SAT and SMT Solving

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SS 2018

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Outline

- Summary of Last Week
- Bounded Model Checking for Verification

Summary of Last Week

Definitions

- theory consists of
  - signature Σ: set of function and predicate symbols
  - axioms T: set of sentences in first-order logic in which only function and predicate symbols of Σ appear
- theory is stably infinite if every satisfiable quantifier-free formula has model with infinite carrier set
- theory T is convex if $F \models_T \bigvee_{i=1}^{n} u_i = v_i$ implies $F \models_T u_i = v_i$ for some $1 \leqslant i \leqslant n$ $\forall$ quantifier-free conjunction F and variables u_i, v_i

Definition

theory combination $T_1 \oplus T_2$ of two theories

- T_1 over signature Σ_1
- T_2 over signature Σ_2

has signature $\Sigma_1 \cup \Sigma_2$ and axioms $T_1 \cup T_2$

Nelson-Oppen Method: Nondeterministic Version

Input quantifier-free conjunction φ in theory combination $T_1 \oplus T_2$

Output satisfiable or unsatisfiable

1. purification

$$\varphi \approx \varphi_1 \wedge \varphi_2 \quad \text{for } \Sigma_1\text{-formula } \varphi_1 \text{ and } \Sigma_2\text{-formula } \varphi_2$$

2. guess and check
   - V is set of shared variables in φ_1 and φ_2
   - guess equivalence relation E on V
   - arrangement $\alpha(V, E)$ is formula

$$\bigwedge_{x\,E\,y} x = y \quad \wedge \quad \bigwedge_{\neg(x\,E\,y)} x \neq y$$

   - if $\varphi_1 \wedge \alpha(V, E)$ is T_1-satisfiable and $\varphi_2 \wedge \alpha(V, E)$ is T_2-satisfiable then return satisfiable else return unsatisfiable

Nelson-Oppen Method: Deterministic Version

Input quantifier-free conjunction φ in combination $T_1 \oplus T_2$ of convex theories T_1 and T_2

Output satisfiable or unsatisfiable

1. purification $\varphi \approx \varphi_1 \wedge \varphi_2$ for Σ_1-formula φ_1 and Σ_2-formula φ_2
2. V: set of shared variables in φ_1 and φ_2
   E: already discovered equalities between variables in V
3. test satisfiability of $\varphi_1 \wedge E$ (and add implied equations)
   - if $\varphi_1 \wedge E$ is T_1-unsatisfiable then return unsatisfiable
   - else add new implied equalities to E
4. test satisfiability of $\varphi_2 \wedge E$ (and add implied equations)
   - if $\varphi_2 \wedge E$ is T_2-unsatisfiable then return unsatisfiable
   - else add new implied equalities to E
5. if E has been extended in steps 3 or 4 then go to step 2
   else return satisfiable

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Bounded Model Checking for Verification

Disastrous Software Bugs

Ariane 5 Flight 501 (1996)

- destroyed 37 seconds after launch
- software for Ariane 4 for was reused
- software error: data conversion from 64-bit floating point to 16-bit integer caused arithmetic overflow
- cost: 370 million $

http://en.wikipedia.org/wiki/Ariane_5_Flight_501

Mars Exploration Rover “Spirit” (2004)

- landed on January 4
- stopped communicating on January 21
- software error: stuck in reboot loop
- reboot failed because of flash memory failure, ultimate problem: too many files

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Heathrow Terminal 5 Opening (2008)

- baggage system collapsed on opening day
- 42,000 bags not shipped with their owners, 500 flights cancelled
- software was tested but did not work properly with real-world load
- cost 50 million £

http://www.zdnet.com/article/it-failure-at-heathrow-t5-what-really-happened

Trading Glitch at Knight Capital (2012)

- bug in trading software resulted in 45 minutes of uncontrolled buys
- company did 11% of US trading that year
- software was run in invalid configuration
- 440 million $ lost

`http://en.wikipedia.org/wiki/Knight_Capital_Group`

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Death in Self-Driving Car Crash (2018)

- person died in accident with Uber's self-driving car
- victim was wrongly classified by software as non-obstacle

`http://www.siliconrepublic.com/companies/uber-bug-crash`

Software is Ubiquituous in Critical Systems

transport, energy, medicine, communication, finance, embedded systems, ...

