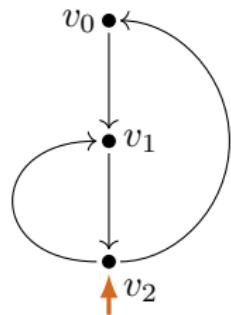


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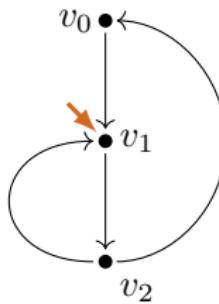
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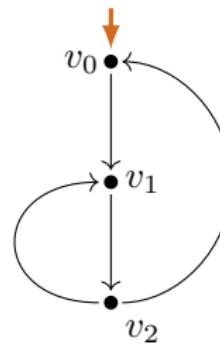
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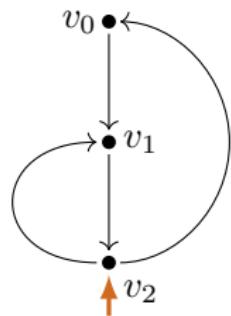


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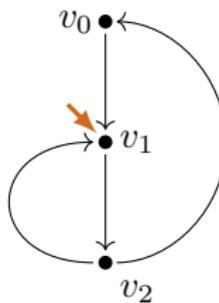
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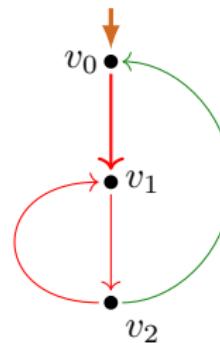
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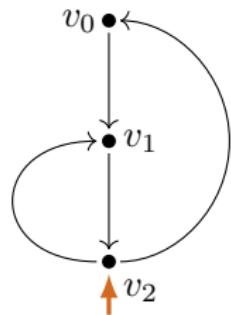


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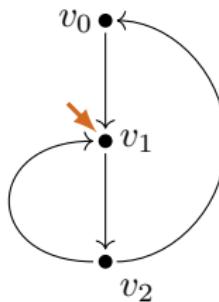
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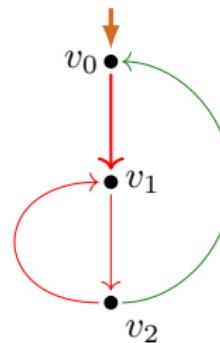
- L-1. There is an infinite path from the **start vertex**.
- L-2. Every infinite path from the **start vertex** returns to **it**.
- L-3. Termination is only possible at the **start vertex**.



loop chart



loop chart



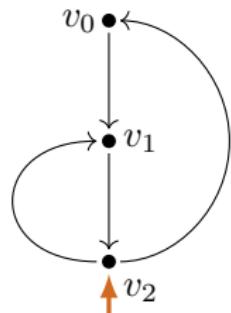
no loop chart

Loop charts (interpretations of innermost iterations)

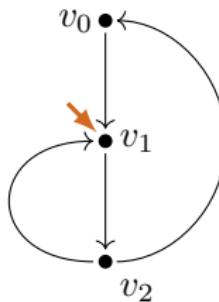
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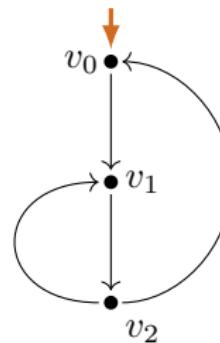
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loop chart

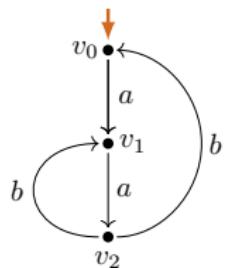


loop chart

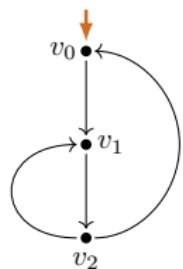


no loop chart

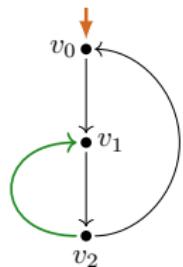
Loop elimination



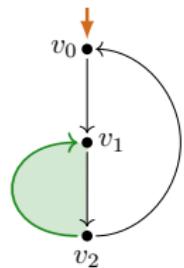
Loop elimination



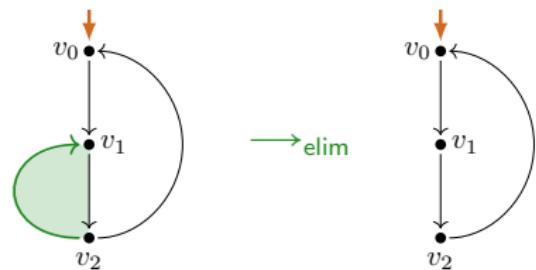
Loop elimination



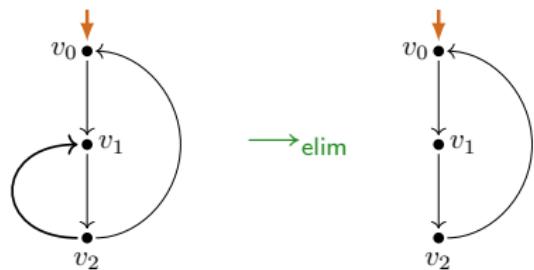
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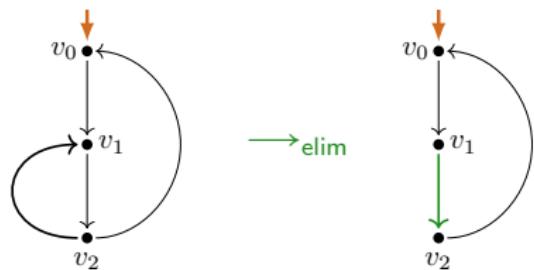
Loop elimination



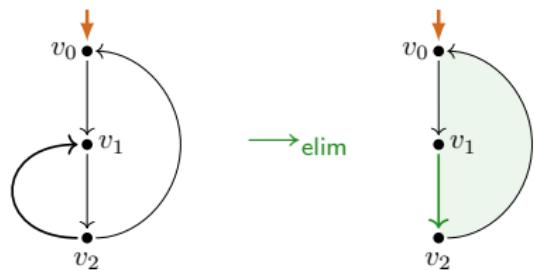
Loop elimination



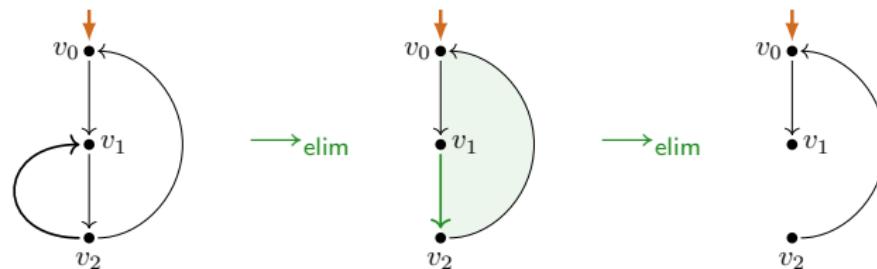
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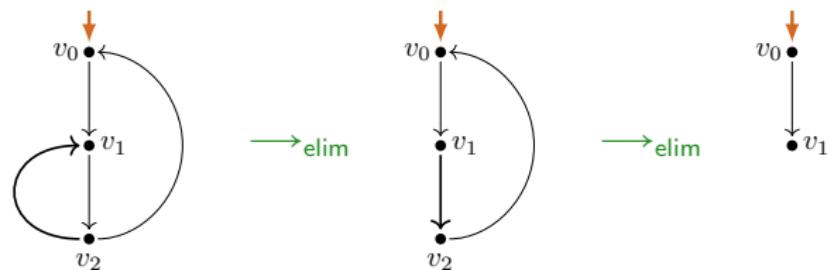
Loop elimination



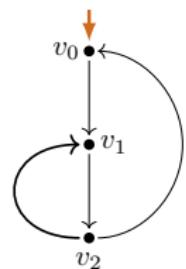
Loop elimination



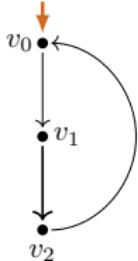
Loop elimination



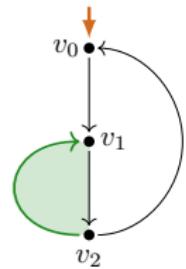
Loop elimination



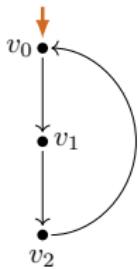
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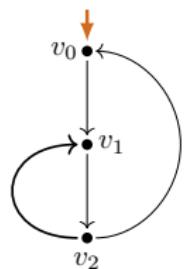
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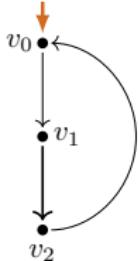
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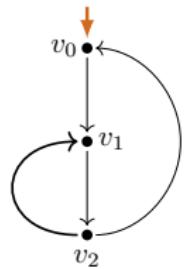
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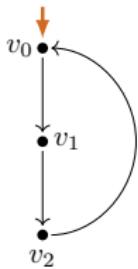
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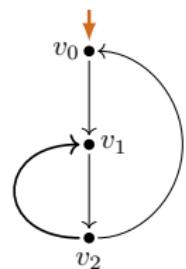
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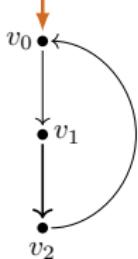
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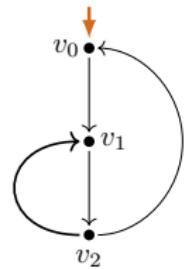
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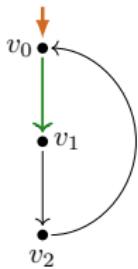
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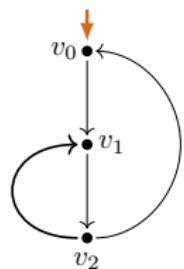
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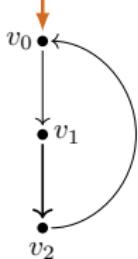
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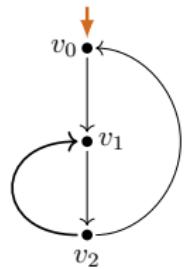
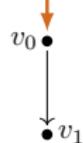
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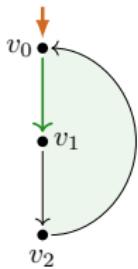
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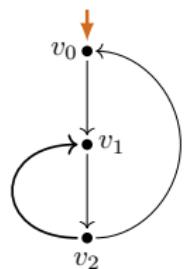
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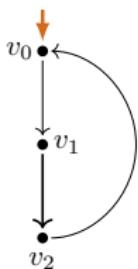
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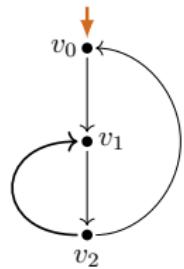
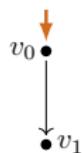
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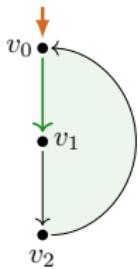
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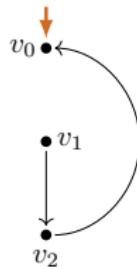
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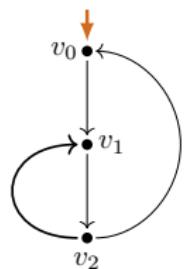
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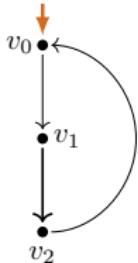
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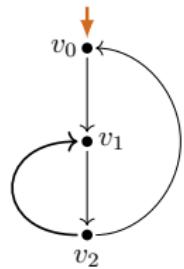
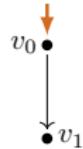
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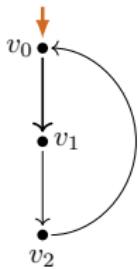
→ elim



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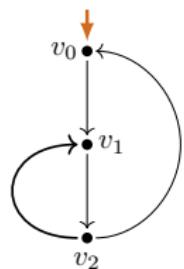
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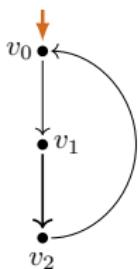
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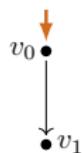
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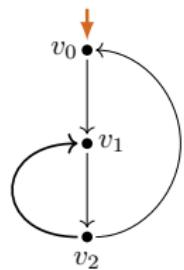
→ elim



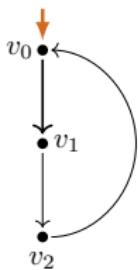
→ elim



→ prune



→ elim



→ elim



Loop elimination, and properties

$\longrightarrow_{\text{elim}}$: eliminate a transition-induced loop by:

- ▶ removing the loop-entry transition(s)
- ▶ garbage collection

$\longrightarrow_{\text{prune}}$: remove a transition to a deadlocking state

Lemma

(i) $\longrightarrow_{\text{elim}} \cup \longrightarrow_{\text{prune}}$ is terminating.

Loop elimination, and properties

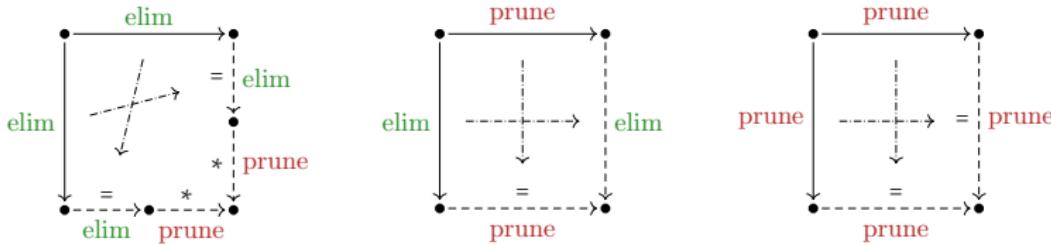
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- (ii) $\rightarrow_{\text{elim}} \cup \rightarrow_{\text{prune}}$ is decreasing, and hence locally confluent.



Loop elimination, and properties

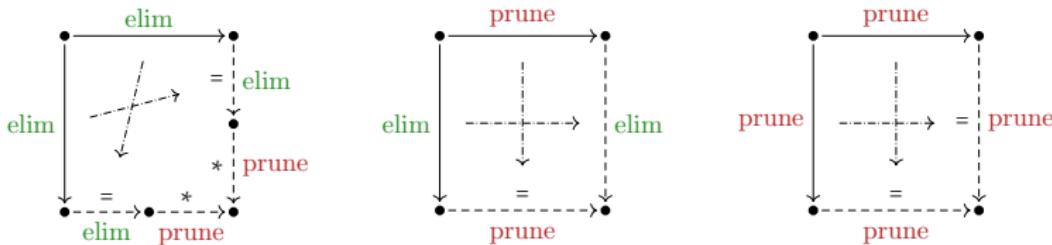
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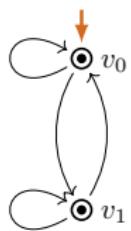
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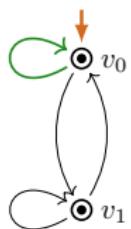
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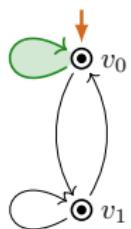
Loop elimination



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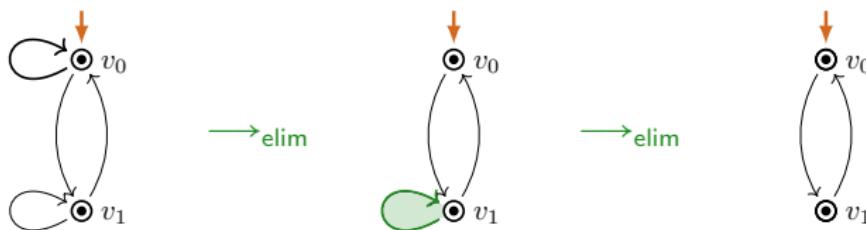
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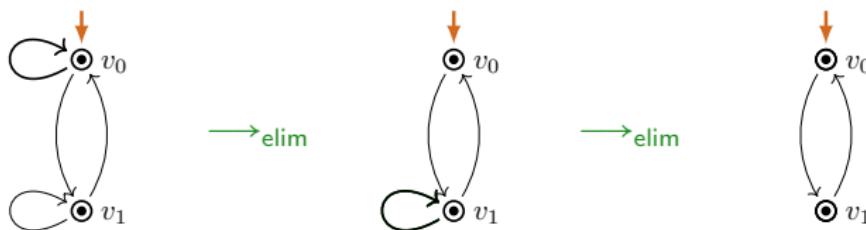
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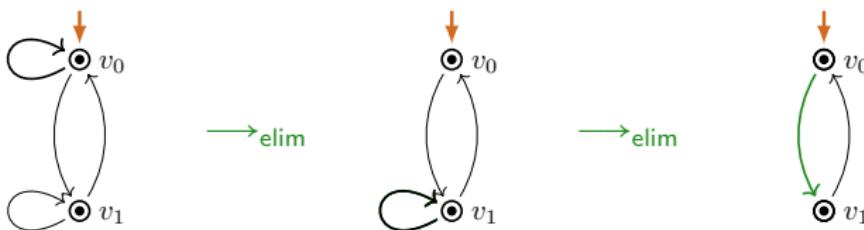
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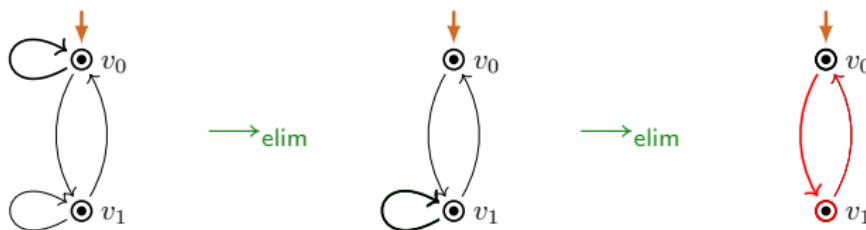
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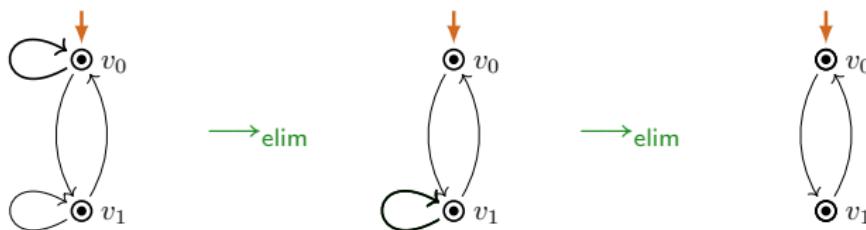
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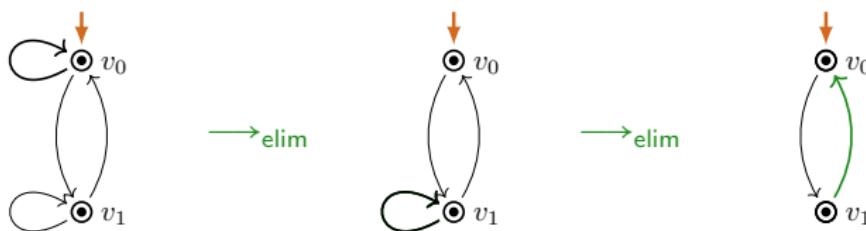
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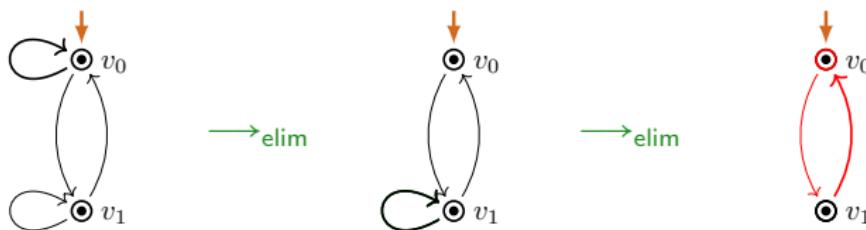
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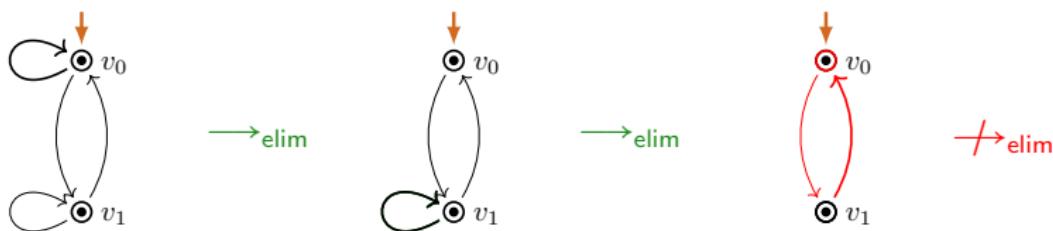
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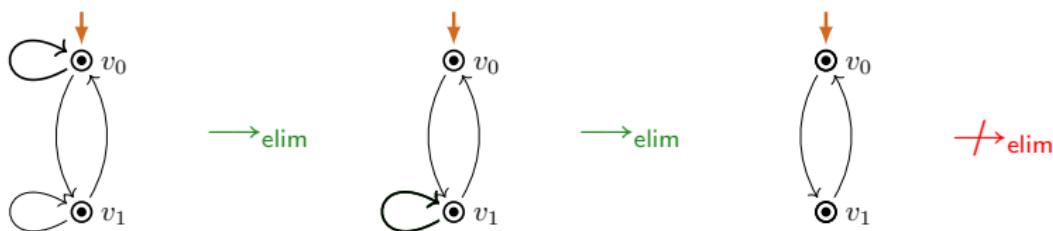
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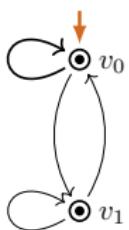
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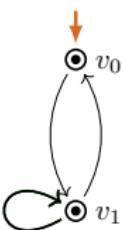
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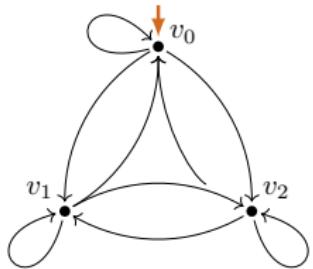
→_{elim}



