Succinct Representation of Concurrent Trace Sets

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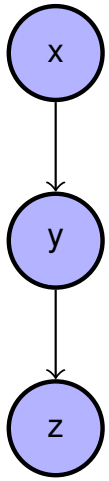
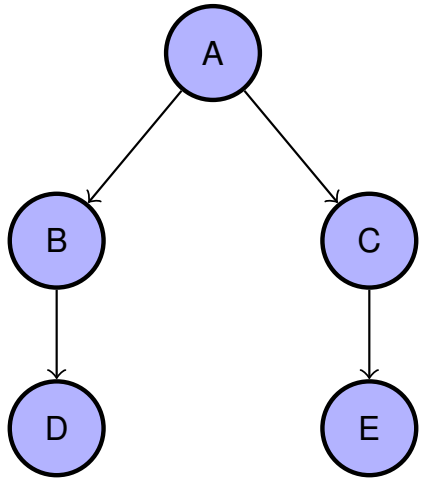
Joint work with Ashutosh Gupta, Tom Henzinger, Arjun Radhakrishna and Thorsten Tarrach

2 December, 2014

Concurrent trace neighbourhoods





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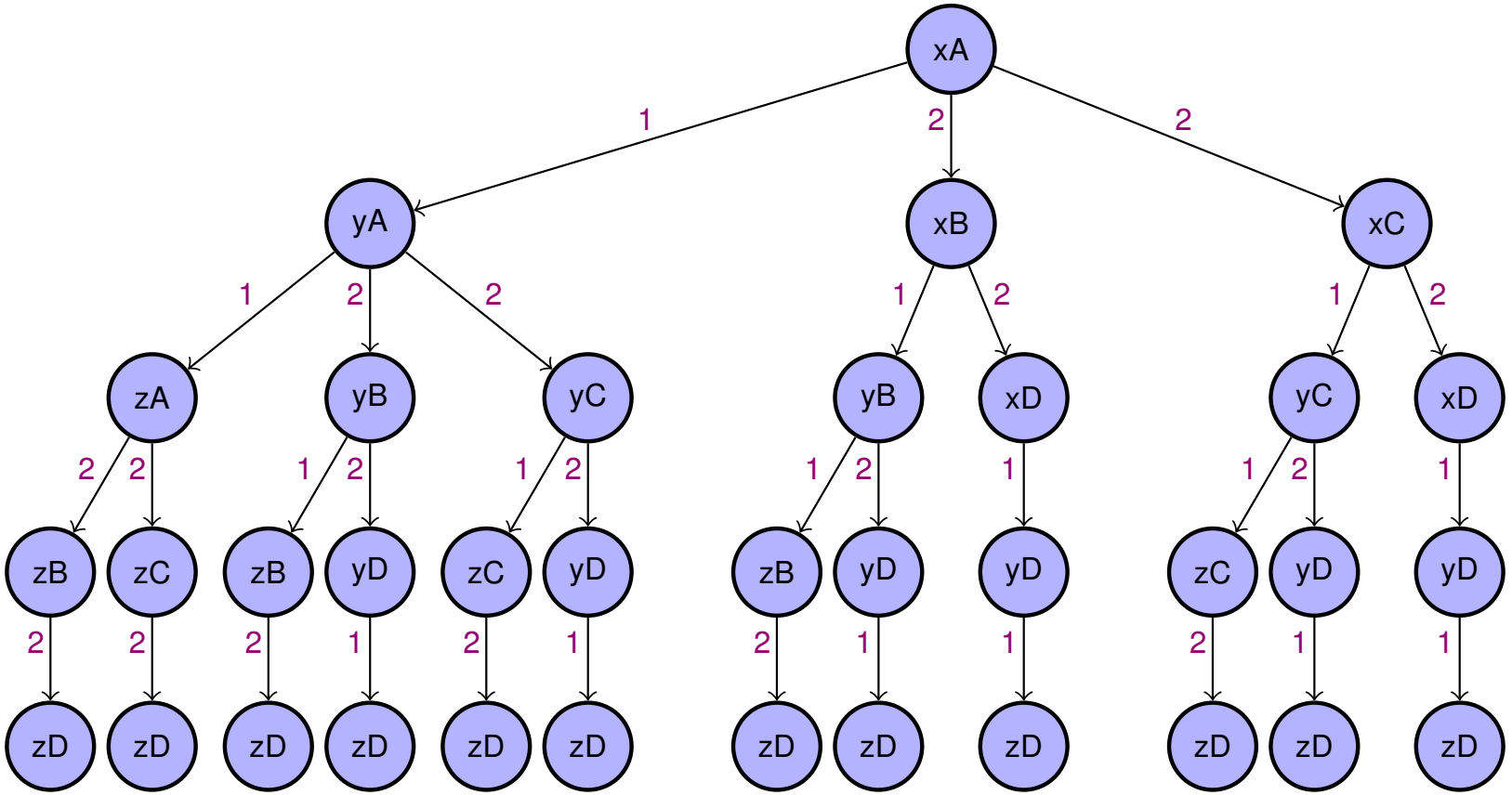

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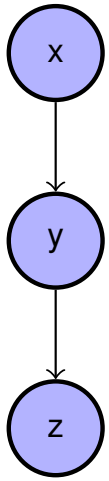

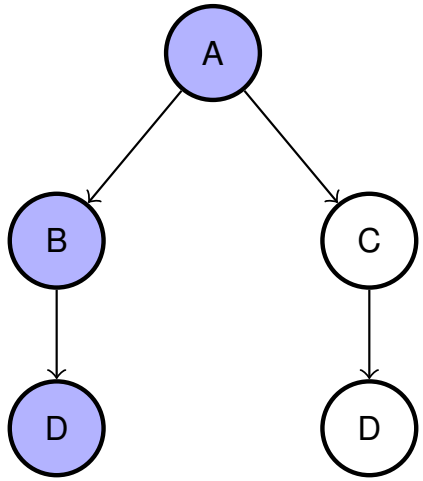

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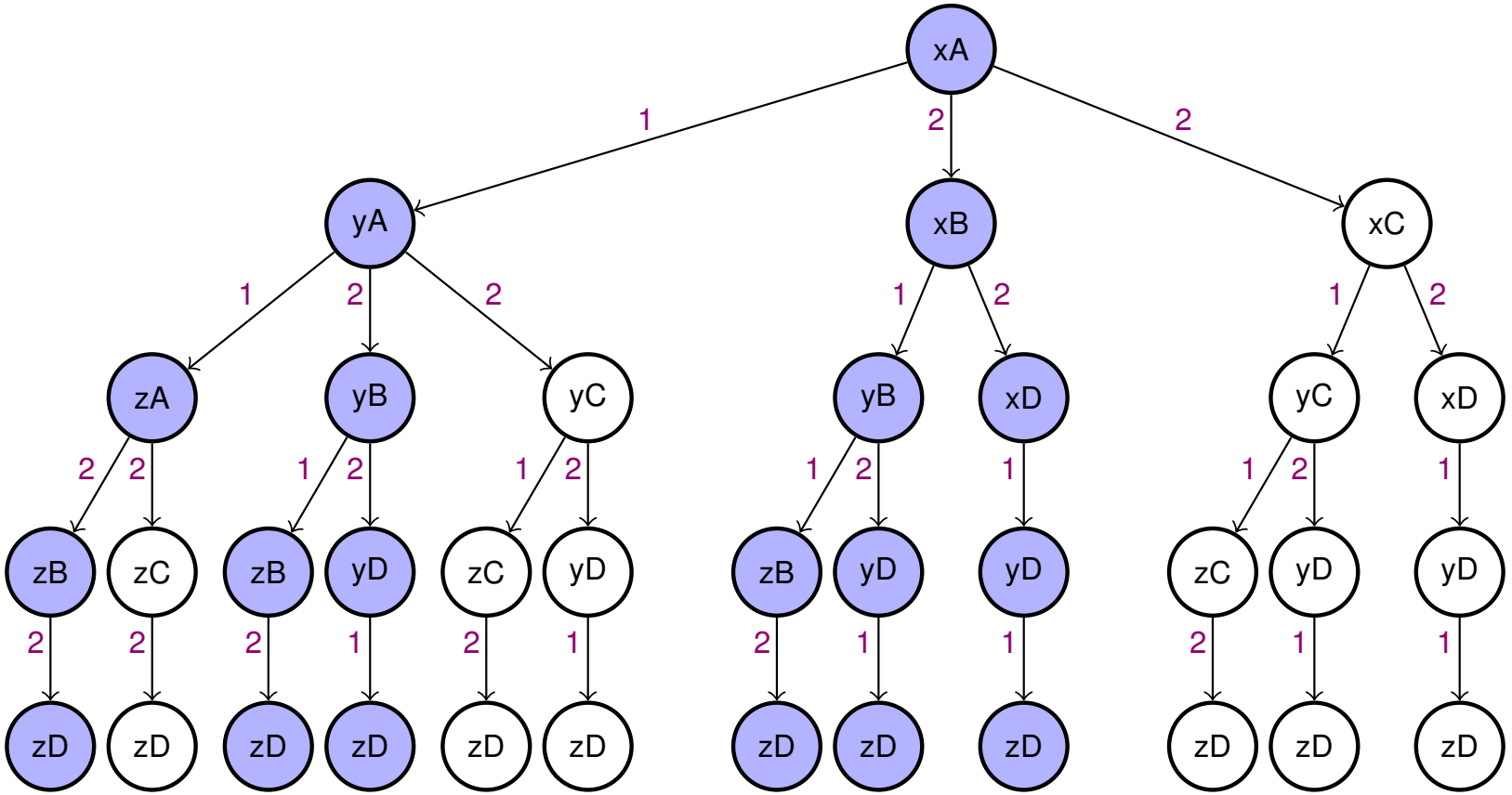

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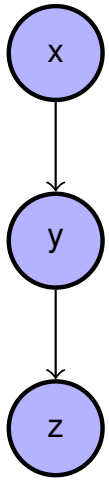