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How to Ensure Correctness of Software?

- testing
  - \+ cheap, simple
  - – checks desired result only for given set of testcases
- verification
  - \+ can prove automatically that system meets specification,
    i.e., desired output is delivered for all inputs
  - – more costly

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Model Checking

- widely used verification approach to
  - find bugs in software and hardware
  - prove correctness of models

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Model Checking

- widely used verification approach to
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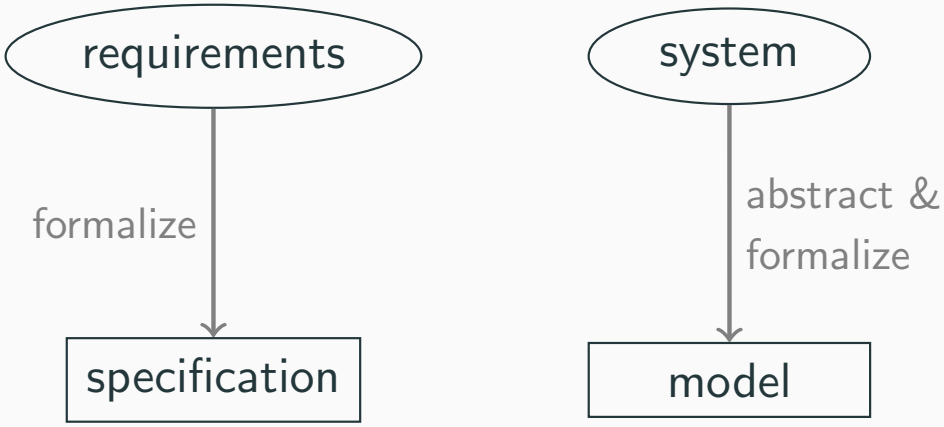
- Turing Award 2007 for Clarke, Emerson, and Sifakis
- bounded model checking can be reduced to SAT/SMT

Model Checking: Workflow



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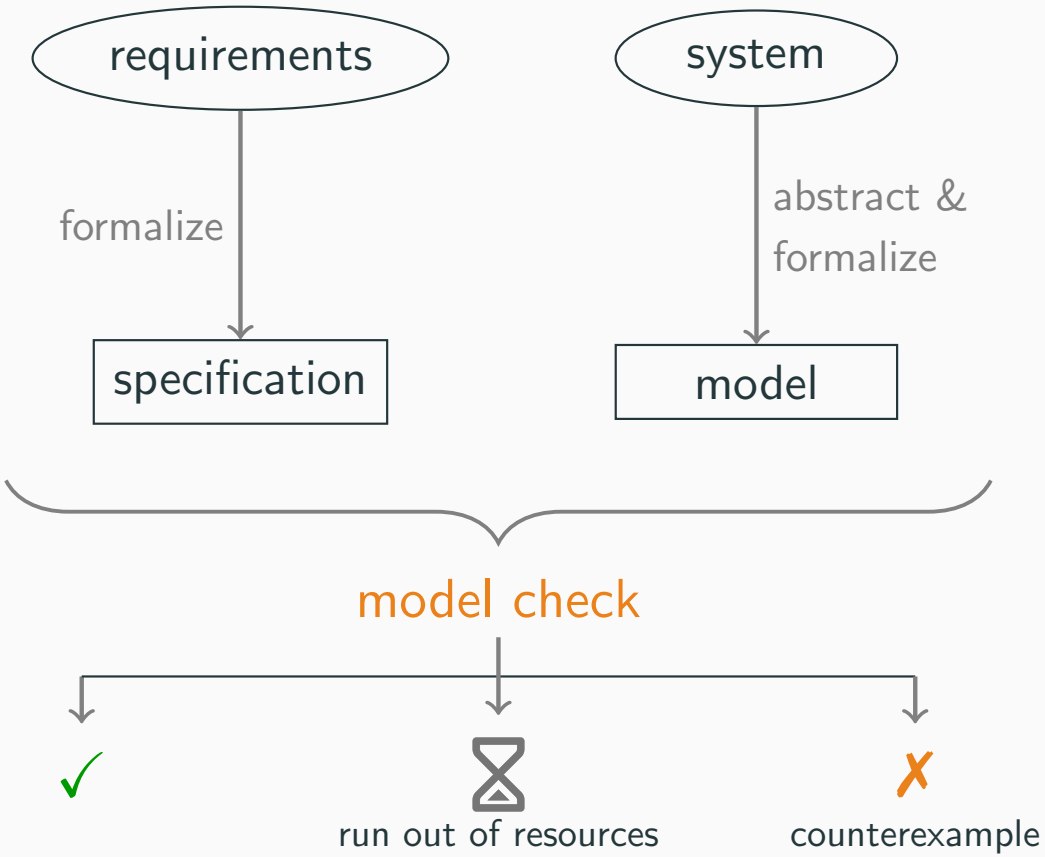

