Example-Guided Abstraction Simplification

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University of Padova

Abstraction Refinements

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  - Identify when and how to refine the underlying abstraction, e.g. abstract domain
  - Goal: remove some false alarms or spurious traces

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- Basic principles
  - Identify when and how to simplify the underlying abstraction
  - Goal: maintain the same approximate behaviour

Example in abstract model checking

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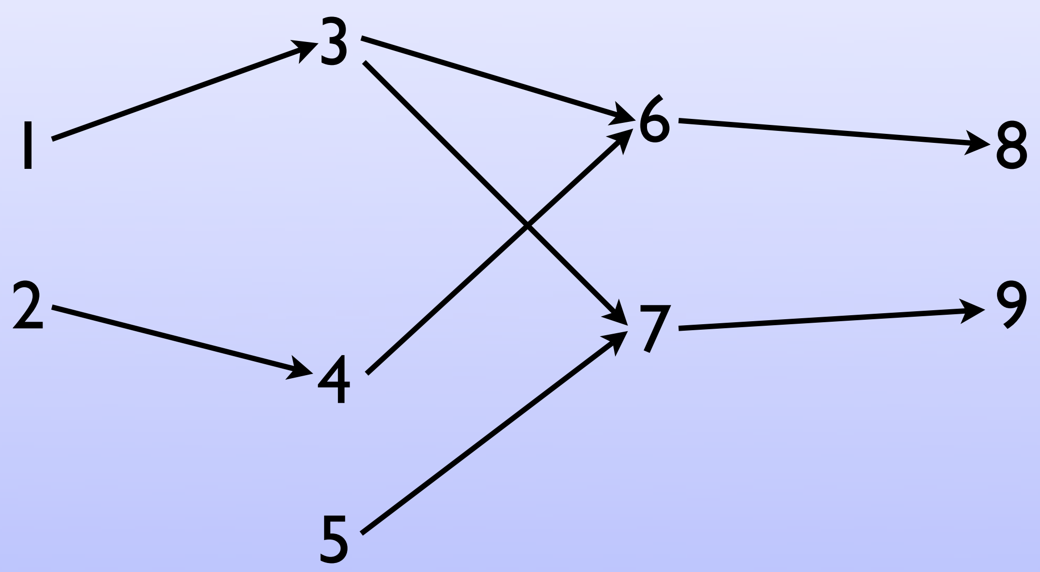

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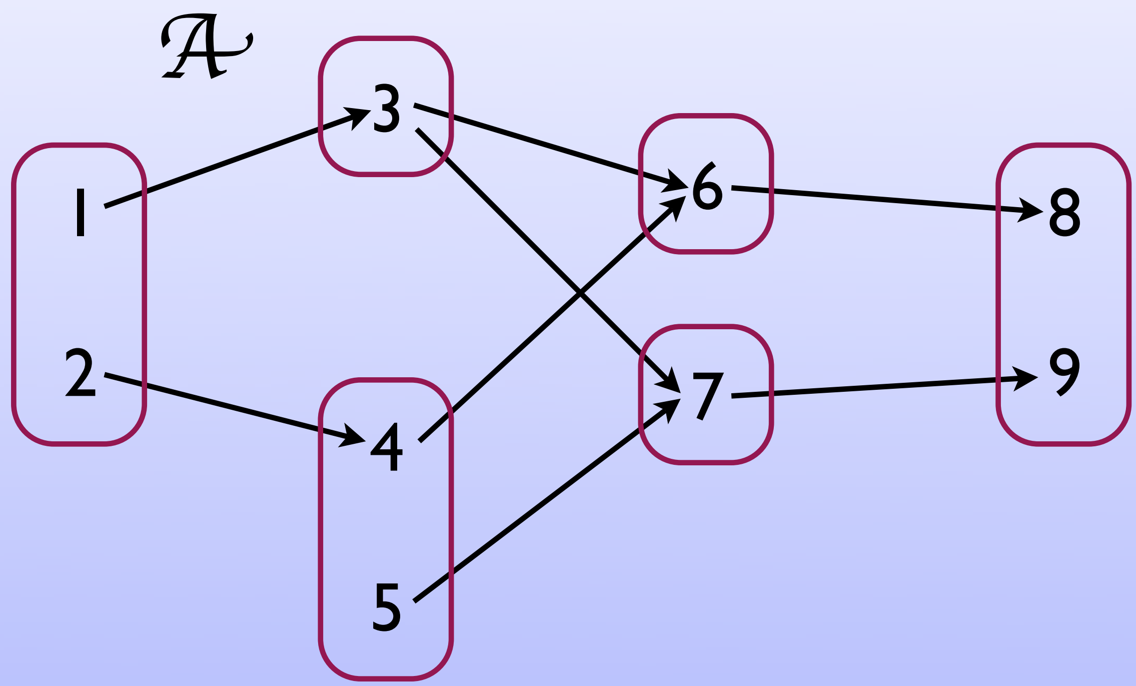

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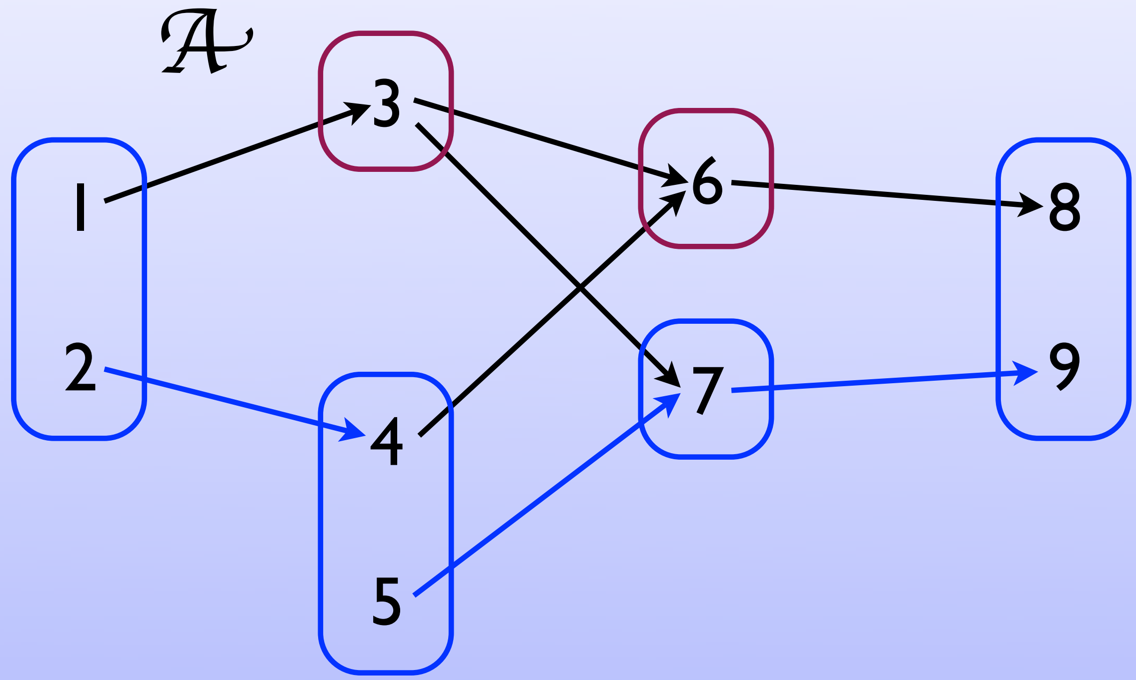

Spurious abstract path: [1,2] → [4,5] → [7] → [8,9]

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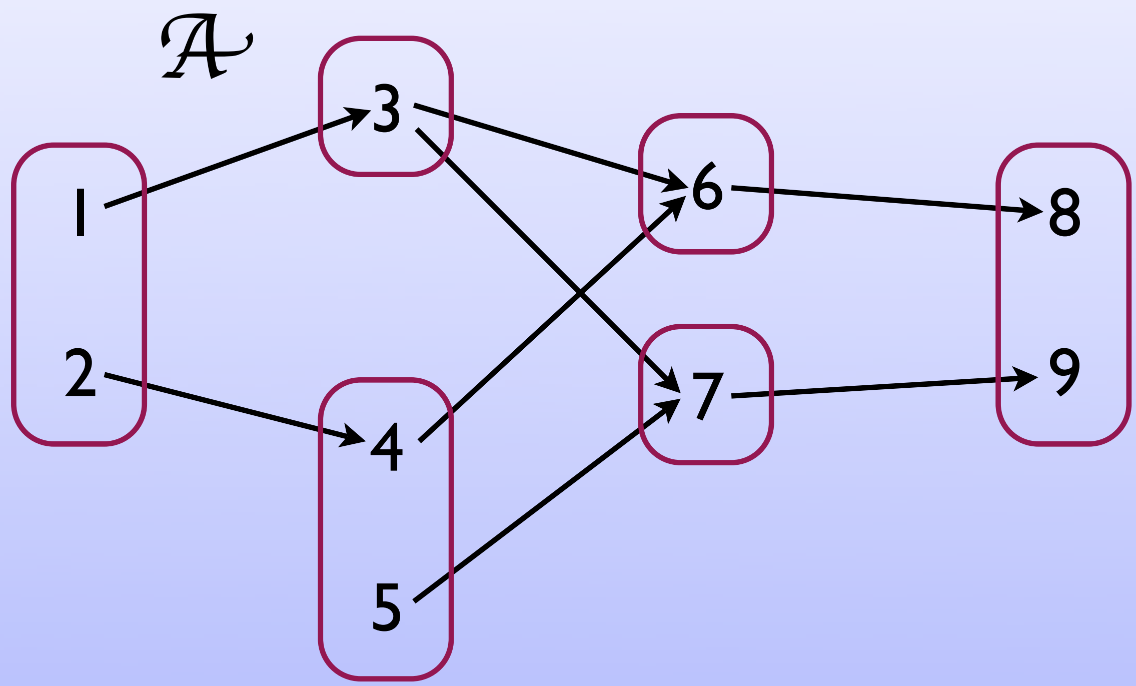

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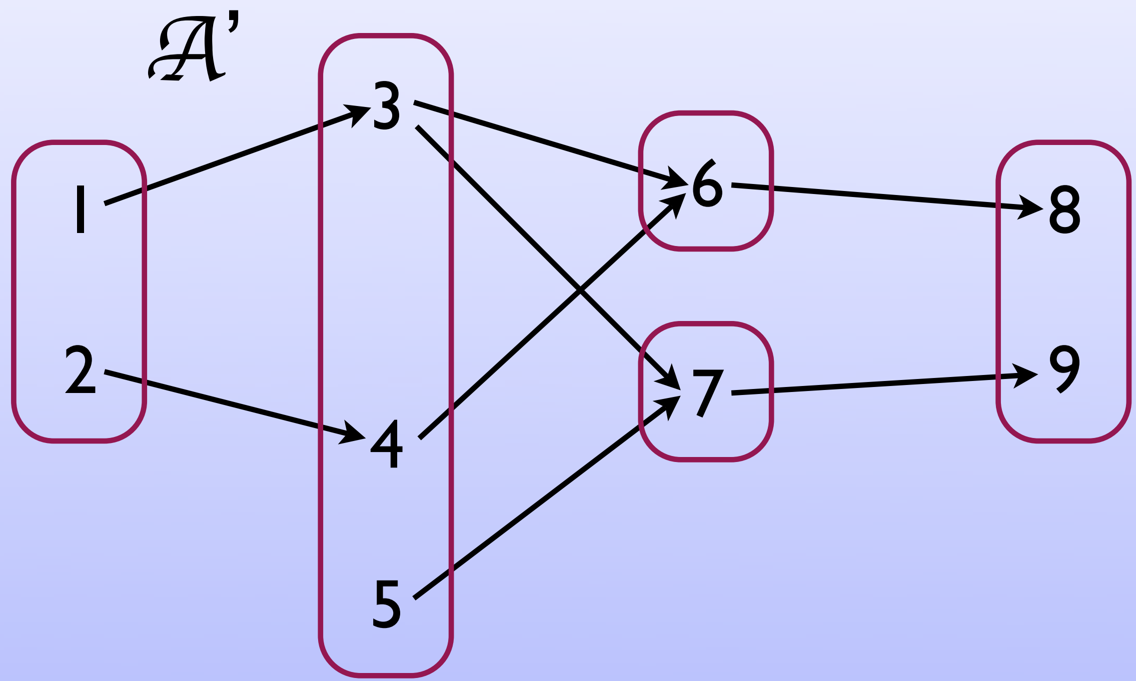