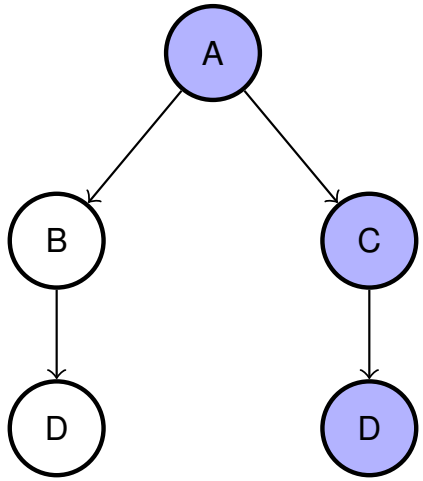

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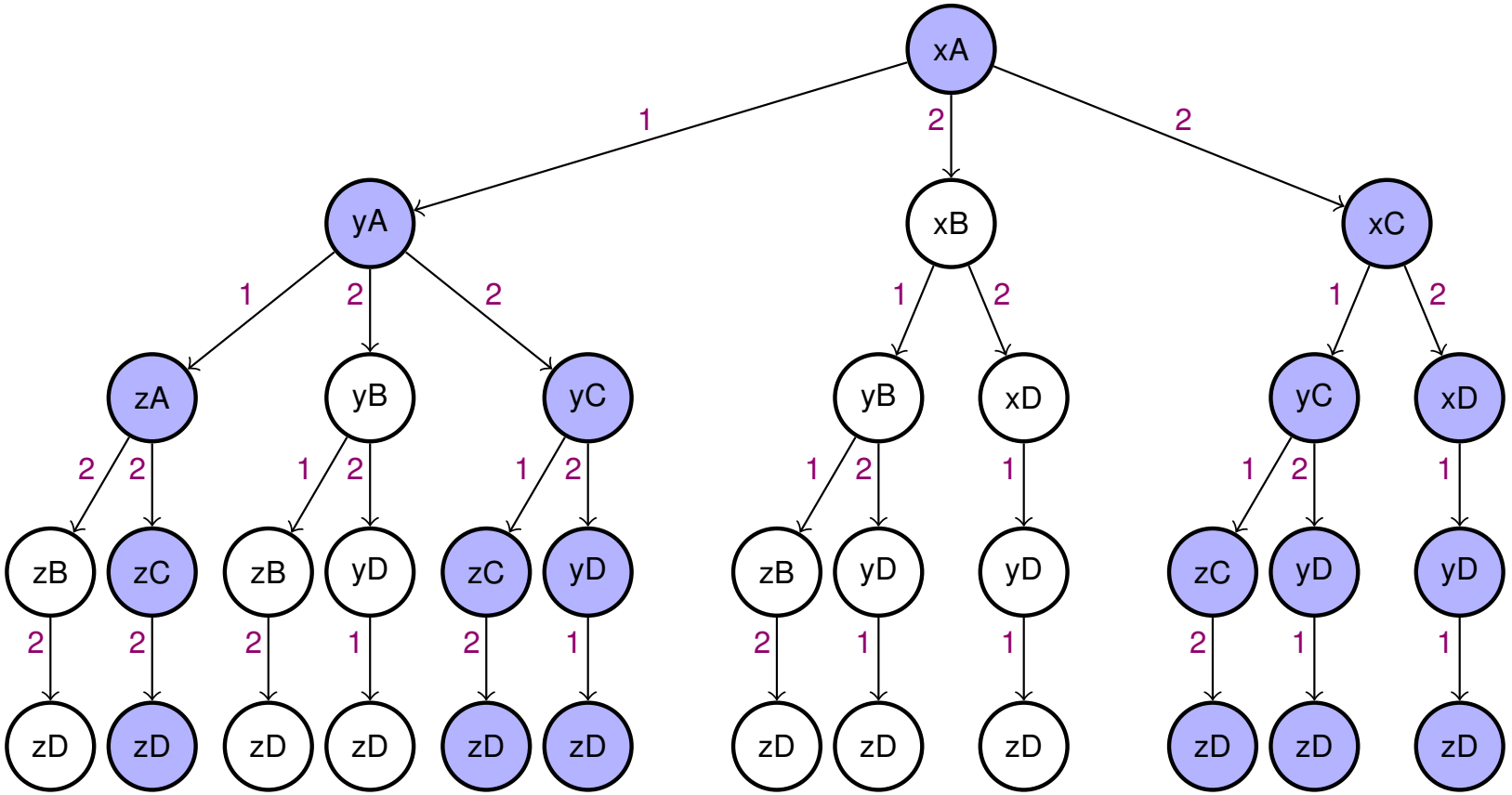
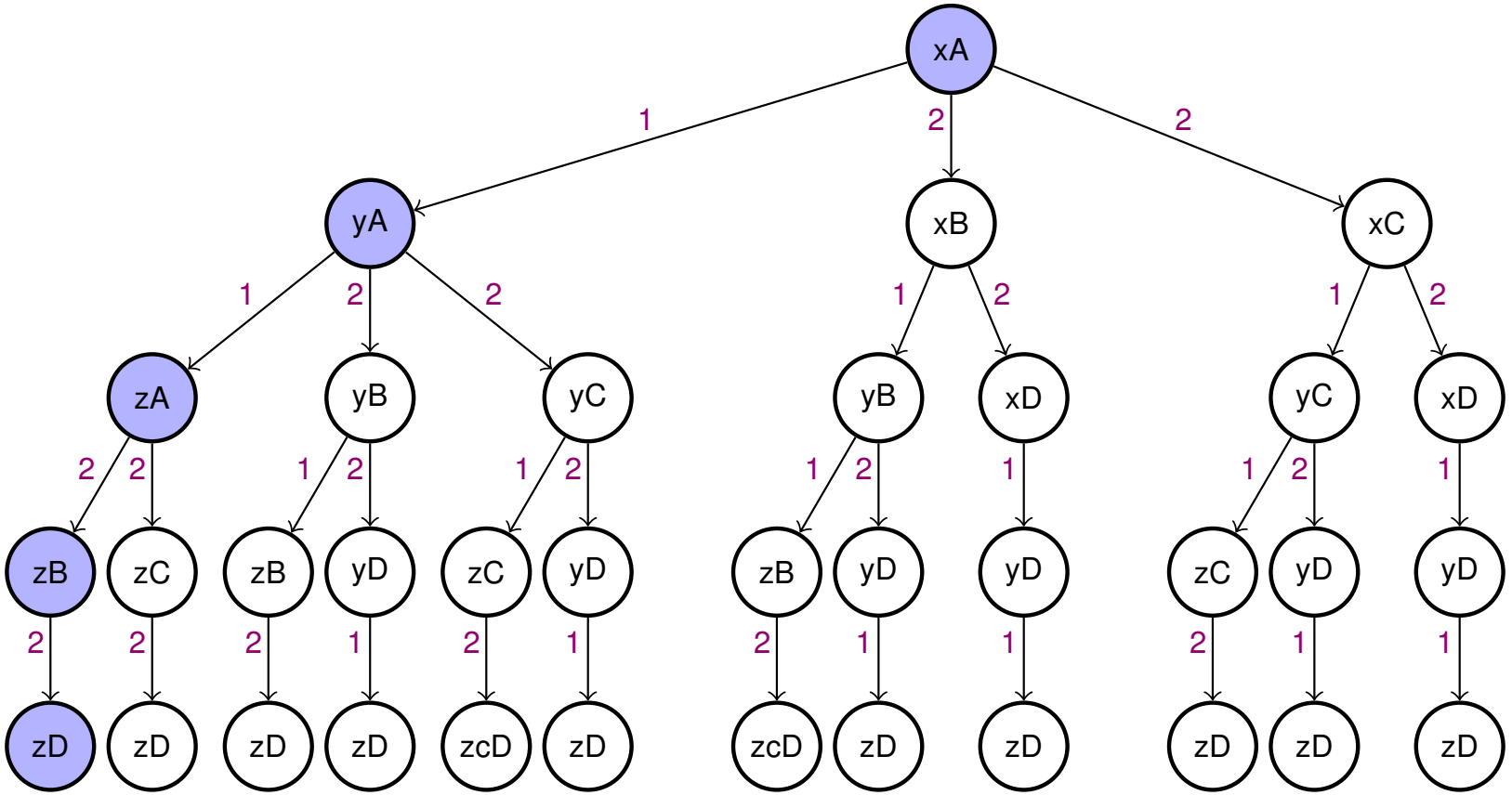


Concurrent trace neighbourhoods



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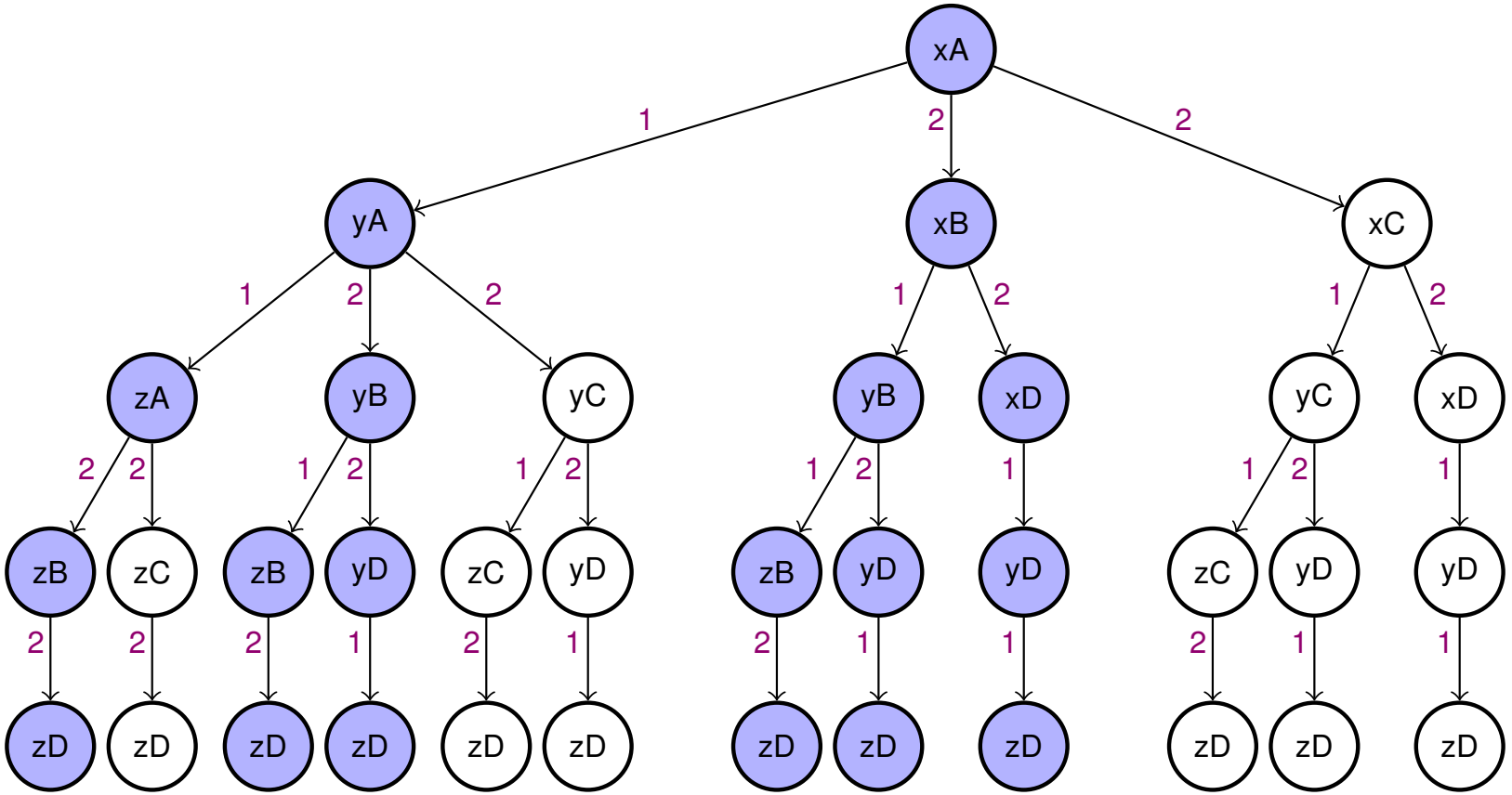