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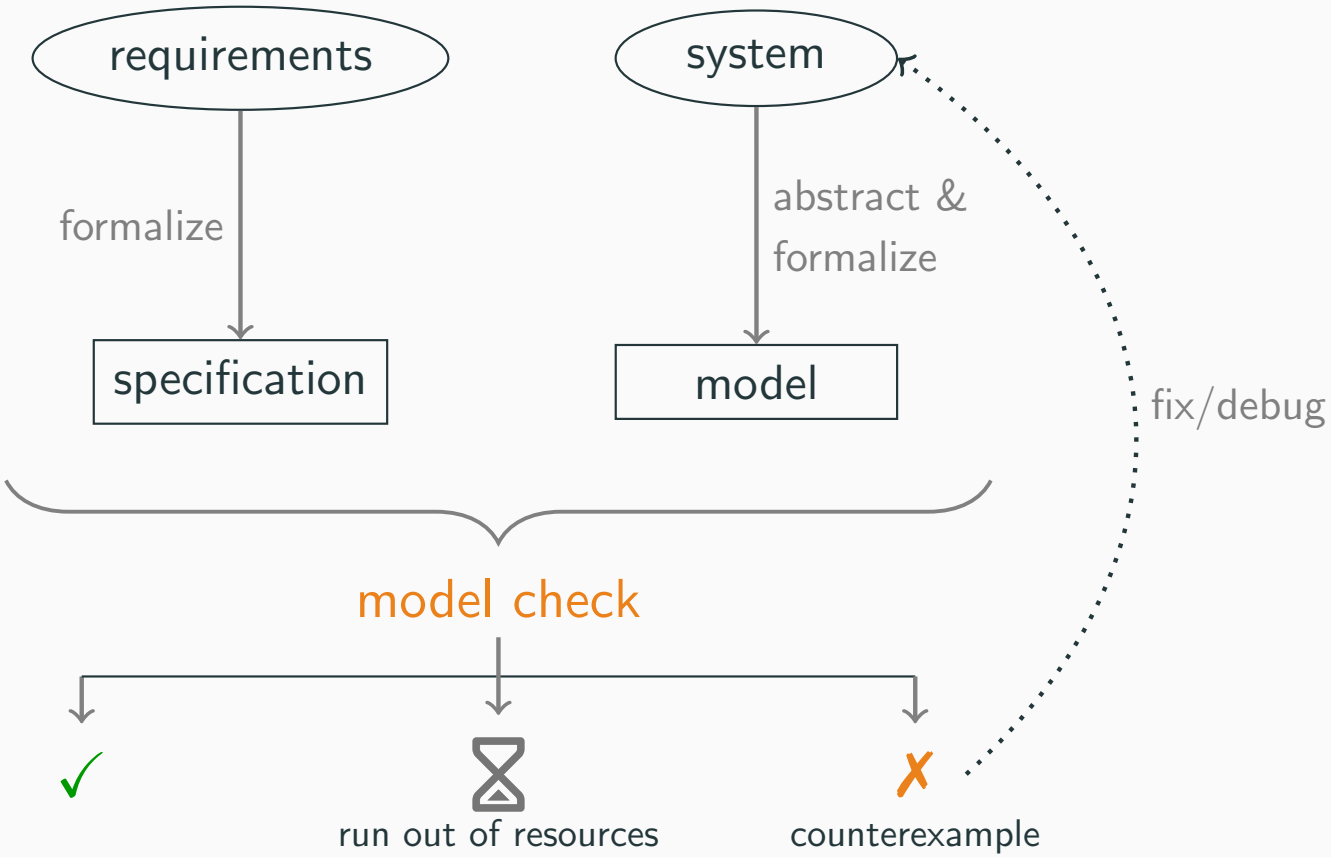