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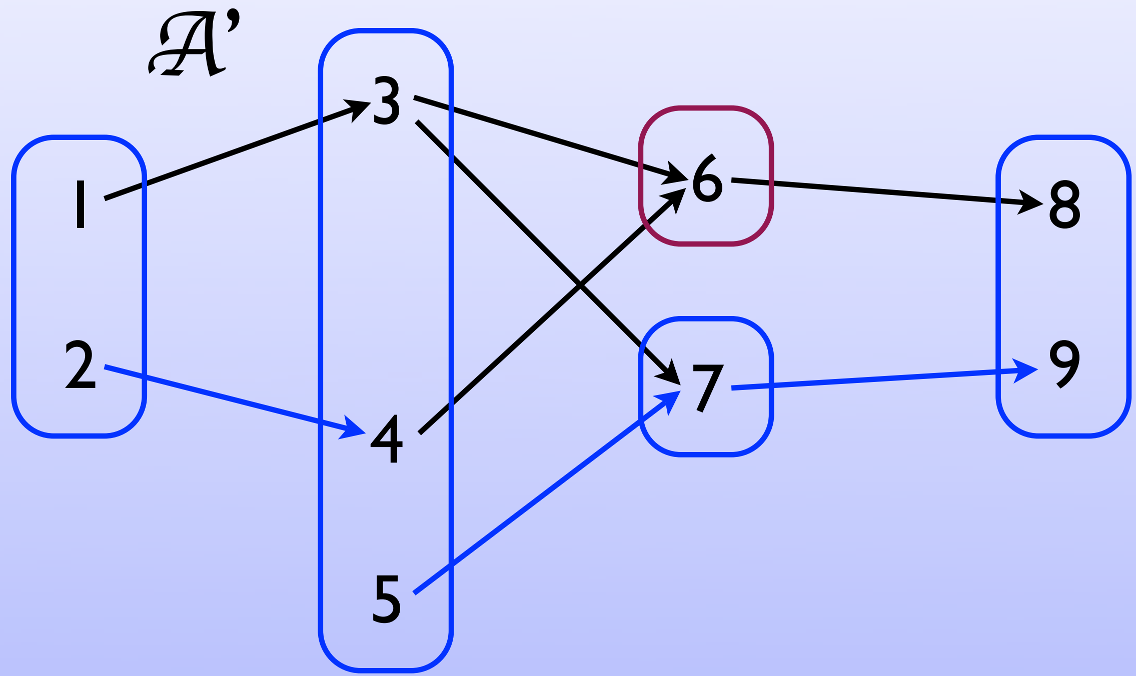

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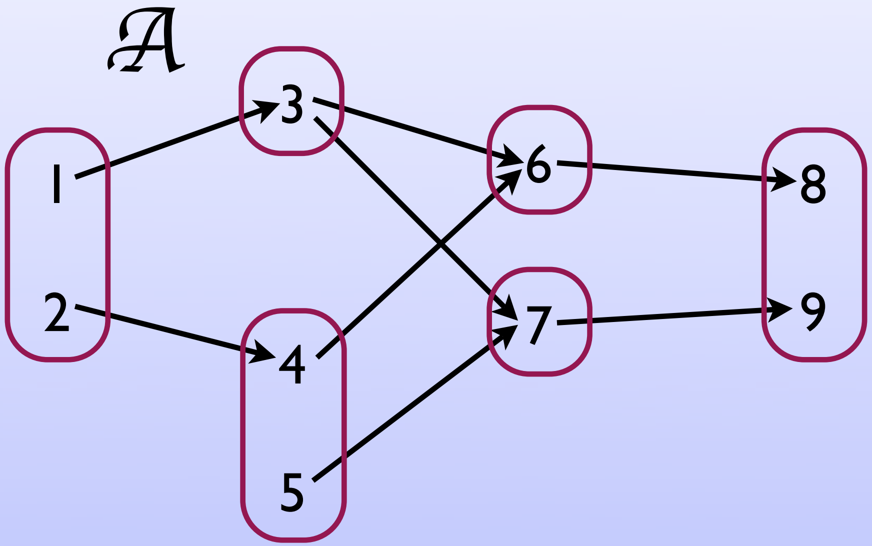

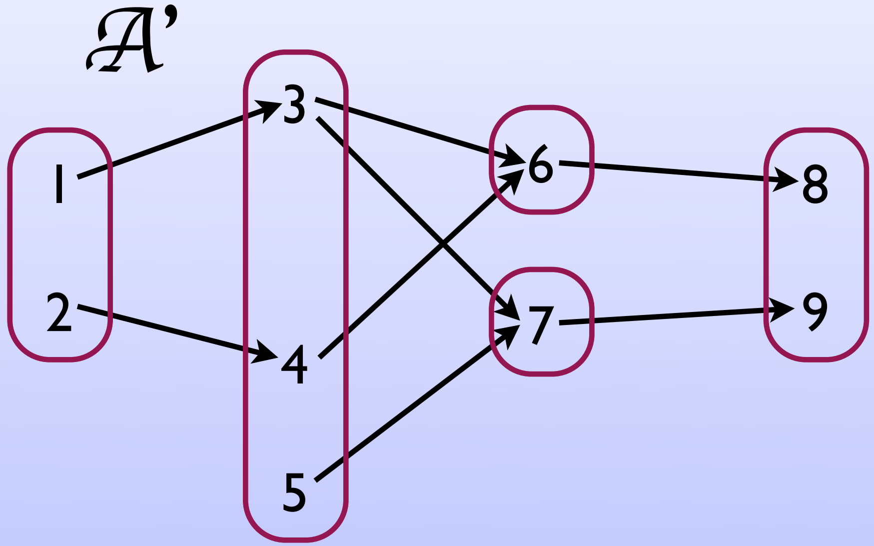

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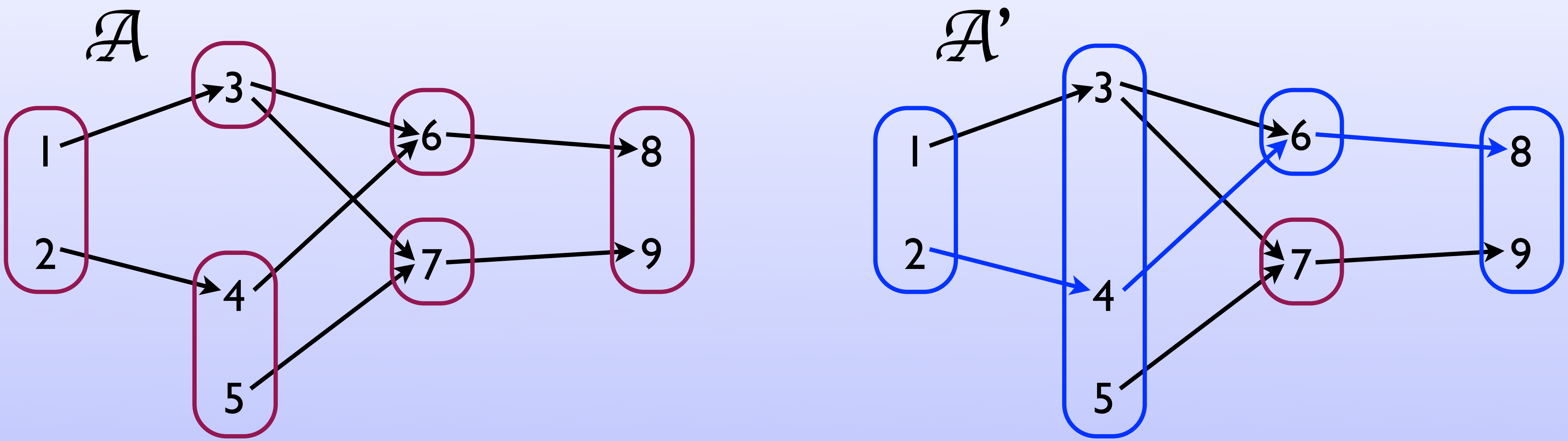

Not spurious abstract path in 𝒜': [1,2] → [3,4,5] → [6] → [8,9]

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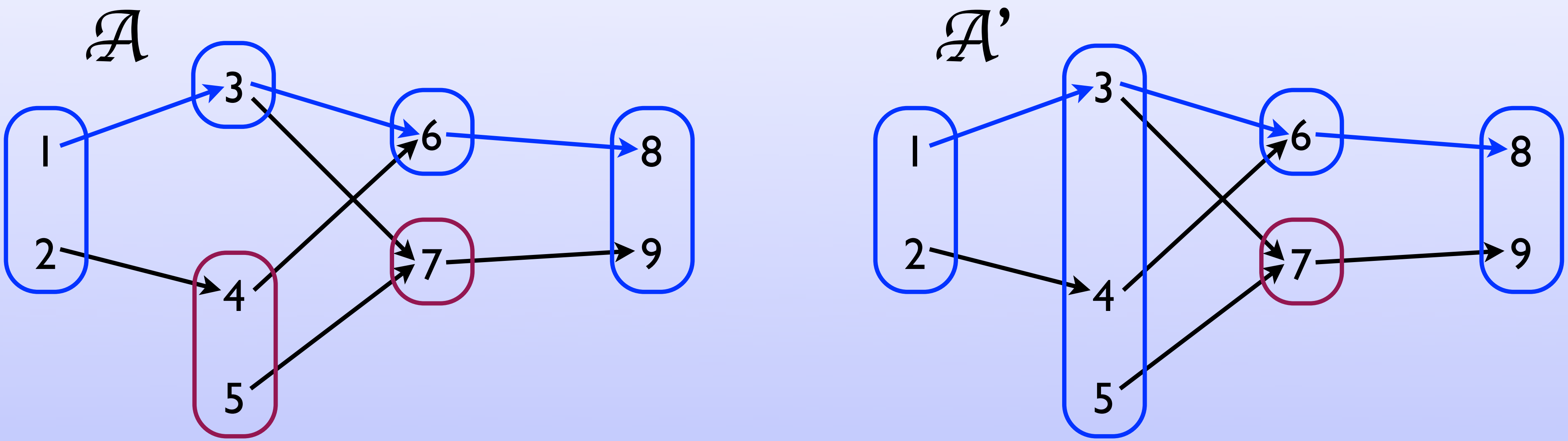