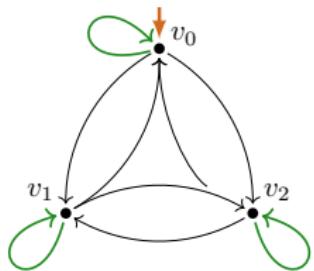
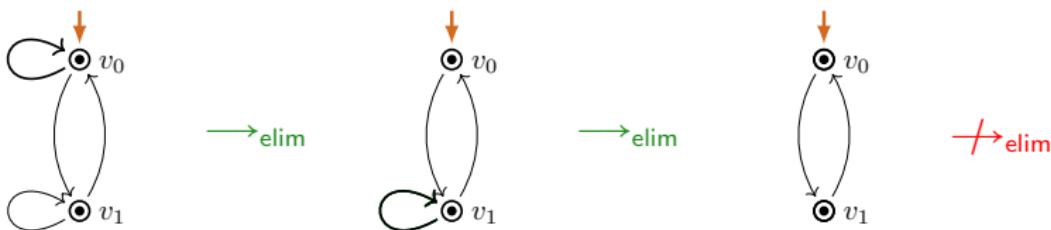
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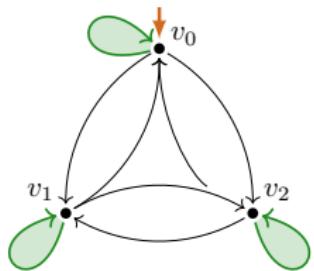
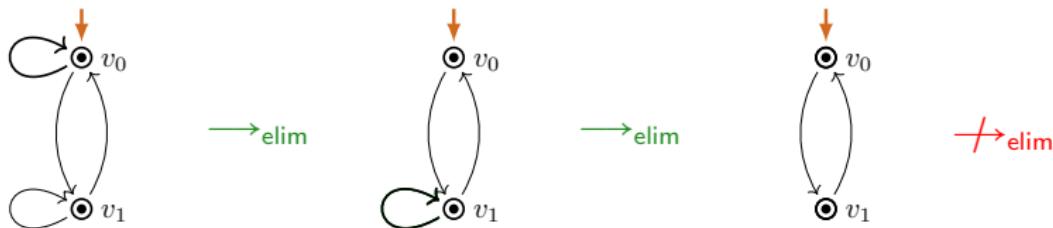
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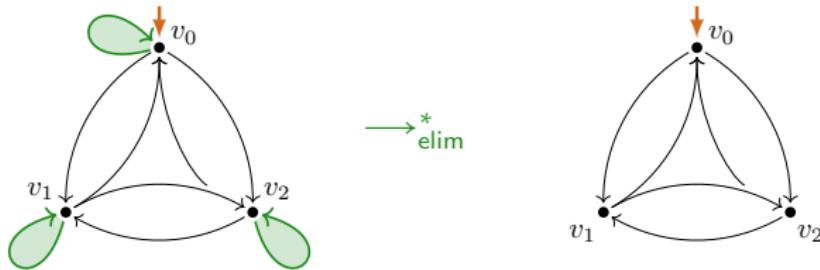
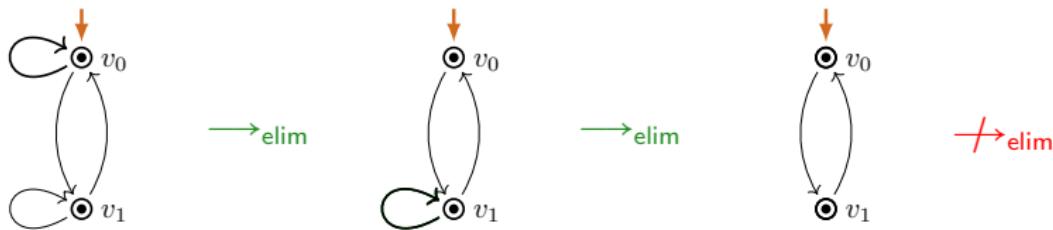
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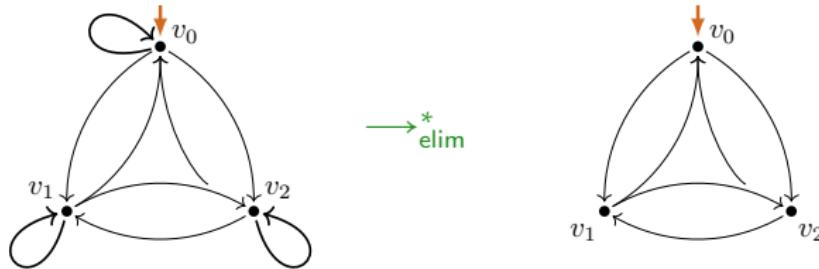
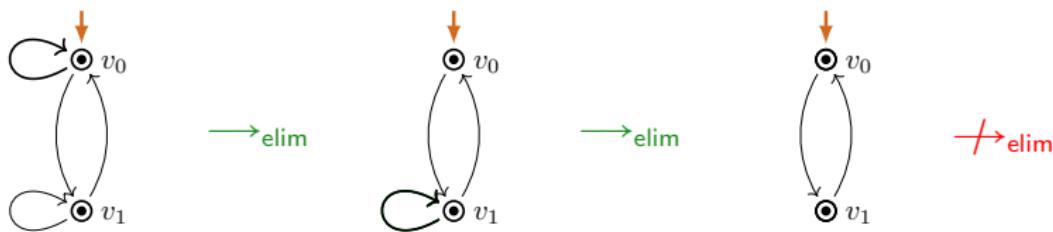
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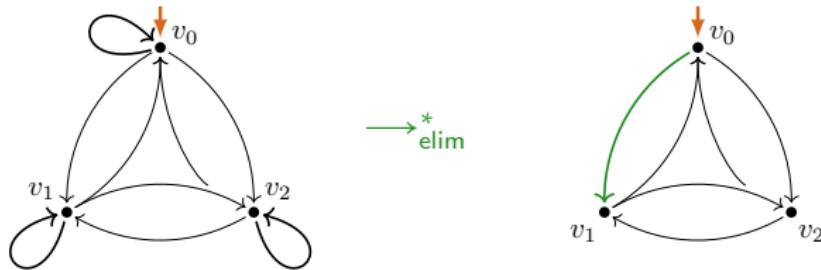
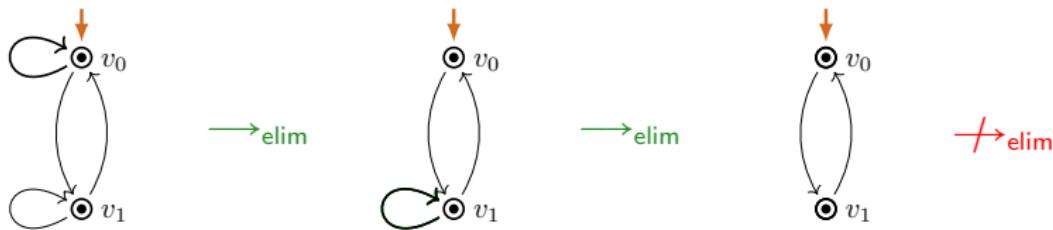
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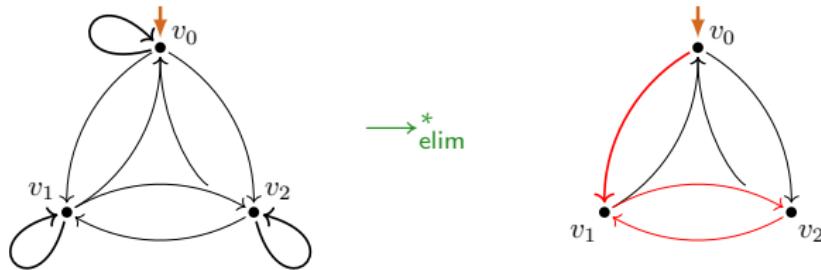
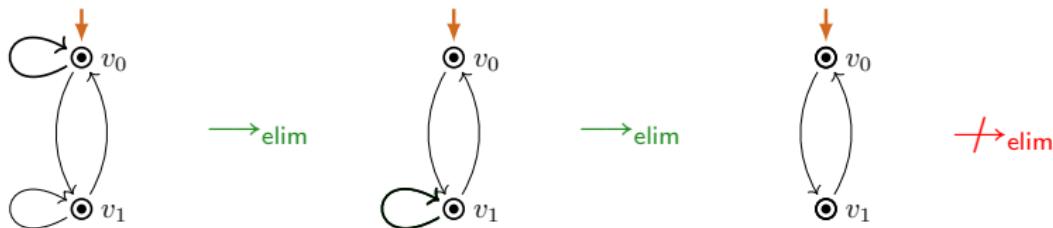
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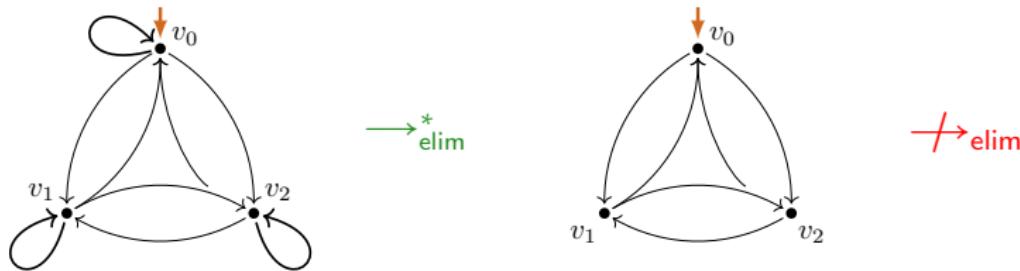
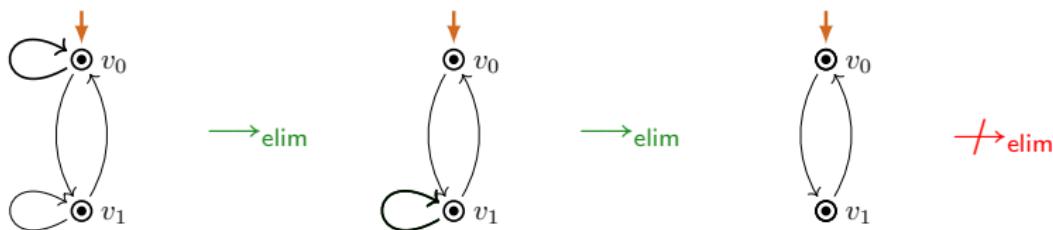
Loop elimination



Loop elimination



Loop elimination



Structure property LEE

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A process graph G satisfies **LEE** (*loop existence and elimination*) if:

$$\exists G_0 \left(G \xrightarrow{*_{\text{elim}}} G_0 \not\rightarrow_{\text{elim}} \wedge G_0 \text{ has no infinite trace} \right).$$

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For every process graph G the following are equivalent:

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$$\exists G_0 \left(G \xrightarrow{\text{elim}}^* G_0 \not\rightarrow_{\text{elim}} \wedge G_0 \text{ has no infinite trace} \right).$$

Lemma (by using termination and confluence)

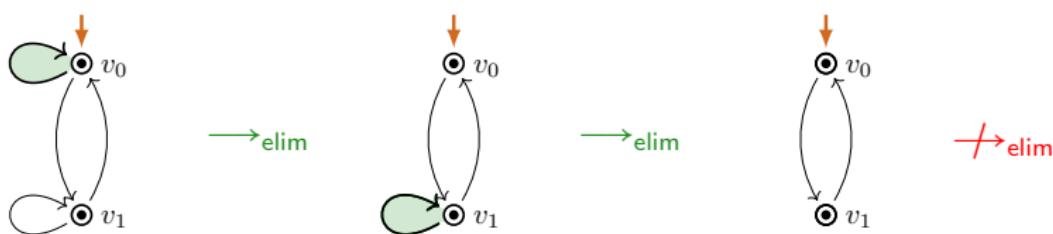
For every process graph G the following are equivalent:

- (i) LEE(G).
- (ii) *There is an* $\xrightarrow{\text{elim}}$ *normal form without* an infinite trace.
- (iii) *There is an* $\xrightarrow{\text{elim,prune}}$ *normal form without* an infinite trace.
- (iv) *Every* $\xrightarrow{\text{elim}}$ *normal form is without* an infinite trace.
- (v) *Every* $\xrightarrow{\text{elim,prune}}$ *normal form is without* an infinite trace.

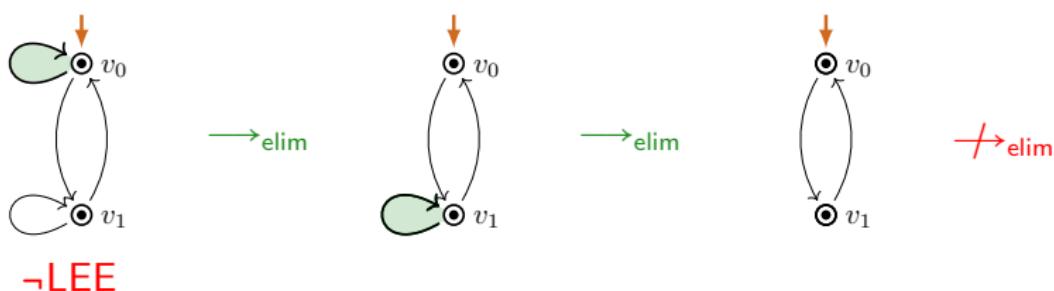
Theorem (efficient decidability)

The problem of deciding LEE(G) for process graphs G is in PTIME.

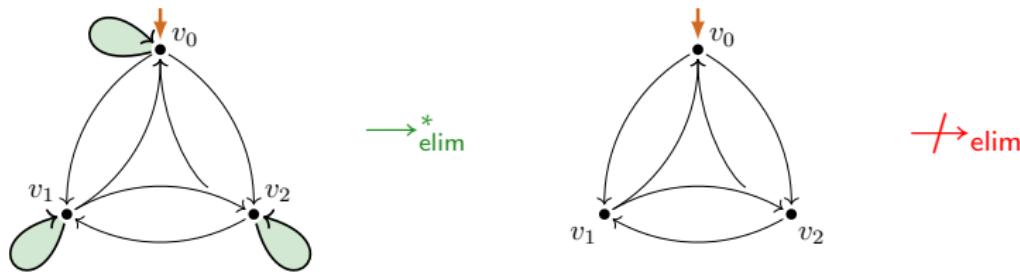
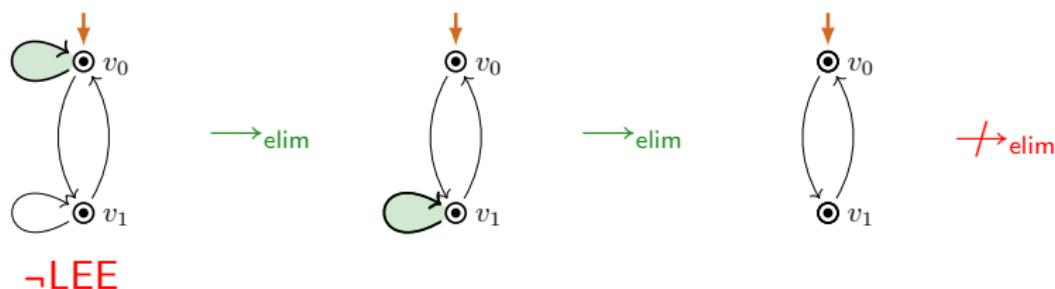
LEE fails



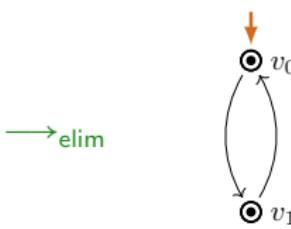
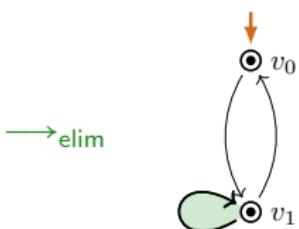
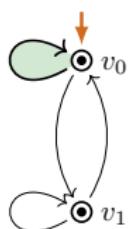
LEE fails



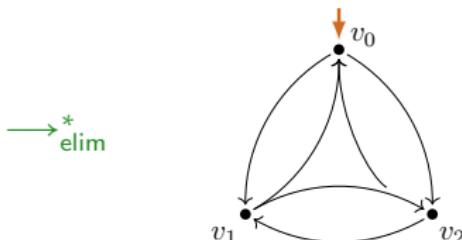
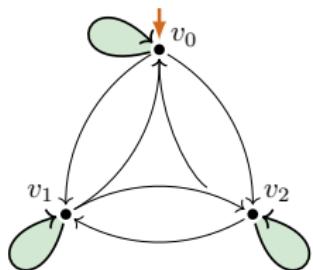
LEE fails