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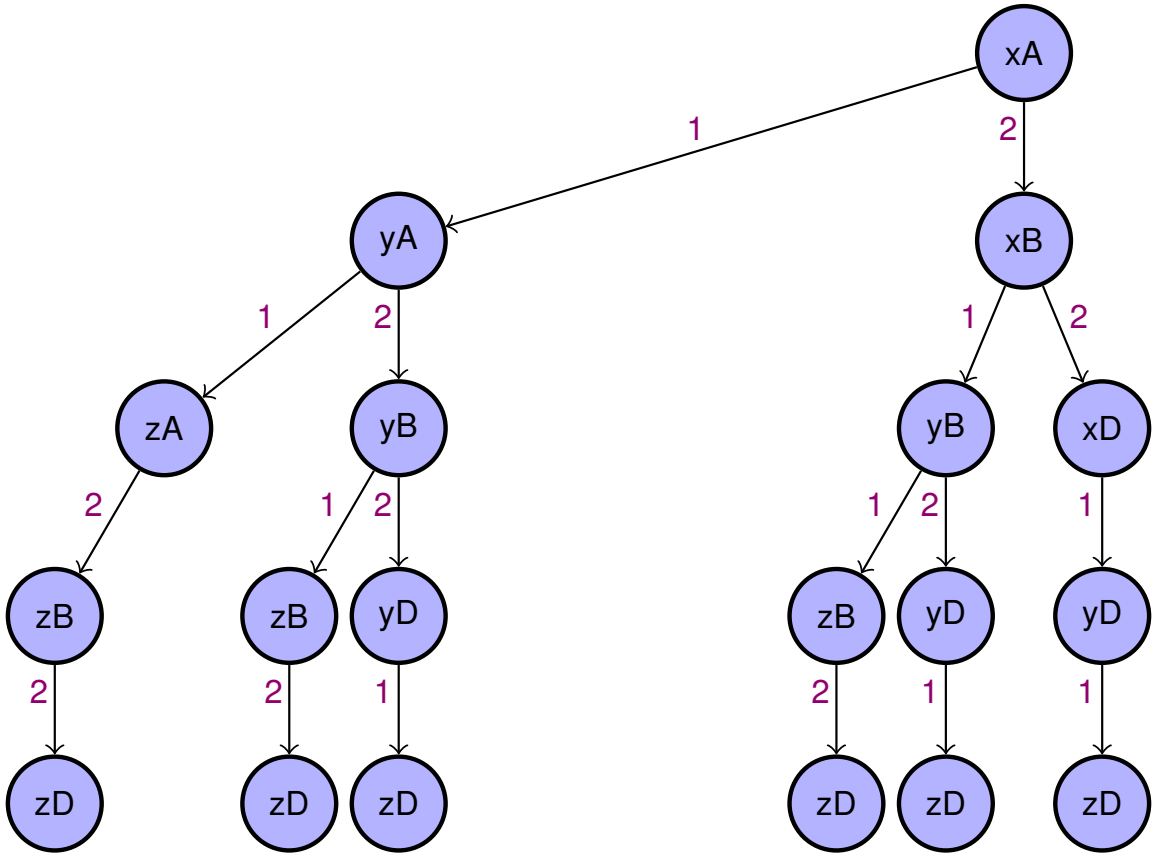

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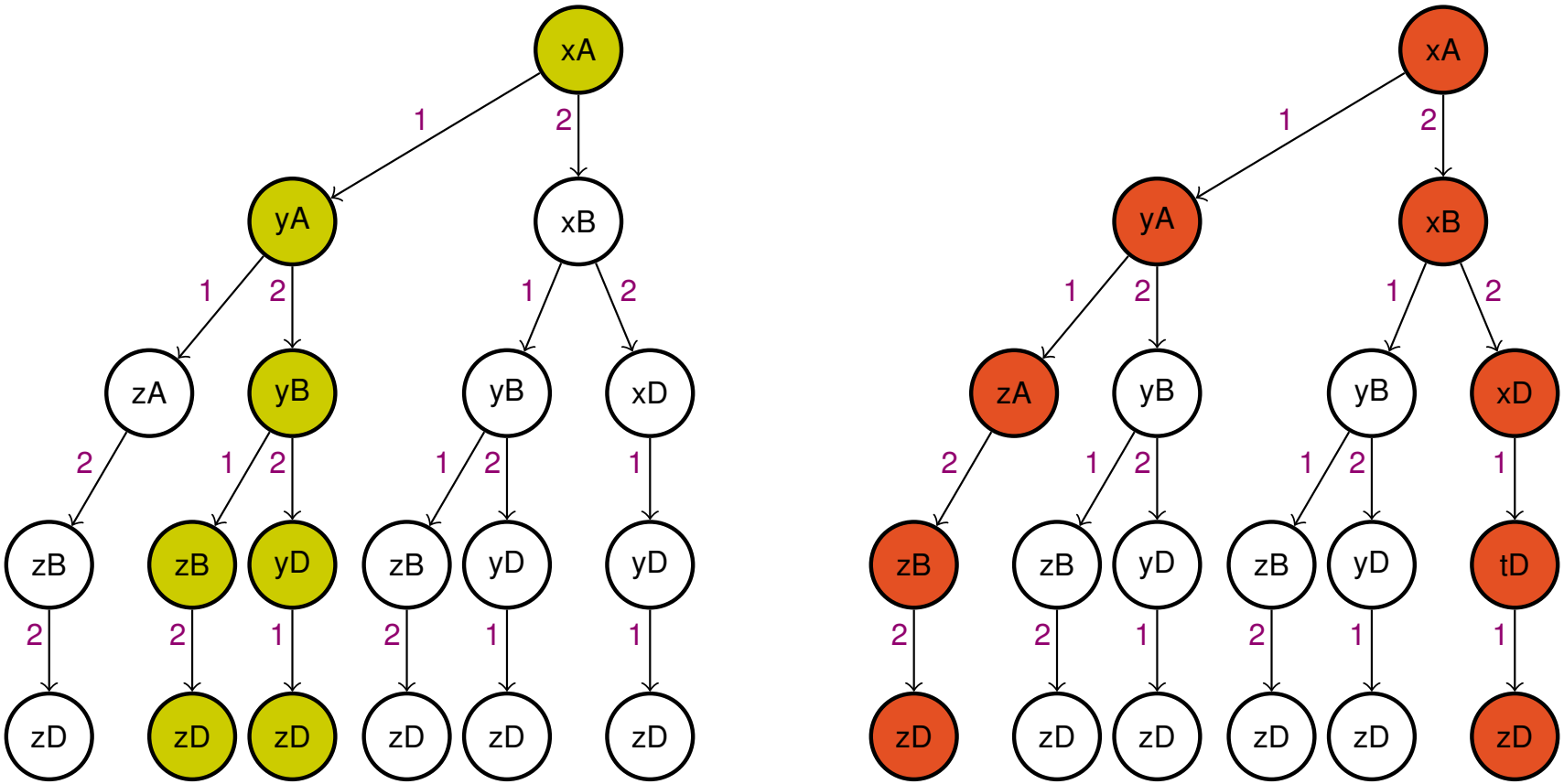
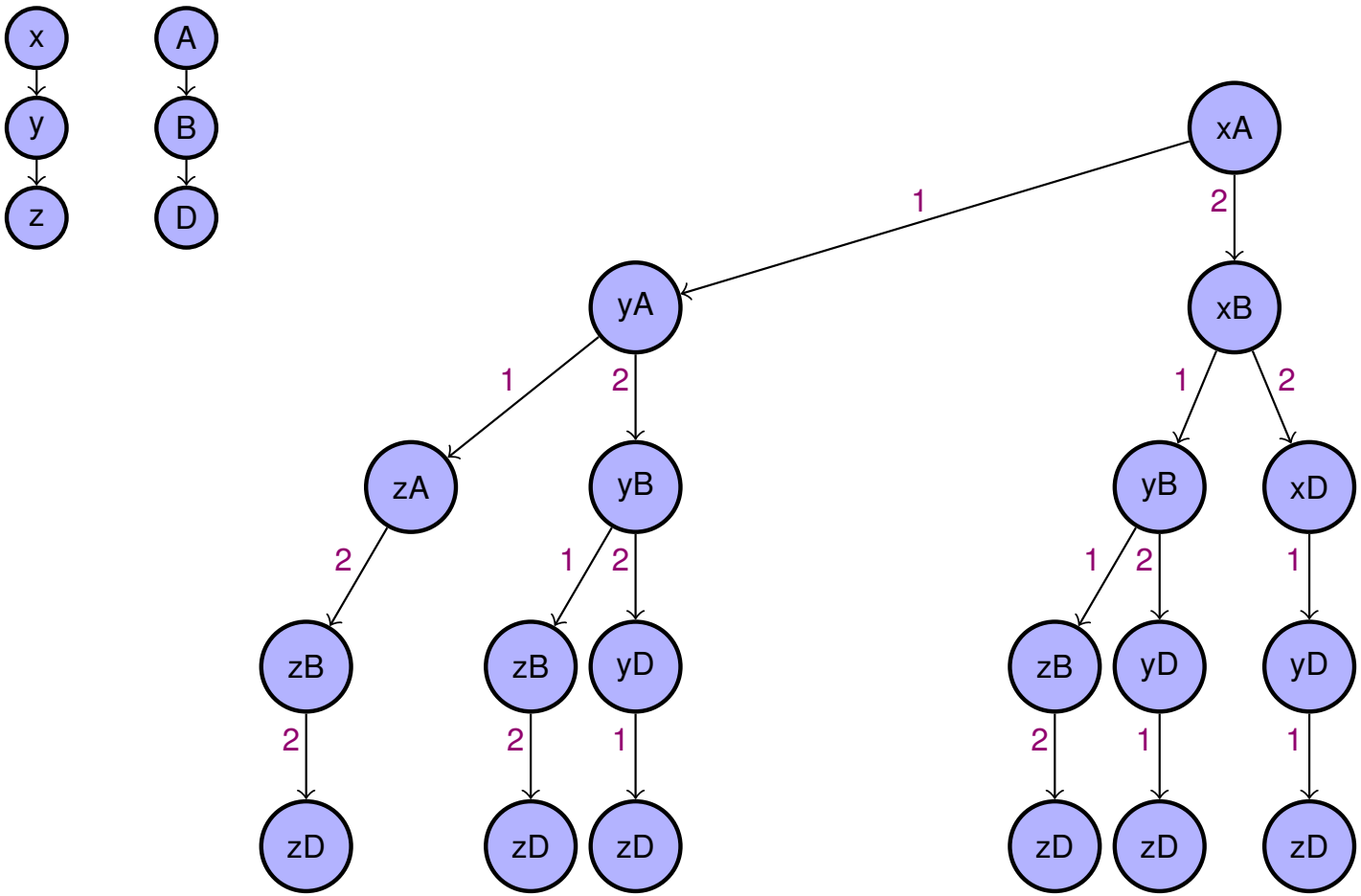