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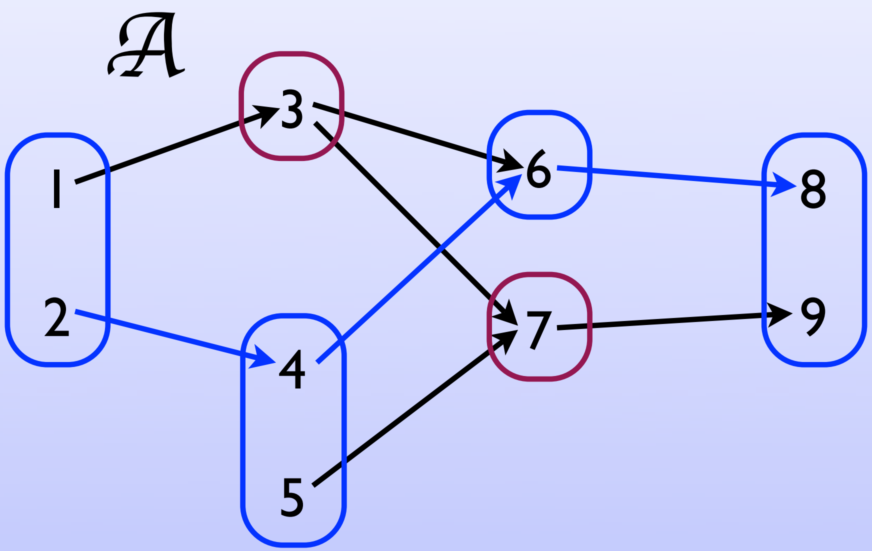

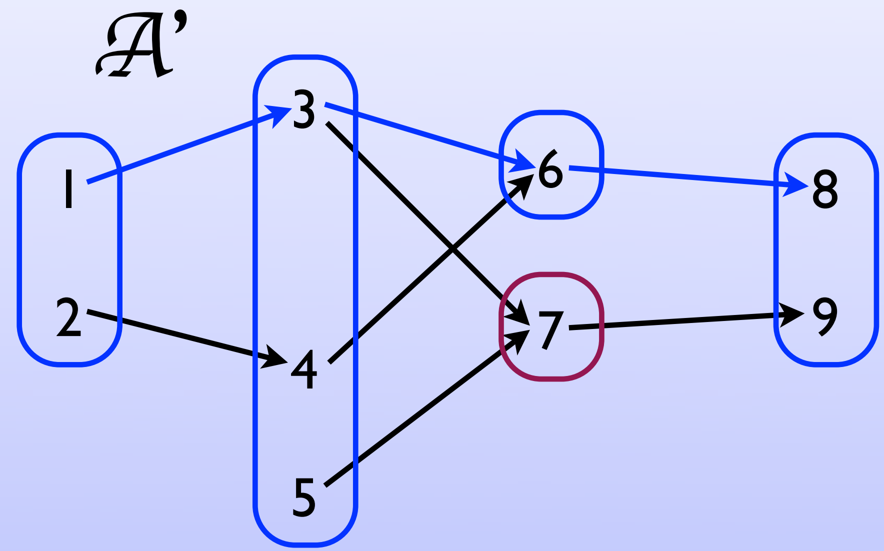

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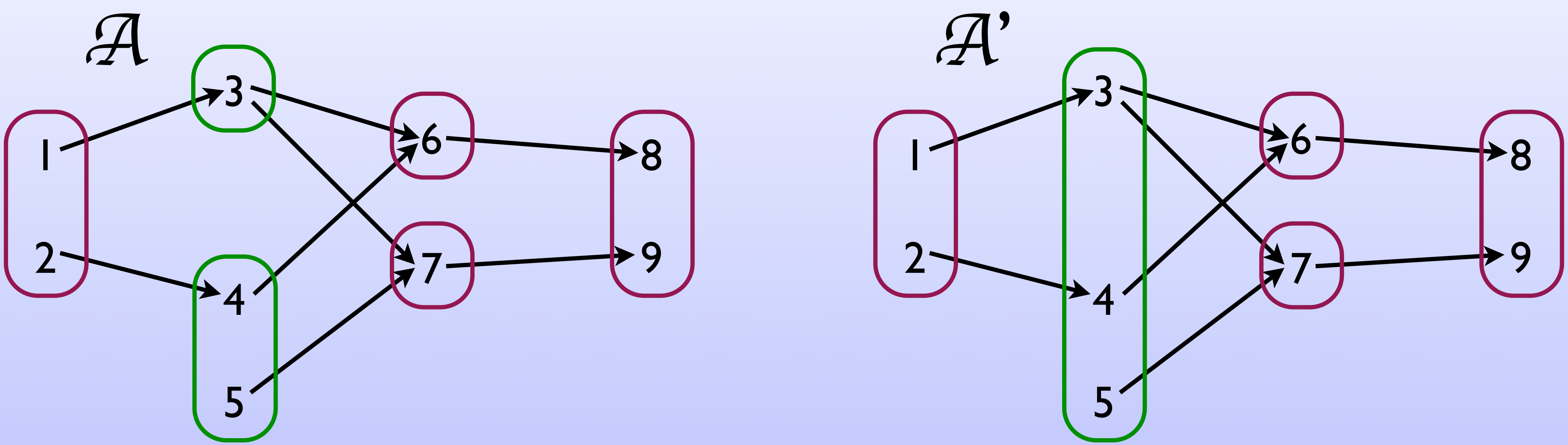

𝒜' keeps the same examples of 𝒜:

if π' is spurious in 𝒜' then there exists a spurious π in 𝒜 such that α(π)= π'

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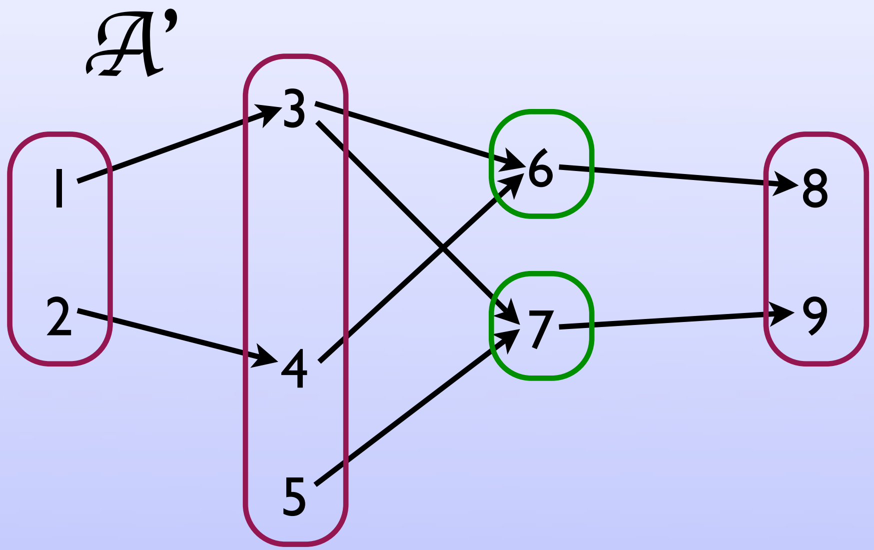

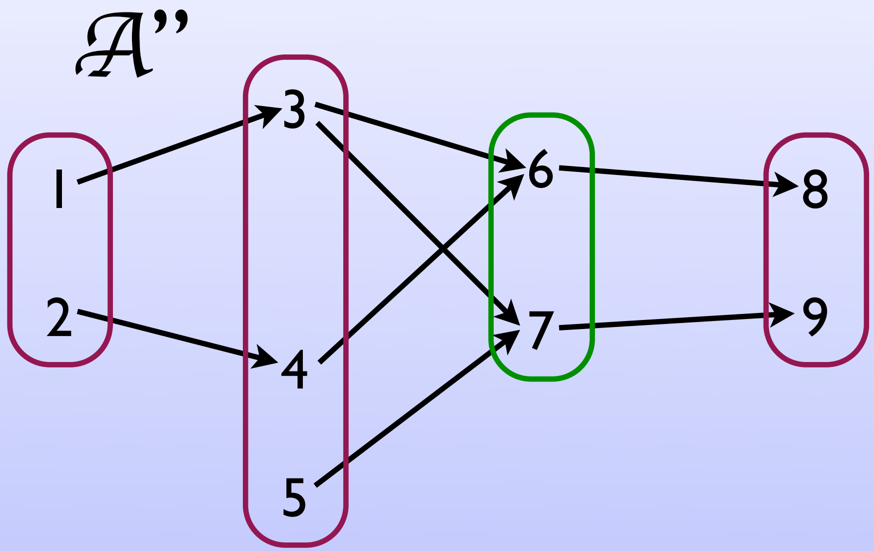

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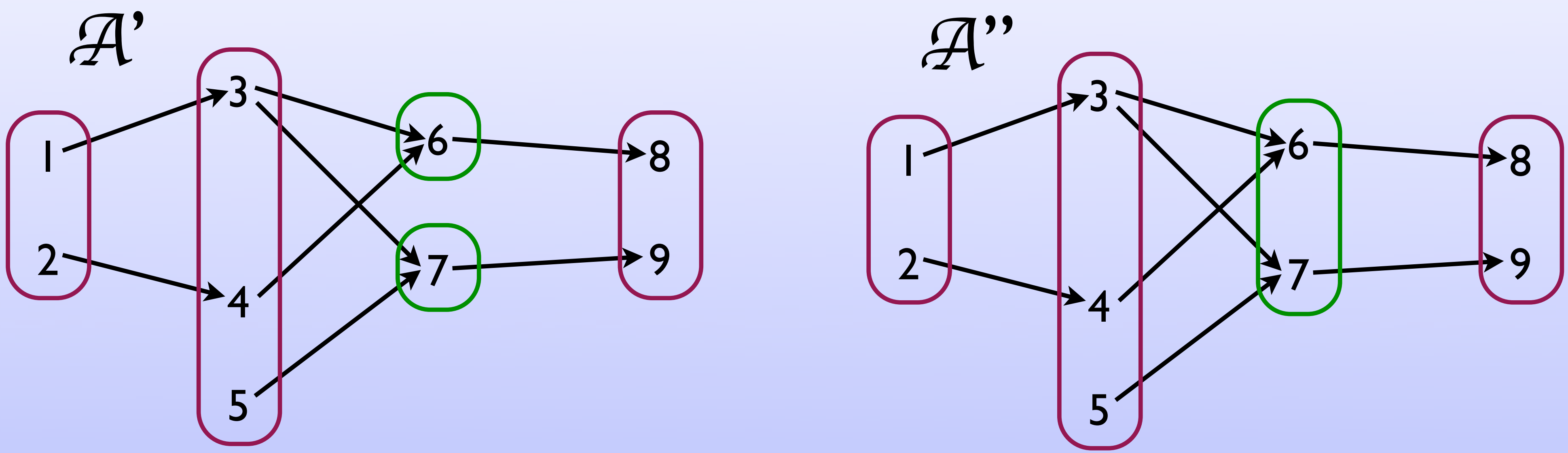