LEE fails

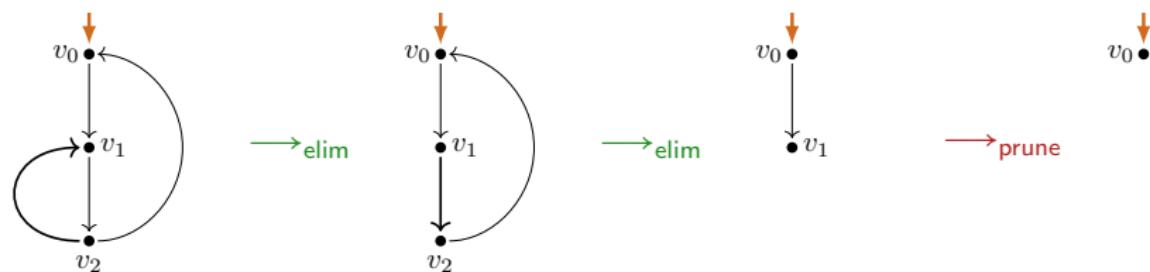


\neg LEE

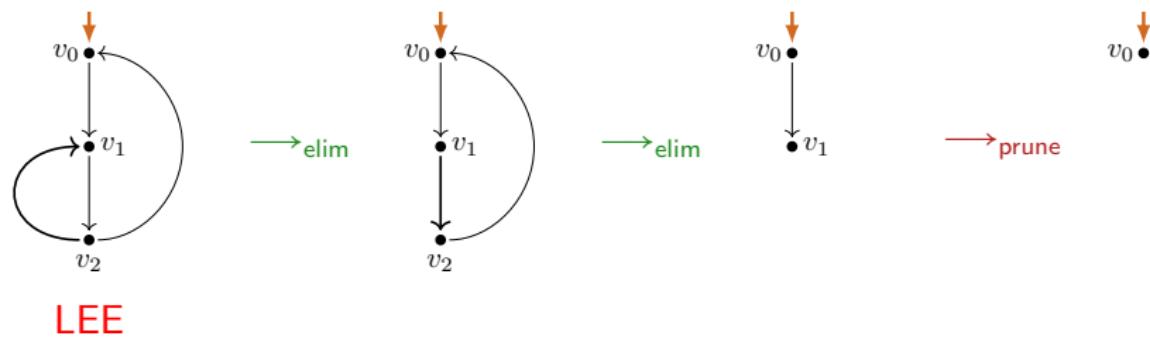


\neg LEE

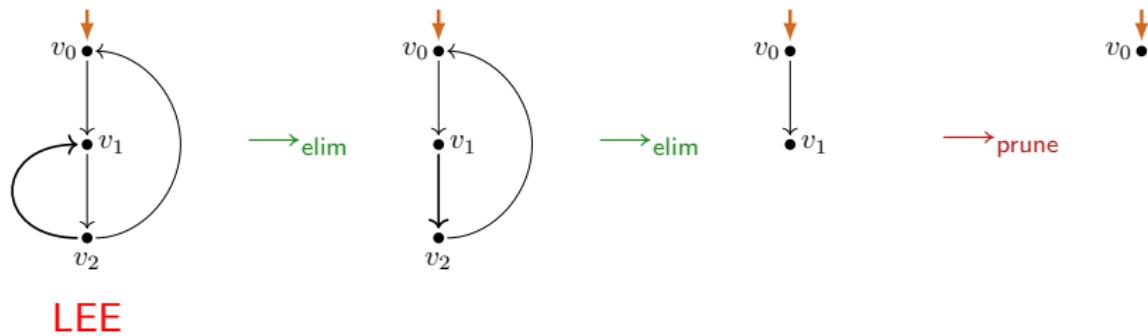
LEE holds



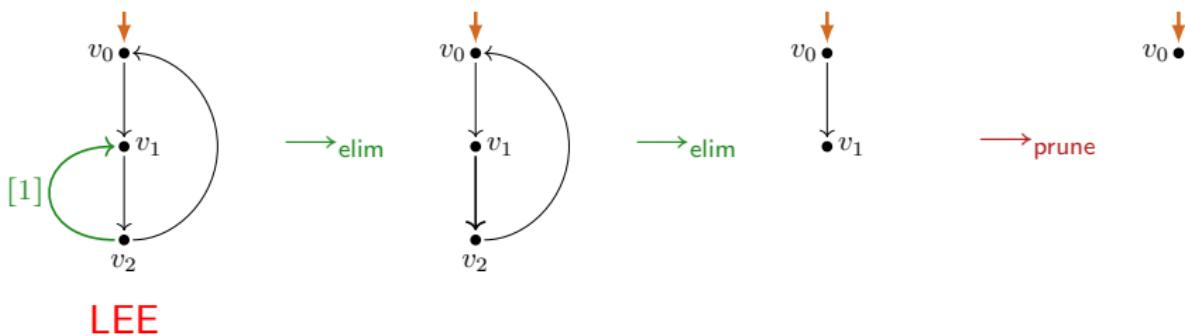
LEE holds



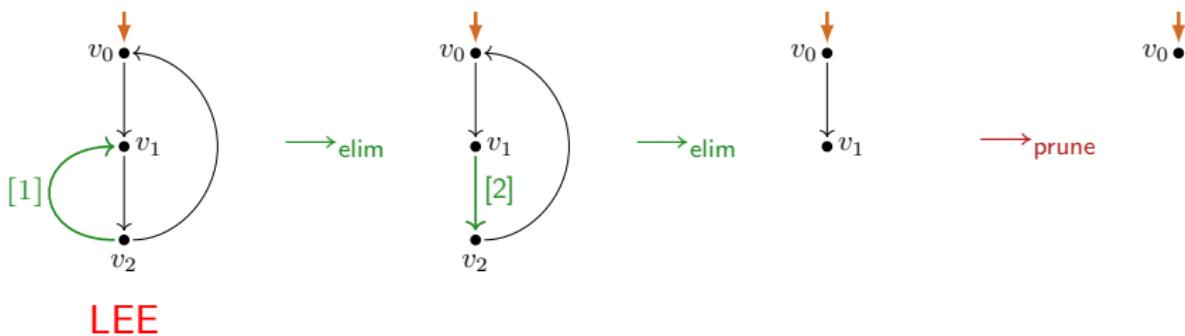
LEE holds / Recording loop elimination



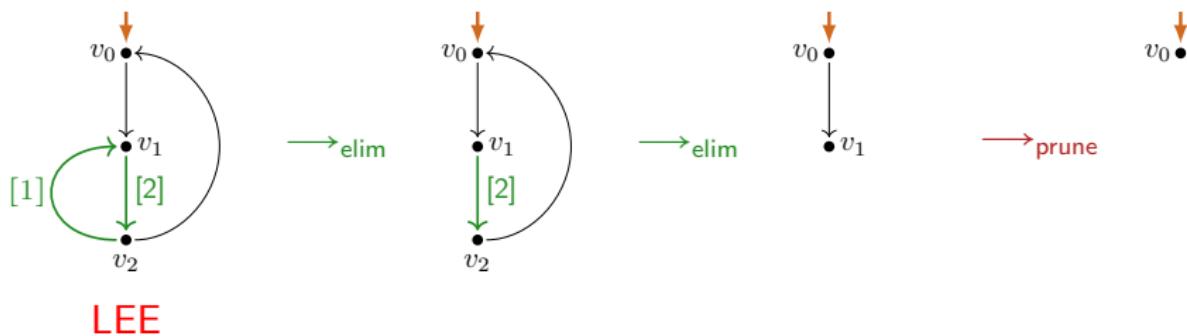
LEE holds / Recording loop elimination



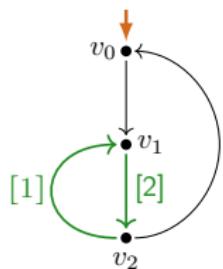
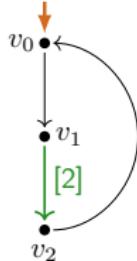
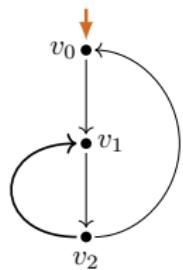
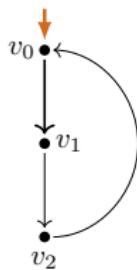
LEE holds / Recording loop elimination



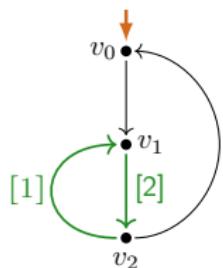
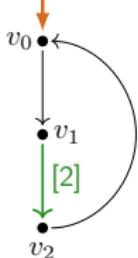
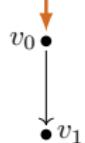
LEE holds / Recording loop elimination



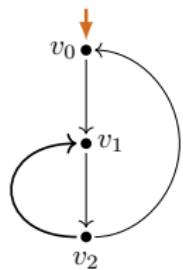
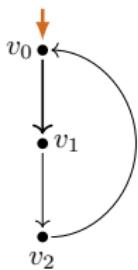
LEE holds / Recording loop elimination

 $\rightarrow \text{elim}$  $\rightarrow \text{elim}$  $\rightarrow \text{prune}$ **LEE** $\rightarrow \text{elim}$  $\rightarrow \text{elim}$ 

LEE holds / Recording loop elimination

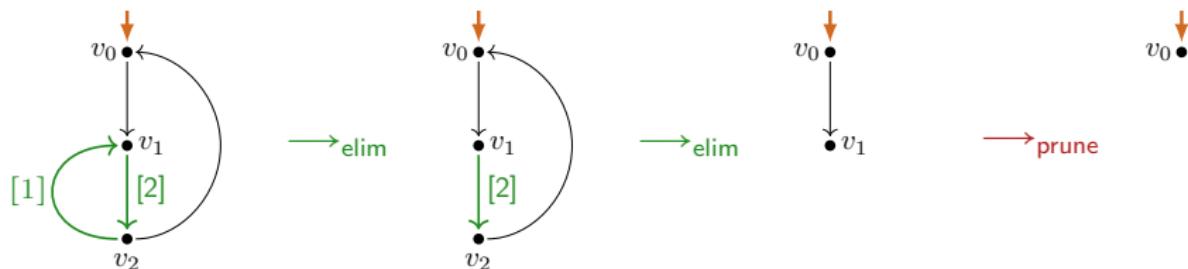
 \rightarrow elim \rightarrow elim \rightarrow prune

LEE

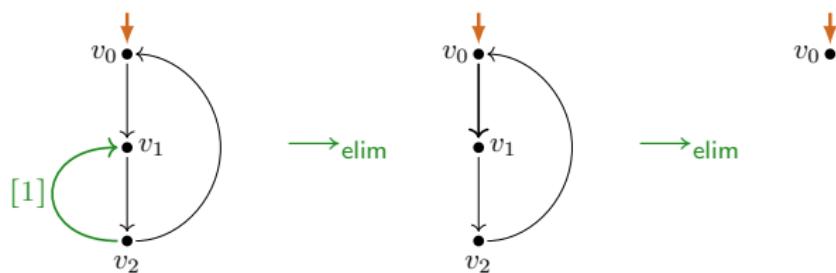
 \rightarrow elim \rightarrow elim

LEE

LEE holds / Recording loop elimination

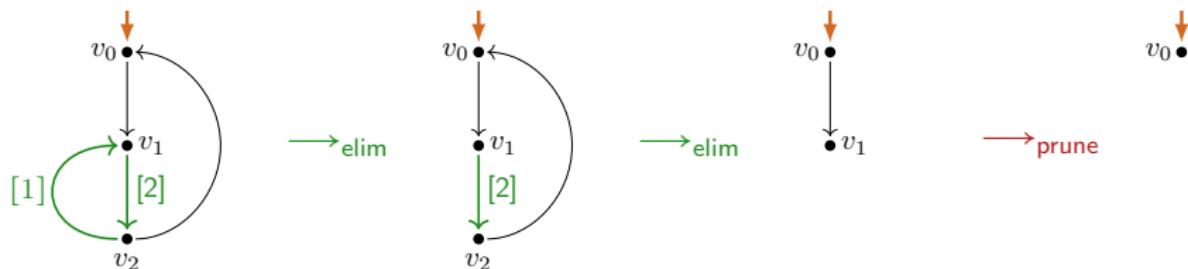


LEE

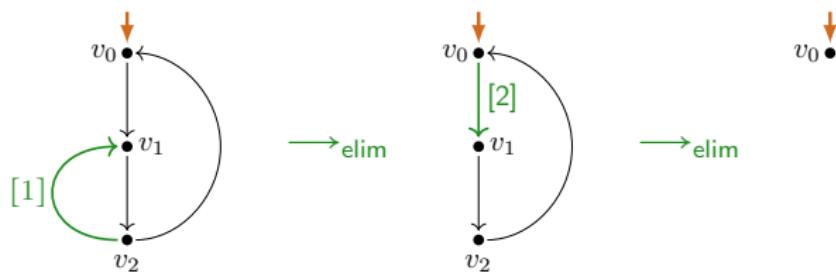


LEE

LEE holds / Recording loop elimination

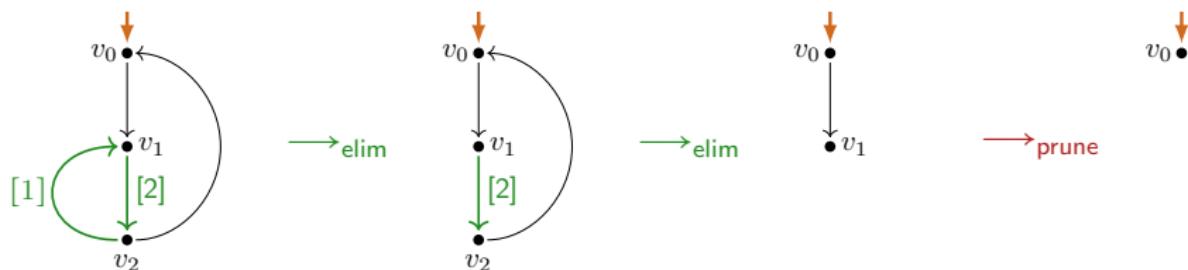


LEE

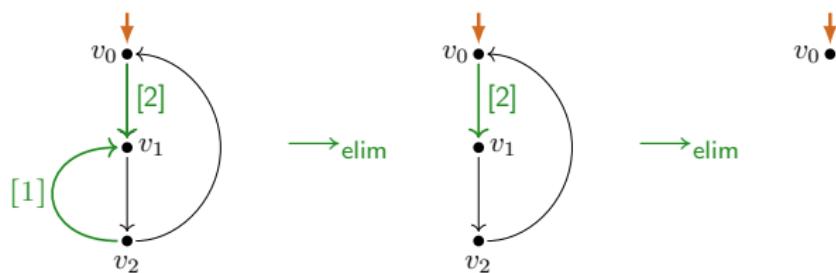


LEE

LEE holds / Recording loop elimination

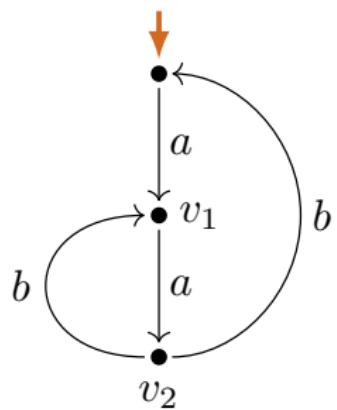


LEE



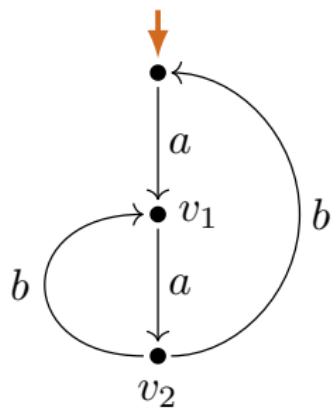
LEE

LEE-witness



LEE-witness

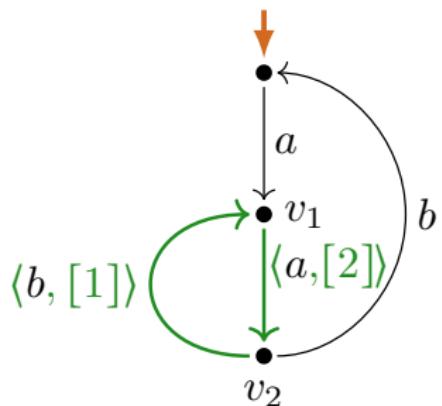
loop–branch labeling: marking transitions \xrightarrow{a} as:



LEE-witness

loop–branch labeling: marking transitions \xrightarrow{a} as:

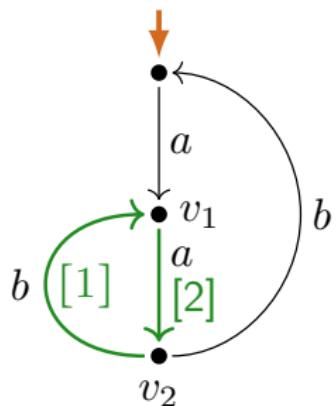
► entry steps $\xrightarrow{(a,[n])}$ for $n \in \mathbb{N}$,



LEE-witness

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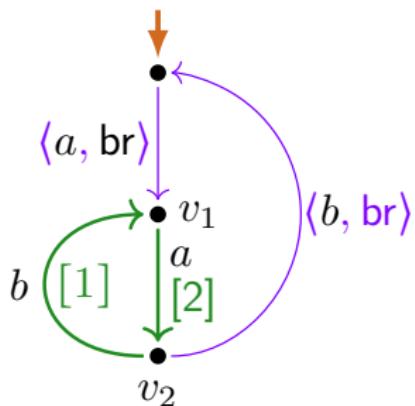
► entry steps $\xrightarrow{(a,[n])}$ for $n \in \mathbb{N}$, written $\xrightarrow{a} [n]$,



LEE-witness

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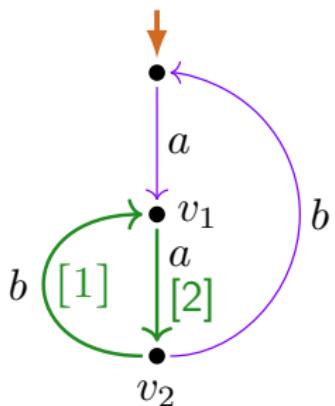
- ▶ entry steps $\xrightarrow{(a,[n])}$ for $n \in \mathbb{N}$, written $\xrightarrow{a} [n]$,
- ▶ branch steps $\xrightarrow{(a,br)}$,



LEE-witness

loop-branch labeling: marking transitions \xrightarrow{a} as:

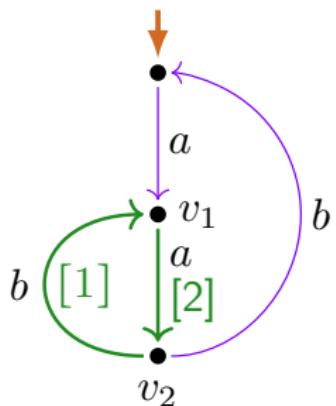
- ▶ entry steps $\xrightarrow{\langle a, [n] \rangle}$ for $n \in \mathbb{N}$, written $\xrightarrow{a} [n]$,
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LEE-witness

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Definition

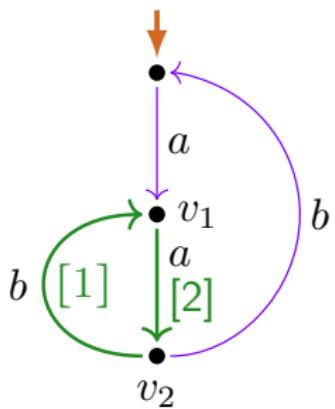
A loop–branch labeling is a LEE-witness, if:

- L1.
- L2.
- L3.

LEE-witness

loop–branch labeling: marking transitions \xrightarrow{a} as:

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Definition

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L2.

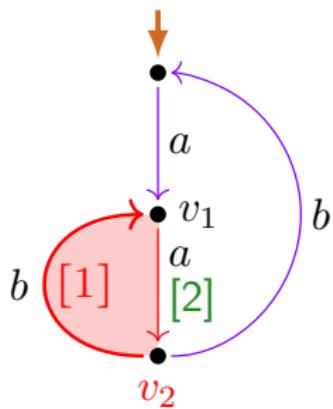
L3.

$\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) :=$ subchart induced
by entry steps $\xrightarrow{[n]}$ from v
followed by branch steps $\xrightarrow{\text{br}}$
or entry steps $\xrightarrow{[m]}$ with $m > n$,
until v is reached again

LEE-witness

loop–branch labeling: marking transitions \xrightarrow{a} as:

- ▶ entry steps $\xrightarrow{(a,[n])}$ for $n \in \mathbb{N}$, written $\xrightarrow{a,[n]}$,
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$$\mathcal{L}(v_2, \xrightarrow{[1]}, \xrightarrow{\text{br},[>1]})$$

Definition

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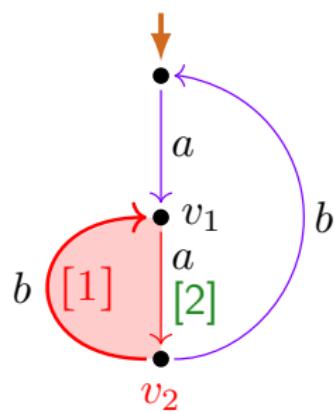
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$\mathcal{L}(v_2, \rightarrow_{[1]}, \rightarrow_{\text{br}, [>1]})$
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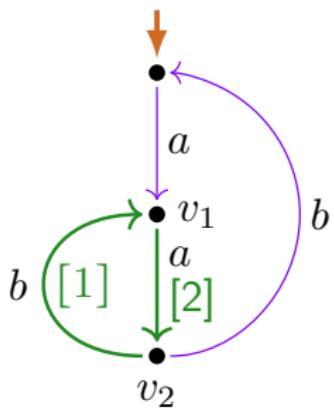
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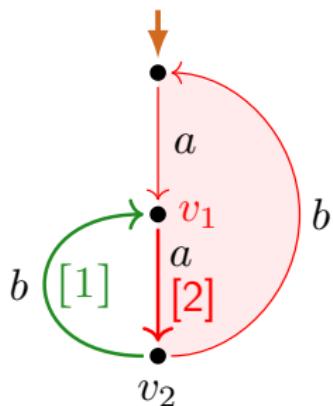
L3.