Representation of trace neighbourhoods



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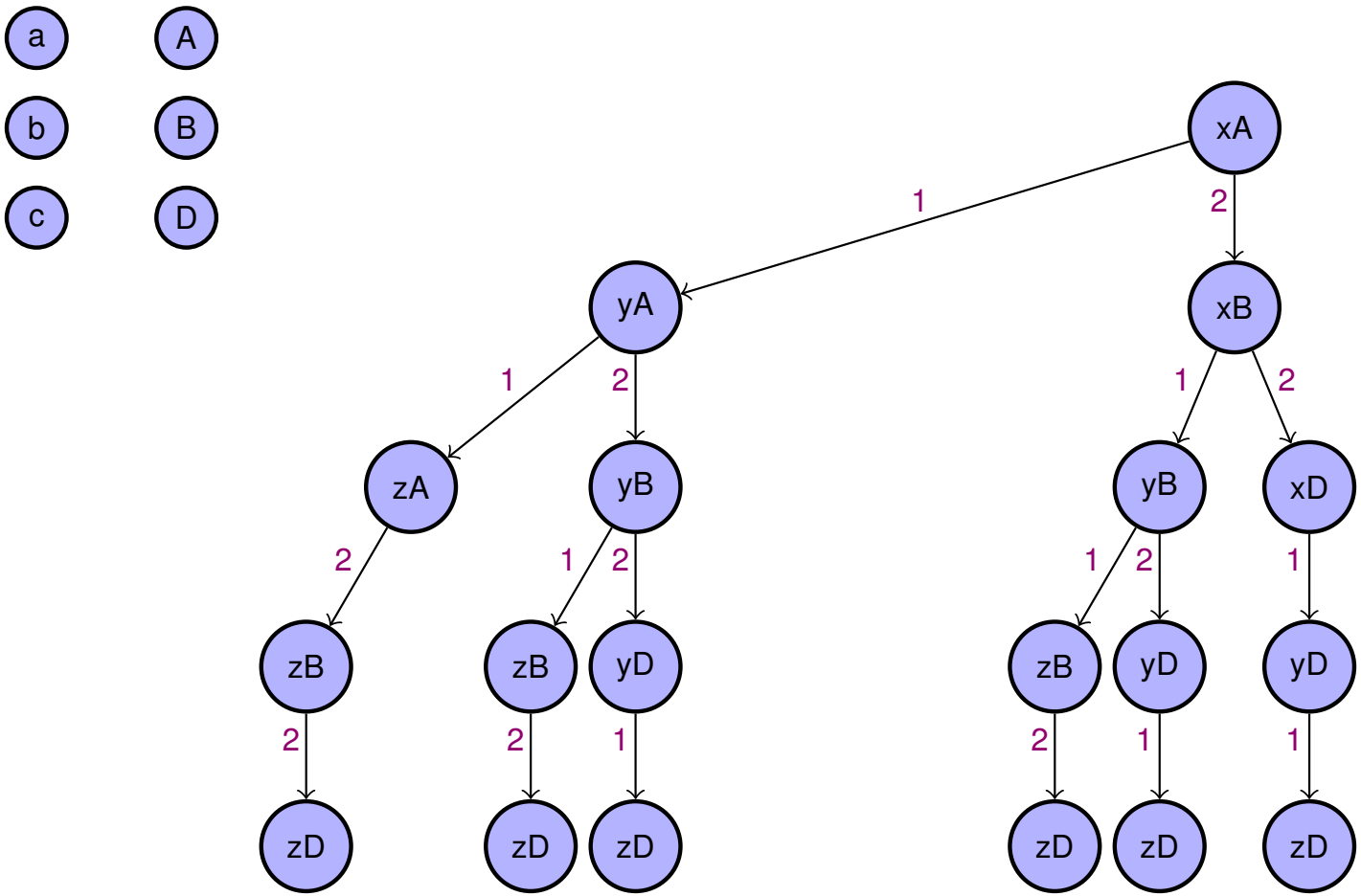

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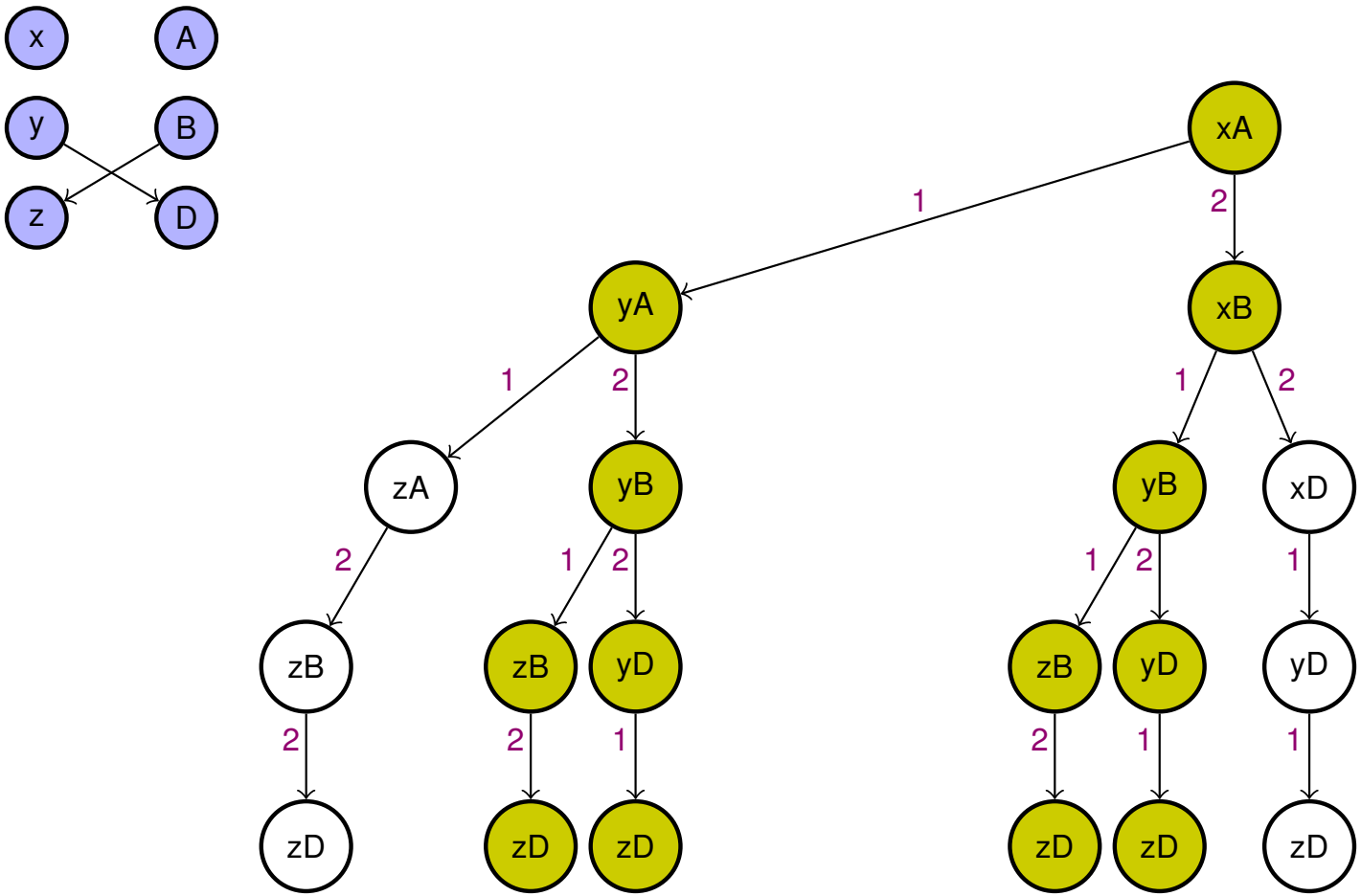

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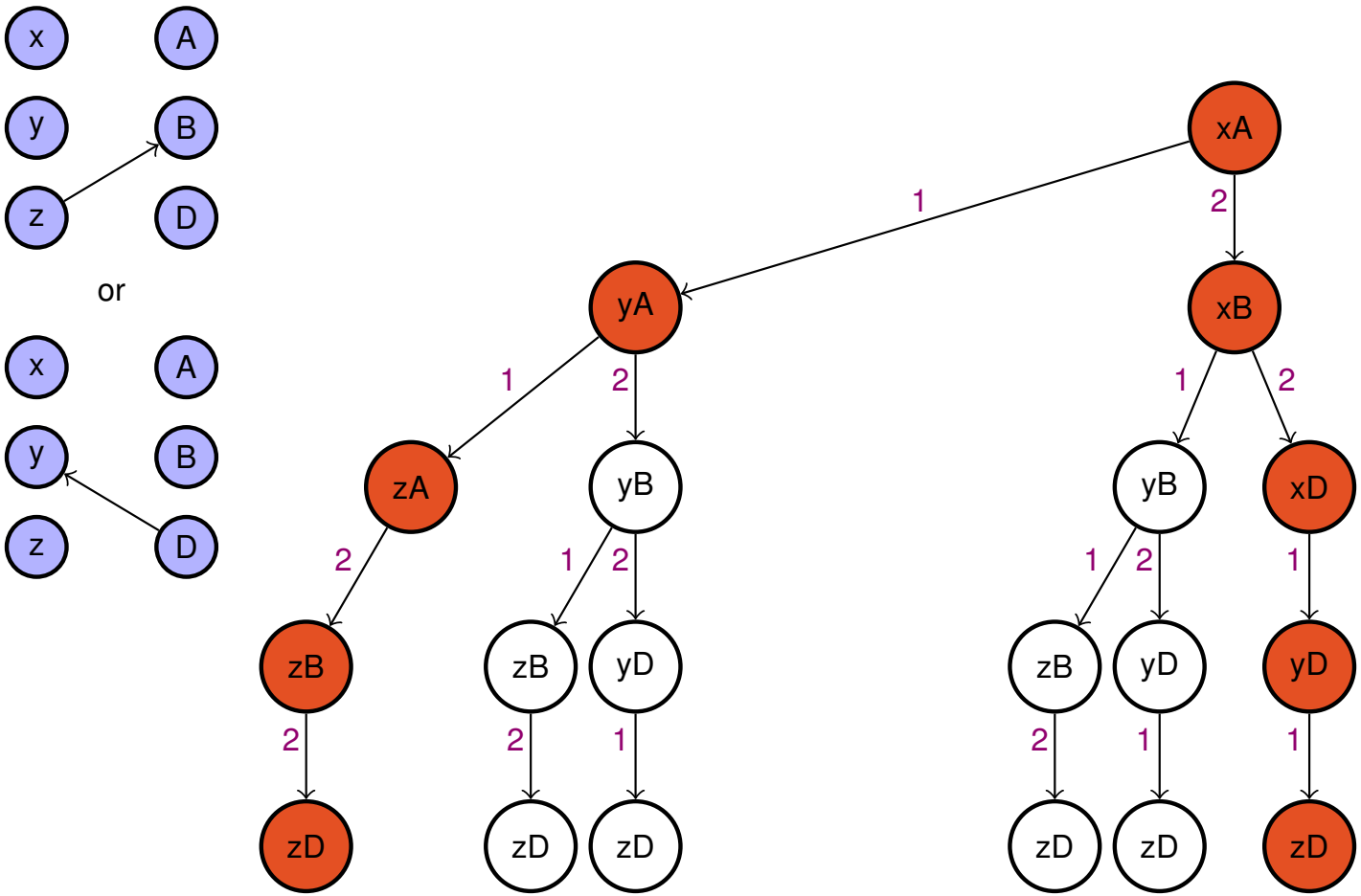