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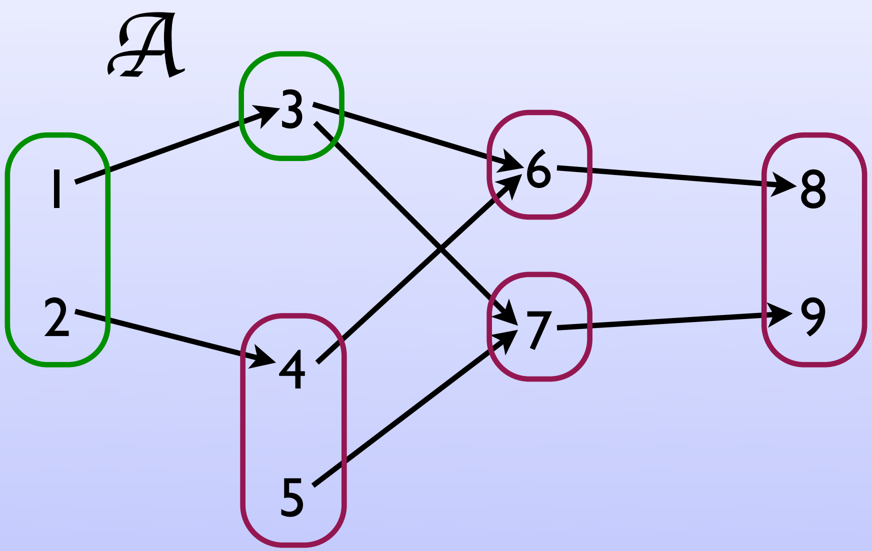

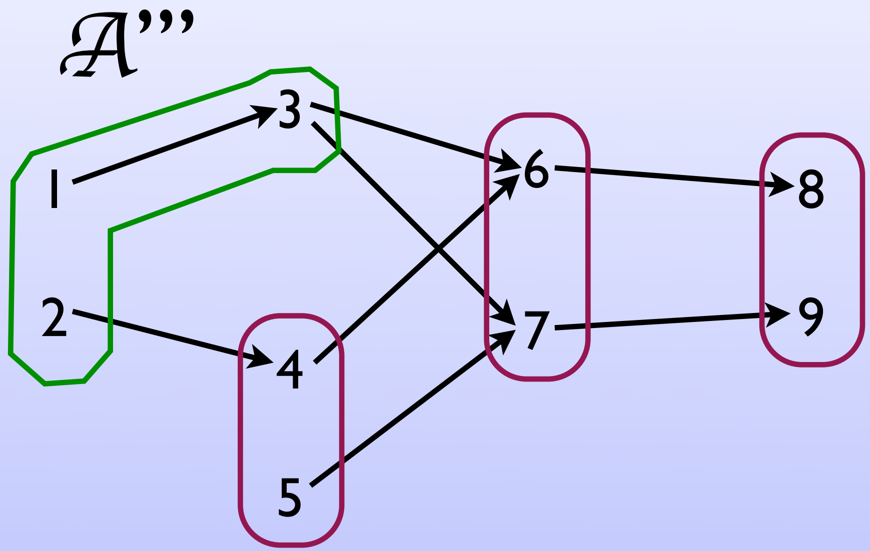

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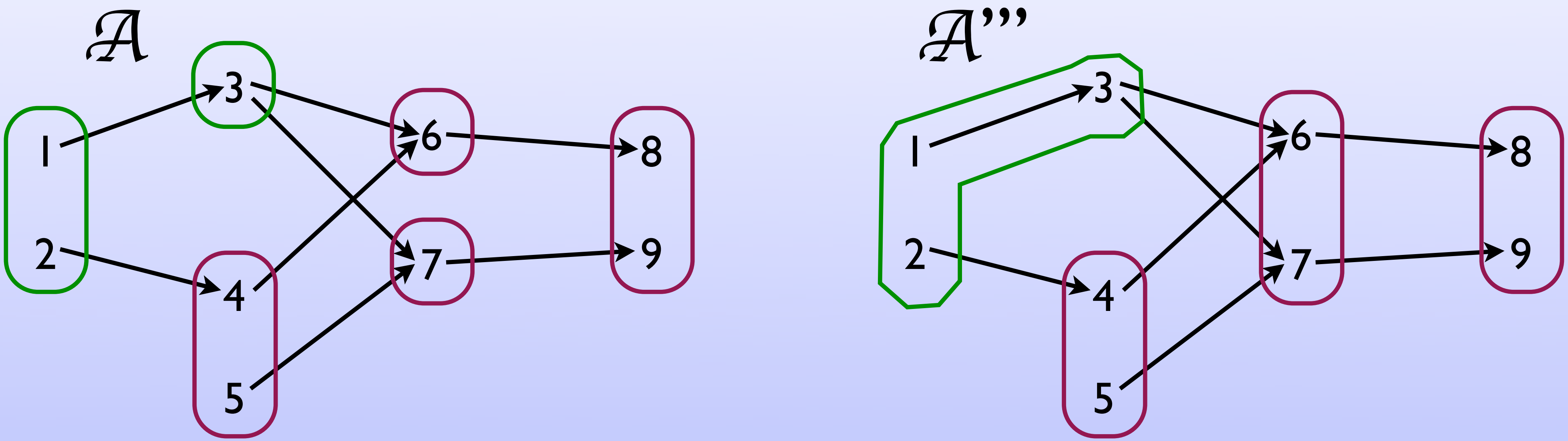

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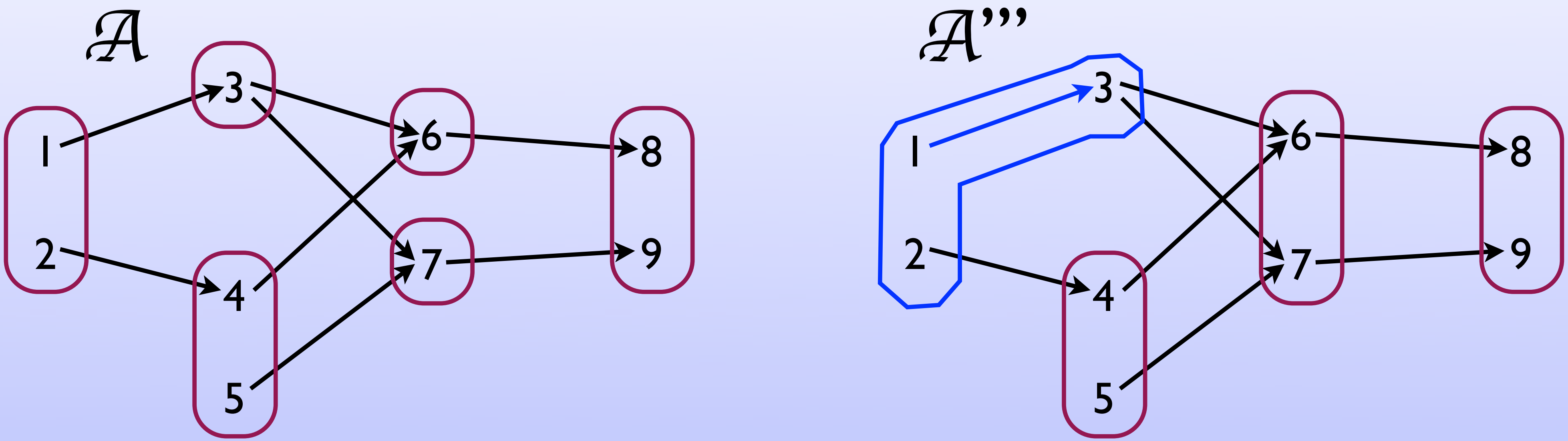

𝒜''' doesn't keep the same examples of 𝒜

Spurious loop path in 𝒜''': [1,2,3] → [1,2,3] → [1,2,3] → ...

BUT no corresponding spurious path in 𝒜

Example in abstract interpretation

$$x{+}{+} : \wp(\mathbb{Z}) \to \wp(\mathbb{Z})$$

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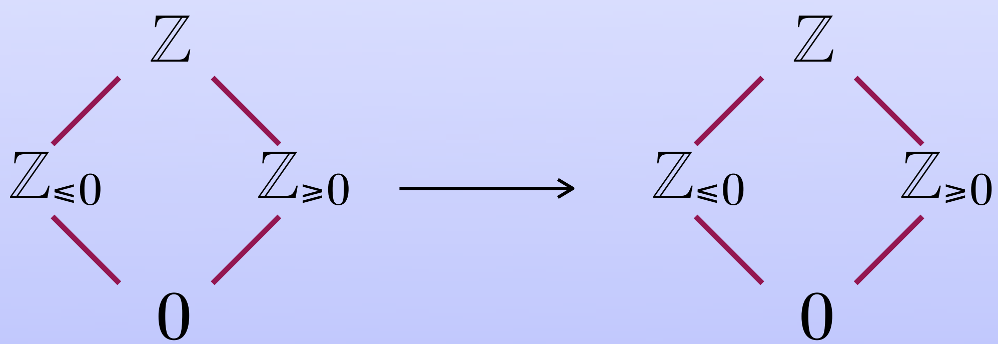
$x{+}{+}^{A_1}$:



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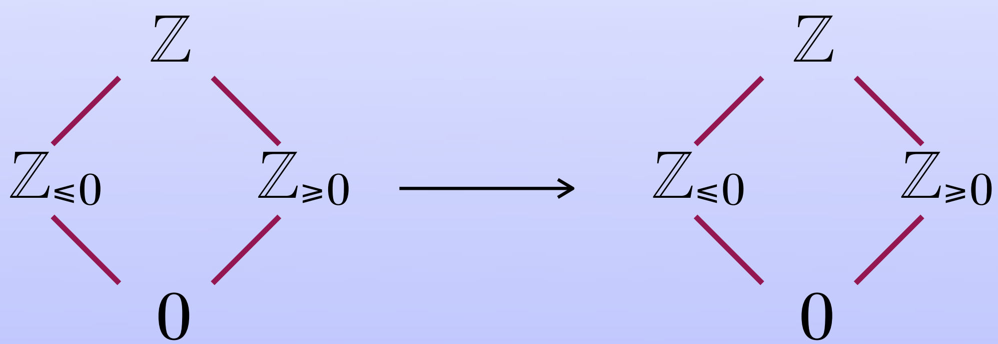

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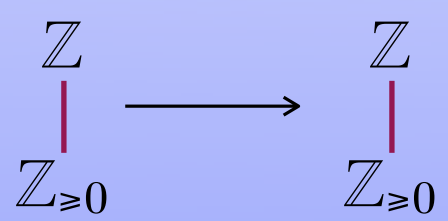

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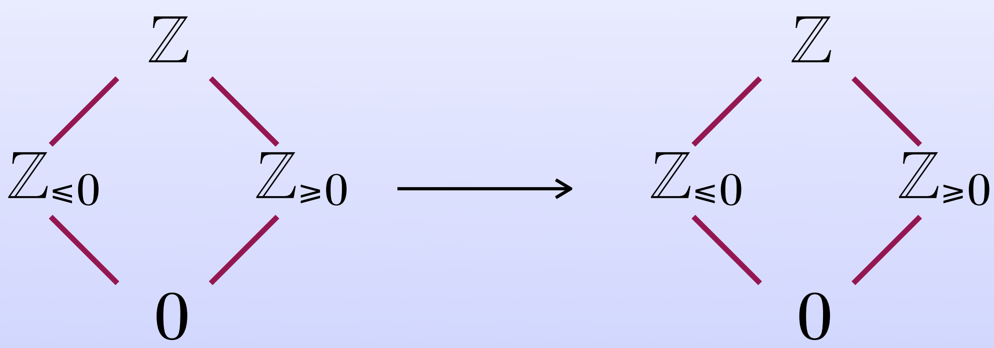

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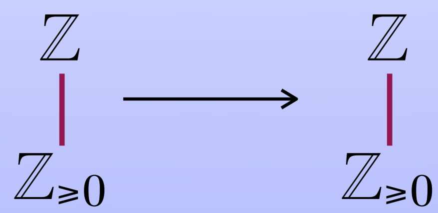