$\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) :=$ subchart induced
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$$\mathcal{L}(v_1, \xrightarrow{[2]}, \xrightarrow{\text{br},[>2]})$$

Definition

A loop–branch labeling is a LEE-witness, if:

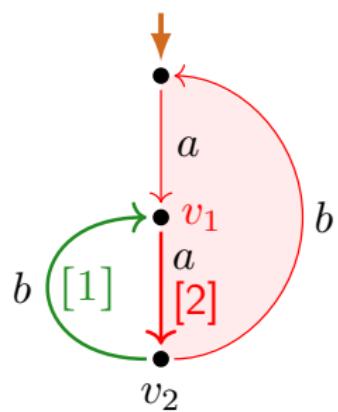
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LEE-witness



$\mathcal{L}(v_1, \rightarrow_{[2]}, \rightarrow_{\text{br}, [>2]})$
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loop–branch labeling: marking transitions \xrightarrow{a} as:

- ▶ entry steps $\xrightarrow{(a, [n])}$ for $n \in \mathbb{N}$, written $\xrightarrow{a}_{[n]}$,
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Definition

A loop–branch labeling is a LEE-witness, if:

L1. $\forall n \in \mathbb{N} \forall v \in V \left(v \xrightarrow{[n]} \Rightarrow \mathcal{L}(v, \rightarrow_{[n]}, \rightarrow_{\text{br}, [>n]}) \text{ is a loop subchart} \right)$.

L2.

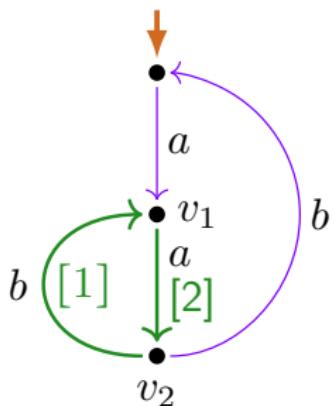
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LEE-witness

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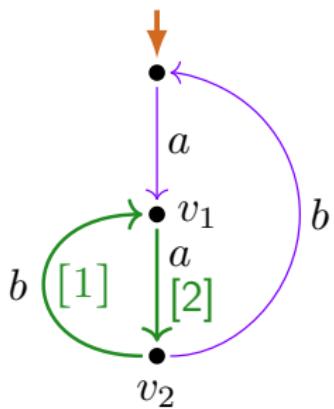
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Definition

A loop–branch labeling is a **LEE-witness**, if:

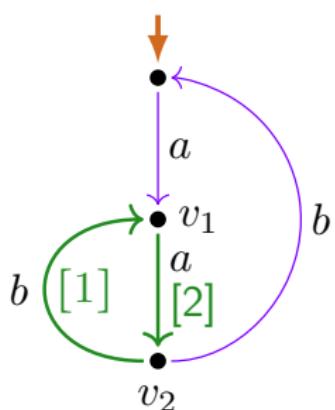
L1. $\forall n \in \mathbb{N} \forall v \in V \left(v \xrightarrow{[n]} \Rightarrow \mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br}, [>n]}) \text{ is a loop subchart} \right)$.

L2. No infinite $\xrightarrow{\text{br}}$ path from **start vertex**.

L3.

$\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br}, [>n]}) :=$ subchart induced
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LEE-witness



loop–branch labeling: marking transitions \xrightarrow{a} as:

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Definition

A loop–branch labeling is a **LEE-witness**, if:

L1. $\forall n \in \mathbb{N} \forall v \in V \left(v \xrightarrow{[n]} \Rightarrow \mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) \text{ is a loop subchart} \right)$.

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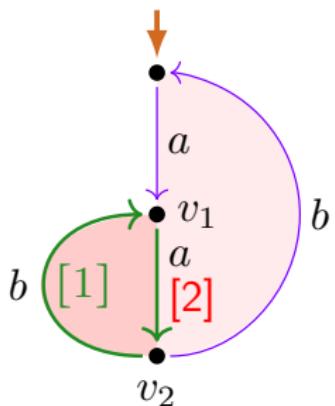
L3. Loop subcharts contained in other loop subcharts have **different entry-step levels**.

$\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) :=$ subchart induced
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LEE-witness

loop–branch labeling: marking transitions \xrightarrow{a} as:

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Definition

A loop–branch labeling is a LEE-witness, if:

L1. $\forall n \in \mathbb{N} \forall v \in V \left(v \xrightarrow{[n]} \Rightarrow \mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) \text{ is a loop subchart} \right)$.

L2. No infinite $\xrightarrow{\text{br}}$ path from start vertex.

L3. Loop subcharts contained in other loop subcharts have different entry-step levels.

$$\mathcal{L}(v_2, \xrightarrow{[1]}, \xrightarrow{\text{br},[>1]})$$

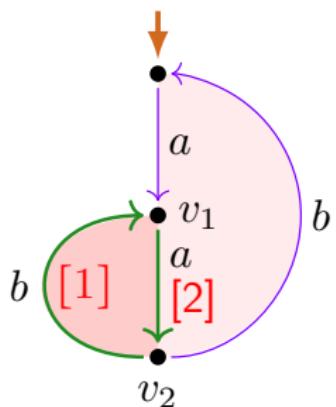
$$\mathcal{L}(v_1, \xrightarrow{[2]}, \xrightarrow{\text{br},[>2]})$$

$\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) :=$ subchart induced by entry steps $\xrightarrow{[n]}$ from v followed by branch steps $\xrightarrow{\text{br}}$ or entry steps $\xrightarrow{[m]}$ with $m > n$, until v is reached again

LEE-witness

loop–branch labeling: marking transitions \xrightarrow{a} as:

- ▶ **entry steps** $\xrightarrow{(a,[n])}$ for $n \in \mathbb{N}$, written $\xrightarrow{a}_{[n]}$,
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$$\begin{aligned}\mathcal{L}(v_2, \xrightarrow{[1]}, \xrightarrow{\text{br},[>1]}) \\ \mathcal{L}(v_1, \xrightarrow{[2]}, \xrightarrow{\text{br},[>2]})\end{aligned}$$

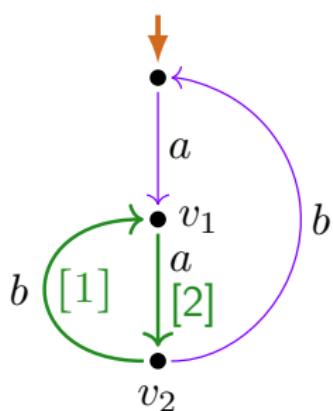
Definition

A loop–branch labeling is a **LEE-witness**, if:

- L1. $\forall n \in \mathbb{N} \forall v \in V \left(v \xrightarrow{[n]} \Rightarrow \mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) \right)$.
is a loop subchart
- L2. No infinite $\xrightarrow{\text{br}}$ path from **start vertex**.
- L3. $\mathcal{L}(w_i, \xrightarrow{[n_i]}, \xrightarrow{\text{br},[>n_i]})$ for $i \in \{1, 2\}$ loop charts
 $\wedge w_1 \neq w_2 \wedge w_1 \in \mathcal{L}(w_2, \dots, \dots) \implies n_1 \neq n_2$.

$\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) :=$ subchart induced
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LEE-witness



LEE-witness

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Definition

A loop–branch labeling is a LEE-witness, if:

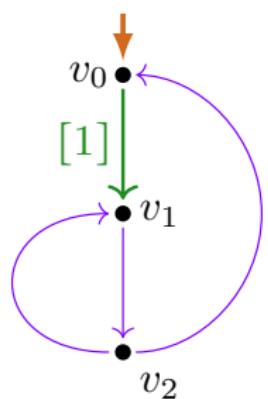
L1. $\forall n \in \mathbb{N} \forall v \in V \left(v \xrightarrow{[n]} \Rightarrow \mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{\text{br},[>n]}) \text{ is a loop subchart} \right)$.

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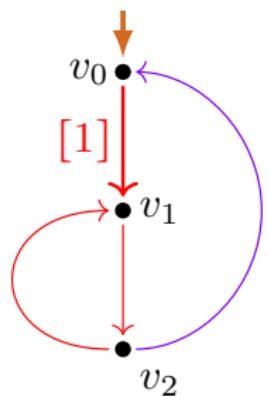
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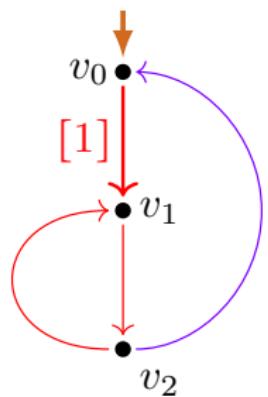
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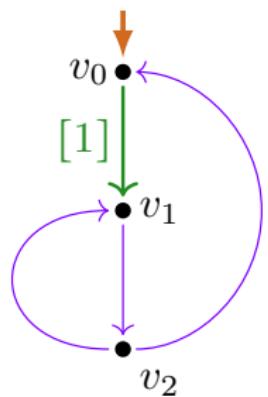
no!

(L1.) violated:

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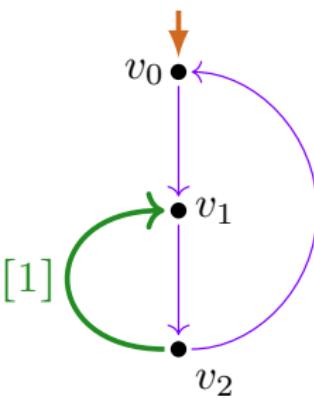
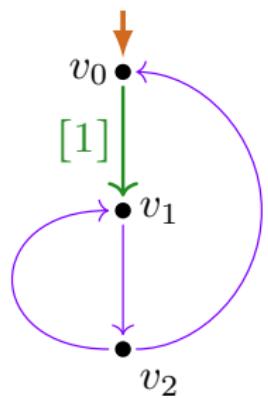
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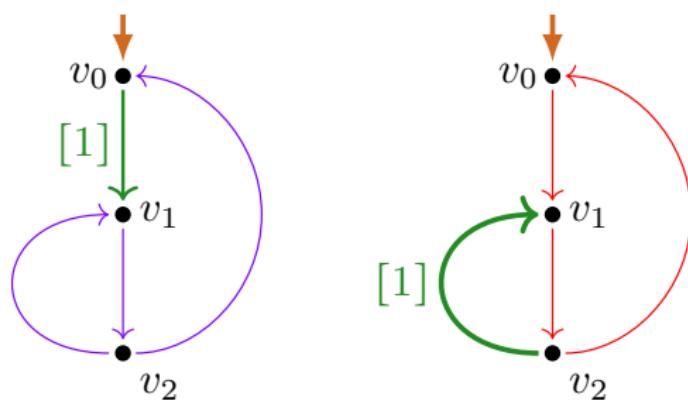
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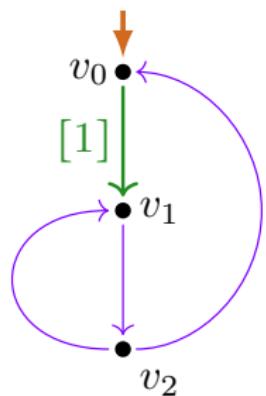
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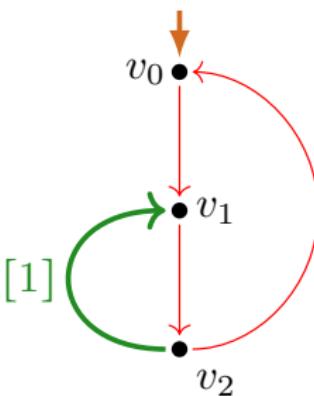


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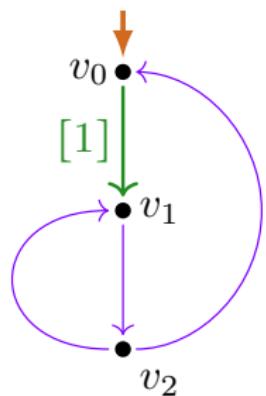
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(L2.) violated:

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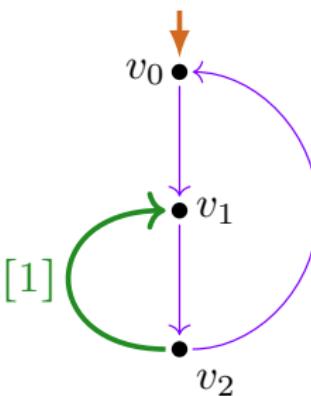


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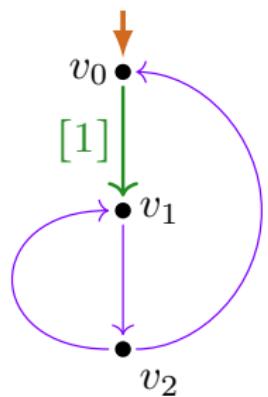
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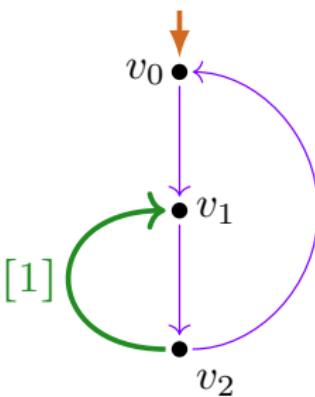
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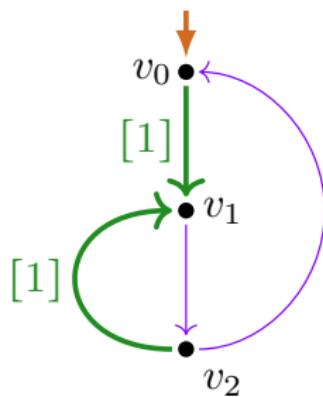
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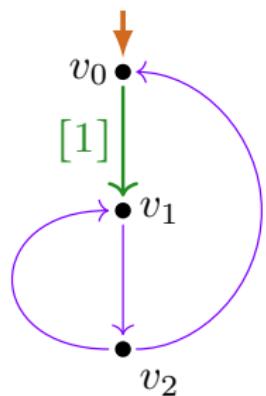
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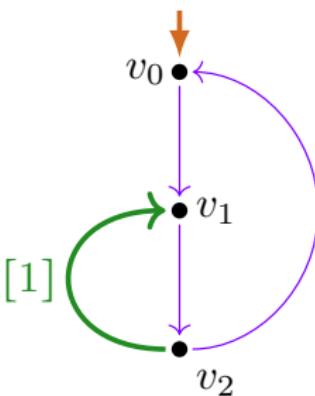
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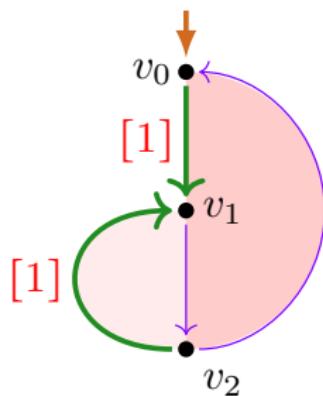
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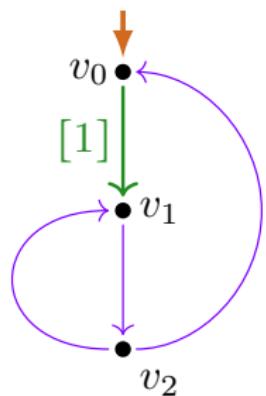
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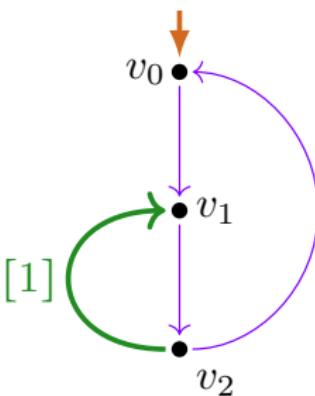
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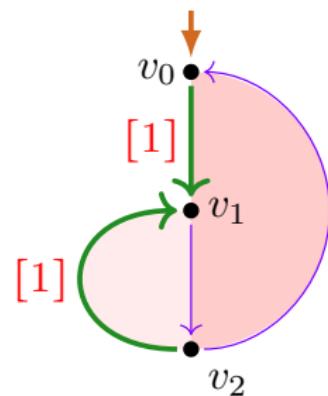
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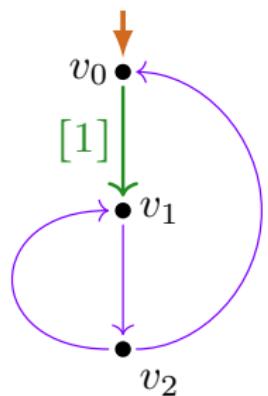


no!

(L3.) violated:

overlapping loop charts
have same level

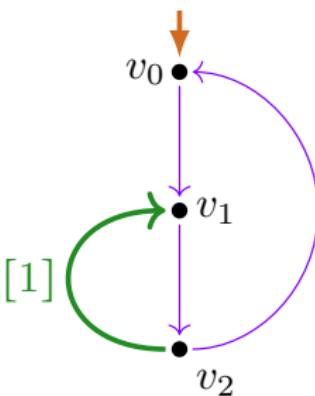
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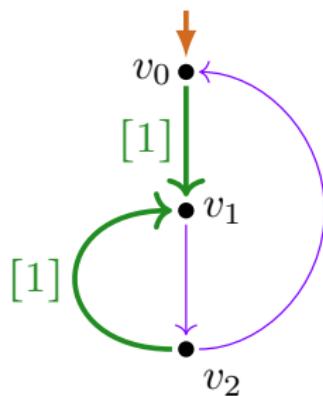
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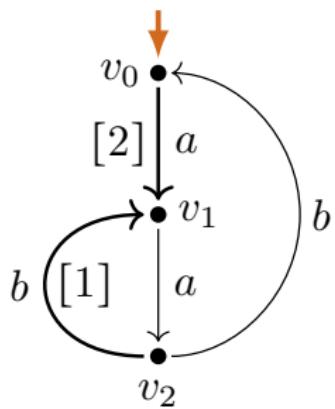


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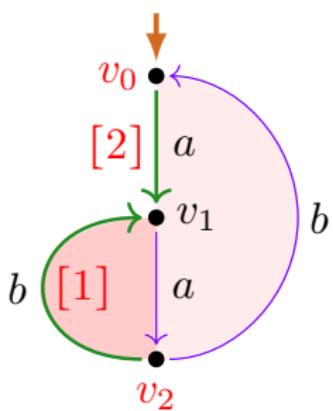
LEE-witness ?



LEE-witness

loop–branch labeling: marking transitions \xrightarrow{a} as:

- ▶ entry steps $\xrightarrow{\langle a, [n] \rangle}$ for $n \in \mathbb{N}$, written $\xrightarrow{a}_{[n]}$,
- ▶ branch steps $\xrightarrow{\langle a, br \rangle}$, written \xrightarrow{a}_{br} or \xrightarrow{a} .



$$\mathcal{L}(v_2, \xrightarrow{[1]}, \xrightarrow{br, [>1]})$$

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LEE-witness

Definition

A loop–branch labeling is a LEE-witness, if:

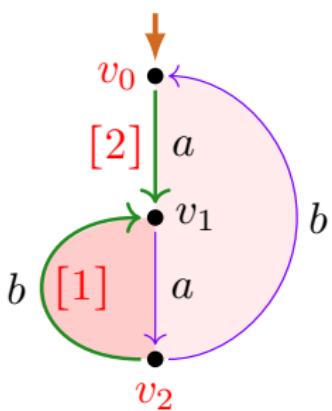
- L1. $\forall n \in \mathbb{N} \forall v \in V \left(\mathcal{L}(v, \xrightarrow{[n]}, \xrightarrow{br, [>n]}) \text{ is a loop subchart, or trivial} \right)$.
- L2. No infinite \xrightarrow{br} path from start vertex.
- L3. $\mathcal{L}(w_i, \xrightarrow{[n_i]}, \xrightarrow{br, [>n_i]})$ for $i \in \{1, 2\}$ loop charts
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Layered LEE-witness

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Definition

A loop–branch labeling is a **layered LEE-witness**, if:

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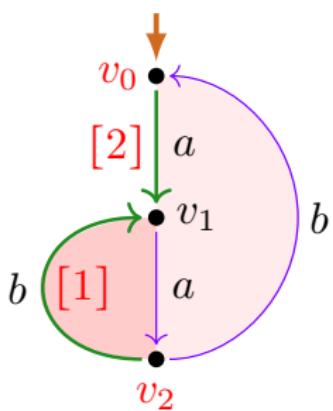
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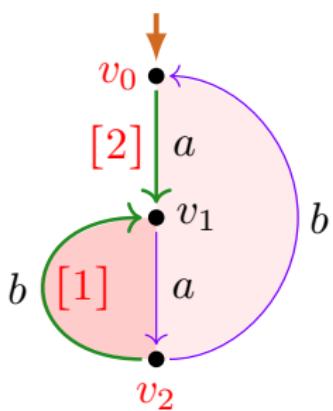
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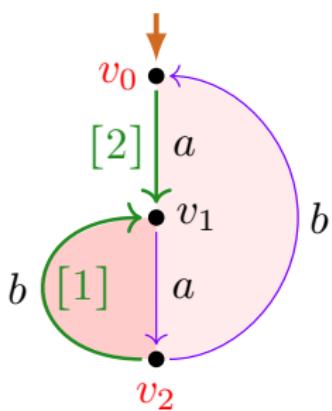
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$$\begin{aligned}\mathcal{L}(v_2, \xrightarrow{[1]}, \xrightarrow{\text{br}}) \\ \mathcal{L}(v_0, \xrightarrow{[2]}, \xrightarrow{\text{br}})\end{aligned}$$

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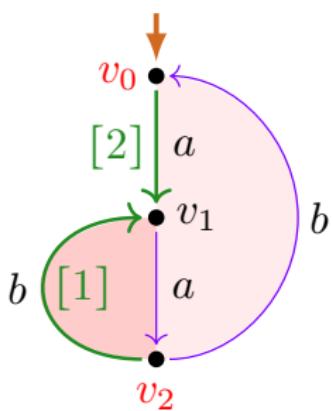
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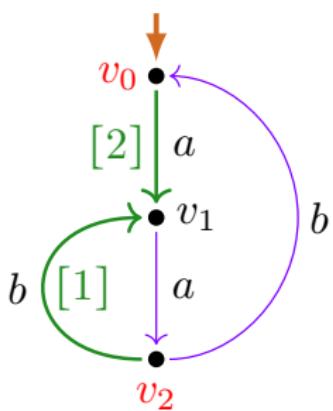
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LEE versus LEE-witness

Theorem

For every process graph G :

$$\text{LEE}(G) \iff G \text{ has a LEE-witness.}$$

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Proof.