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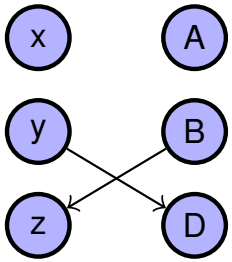
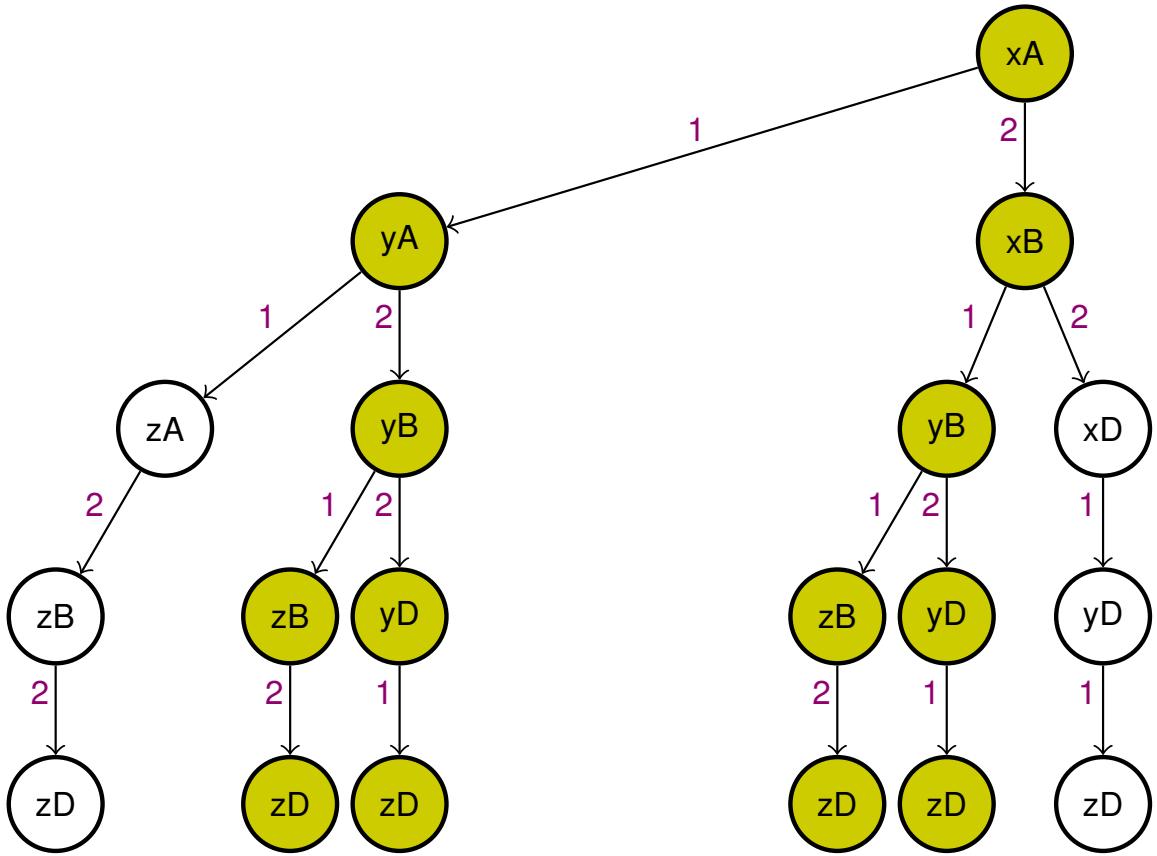


$hb(B, z) \wedge hb(y, D)$



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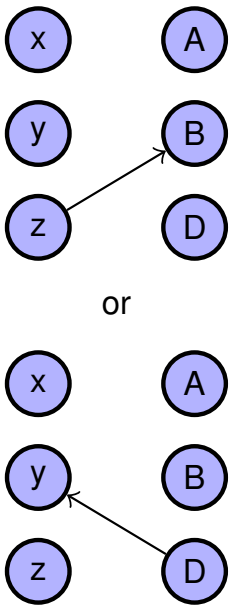
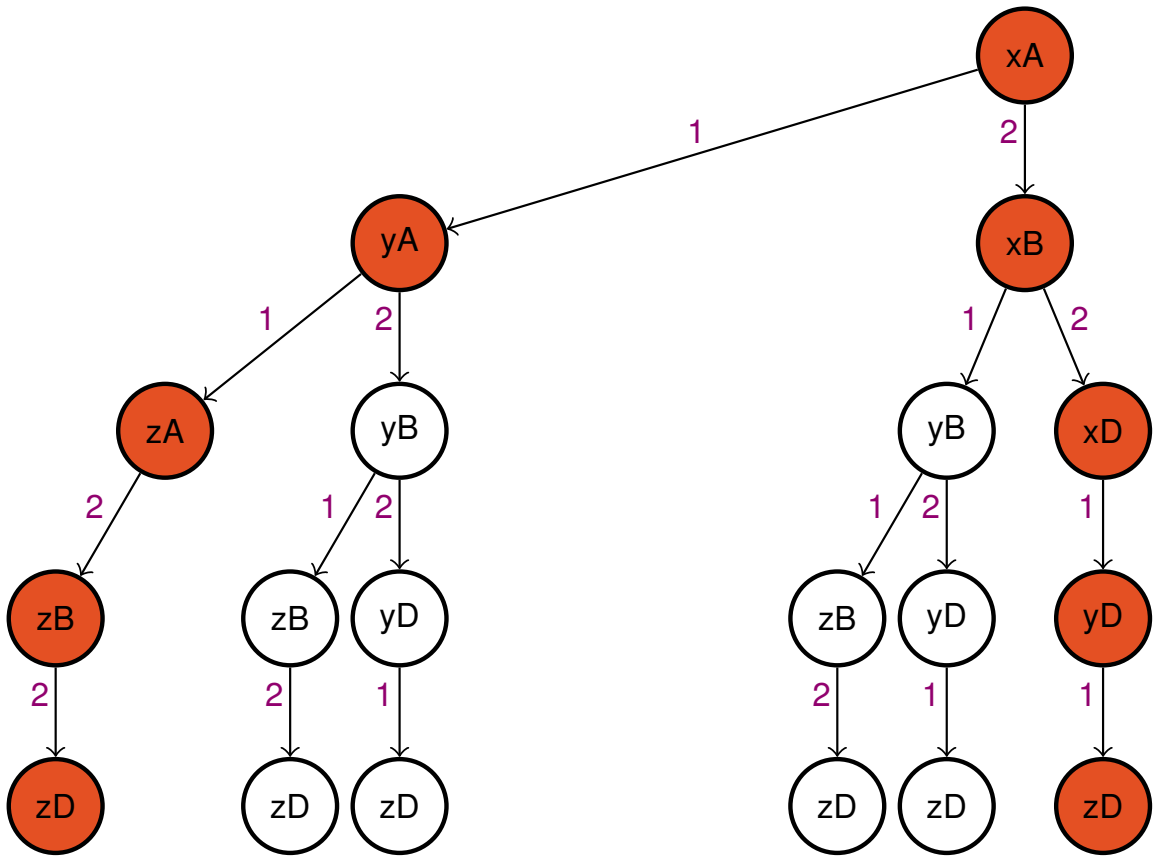


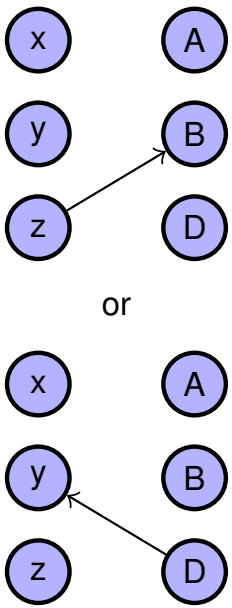
$hb(z, B) \vee hb(D, y)$



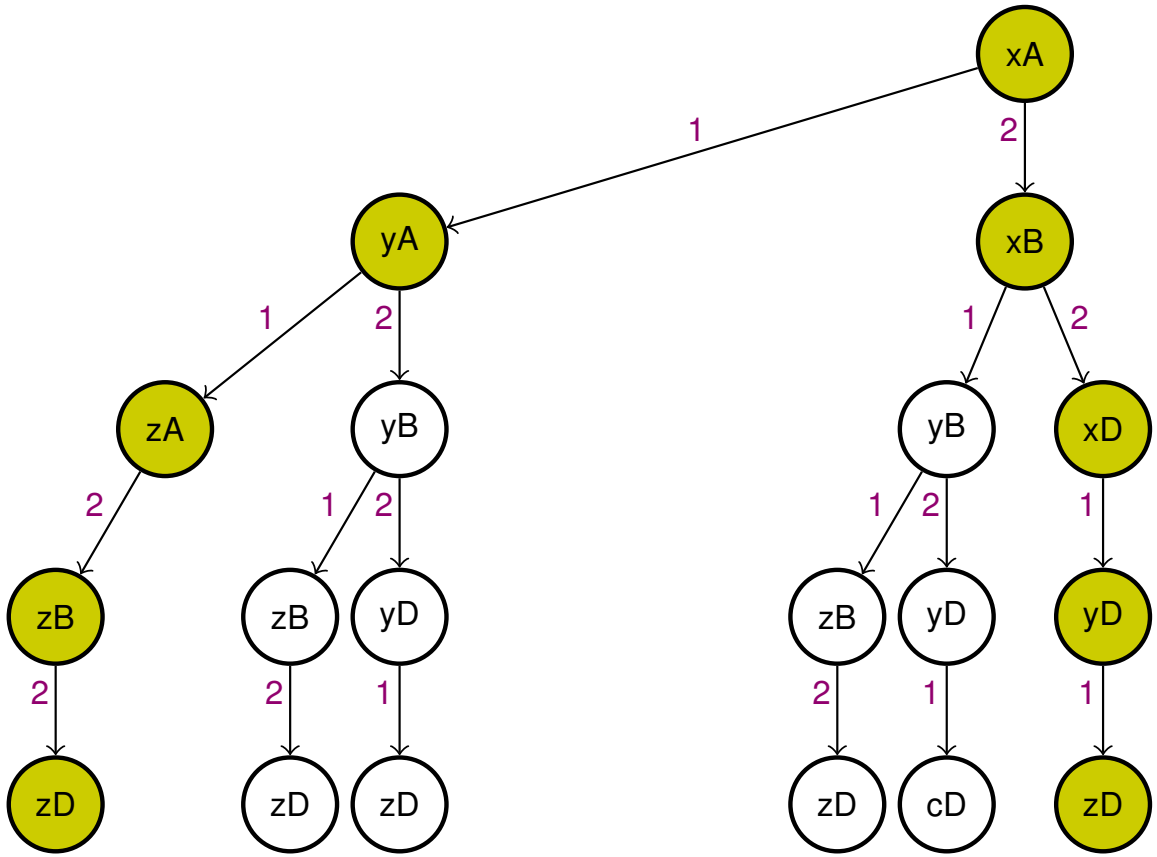
Representation of trace neighbourhoods

- HB-formulas - novel representation for concurrent trace sets
  - Can express arbitrary trace sets
  - Efficient computation of $\cup\{\text{trace sets}\}$
  - Succinct representations of good/bad trace neighbourhoods
  - Intuitively appealing
  - Can drive diverse concurrency applications . . .