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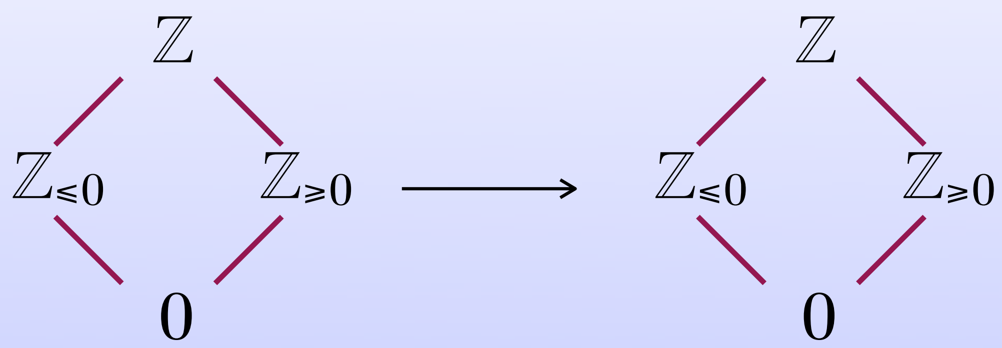

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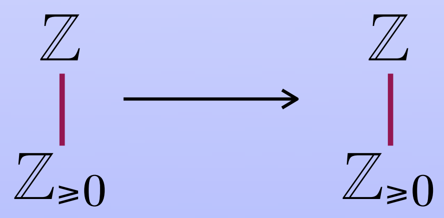

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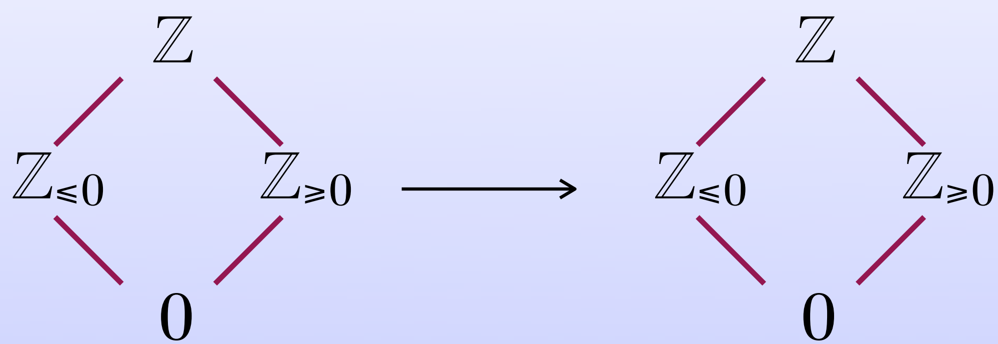

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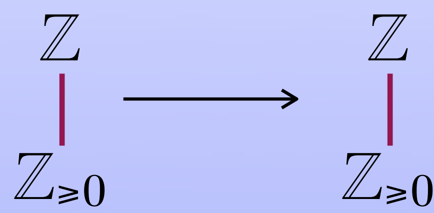

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$$(\gamma_{A_1} \circ \alpha_{A_1}) \circ x{+}{+} \circ (\gamma_{A_1} \circ \alpha_{A_1}) = (\gamma_{A_2} \circ \alpha_{A_2}) \circ x{+}{+} \circ (\gamma_{A_2} \circ \alpha_{A_2})$$

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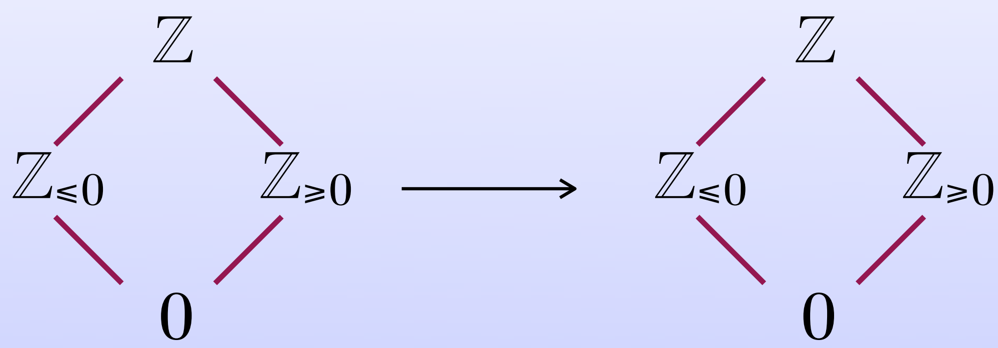

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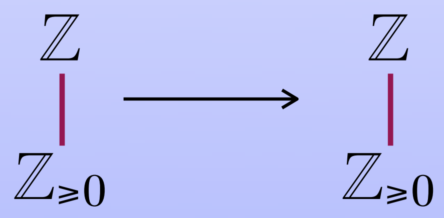

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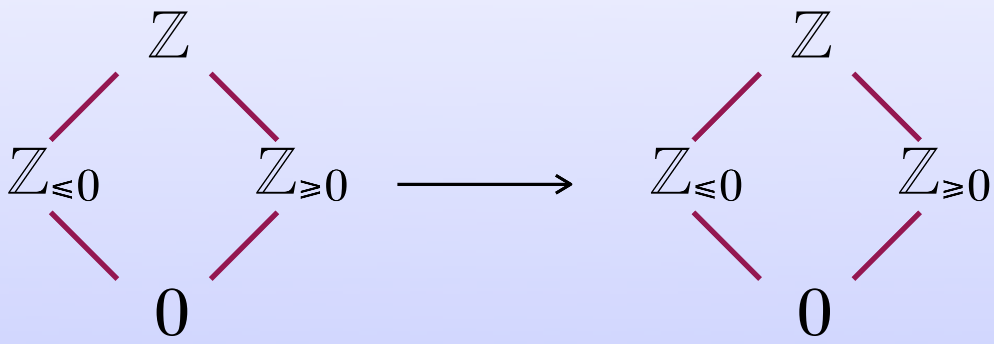

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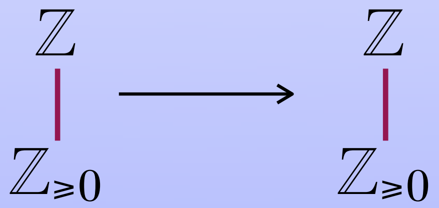

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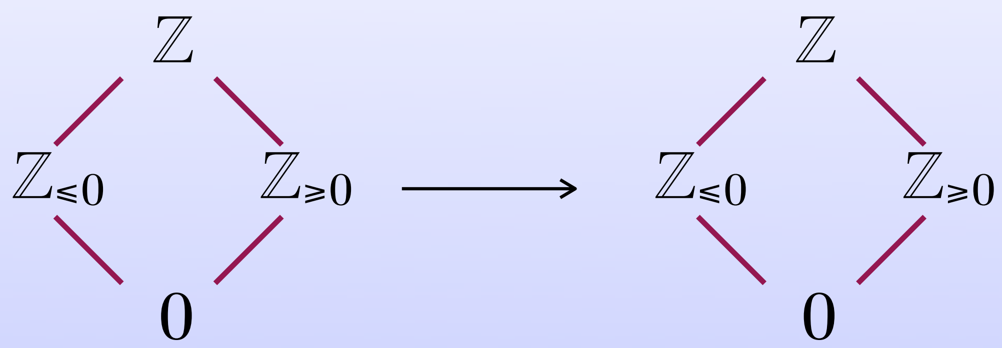

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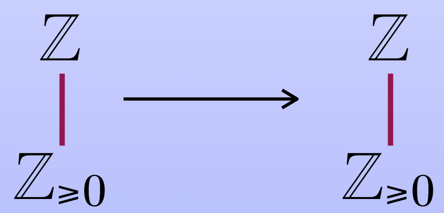

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0 and $\mathbb{Z}_{\leq 0}$ are "irrelevant" in A_1 for approximating $x{+}{+}$

$$\{0,-2,-7\} \xrightarrow{A_1} \mathbb{Z}_{\leq 0} \xrightarrow{++} \{\mathrm{x}\leq 1\} \xrightarrow{A_1} \mathbb{Z}$$

$$\{0,-2,-7\} \xrightarrow{A_2} \mathbb{Z} \xrightarrow{++} \mathbb{Z} \xrightarrow{A_2} \mathbb{Z}$$

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  - Concrete objects c have best correct approximations $\alpha(c)$
  - Semantic functions $f : C \to C$ have best correct approximations $f^A \stackrel{\text{def}}{=} \alpha \circ f \circ \gamma : A \to A$

Correctness Kernel

Concrete semantic function $f: C \rightarrow C$

Abstract domain $A \in Abs(C)$

$\alpha_A: C \rightarrow A \qquad \gamma_A: A \rightarrow C$

Abstract domain $B \in Abs(C)$

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$f^A = f^B$ when
$(\gamma_A\alpha_A) \circ f \circ (\gamma_A\alpha_A) = (\gamma_B\alpha_B) \circ f \circ (\gamma_B\alpha_B)$

That is, the best correct approximations of function f in A and B coincide when encoded within C

Correctness Kernel

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Correctness kernel $K_f(A)$ of A for f:

$K_f(A) \stackrel{\text{def}}{=}$ most abstract domain B such that $f^B = f^A$

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Main Technical Result

If $f \circ (\gamma_A \alpha_A)$ is continuous then $K_f(A)$ exists and

$$K_f(A) = img(f^A) \cup \bigcup_{y \in img(f^A)} \max(\{x \in A \mid f^A(x) = y\})$$

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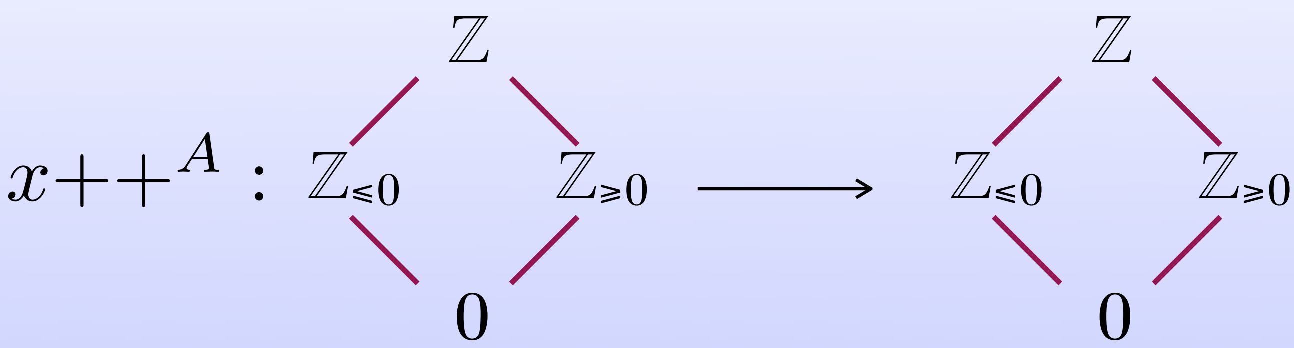
Proof relies on the notion of complete abstract interpretation