\Rightarrow : record loop elimination

LEE versus LEE-witness

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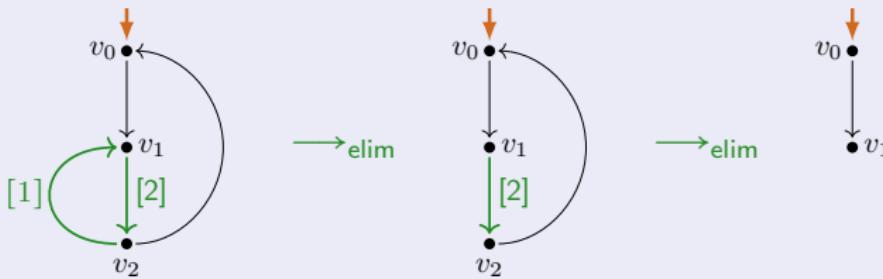
For every process graph G :

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Proof.

\Rightarrow : record loop elimination

\Leftarrow : carry out loop-elimination as indicated in the LEE-witness,
in *inside-out* direction, e.g.:



LEE and (layered) LEE-witness

Lemma

Every layered LEE-witness is a LEE-witness.

Lemma

Every LEE-witness \widehat{G} of a process graph G

can be transformed by an effective procedure (cut-elimination-like)
into a layered LEE-witness \widehat{G}' of G .

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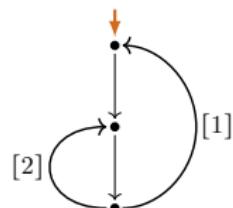
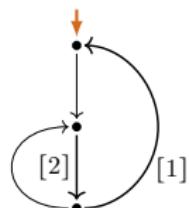
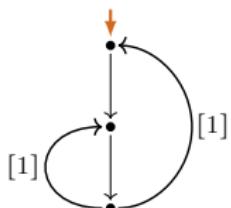
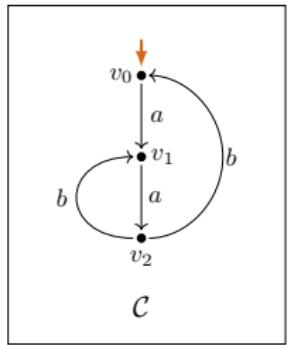
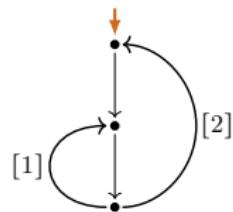
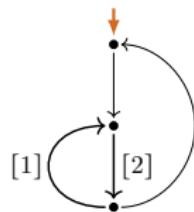
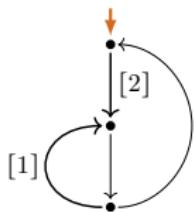
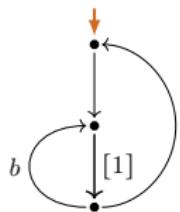
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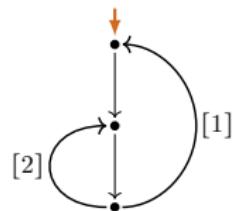
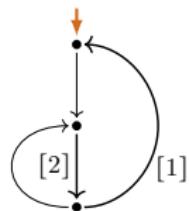
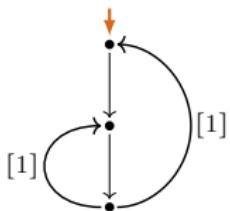
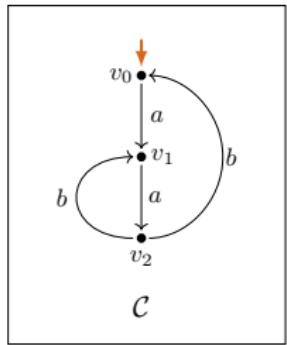
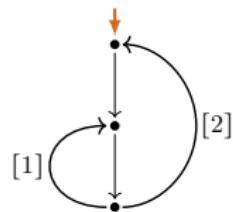
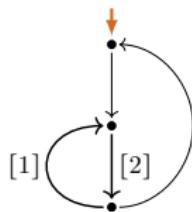
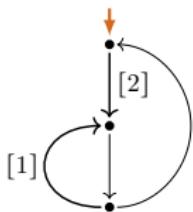
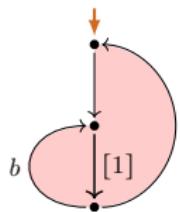
For every process graph G the following are equivalent:

- (i) $\text{LEE}(G)$.
- (ii) G has a LEE-witness.
- (iii) G has a layered LEE-witness.

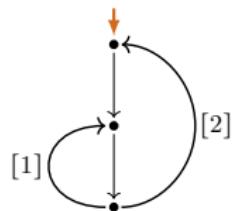
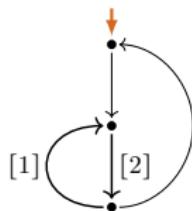
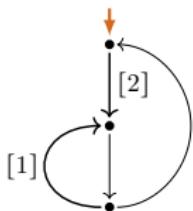
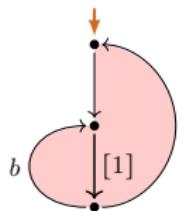
7 LEE-witnesses



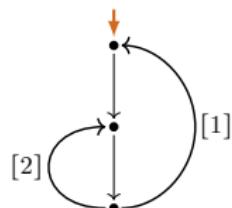
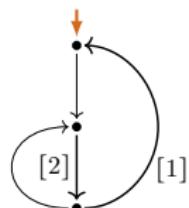
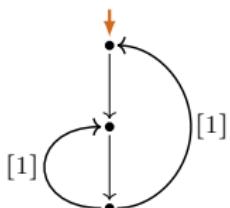
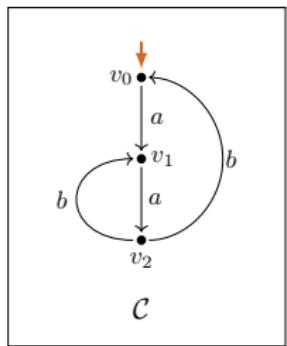
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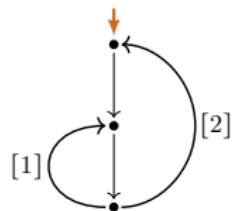
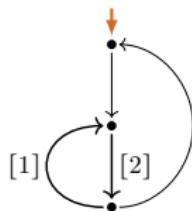
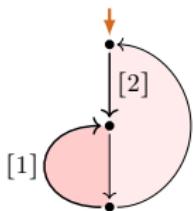
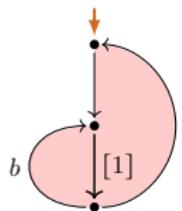
7 LEE-witnesses



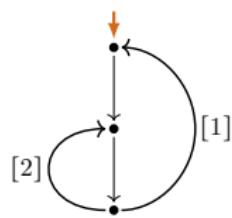
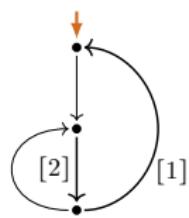
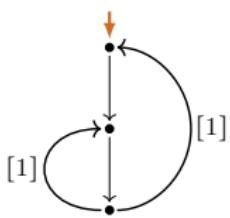
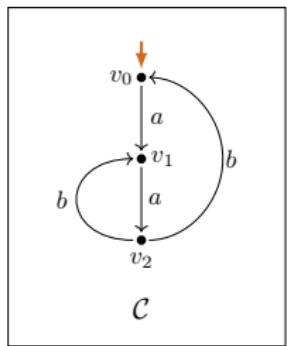
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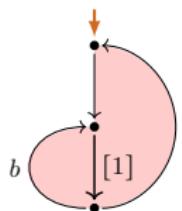
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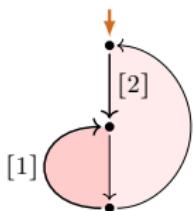
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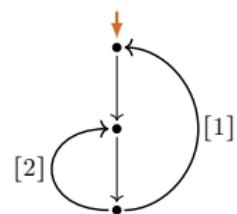
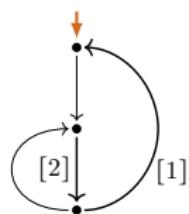
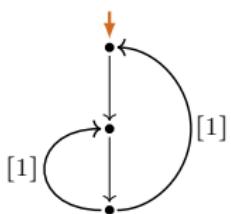
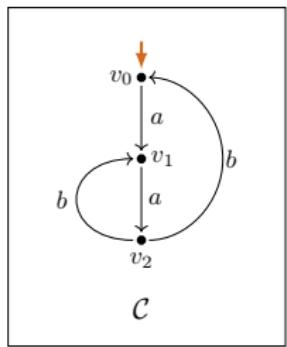
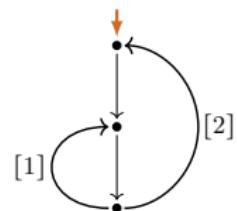
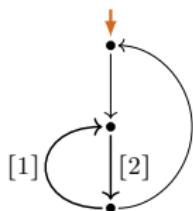
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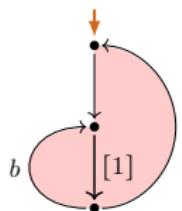
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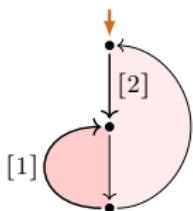
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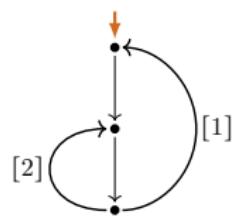
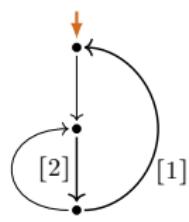
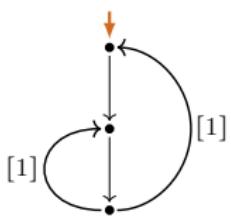
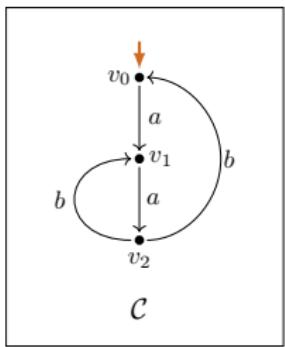
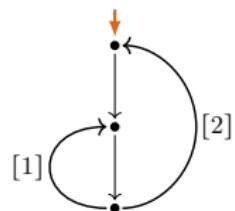
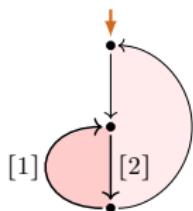
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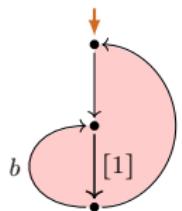
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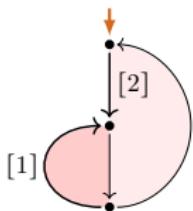
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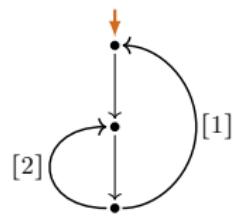
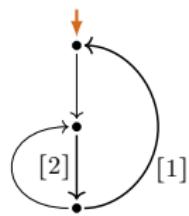
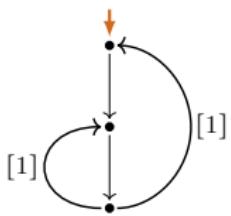
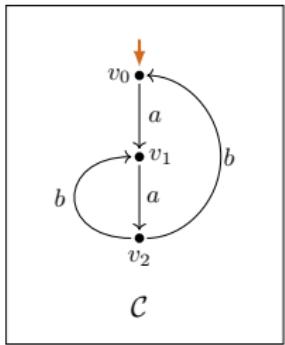
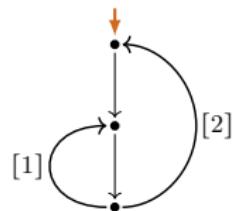
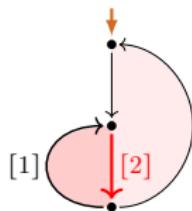
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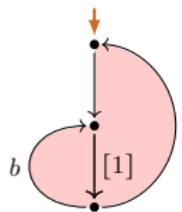
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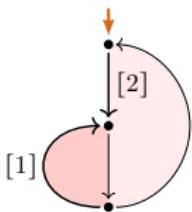
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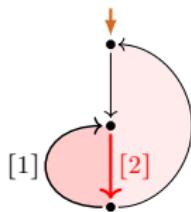
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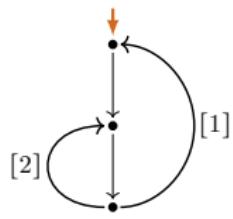
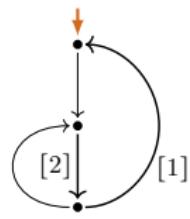
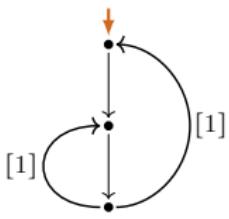
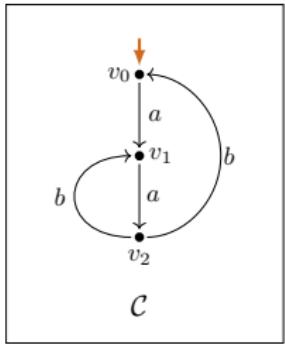
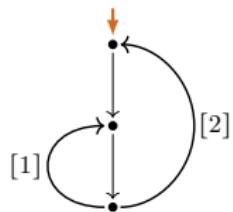
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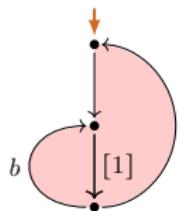
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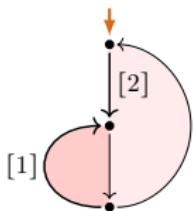
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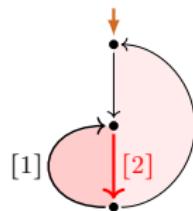
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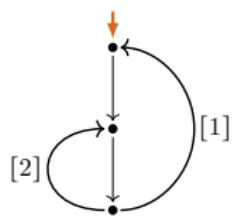
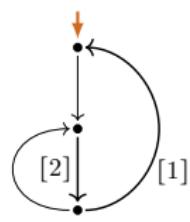
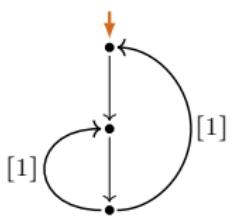
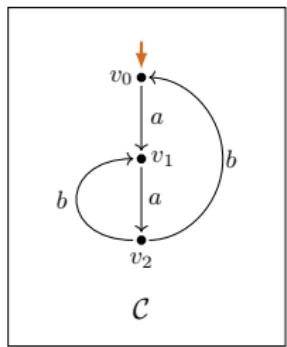
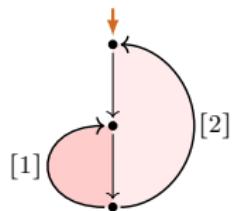
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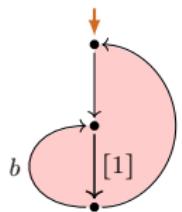
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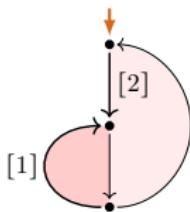
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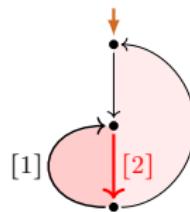
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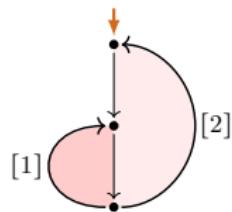
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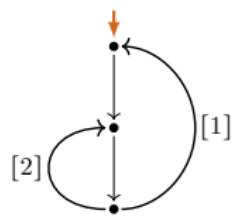
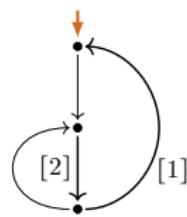
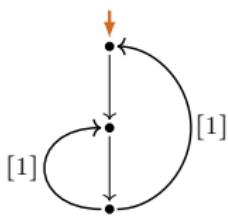
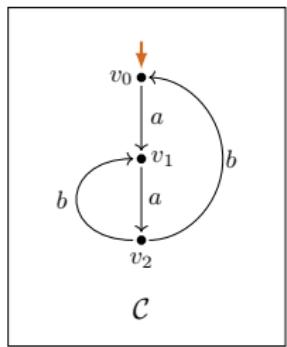
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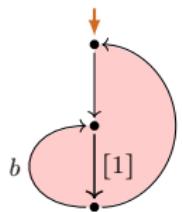
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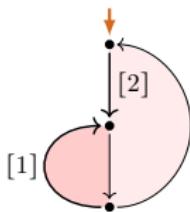
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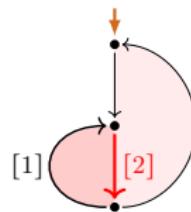
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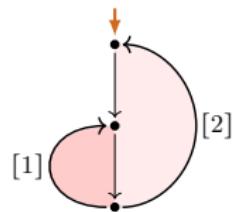
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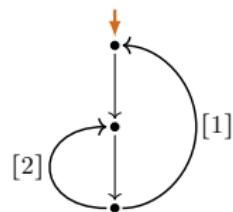
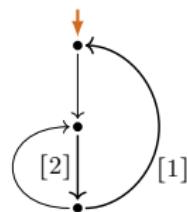
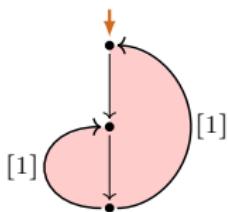
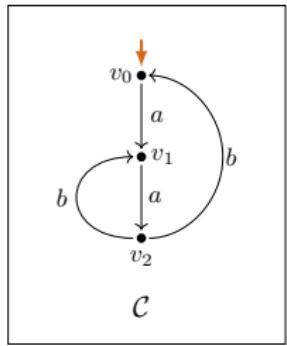
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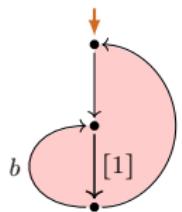
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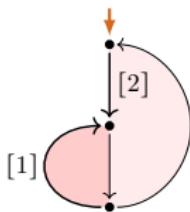
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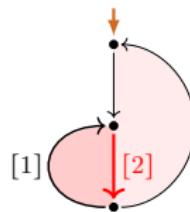
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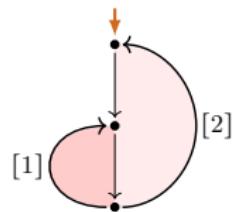
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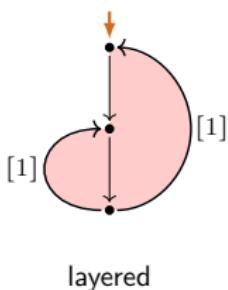
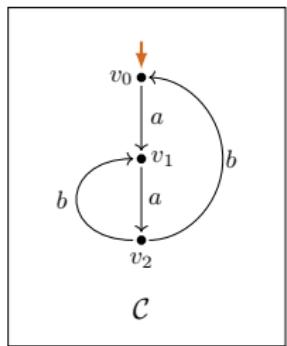
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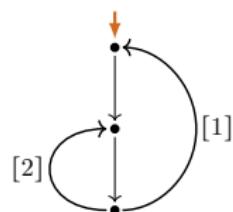
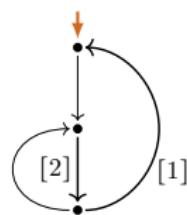
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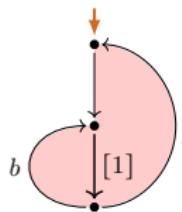
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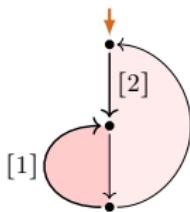
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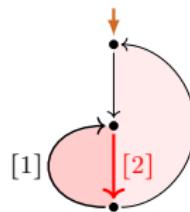
7 LEE-witnesses