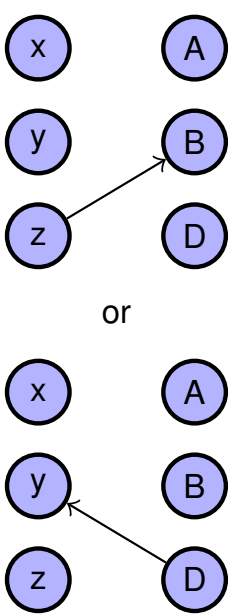
Application: synchronization synthesis



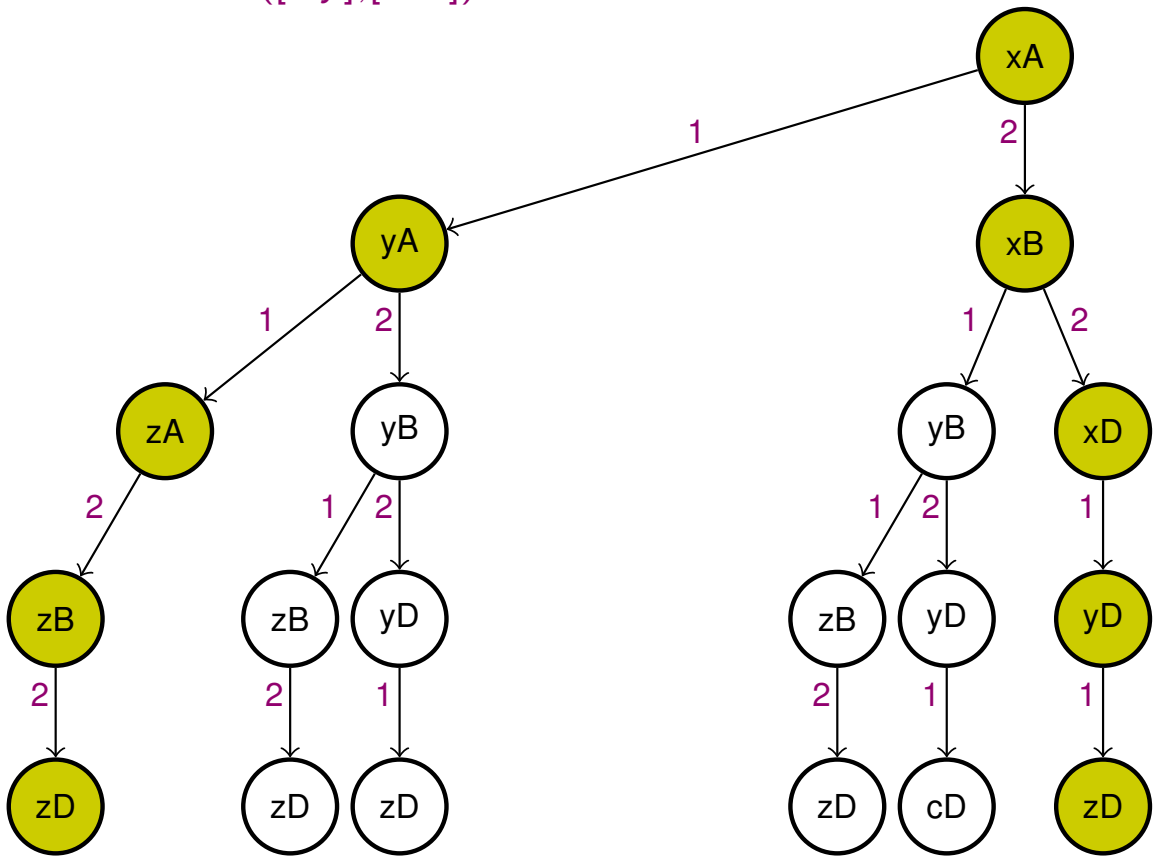
$hb(z, B) \vee hb(D, y)$



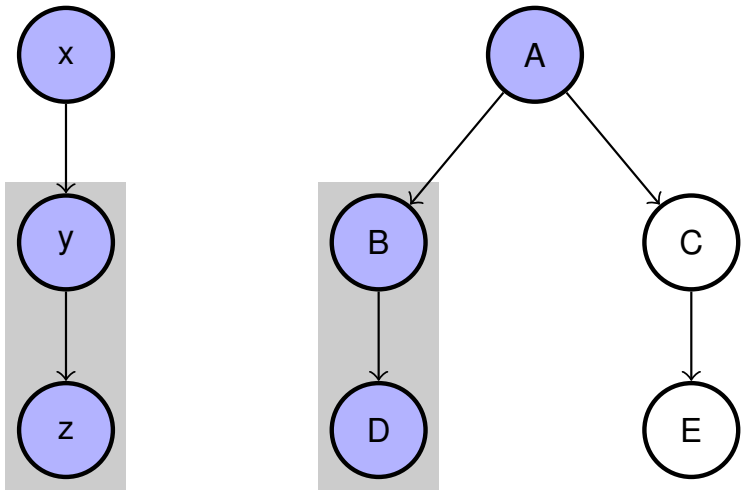
Application: synchronization synthesis



$$\frac{hb(z,B) \vee hb(D,y)}{\texttt{Lock}([x{:}y],[B{:}D])}$$



Application: synchronization synthesis

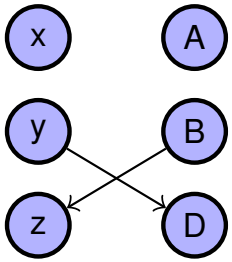


$$\frac{hb(z,B) \vee hb(D,y)}{\texttt{Lock}([x{:}y],[B{:}D])}$$

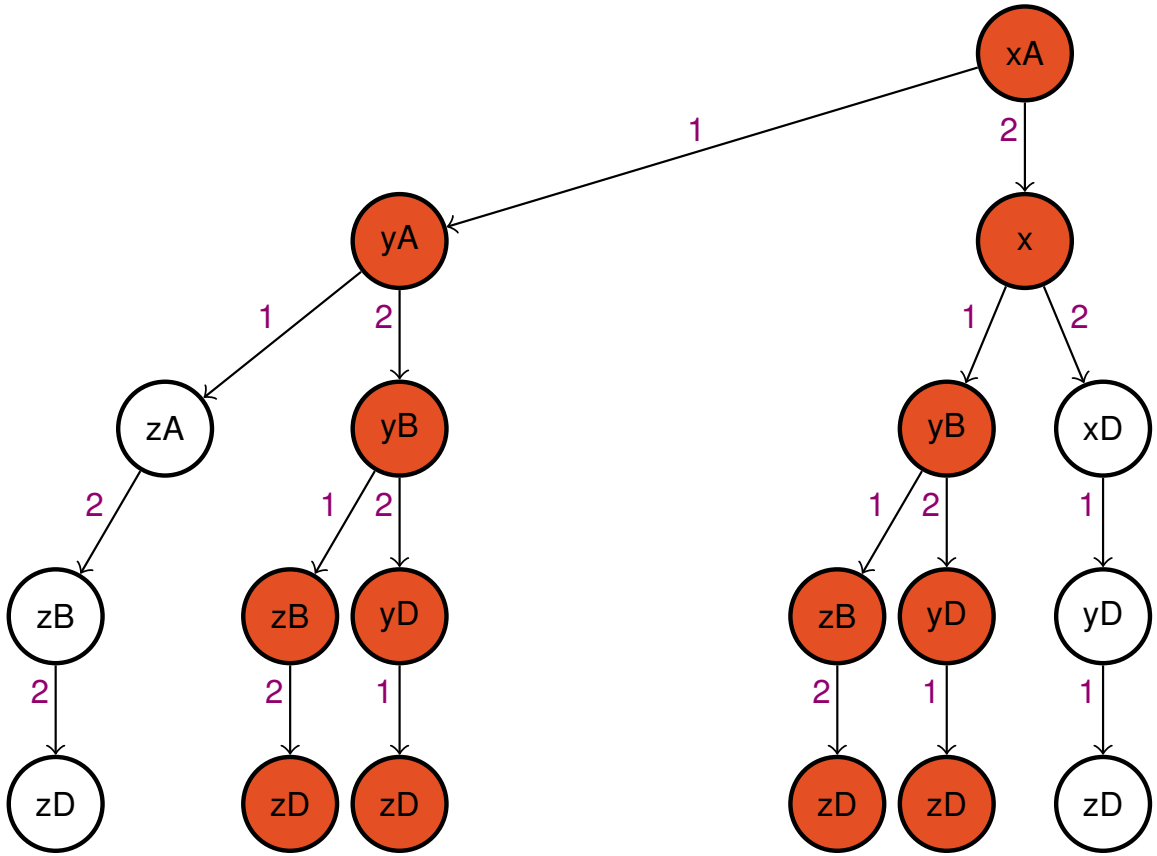
Application: synchronization synthesis

- Automated program completion
- Rewrite rules for synchronization synthesis
  - Identification of HB-formula patterns for sync. primitives
  - Mutex locks, barriers, shared-exclusive locks, wait-notify