Example



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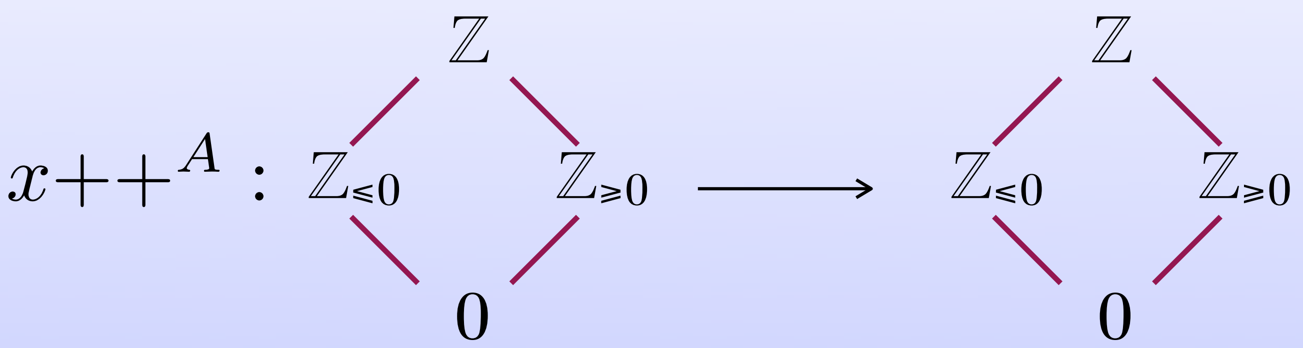

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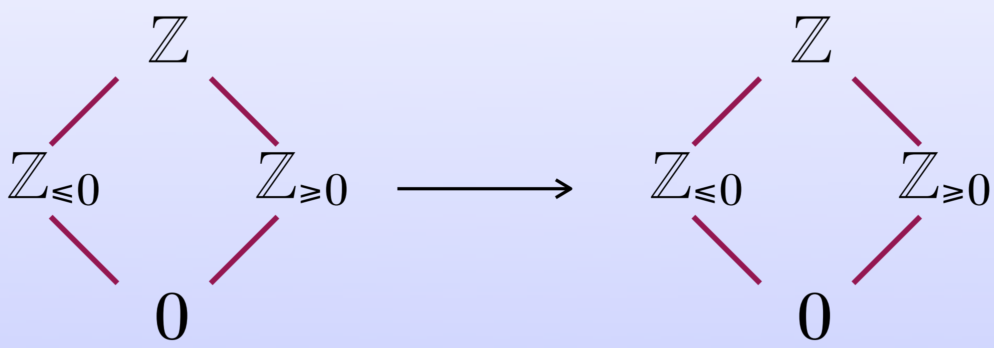
$$\mathrm{img}({+}{+}^A) = \{\, \mathbb{Z}, \mathbb{Z}_{\geq 0} \,\}$$

$$\max(\{x \in A \mid {+}{+}^A(x) = \mathbb{Z}\}) = \max(\{\mathbb{Z}_{\leq 0}, \mathbb{Z}\}) = \mathbb{Z}$$

$$\max(\{x \in A \mid {+}{+}^A(x) = \mathbb{Z}_{\geq 0}\}) = \max(\{0, \mathbb{Z}_{\geq 0}\}) = \mathbb{Z}_{\geq 0}$$

Example

$x{+}{+}^A$:



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$$\max(\{x \in A \mid {+}{+}^A(x) = \mathbb{Z}_{\geq 0}\}) = \max(\{0, \mathbb{Z}_{\geq 0}\}) = \mathbb{Z}_{\geq 0}$$

$$K_{++}(A) = \{\, \mathbb{Z}, \mathbb{Z}_{\geq 0} \,\}$$

Abstract Model Checking

Concrete Kripke structure $< \Sigma, \rightarrow, \ell >$

Abstract Model Checking

Concrete Kripke structure $<\Sigma, \rightarrow, \ell>$

Abstract state space P is a partition of Σ

Abstract Kripke structure $<P, \rightarrow^{\exists\exists}, \ell>$

$B \rightarrow^{\exists\exists} C$ iff there exist $x \in B$ and $y \in C$ s.t. $x \rightarrow y$

Abstract Model Checking

Concrete functions:

predecessor pre: $\wp(\Sigma) \rightarrow \wp(\Sigma)$

successor post: $\wp(\Sigma) \rightarrow \wp(\Sigma)$

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Abstract Model Checking

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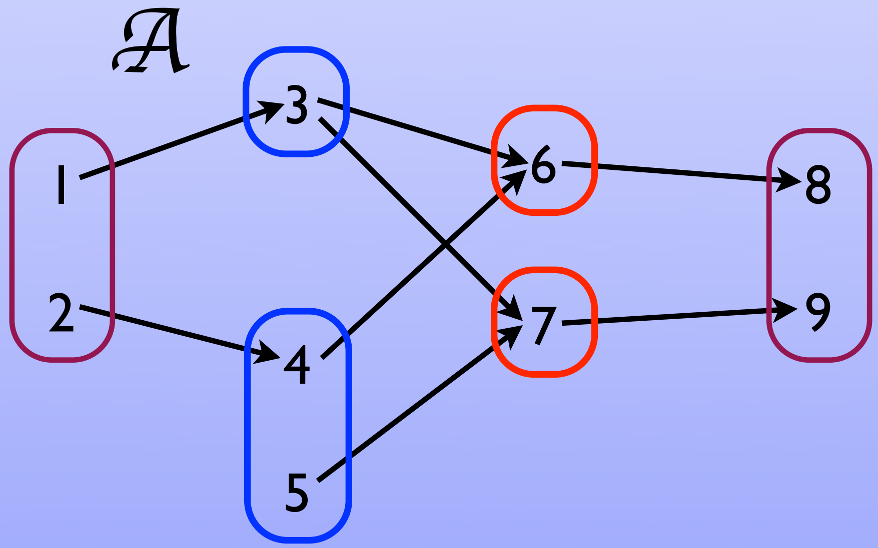

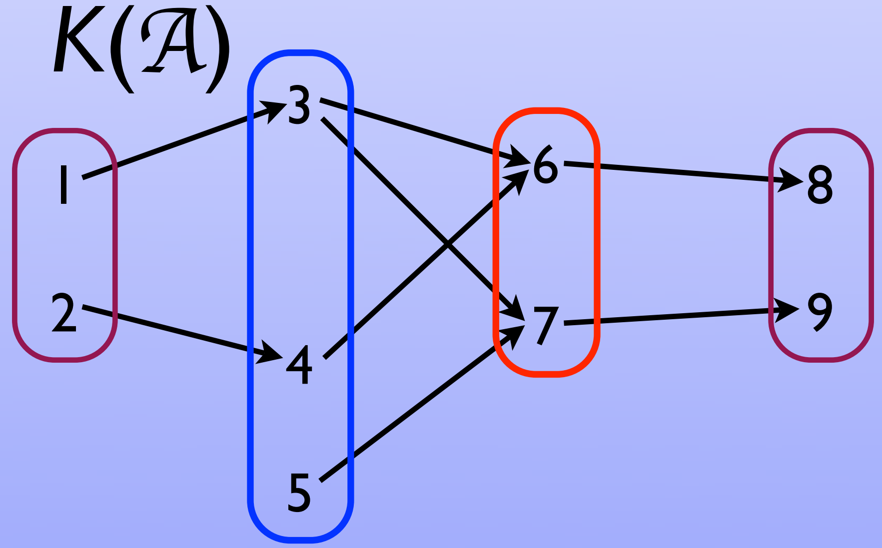

EGAS

EGAS: Example-Guided Abstraction Simplification

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Abstract Kripke structure $<P , \rightarrow^{\exists\exists}>$

Correctness Kernel $<K(P) , \rightarrow^{\exists\exists}>$

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Abstract Kripke structure $<P , \rightarrow^{\exists\exists}>$

Correctness Kernel $<\mathit{K}(P) , \rightarrow^{\exists\exists}>$

Correctness kernels do not add spurious paths

if π is a spurious path in $\mathit{K}(P)$ then there exists a spurious path σ in P such that $\alpha(\sigma)= \pi$

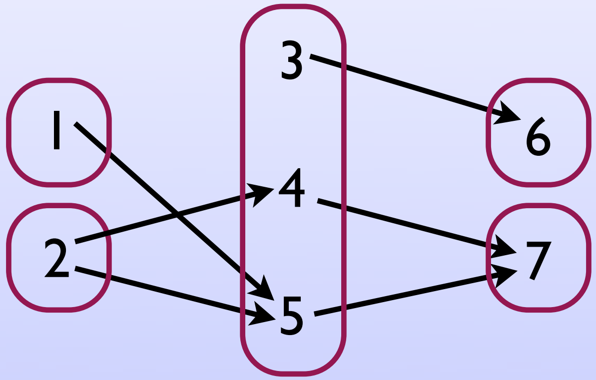
CEGAR

1) Model checker provides an abstract path (i.e. a counterexample)
$\pi = B_1 \rightarrow^{\exists\exists} B_2 \rightarrow^{\exists\exists} B_3 \ldots \rightarrow^{\exists\exists} B_n$

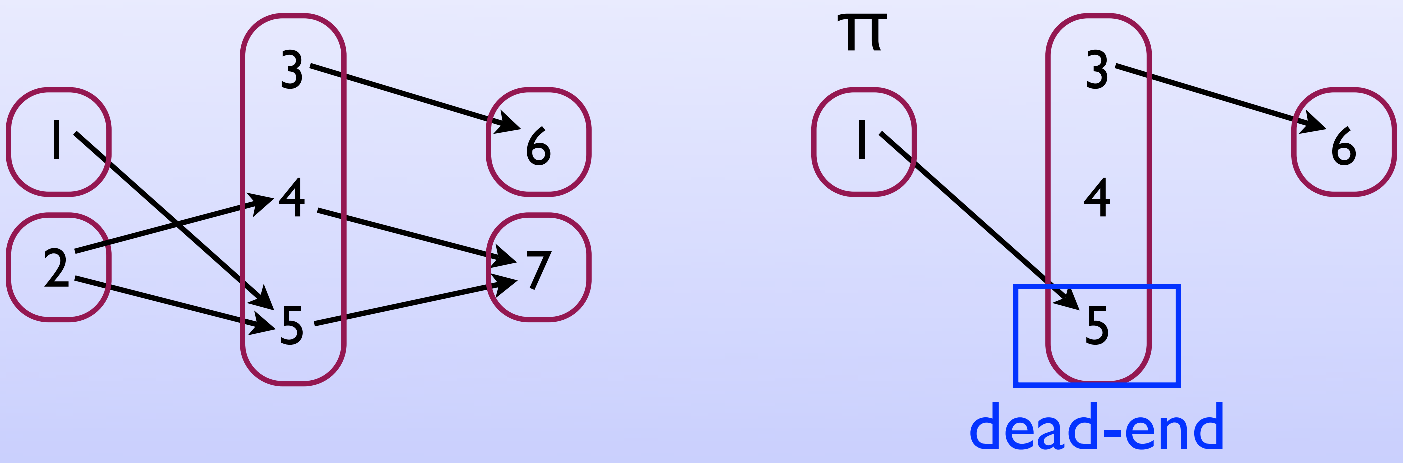
2) CEGAR determines whether π is spurious or not

3) Spuriousness of π depends on some block B_k of π with bad and dead-end states. Thus, CEGAR splits B_k in order to separate bad and dead-end states.