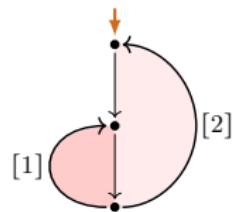
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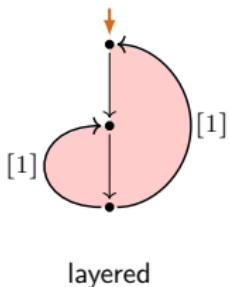
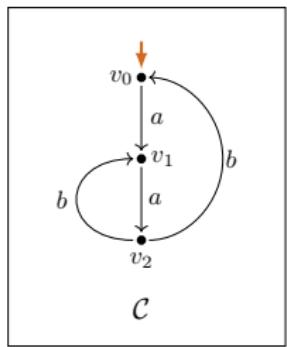
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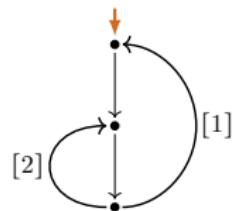
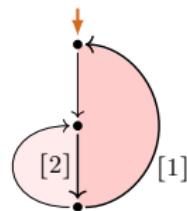
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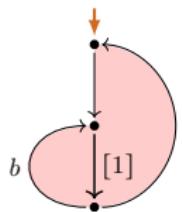
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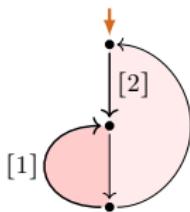
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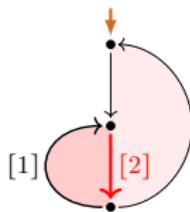
7 LEE-witnesses



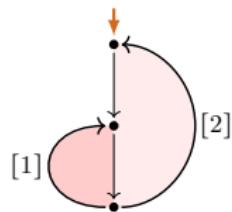
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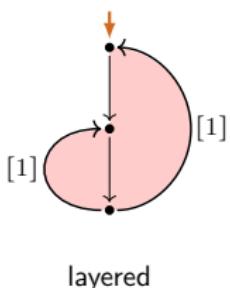
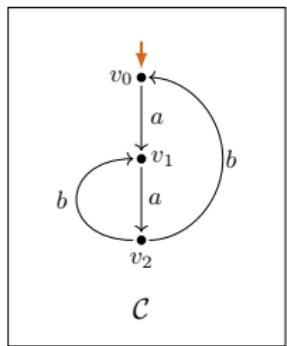
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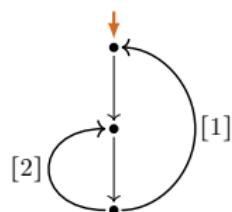
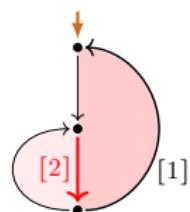
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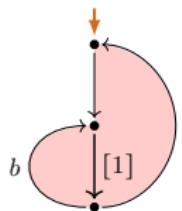
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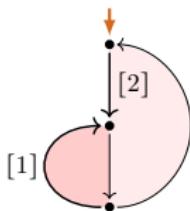
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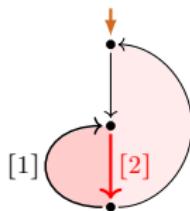
7 LEE-witnesses



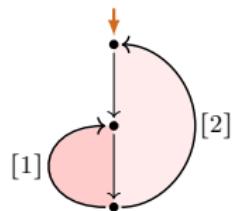
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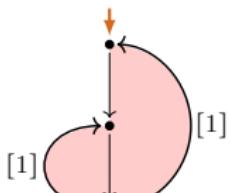
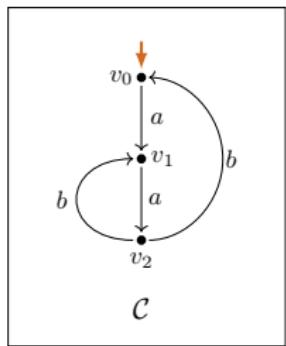
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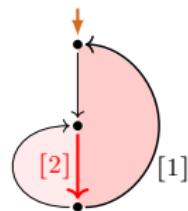
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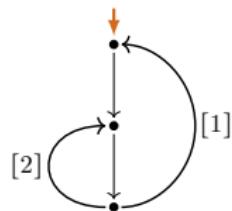
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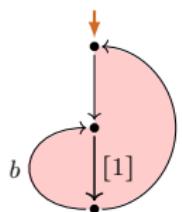
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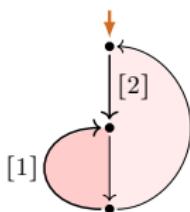
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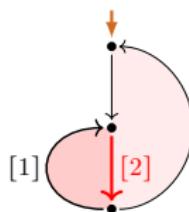
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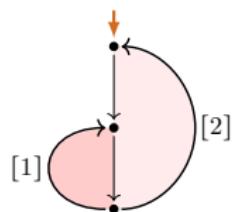
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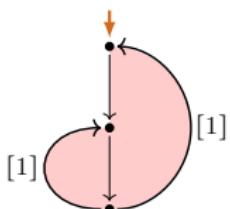
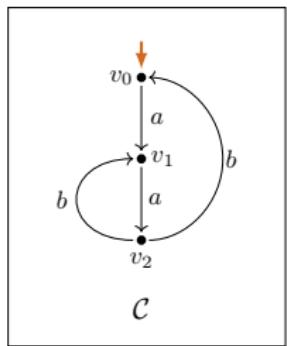
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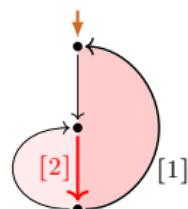
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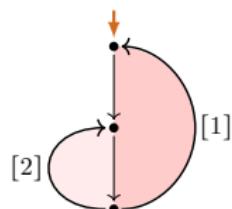
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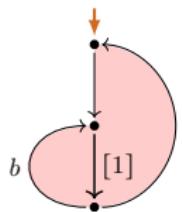
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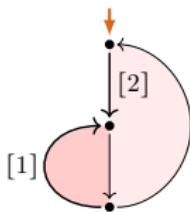
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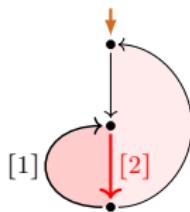
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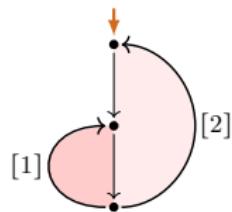
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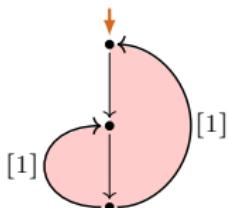
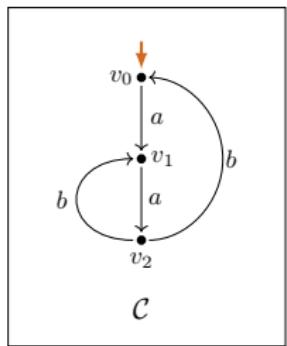
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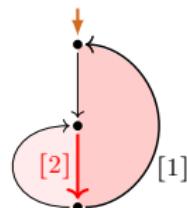
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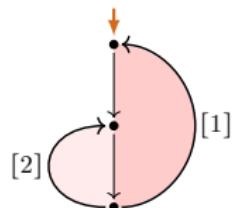
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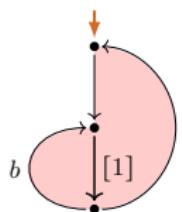


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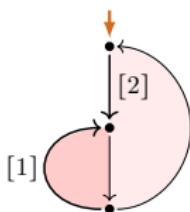


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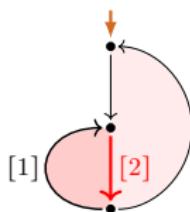
7 LEE-witnesses



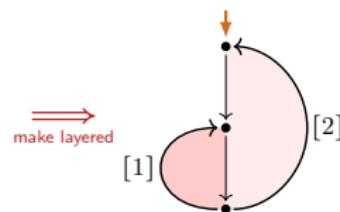
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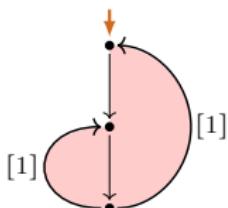
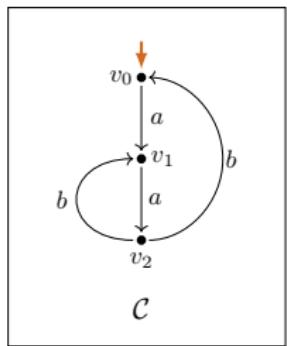
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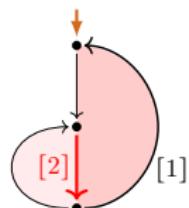
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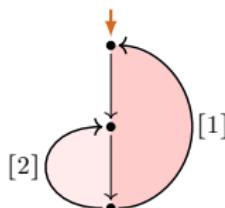
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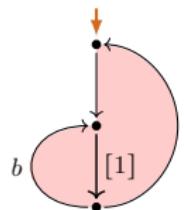


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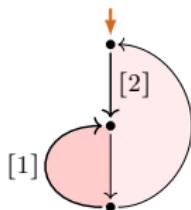


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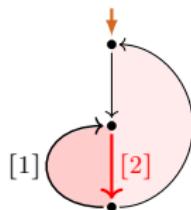
7 LEE-witnesses



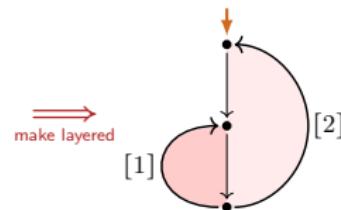
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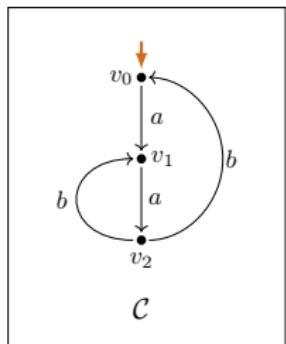
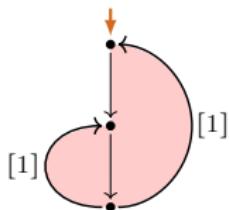
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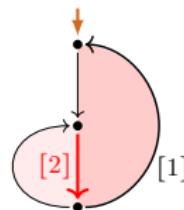
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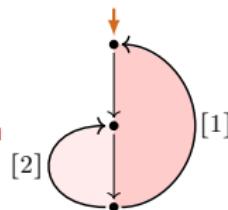
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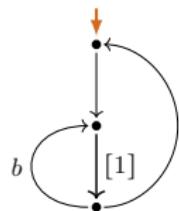


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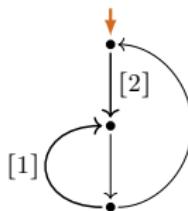


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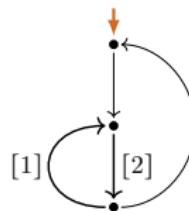
7 LEE-witnesses



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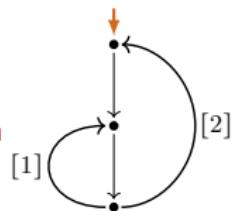


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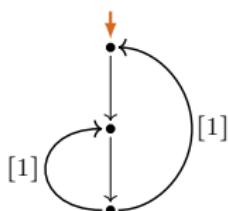
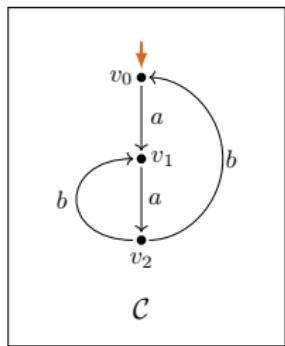


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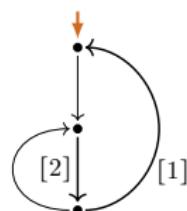
make layered



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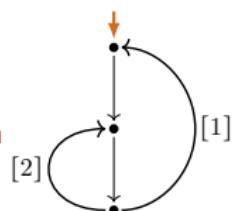


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make layered



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LEE under bisimulation?

LEE under bisimulation

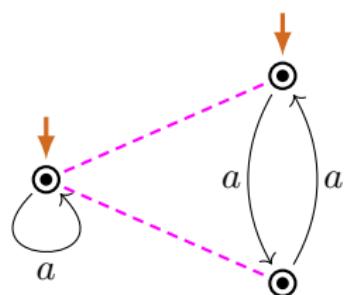
Observation

- ▶ LEE is **not** invariant under bisimulation.

LEE under bisimulation

Observation

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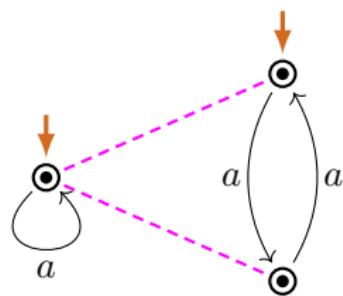
LEE

\neg LEE

LEE under bisimulation

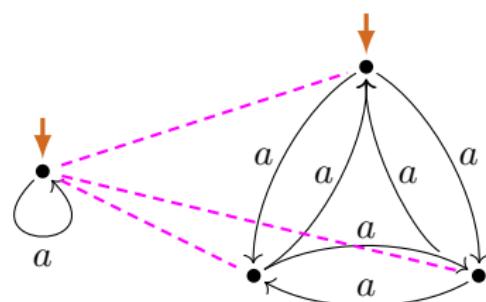
Observation

- ▶ LEE is **not** invariant under bisimulation.



LEE

\neg LEE



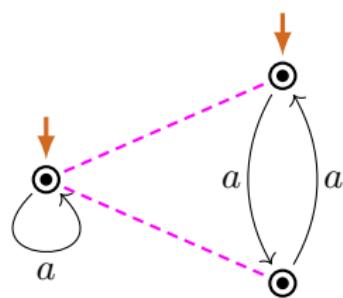
LEE

\neg LEE

LEE under bisimulation

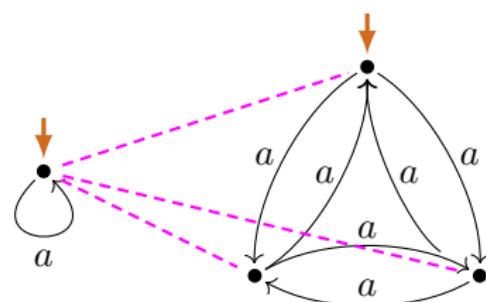
Observation

- ▶ LEE is **not** invariant under bisimulation.
- ▶ LEE is **not** preserved by converse functional bisimulation.



LEE

\neg LEE



LEE

\neg LEE

LEE under functional bisimulation

Lemma

(i) LEE is preserved by *functional bisimulations*:

$$\text{LEE}(G_1) \wedge G_1 \mathrel{\sqsupseteq} G_2 \implies \text{LEE}(G_2).$$

LEE under functional bisimulation

Lemma

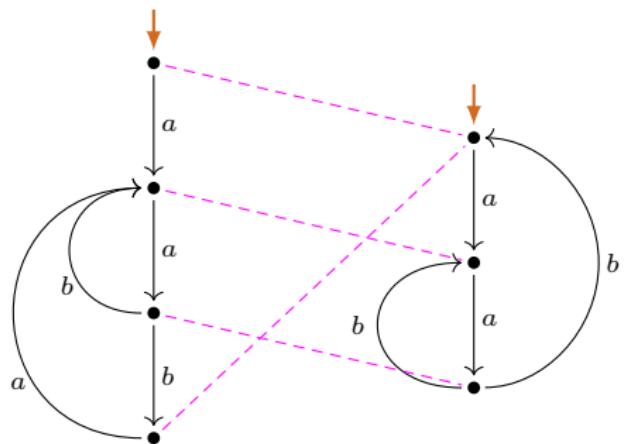
(i) LEE is preserved by *functional bisimulations*:

$$\text{LEE}(G_1) \wedge G_1 \mathrel{\sqsupseteq} G_2 \implies \text{LEE}(G_2).$$

Proof (Idea).

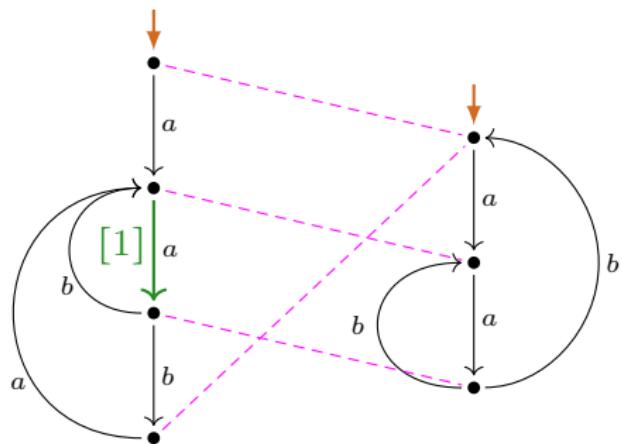
Use loop elimination in G_1 to carry out loop elimination in G_2 .

Collapsing LEE-witnesses



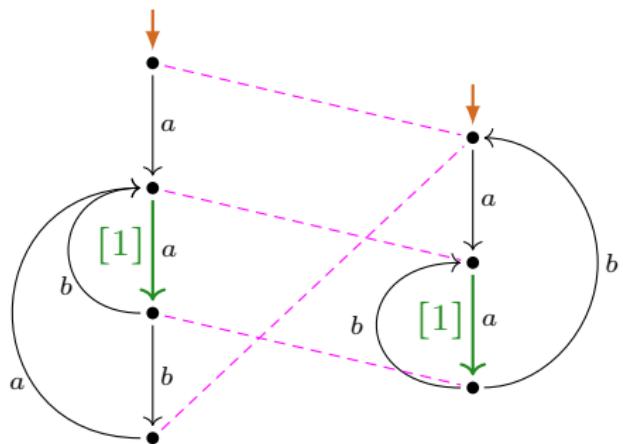
$$P(a(a(b + ba))^*0)$$

Collapsing LEE-witnesses



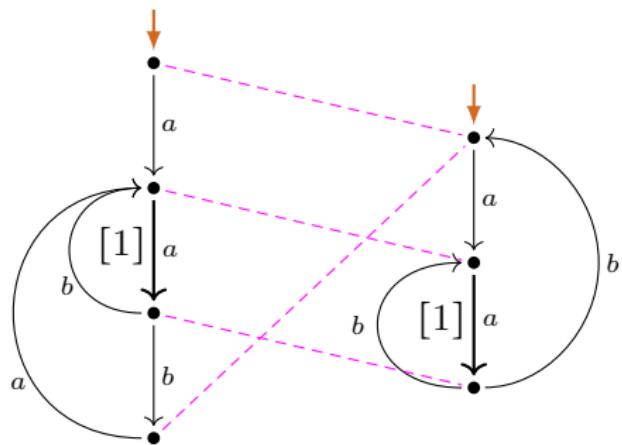
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Collapsing LEE-witnesses



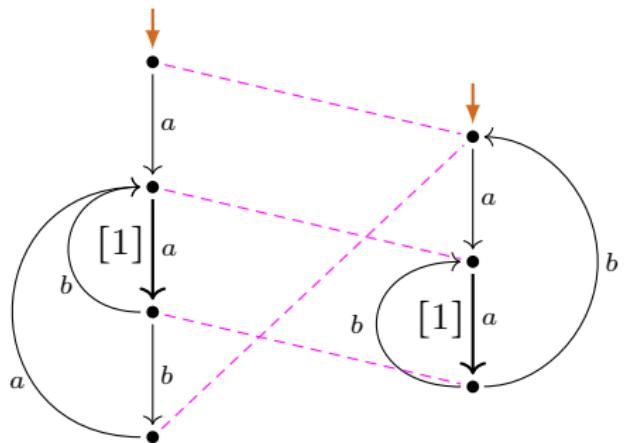
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Collapsing LEE-witnesses