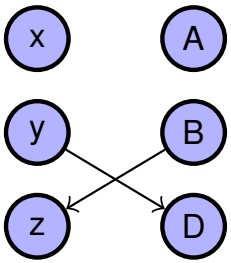
Application: bug summarization



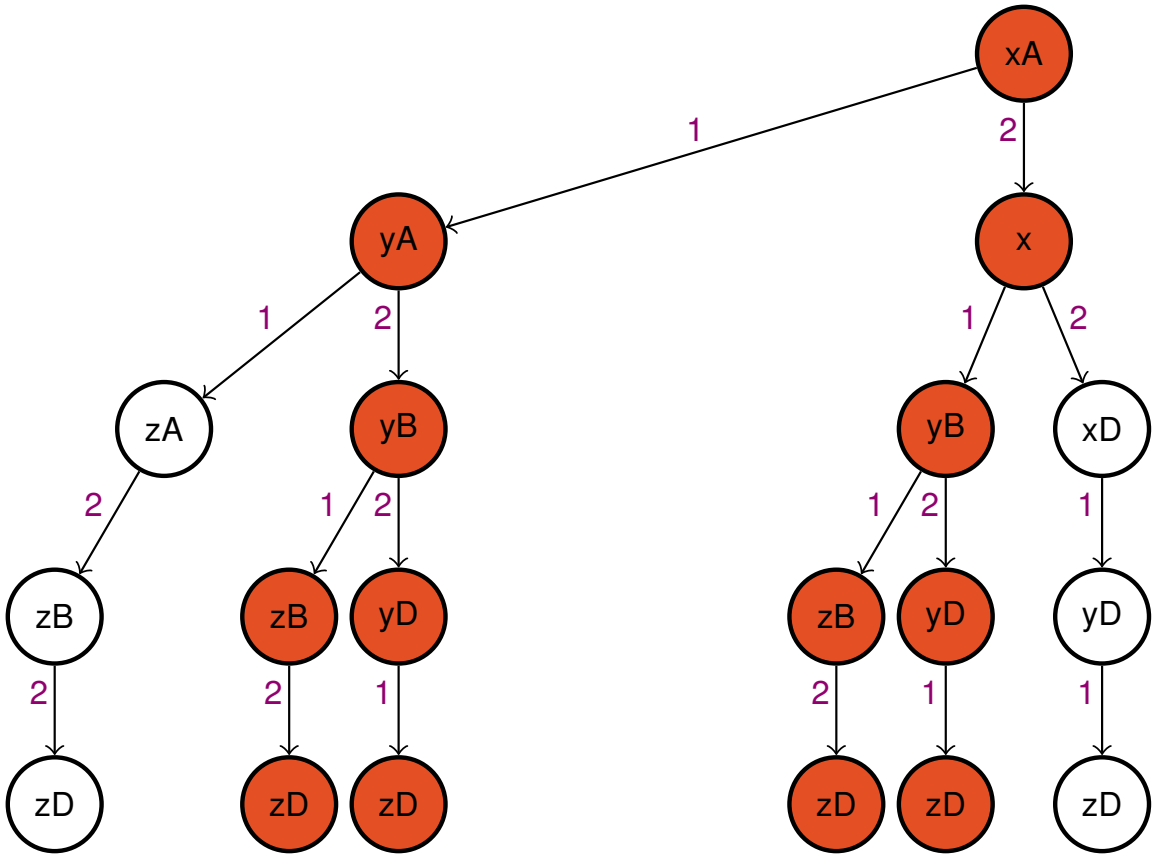
$hb(B, z) \wedge hb(y, D)$



Application: bug summarization



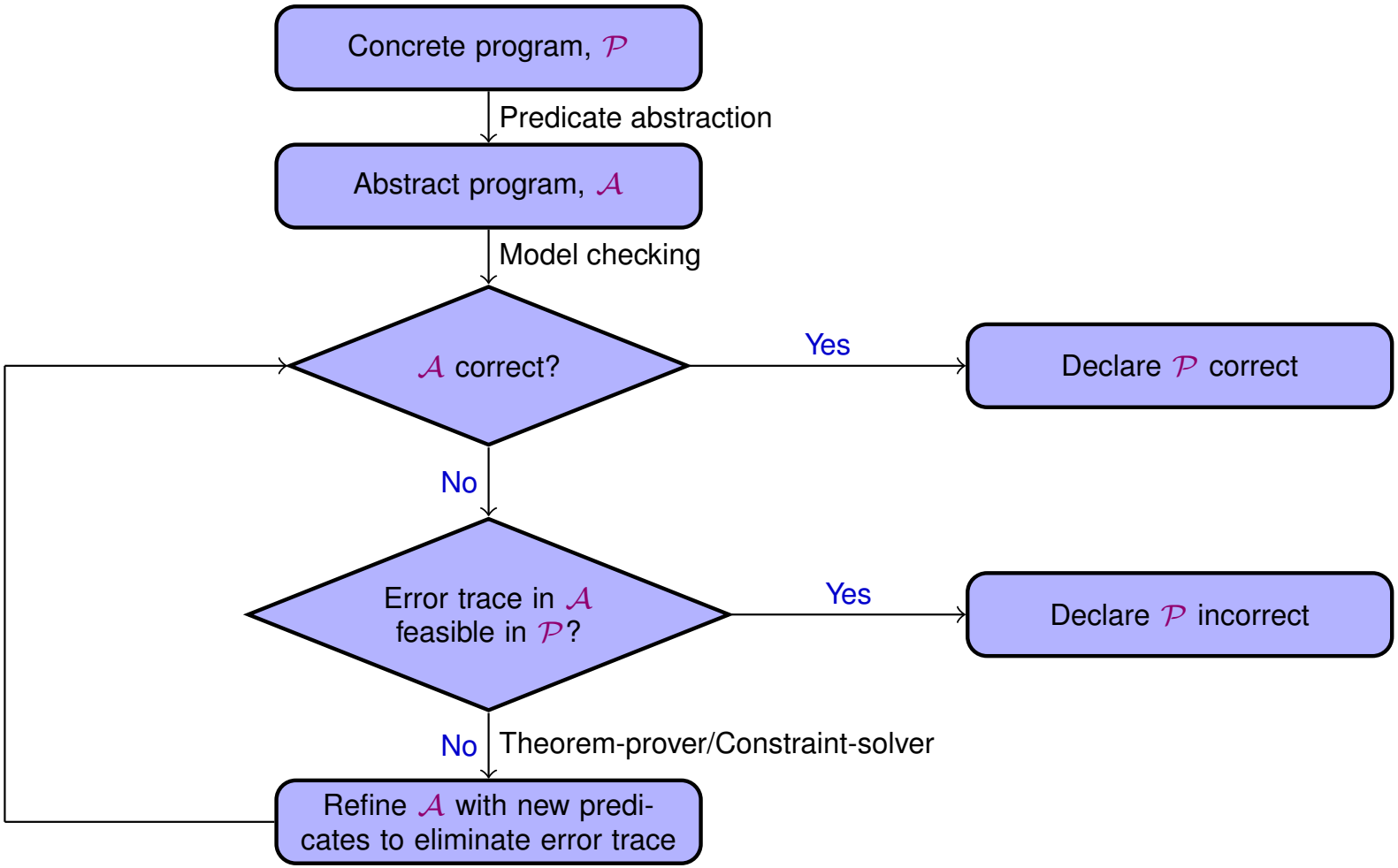
$$\frac{hb(B,z) \wedge hb(y,D)\ access(y,v)\ access(z,v)\ access(B,v)\ access(D,v)}{\texttt{AtomicityViolation}([x{:}y],[B{:}D])}$$



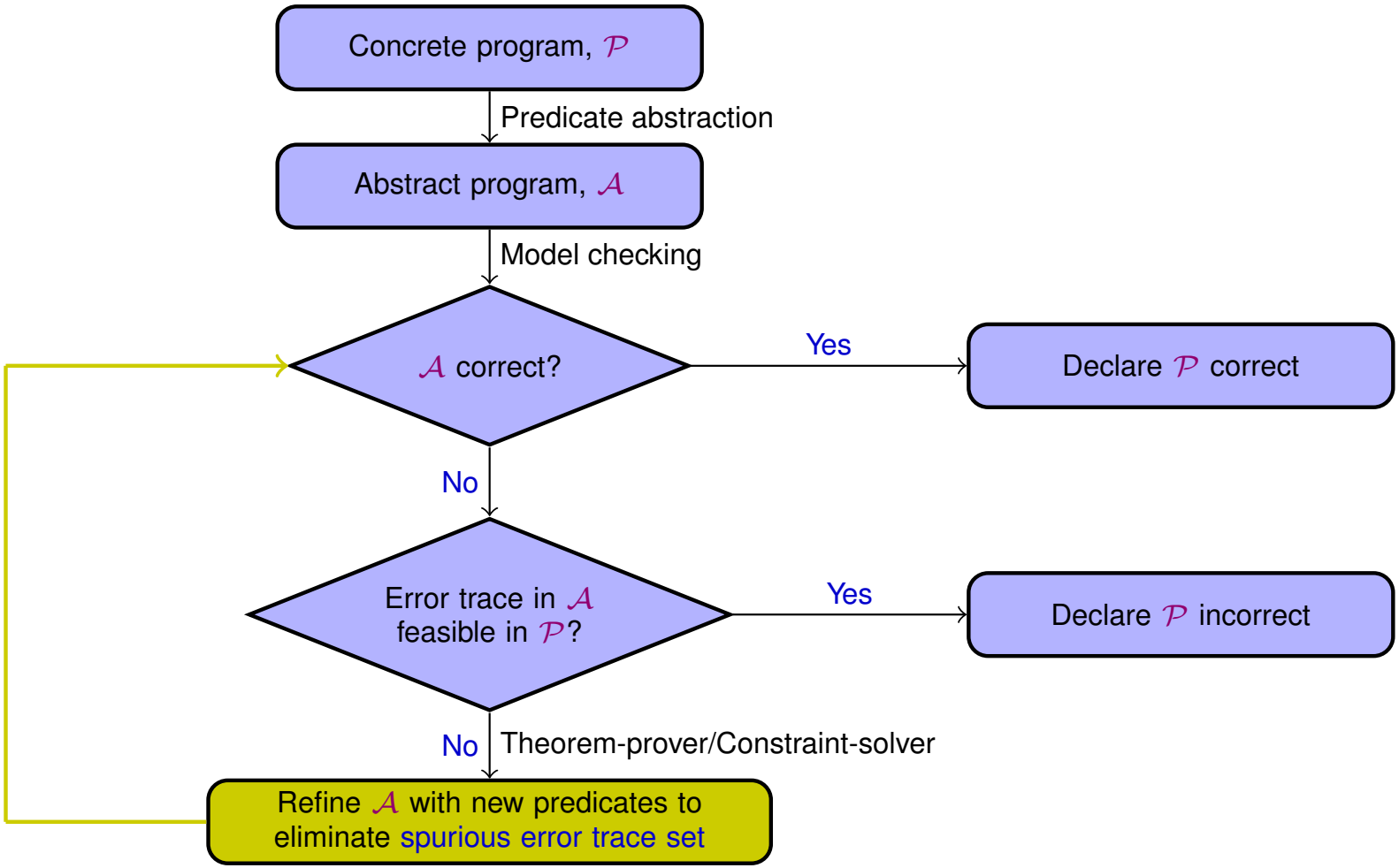
Application: bug summarization

- HB-formula as a counterexample summary
- Inference rules for more precise bug summaries
  - Identification of HB-formula and data access patterns for bugs
  - Data races, atomicity violations, two stage access bugs, define-use order violations

Application: CEGAR acceleration



Application: CEGAR acceleration



Application: CEGAR acceleration

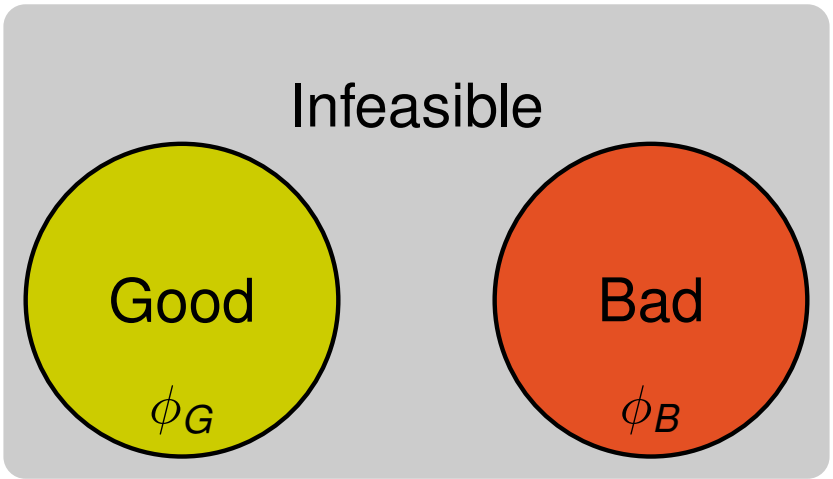
- Representation of abstract, spurious, bad trace sets using HB-formulas
- Simultaneous learning of refinement predicates from multiple abstract cexs

Goal

Given a trace τ and a specification, generate:

- HB-formula ϕ_B representing **nhood**(τ), and,
- HB-formula ϕ_G representing **nhood**(τ).