CEGAR



CEGAR



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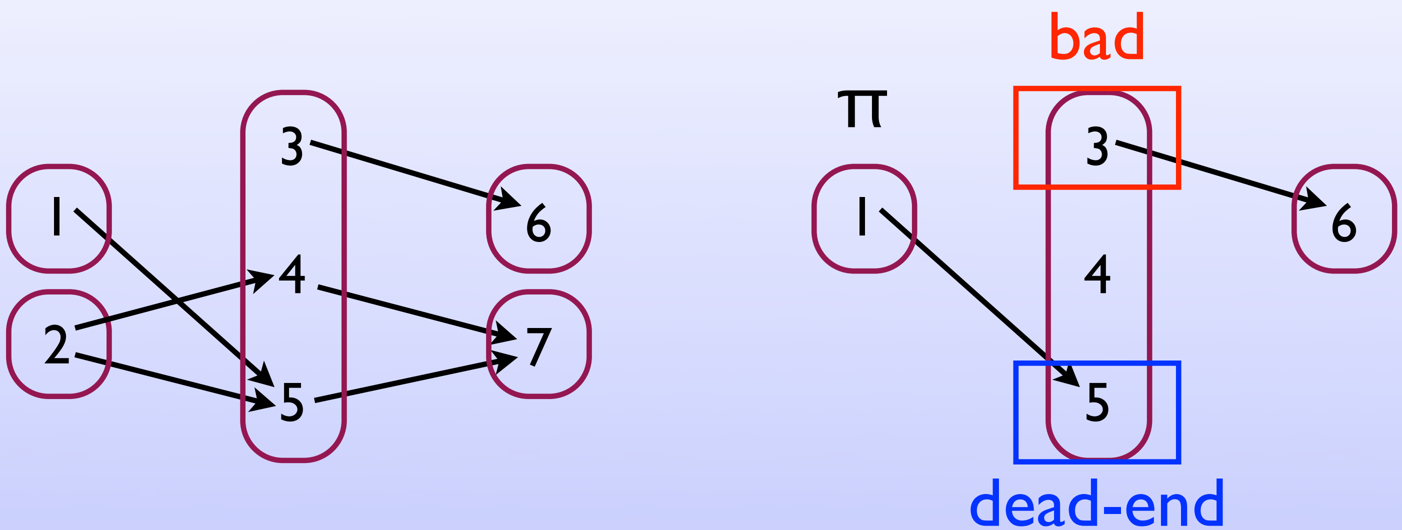

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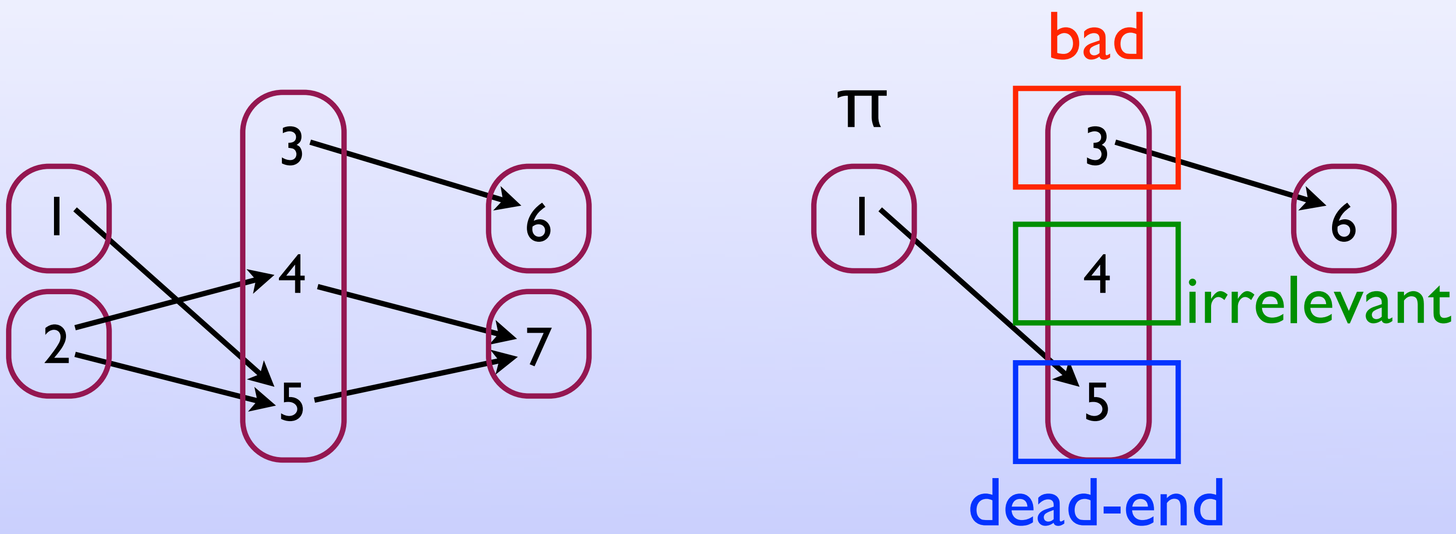

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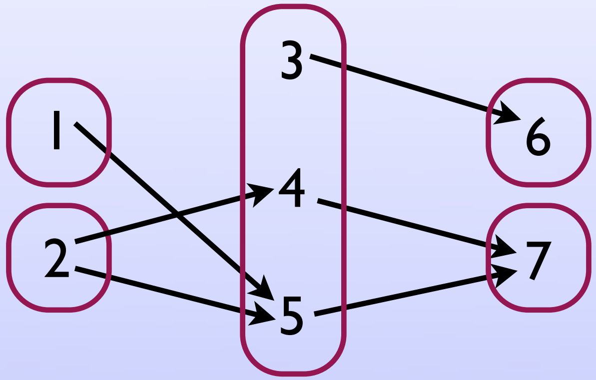
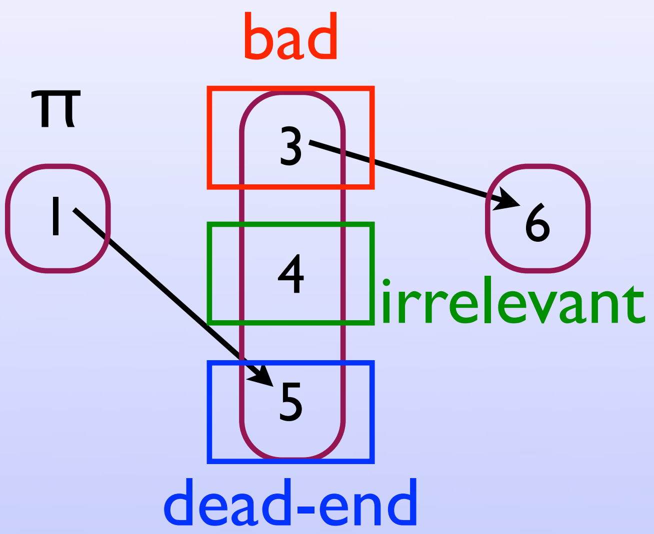
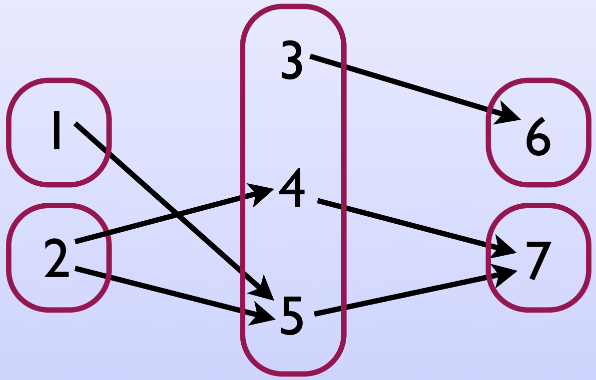
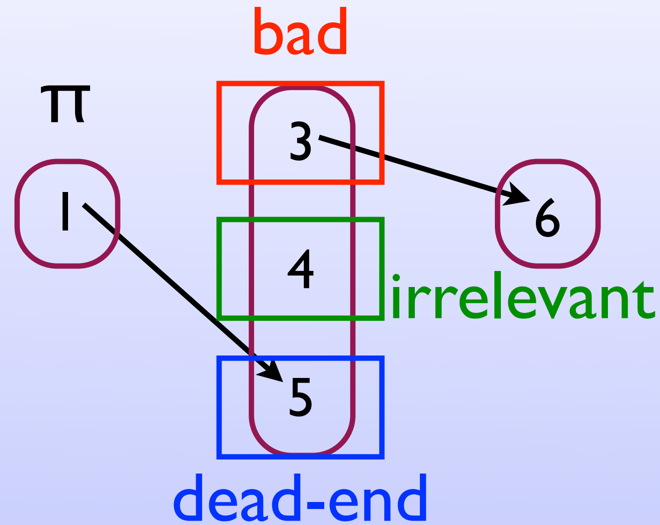




Finding the coarsest refinement is NP-hard
CEGAR heuristics: split into dead-end and bad U irrelevant

CEGAR





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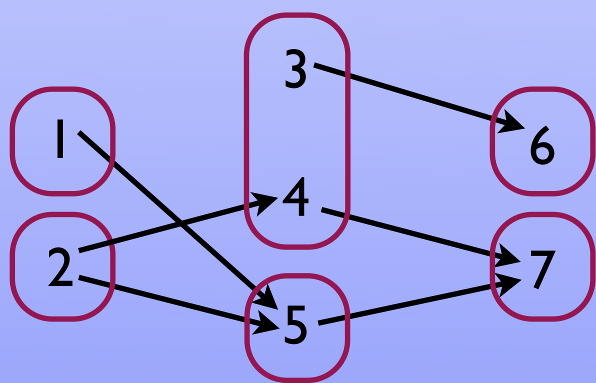

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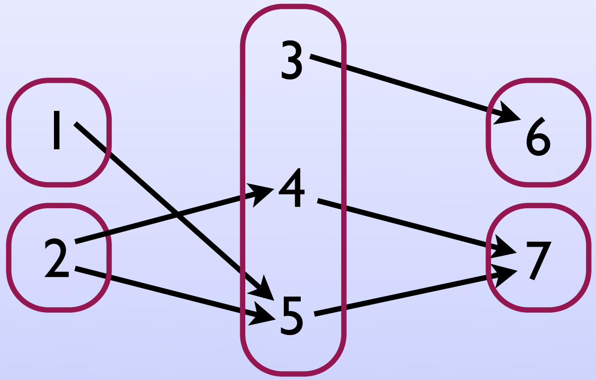

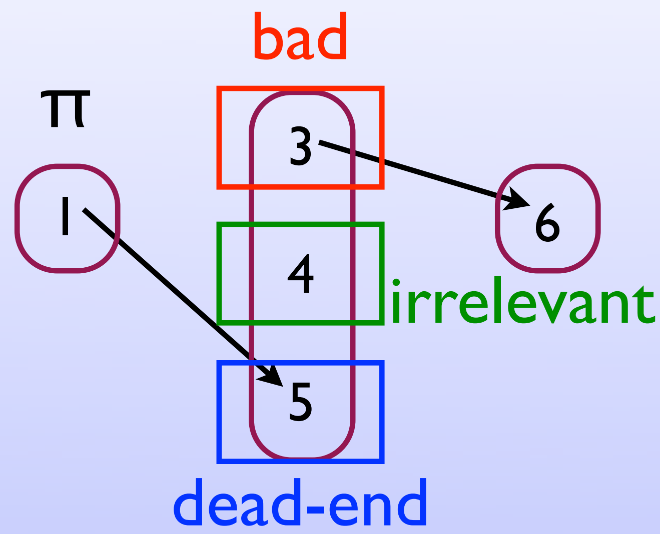

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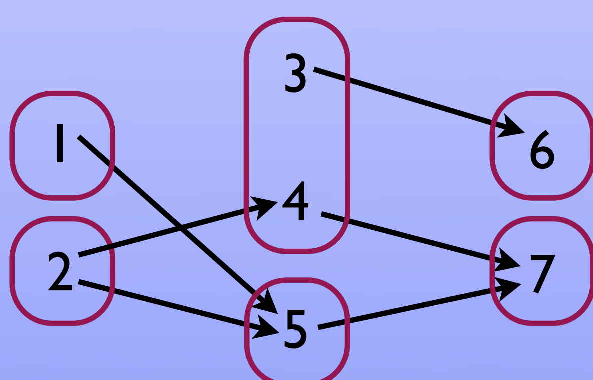