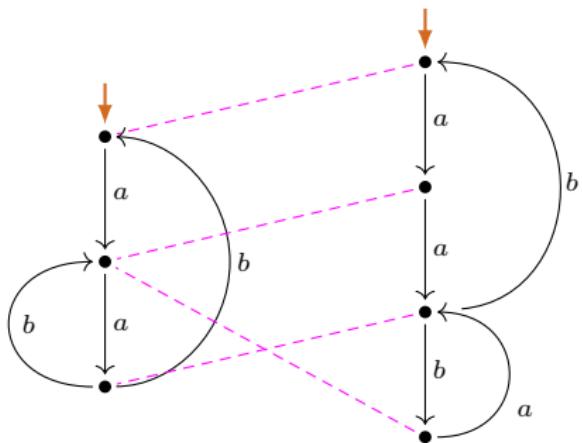


$$P(a(a(b+ba))^*0)$$

Collapsing LEE-witnesses

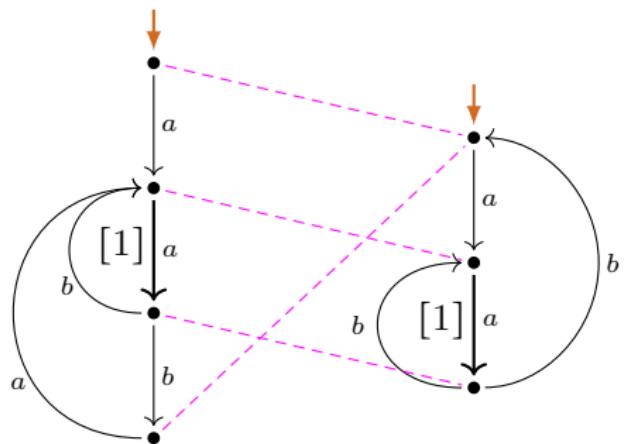
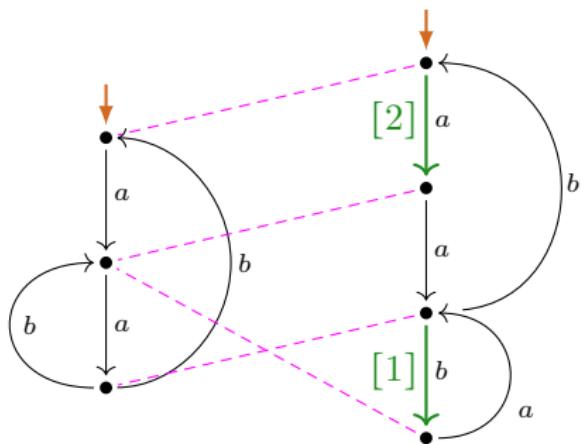


$\textcolor{violet}{P}(a(a(b+ba))^*0)$

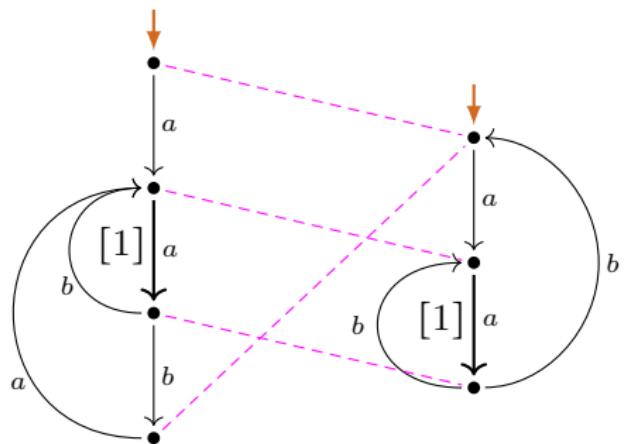


$\textcolor{violet}{P}((aa(ba)^*b)^*0)$

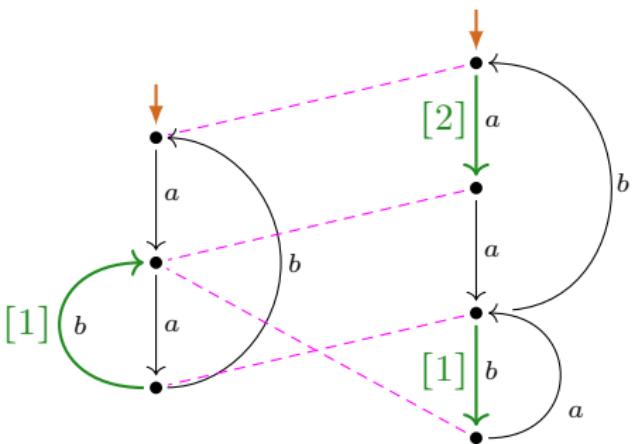
Collapsing LEE-witnesses


 $P(a(a(b+ba))^*0)$

 $P((aa(ba)^*b)^*0)$

Collapsing LEE-witnesses

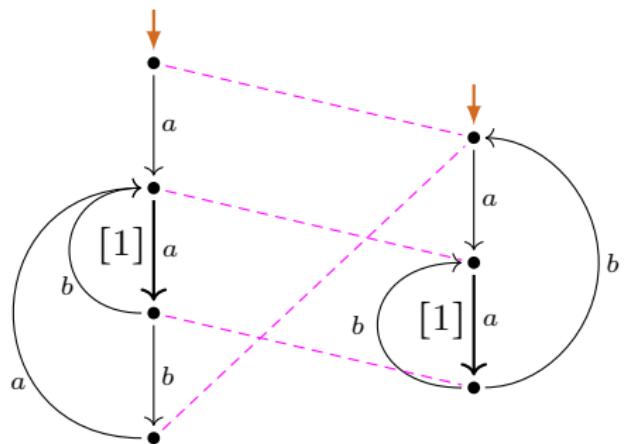
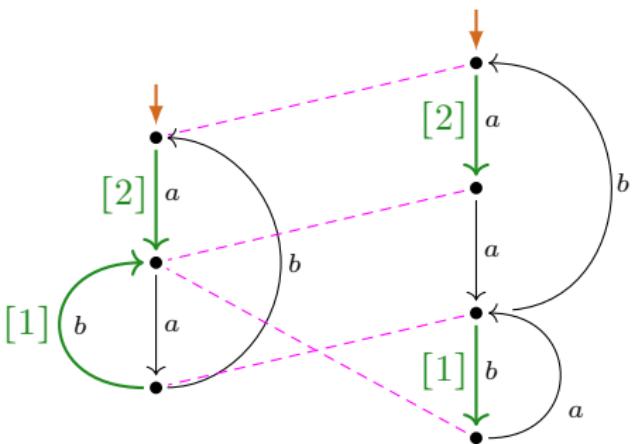


$P(a(a(b+ba))^*0)$

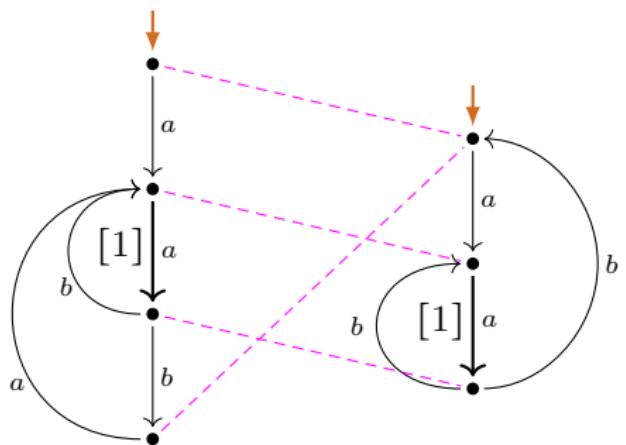
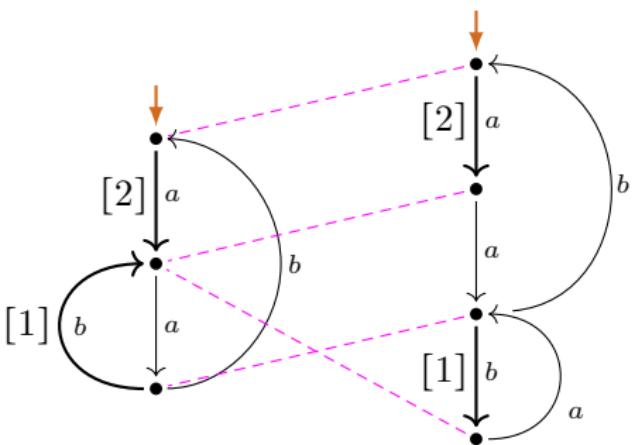


$P((aa(ba)^*b)^*0)$

Collapsing LEE-witnesses

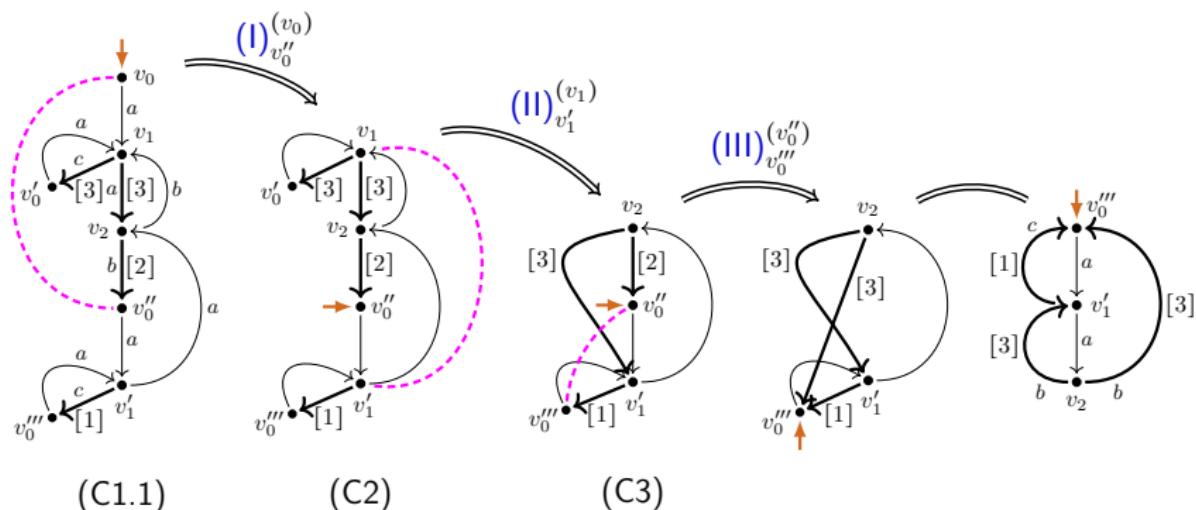

 $P(a(a(b+ba))^*0)$

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Collapsing LEE-witnesses


 $P(a(a(b+ba))^*0)$

 $P((aa(ba)^*b)^*0)$

LLEE-preserving collapse of LLEE-charts (G/Fokkink, LICS'20)

(no 1-transitions!)



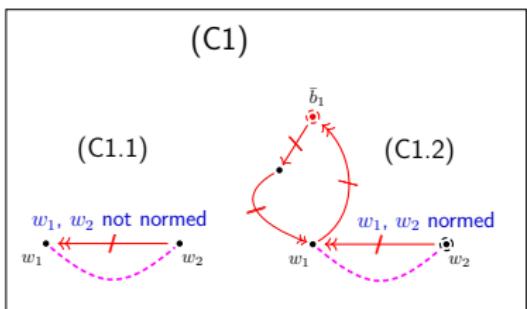
Lemma

The bisimulation collapse of a LLEE-chart is again a LLEE-chart.

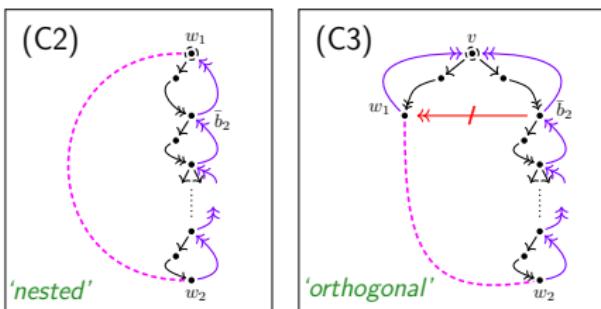
Reduced bisimilarity redundancies in LLEE-charts (no 1-trans.!)

(G/Fokkink, LICS'20)

w_1, w_2 in different scc's



w_1, w_2 in the same scc



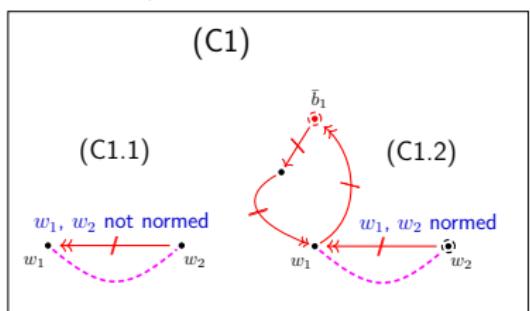
Lemma

Every *not collapsed* LLEE-chart contains bisimilar vertices $w_1 \neq w_2$ of kind (C1), (C2), or (C3) (a *reduced bisimilarity redundancy* $\langle w_1, w_2 \rangle$):

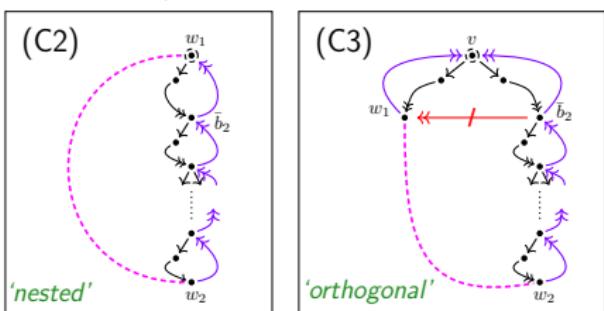
Reduced bisimilarity redundancies in LLEE-charts (no 1-trans.!)

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w_1, w_2 in the same scc



Lemma

Every *not collapsed LLEE-chart* contains bisimilar vertices $w_1 \neq w_2$ of kind (C1), (C2), or (C3) (a *reduced bisimilarity redundancy* $\langle w_1, w_2 \rangle$):

Lemma

Every *reduced bisimilarity redundancy* in a LLEE-chart can be eliminated LLEE-preservingly.

LEE under functional bisimulation

Lemma

(i) LEE is preserved by *functional bisimulations*:

$$\text{LEE}(\textcolor{violet}{G}_1) \wedge \textcolor{violet}{G}_1 \mathrel{\sqsupseteq} \textcolor{violet}{G}_2 \implies \text{LEE}(\textcolor{violet}{G}_2).$$

Idea of Proof for (i)

Use loop elimination in $\textcolor{violet}{G}_1$ to carry out loop elimination in $\textcolor{violet}{G}_2$.

LEE under functional bisimulation / bisimulation collapse

Lemma

(i) LEE is preserved by *functional bisimulations*:

$$\text{LEE}(\textcolor{violet}{G}_1) \wedge G_1 \mathrel{\underrightarrow{}} G_2 \implies \text{LEE}(\textcolor{violet}{G}_2).$$

(ii) LEE is preserved from a process graph to its *bisimulation collapse*:

$$\text{LEE}(\textcolor{violet}{G}) \wedge \textcolor{brown}{C} \text{ is bisimulation collapse of } \textcolor{violet}{G} \implies \text{LEE}(\textcolor{brown}{C}).$$

Idea of Proof for (i)

Use loop elimination in $\textcolor{violet}{G}_1$ to carry out loop elimination in $\textcolor{violet}{G}_2$.

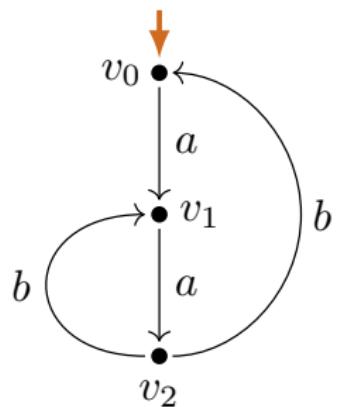
Readback

Lemma

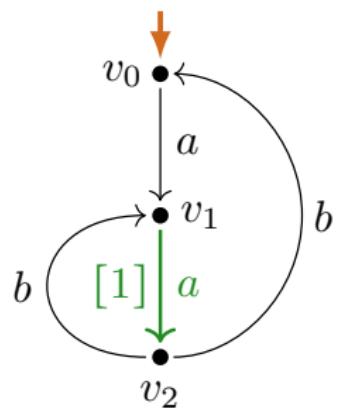
Process graphs with LEE are $P(\cdot)$ -expressible:

$$\text{LEE}(\textcolor{violet}{G}) \implies \exists e \in \text{Reg}(A) (\textcolor{violet}{G} \xrightarrow{\sim} P(e)).$$

Readback from layered LEE-witness (example)

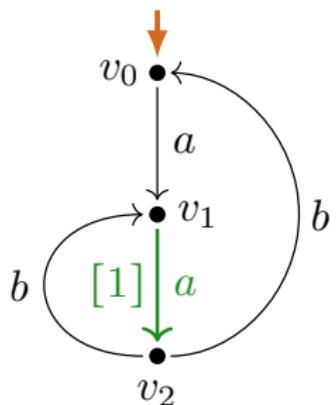


Readback from layered LEE-witness (example)



layered
LEE-witness

Readback from layered LEE-witness (example)



$$s(v_0) = 0^* \cdot a \cdot s(v_1)$$

$$=_{\text{Mil}} a \cdot s(v_1)$$

$$=_{\text{Mil}} a \cdot (a \cdot (b + b \cdot a))^* \cdot 0$$

$$s(v_1) = (a \cdot s(v_2, v_1))^* \cdot 0$$

$$=_{\text{Mil}} (a \cdot (b + b \cdot a))^* \cdot 0$$

$$s(v_2, v_1) = 0^* \cdot (b \cdot s(v_1, v_1) + b \cdot s(v_0, v_1))$$

$$=_{\text{Mil}} 0^* \cdot (b \cdot 1 + b \cdot a)$$

$$=_{\text{Mil}} b + b \cdot a$$

$$s(v_1, v_1) = 1$$

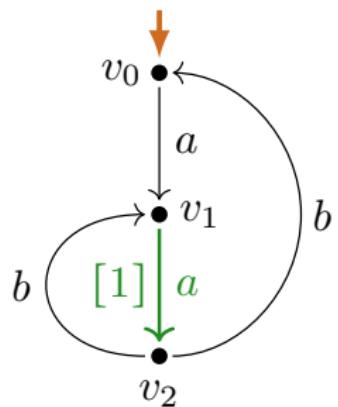
$$s(v_0, v_1) = 0^* \cdot a \cdot s(v_1, v_1)$$

$$= 0^* \cdot a \cdot 1$$

$$=_{\text{Mil}} a$$

Readback from layered LEE-witness (example)

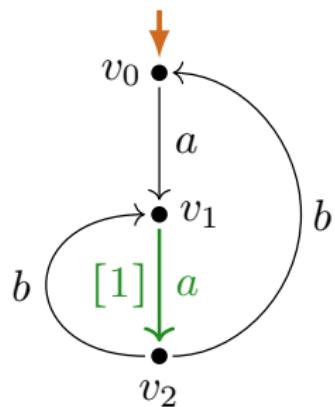
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layered
LEE-witness

Readback from layered LEE-witness (example)

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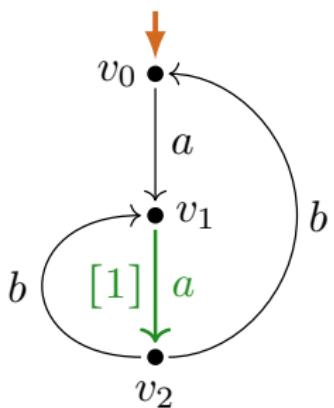


$$s(v_1) = (a \cdot s(v_2, v_1))^* \cdot 0$$

layered
LEE-witness

Readback from layered LEE-witness (example)

$$s(v_0) = 0^* \cdot a \cdot s(v_1)$$

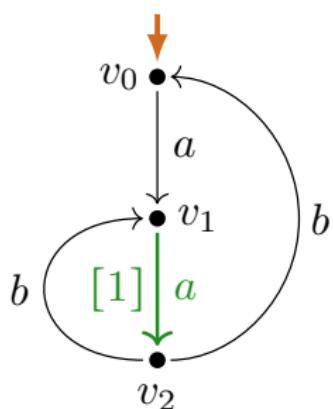


$$s(v_1) = \left(\textcolor{red}{a} \cdot s(v_2, v_1) \right)^* \cdot 0$$

$$s(v_2, v_1) = 0^* \cdot (b \cdot s(v_1, v_1) + b \cdot s(v_0, v_1))$$

layered LEE-witness

Readback from layered LEE-witness (example)