First attempt



First attempt

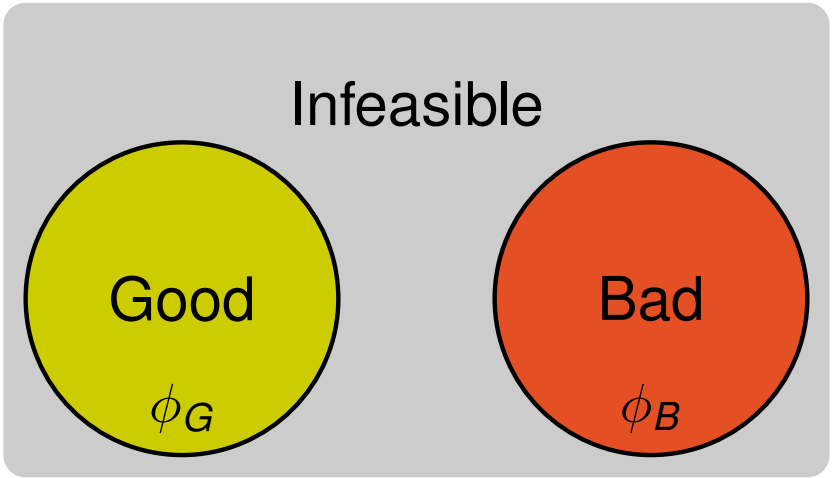
- Formulate Φ [WKGG09]:
  - Quantifier-free first-order formula over vars & *hb* constraints
  - Execution $\pi \in \mathbf{nhood}(\tau)$ iff $\pi \approx$ model of Φ
- To compute ϕ_B:
  - Initially, $\phi_B = \texttt{false}$
  - In each step:
    - Obtain a model π of Φ not subsumed by current ϕ_B
    - Generalize π into an HB-formula φ
    - $\phi_B = \phi_B \vee \varphi$
  - Generalization: *partial satisfying assignments*

ϕ_B exactly represents $\mathbf{nhood}(\tau)$

First attempt

- Issues:
  - Inefficient in practice
  - Unclear how to generate ϕ_G

Second attempt



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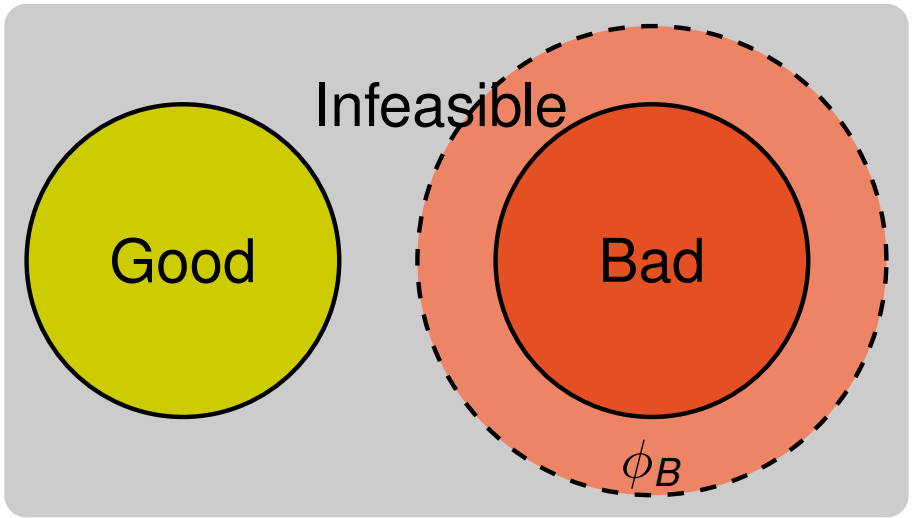

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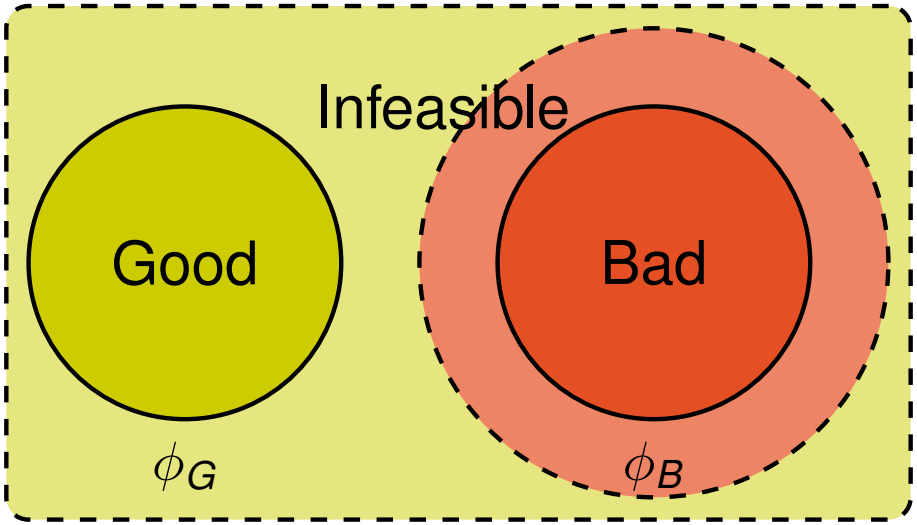

Second attempt

- Formulate Φ [WKGG09]:
  - Quantifier-free first-order formula over vars & *hb* constraints
  - Execution $\pi \in$ **nhood**(τ) iff $\pi \approx$ model of Φ
- To compute ϕ_B:
  - Initially, $\phi_B = \texttt{false}$
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    - Generalize π into an HB-formula φ
    - $\phi_B = \phi_B \vee \varphi$
  - Generalization: *data-flow analysis + minimal unsat core*

ϕ_B soundly overapproximates **nhood**(τ)

Second attempt

- Formulate Φ [WKGG09]:
  - Quantifier-free first-order formula over vars & *hb* constraints
  - Execution $\pi \in$ **nhood**(τ) iff $\pi \approx$ model of Φ
- To compute ϕ_B:
  - Initially, $\phi_B = \texttt{false}$
  - In each step:
    - Obtain a model π of Φ not subsumed by current ϕ_B
    - Generalize π into an HB-formula φ
    - $\phi_B = \phi_B \vee \varphi$
  - Generalization: data-flow analysis + minimal unsat core
- To compute ϕ_G: $\neg\phi_B$

ϕ_G soundly overapproximates the good neighbourhood of τ

Experiments using TARA for ϕ_B generation

Name	#P/#I	#π/#Disj.	Iterations		Total time		Size of ϕ_B	
			Alg.1	Alg.2	Alg.1	Alg.2	Alg.1	Alg.2
reorder_2	2/3	2/2.0	1	1	18ms	28ms	1/2.0	1/2.0
define_use	2/4	2/2.0	1	1	15ms	22ms	1/2.0	1/1.0
em28xx	2/8	4/2.0	1	1	16ms	25ms	1/2.0	1/1.0
locks	3/8	10/1.6	12	2	27ms	37ms	12/5.5	2/4.0
2stage	2/8	5/1.4	8	1	26ms	32ms	8/3.8	1/2.0
drbd_receiver	2/9	5/1.6	40	1	42ms	28ms	40/3.9	1/1.0
md	3/11	4/1.8	40	1	76ms	33ms	40/6.1	1/1.0
lazy01	3/12	6/3.7	2	2	31ms	57ms	2/3.0	2/2.0
locks_hb	4/13	10/2.2	>29.0k	7	TO	119ms	TO	6/3.0
lc_rc	4/14	8/2.0	4.6k	1	21.4s	37ms	4.6k/16.7	1/1.0
barrier_locks	3/18	17/2.6	10.6k	6	1.4min	521ms	10.6k/10.0	4/1.5
stateful01	3/19	10/3.4	2.3k	2	10.5s	84ms	2.3k/9.4	2/1.0
read_write_lock	4/22	16/3.4	9.2k	4	1.6min	319ms	9.2k/16.1	4/3.0
loop	2/38	14/2.7	2	1	38ms	72ms	2/3.0	1/2.0
fib_bench	3/39	24/3.6	>20.5k	2	TO	2.3s	TO	2/10.0
i2c_hid	2/42	26/4.5	>23.4k	3	TO	615ms	TO	3/1.3
rtl8169-1	7/71	22/2.7	>20.4k	1	TO	111ms	TO	1/2.0
rtl8169-2	7/116	41/2.3	>7.3k	1	TO	463ms	TO	1/1.0
rtl8169-5	7/134	48/3.1	>5.5k	1	TO	1.5s	TO	1/1.0
rtl8169-4	7/142	48/3.0	>8.4k	9	TO	3.8s	TO	2/1.0
rtl8169-6	7/144	52/2.9	>8.1k	1	TO	887ms	TO	1/1.0
usb_serial-1	7/151	87/3.7	>5.5k	1	TO	1.9s	TO	1/1.0
usb_serial-2	7/163	93/3.6	>4.4k	3	TO	4.4s	TO	1/1.0
rtl8169-3	8/174	61/3.6	>4.2k	2	TO	2.7s	TO	1/1.0
usb_serial-3	7/178	100/3.7	>4.3k	1	TO	2.1s	TO	1/1.0

Goal

Given a trace τ and a specification,
synthesize synchronization to eliminate **nhood**(τ).

Basic idea

- Use ϕ_G (in CNF)
- Identify HB-formula patterns for various synchronization primitives
- Formulate rewrite rules
- Repeatedly rewrite patterns into synchronization primitives
- Obtain CNF formula over synchronization primitives
- Pick a set $\mathcal{S}$ of synchronization pritmitives, one from each conjunct

Examples

$$\frac{\mathit{hb}(\mathtt{T}_1[\ell_1], \mathtt{T}_2[\ell_2]) \vee \psi}{\mathtt{WaitNotify}(\mathtt{T}_2[\ell_2], \mathtt{T}_1[\ell_1]) \vee \psi} \text{ ADD.WAITNOTIFY}$$

Examples

$$\frac{\mathit{hb}(\mathtt{T}_1[\ell'_1], \mathtt{T}_2[\ell_2]) \vee \mathit{hb}(\mathtt{T}_2[\ell'_2], \mathtt{T}_1[\ell_1]) \vee \psi \quad \ell_1 \leq \ell'_1 \quad \ell_2 \leq \ell'_2}{\mathtt{Lk}\left(\mathtt{T}_1[\ell_1 : \ell'_1], \mathtt{T}_2[\ell_2 : \ell'_2]\right) \vee \psi} \textsc{Add.Lock}$$

Examples

$$\frac{\left(\mathit{hb}(\mathtt{T}_1[\ell_1 - 1], \mathtt{T}_2[\ell_2]) \vee \psi\right) \wedge \left(\mathit{hb}(\mathtt{T}_2[\ell_2 - 1], \mathtt{T}_1[\ell_1]) \vee \psi\right)}{\mathtt{Barrier}\left(\mathtt{T}_1[\ell_1], \mathtt{T}_2[\ell_2]\right) \vee \psi} \quad \textsc{Add.Barrier}$$

Examples

Additional rewrite rules for:

- Shared exclusive locks
- Multithreaded locks
- Multithreaded barriers
- Merging locks (to avoid deadlocks)

Soundness of rewrite rules

Given a trace τ of a concurrent program $\mathcal{P}$,
let $\mathcal{P}^{\mathcal{S}}$ be obtained by inserting synchronization primitives from $\mathcal{S}$.
Let $\pi \in \textbf{nhood}(\tau)$ be a deadlock-free execution of $\mathcal{P}^{\mathcal{S}}$.
Then, π is not bad.

Experiments

Name	#L	#B	#WN	Name	#L	#B	#WN
reorder_2	1	0	0	loop	1	0	0
define_use	0	0	1	fib_bench	1	0	0
em28xx	0	0	1	i2c_hid	1	0	2
locks	1	0	0	rtl8169-1	0	0	1
2stage	0	0	1	rtl8169-2	0	0	1
drbd_receiver	0	0	1	rtl8169-5	0	0	1
md	0	0	1	rtl8169-4	0	0	2
lazy01	0	0	2	rtl8169-6	0	0	1
locks_hb	1	0	2	usb_serial-1	0	0	1
lc_rc	0	0	1	usb_serial-2	0	0	1
barrier_locks	1	1	0	rtl8169-3	0	0	1
stateful01	0	0	2	usb_serial-3	0	0	1
read_write_lock	4	0	0				

Summary

- A method and a tool TARA for succinct representations of sound overapproximations of **nhood**(τ) and **nhood**(τ)
- Three successful case studies using TARA
  - Synchronization synthesis
  - Bug summarization
  - CEGAR acceleration
- Other applications?

Thank you.