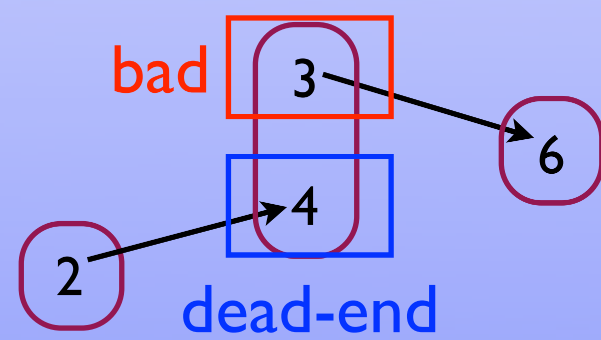

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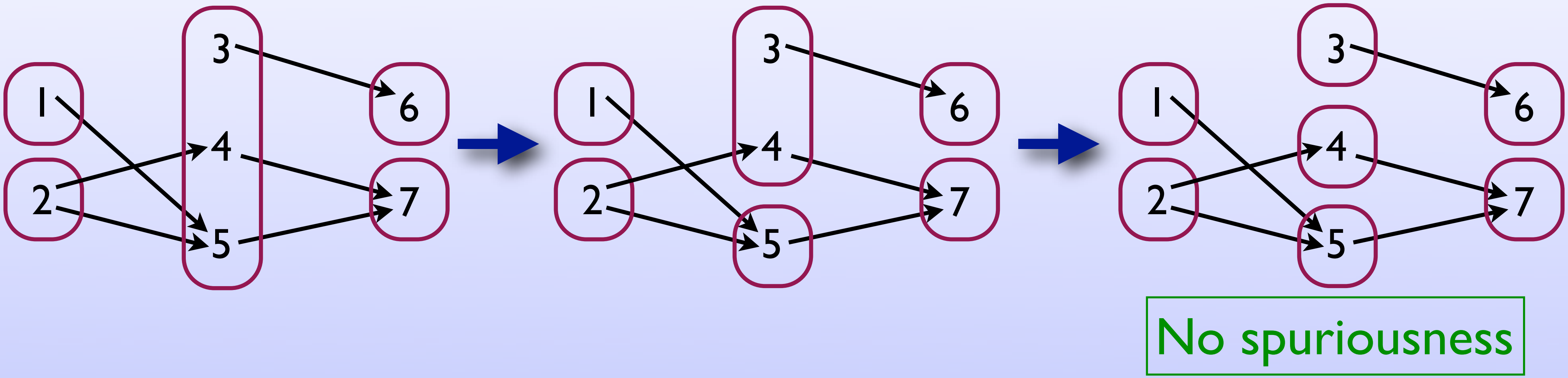

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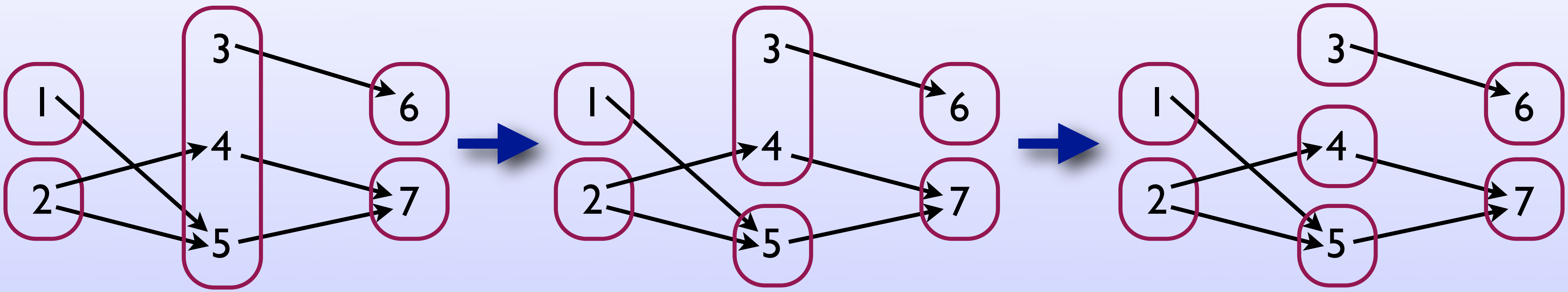
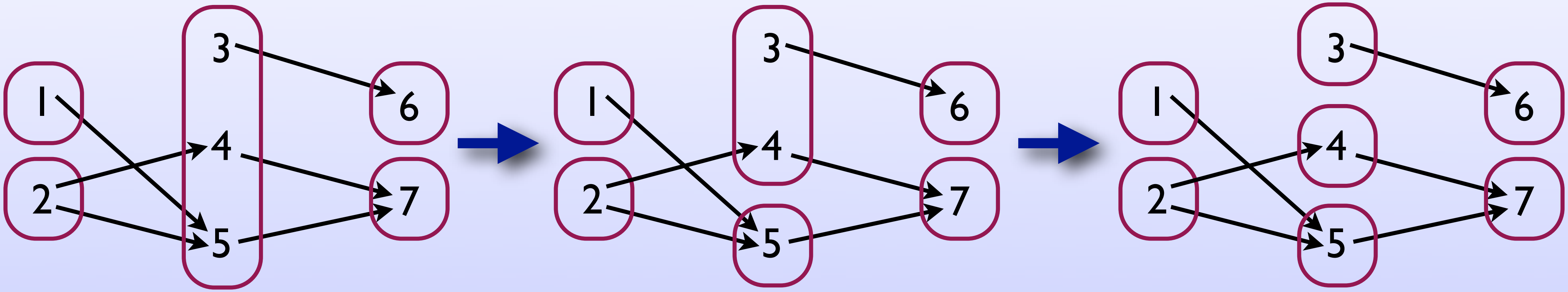


No spuriousness

When irrelevant are joined with dead-end:

CEGAR



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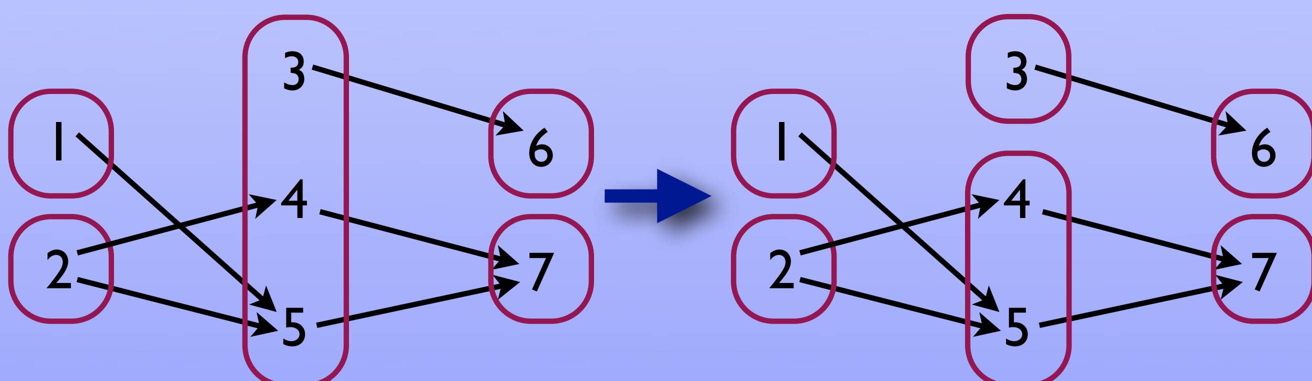

No spuriousness

EGAS and CEGAR

CEGAR heuristics may lead to ineffective abstraction refinements

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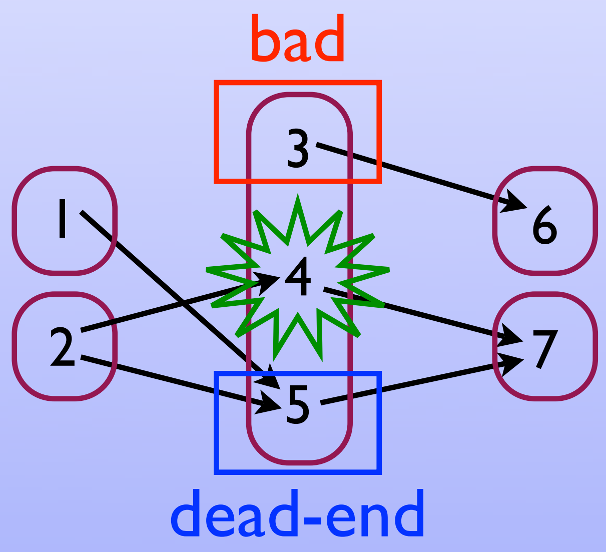

The state irrelevant 4 is dead-irrelevant
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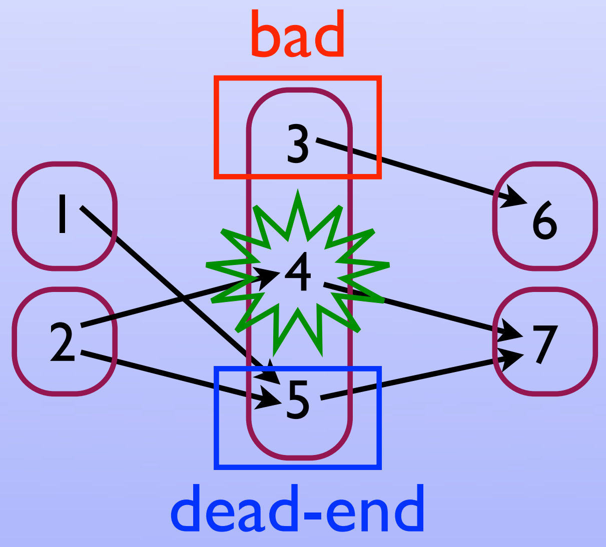

The state irrelevant 4 is dead-irrelevant
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Thus, by EGAS, merging dead-irrelevant states with dead-end states does not add spurious paths wrt keeping them separate

EGAS Refinement Heuristics

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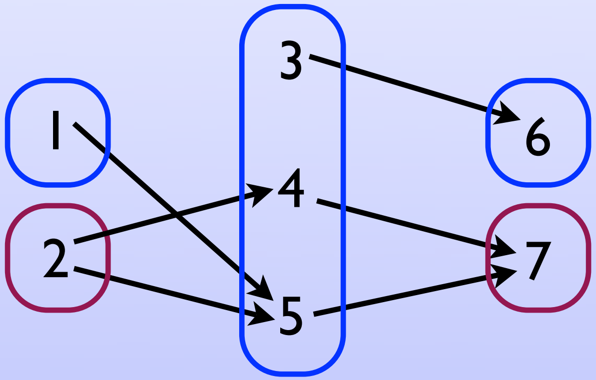
Fully-irrelevant states
1) neither bad- nor dead-irrelevant OR
2) both bad- and dead-irrelevant

EGAS Refinement Heuristics



EGAS Refinement Heuristics

Related Work

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  - Given an abstract domain property P, this is the most concrete simplification of A that satisfies P
- Compressor of an abstract domain [Giacobazzi et al.]
  - Given a refinement Ref, this is the most abstract simplification of A such that: Ref(Compressor(A))=Ref(A)

Conclusions

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- Future work

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