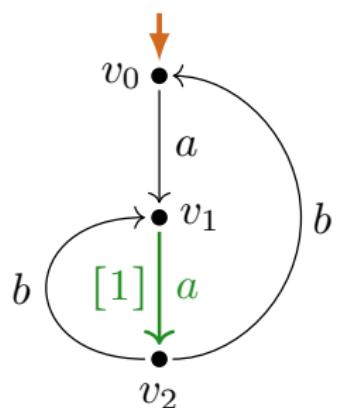
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Readback from layered LEE-witness (example)



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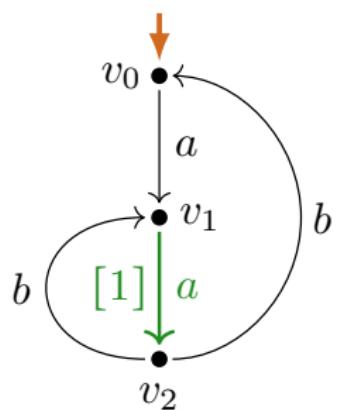
$$s(v_1) = (a \cdot s(v_2, v_1))^* \cdot 0$$

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Readback from layered LEE-witness (example)



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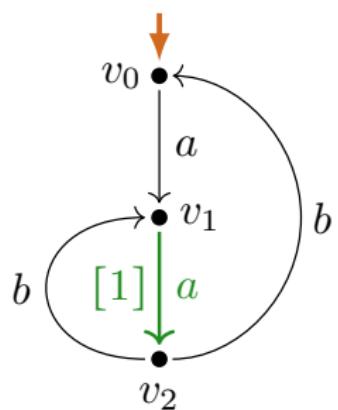
$$s(v_1) = (\textcolor{green}{a} \cdot s(v_2, v_1))^* \cdot 0$$

$$s(v_2, v_1) = 0^* \cdot (b \cdot s(v_1, v_1) + b \cdot s(v_0, v_1))$$

$$s(v_1, v_1) = 1$$

$$\begin{aligned} s(v_0, v_1) &= 0^* \cdot a \cdot s(v_1, v_1) \\ &= 0^* \cdot a \cdot 1 \end{aligned}$$

Readback from layered LEE-witness (example)



$$s(v_0) = 0^* \cdot a \cdot s(v_1)$$

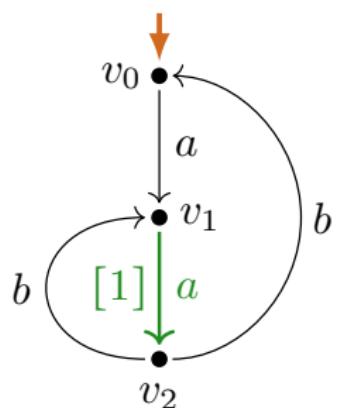
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$$s(v_1, v_1) = 1$$

$$\begin{aligned} s(v_0, v_1) &= 0^* \cdot a \cdot s(v_1, v_1) \\ &= 0^* \cdot a \cdot 1 \\ &= \textcolor{blue}{\text{Mil}}^- a \end{aligned}$$

Readback from layered LEE-witness (example)



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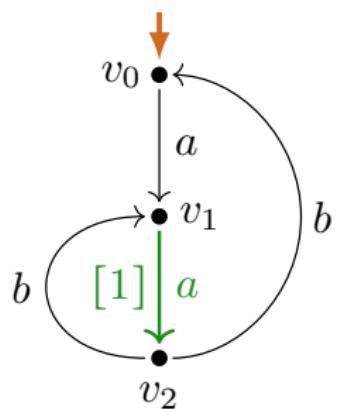
$$s(v_1) = (\textcolor{green}{a} \cdot s(v_2, v_1))^* \cdot 0$$

$$\begin{aligned} s(v_2, v_1) &= 0^* \cdot (b \cdot s(v_1, v_1) + b \cdot s(v_0, v_1)) \\ &= \textcolor{purple}{\text{Mil}} 0^* \cdot (b \cdot 1 + b \cdot a) \end{aligned}$$

$$s(v_1, v_1) = 1$$

$$\begin{aligned} s(v_0, v_1) &= 0^* \cdot a \cdot s(v_1, v_1) \\ &= 0^* \cdot a \cdot 1 \\ &= \textcolor{purple}{\text{Mil}} a \end{aligned}$$

Readback from layered LEE-witness (example)



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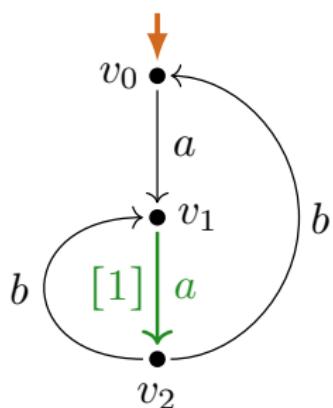
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Readback from layered LEE-witness (example)



layered
LEE-witness

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$$=_{\textcolor{purple}{\text{Mil}}} (\textcolor{green}{a} \cdot (b + b \cdot a))^* \cdot 0$$

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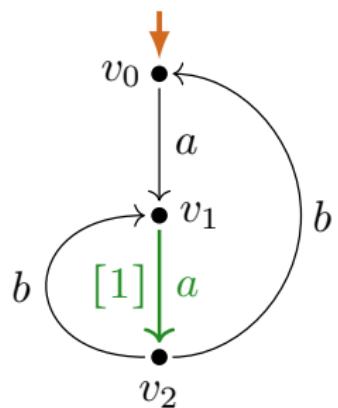
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Readback from layered LEE-witness (example)



$$\begin{aligned}s(v_0) &= 0^* \cdot a \cdot s(v_1) \\ &=_{\text{Mil}} a \cdot s(v_1)\end{aligned}$$

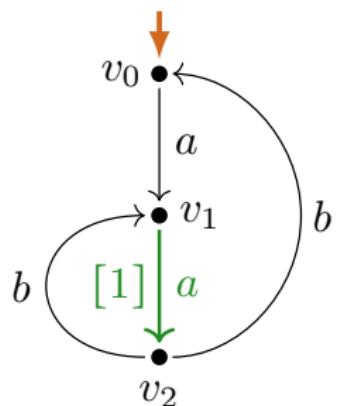
$$\begin{aligned}s(v_1) &= (a \cdot s(v_2, v_1))^* \cdot 0 \\ &=_{\text{Mil}} (a \cdot (b + b \cdot a))^* \cdot 0\end{aligned}$$

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$$s(v_1, v_1) = 1$$

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1-return-less regular expressions

Lemma

Process graphs with LEE are $P(\cdot)$ -expressible:

$$\text{LEE}(G) \implies \exists e \in \text{Reg}(A) (G \xrightarrow{*} P(e)).$$

1-return-less regular expressions

Lemma

Process graphs with LEE are $\llbracket \cdot \rrbracket_P^{1r\backslash\star}$ -expressible:

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1-return-less regular expressions

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Definition (Corradini, De Nicola, Labella (here intuitive version))

A regular expression e is 1-return-less(-under- \star) ($e \in \text{Reg}^{1\text{-}\star}(A)$) if:

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Non-/Examples of 1-return-less regular expressions

- ▶ $(a \cdot (1 + b))^*$

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Non-/Examples of 1-return-less regular expressions

- ▶ $(a \cdot (1 + b))^*$ ✗

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Non-/Examples of 1-return-less regular expressions

- ▶ $(a \cdot (1 + b))^*$ X
- ▶ $(a \cdot (0^* + b))^*$

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- ▶ $(a \cdot (1 + b))^*$ X
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Non-/Examples of 1-return-less regular expressions

- ▶ $(a \cdot (1 + b))^*$ ✗
- ▶ $(a \cdot (0^* + b))^*$ ✗
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- | | | |
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$$\text{LEE}(G) \implies \exists e \in \text{Reg}^{1\text{-}\star}(A) (G \sqsubseteq P(e)).$$

Definition (Corradini, De Nicola, Labella (here intuitive version))

A regular expression e is 1-return-less(-under- \star) ($e \in \text{Reg}^{1\text{-}\star}(A)$) if:

- ▶ for no iteration subexpression f^* of e does $P(f)$ proceed to a process p such that:
 - ▶ p has the option to immediately terminate, and
 - ▶ p has the option to do a proper step, and terminate later.

Non-/Examples of 1-return-less regular expressions

- | | | | |
|---|---|---------------------------------|---|
| ▶ $(a \cdot (1 + b))^*$ | ✗ | ▶ $(a^* (b^* + c \cdot 0)^*)^*$ | ✗ |
| ▶ $(a \cdot (0^* + b))^*$ | ✗ | ▶ $(a^* (b^* + c \cdot 0))^*$ | ✗ |
| ▶ $a \cdot (a \cdot (b + b \cdot a))^* \cdot 0$ | ✓ | ▶ $(a^* (b + c \cdot 0))^*$ | ✓ |

Characterization of expressibility^{1r\star}

Theorem

For every process graph G with bisimulation collapse C the following are equivalent:

- (i) G is $\llbracket \cdot \rrbracket_P^{1r\star}$ -expressible.
- (ii) LEE(C).
- (iii) C has a LEE-witness.
- (iv) C has a layered LEE-witness.

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Q1. Which structural property of finite process graphs characterizes $P(\cdot)$ -expressibility?

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Milners characterization question restricted, and adapted:

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Answering Milners characterization question restricted, and adapted:

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- The loop-existence and elimination property LEE.

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Also yields: efficient decision method of $\llbracket \cdot \rrbracket_P^{1r\star}$ -expressibility?

Structure constrained finite process graphs

graphs with LEE / a (layered) LEE-witness

Benefits of the class of process graphs with LEE:

- ▶ is closed under \preceq
- ▶ forth-/back-correspondence with 1-return-less regular expressions

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Structure constrained finite process graphs

- loop-exit palm trees $\subseteq \llbracket \cdot \rrbracket_P^{1r\backslash\star}$ -expressible graphs
- \subseteq graphs with LEE / a (layered) LEE-witness
- \subseteq graphs whose collapse satisfies LEE
- = graphs that are $\llbracket \cdot \rrbracket_P^{1r\backslash\star}$ -expressible
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Application to Milner's questions yields partial results:

Q1: characterization/efficient decision of $\llbracket \cdot \rrbracket_P^{1r\backslash\star}$ -expressibility

Q2: alternative compl. proof of Mil on **1-return-less** expressions (C/DN/L)

Milner's Proof System for Regular Expressions Modulo Bisimilarity is Complete

Crystallization: Near-Collapsing Process Graph Interpretations of Regular Expressions

Clemens Grabmayer (Department of Computer Science, Gran Sasso Science Institute, Viale F. Crispi, 7, 67100 L'Aquila AQ, Italy)

Abstract

We report on a lengthy completeness proof for Robin Milner's proof system **Mil** (1984) for bisimilarity of regular expressions in the process semantics. Central for our proof are the recognitions:

1. Process graphs with 1-transitions (1-charts) and the loop existence/elimination property **LLEE** are **not** closed under bisimulation collapse,
2. Such process graphs can be **'crystallized'** to 'near-collapsed' 1-charts with some strongly connected components of 'twin-crystal' form.

The Process Semantics of Regular Expressions

Milner (1984) introduced a process semantics for regular expressions: the interpretation of 0 is *deadlock*, of 1 is an *empty step to termination*, letters *a* are *atomic actions*, the operators + and · stand for *choice* and *concatenation* of processes, and unary Kleene star (\cdot^*) represents *(unbounded) iteration*. Formally, Milner defined chart (finite process graph) interpretations $\mathcal{C}(e)$ of regular expressions e .

Milner's Proof System

As axiomatization of the relation $e_1 =_{\text{P}} e_2$ on regular expressions e_1 and e_2 defined by $\mathcal{C}(e_1) \sqsubseteq \mathcal{C}(e_2)$ (as bisimilarity \sqsubseteq of chart interpretations), Milner asked whether the following system **Mil** is complete:

- (A1) $e + (f + g) = (e + f) + g$ (A7) $e = 1 \cdot e$
 - (A2) $e + 0 = e$ (A8) $e = e \cdot 1$
 - (A3) $e \cdot f = f \cdot e$ (A9) $0 = 0 \cdot e$
 - (A4) $e + e = e$ (A10) $e^* = 1 + e \cdot e^*$
 - (A5) $e \cdot (f \cdot g) = (e \cdot f) \cdot g$ (A11) $e^* = (1 + e)^*$
 - (A6) $e \cdot (f + g) = e \cdot f + g \cdot f$
- $e = f \cdot g$ RSP* (if f does not terminate immediately)
 $e = f \cdot g$

This system is a variation of Salomaa's complete axiom system (1966) for language equality of regular expressions, missing left-distributivity $e \cdot (f + g) = e \cdot f + e \cdot g$ and $e \cdot 0 = 0$, which are unsound here.

Loop Existence and Elimination

The process semantics is incomplete: not every finite process graph is *expressible* by (=bisimilar to the interpretation of) a regular expression. A sufficient condition for expressibility is the (*layered*) **loop existence and elimination property LLEE**. It is defined via elimination of 'loops' (loop subcharts):

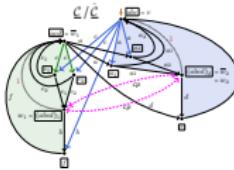


LLEE holds if a graph without infinite behavior can be obtained. Important features of LLEE:

- (US) Every guarded LLEE-1-chart (chart, maybe 1-transitions, with LLEE) is uniquely Mil-provably solvable modulo provability in **Mil** (CALCO 2021).
- (IV) The chart interpretation $\mathcal{C}(e)$ of a regular expression e always can be expanded under bisimilarity to a LLEE-1-chart $\mathcal{C}(e)$ (TERMGRAPH 2020).
- (CJ) LLEE-charts (without 1-transitions) are preserved by bisimulation collapse (G/Fokkink, LICS'20).

LLEE-preserving Collapse Fails

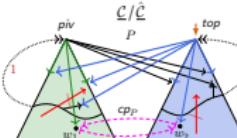
LLEE-1-charts with 1-transitions, however, are **not** preserved under bisimulation collapse. A counterexample is provided by the following LLEE-1-chart \mathcal{L} :



Identifying the bisimilar vertices w_1 and w_2 yields a chart for which LLEE fails. Also, the subcharts of \mathcal{L} that are rooted at w_1 and w_2 are **not** LLEE-preservingly jointly minimizable under bisimilarity.

Twin-Crystals

The counterexample to LLEE-preserving collapse is symmetric, and its structure can be abstracted as:



It is a LLEE-1-chart with a single scc (strongly connected component) P that consists of a *pivot part* P_1 below *pivot vertex* piv , and a *top part* P_2 below *top vertex* top . P_1 and P_2 are connected only via transitions from piv and from top . While both P_1 and P_2 are collapsed, P contains *bisimilarity redundancies* (\neq distinct bisimilar vertices) such as $\{w_1, w_2\}$ that are linked by a self-inverse counterpart function cp_P . We call such an scc a *twin-crystal*. We have:

(CC) Every Mil-provable solution of a twin-crystal gives rise to a Mil-provable solution of its bisimulation collapse (which often is not a LLEE-1-chart).

Crystallization of LLEE-1-charts

By *crystallization* of a LLEE-1-chart \mathcal{L} we mean:

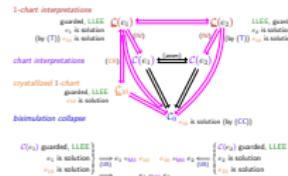
- ▷ a process of minimization of \mathcal{L} under bisimilarity by steps that **eliminate most** (all but crystalline) bisimilarity redundancies $\{w_1, w_2\}$, roughly by redirecting transitions that target w_1 over to w_2 ;
- ▷ hereby only **reduced** bisimilarity redundancies can be eliminated LLEE-preservingly, which exist whenever a LLEE-1-chart is **not collapsed**;
- ▷ the result is a **crystallized** LLEE-1-chart that is bisimilar to \mathcal{L} , and collapsed **apart from** within some its scc's that are twin-crystals.

The *crystallization process* facilitates to show:

- (CR) From every LLEE-1-chart a bisimilar crystallized LLEE-1-chart can be obtained.

Completeness Proof

Let $\mathcal{C}(e_1) \sqsubseteq \mathcal{C}(e_2)$ be bisimilar chart interpretations of regular expressions e_1 and e_2 . To secure LLEE, $\mathcal{C}(e_1)$ and $\mathcal{C}(e_2)$ are expanded to their 1-chart interpretations $\mathcal{Q}(e_1)$ and $\mathcal{Q}(e_2)$. One of them, say $\mathcal{Q}(e_1)$, is crystallized to \mathcal{C}_0 . All (1-)charts are linked by (1-)bisimulations to their bisimulation collapse \mathcal{C}_0 .



From \mathcal{C}_0 a provable solution e_{00} can be extracted due to LLEE, transferred (T) to the collapse \mathcal{C}_0 , and then to $\mathcal{Q}(e_1)$ and $\mathcal{Q}(e_2)$. On the LLEE-1-charts $\mathcal{Q}(e_1)$ and $\mathcal{Q}(e_2)$, e_{00} can be proved equal to the solutions e_1 and e_2 there, respectively. By transitivity, $e_1 =_{\text{Mil}} e_2$ (provability of $e_1 = e_2$ in Mil) follows.

Theorem. *Milner's system Mil is complete: $e_1 =_{\text{P}} e_2$ implies $e_1 =_{\text{Mil}} e_2$, for reg. expr.'s e_1, e_2 .*

Next Steps and Projects

- ▷ Monograph project: proof in fine-grained details.
- ▷ Build an animation tool for crystallization.
- ▷ Apply crystallization to find an efficient algorithm for expressivity of finite process graphs by a regular expression modulo bisimilarity.

Contact

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Resources (process interpretation)

- ▶ CG: Modeling Terms by Graphs with Structure Constraints
 - ▶ TERMGRAPH 2018 Post-Proceedings,
EPTCS 288, arXiv:1902.02010.
- ▶ CG: Structure-Constrained Process Graphs for
the Process Semantics of Regular Expressions
 - ▶ TERMGRAPH 2020 Post-Proceedings,
EPTCS 334, arXiv:2012.10869.
- ▶ CG, Wan Fokkink: A Complete Proof System for
1-Free Regular Expressions Modulo Bisimilarity
 - ▶ LICS 2020, arXiv:2004.12740, video on youtube.
- ▶ CG: Milner's Proof System for
Regular Expressions Modulo Bisimilarity is Complete
 - ▶ LICS 2022, arXiv:2209.12188, poster.
- ▶ CG: A Coinductive Version/Reformulation of Milner's Proof System
for Regular Expressions Modulo Bisimilarity
 - ▶ CALCO 2021, arXiv:2108.13104.
 - ▶ LMCS 2023, arXiv:2303.14219.

Outlook

correspondences found

- ▶ process graphs with LEE
 - ~ $P(\cdot)$ -interpretations of 1-return-less regular expressions
- ▶ process graphs with 1-transitions and with LEE
 - ~ $P(\cdot)$ -interpretations of regular expressions
- ▶ facilitate/may facilitate:
efficient manipulation/recognition of $P(\cdot)$ -expressible process graphs

slides and resources: clegra.github.io

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- ▶ facilitate/may facilitate:
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current projects

- ▶ PTIME-decidability of LEE (LLEE) and $\llbracket \cdot \rrbracket_P^{1r\backslash *}$ -expressibility
- ▶ refinability into LEE-graphs by adding 1-transitions (in PTIME?)
- ▶ $\llbracket \cdot \rrbracket_P$ -expressibility: \iff expansion and refinability into a crystallized LLEE-1-process-graph (in FPT?)
- ▶ full completeness proof of Mil via crystallization
 - (two parts: motivation / procedure)

slides and resources: clegra.github.io

Comparison results: structure-constrained graphs

λ -calculus with letrec under $=_{\lambda^\infty}$

Not available: graph interpretation that is studied under \leftrightarrow

Regular expressions under \leftrightarrow_P

Given: graph interpretation $P(\cdot)$, studied under bisimulation \leftrightarrow

- ▶ not closed under \supseteq , and \leftrightarrow , incomplete under \leftrightarrow

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Defined: int's $\llbracket \cdot \rrbracket_{\mathcal{H}} / \llbracket \cdot \rrbracket_{\mathcal{T}}$ as higher-order/first-order λ -term graphs

- ▶ closed under \succeq (hence under collapse)
- ▶ back-/forth correspondence with λ -calculus with letrec
 - ▶ efficient translation and readback
 - ▶ translation is inverse of readback

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Regular expressions under \leftrightarrow_P

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Defined: class of process graphs with LEE / (layered) LEE-witness

- ▶ closed under \succeq (hence under collapse)
- ▶ back-/forth correspondence with 1-return-less expr's
- ▶ contains the collapse of a process graph G
 - $\iff G$ is $\llbracket \cdot \rrbracket_P^{1\text{-R}^*}$ -expressible