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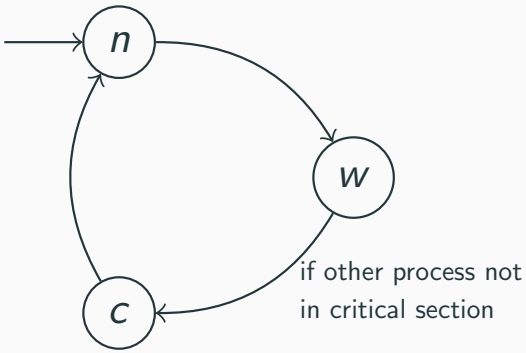
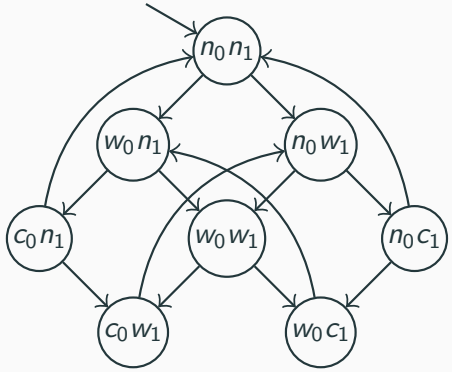
- process can be abstracted to model $\mathcal{M} = \langle S, R \rangle$ with states $S = \{n, w, c\}$ and transitions R:



Model Checking Example: Mutex (2)

- obtain model for 2 processes by product construction: write $s_0 s_1$ for P_0 being in state s_0 and P_1 in state s_1



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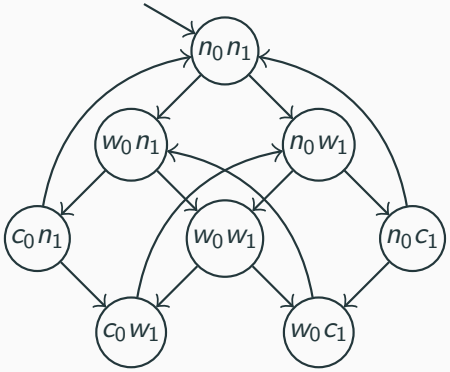

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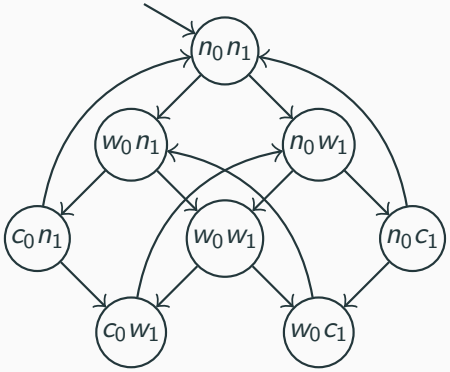

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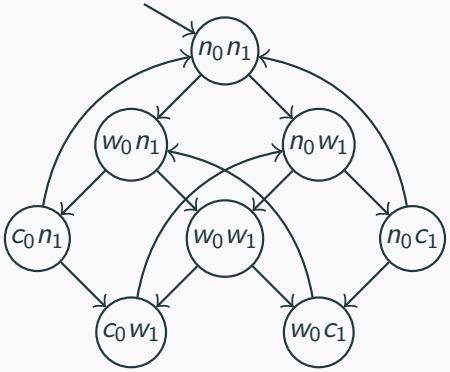

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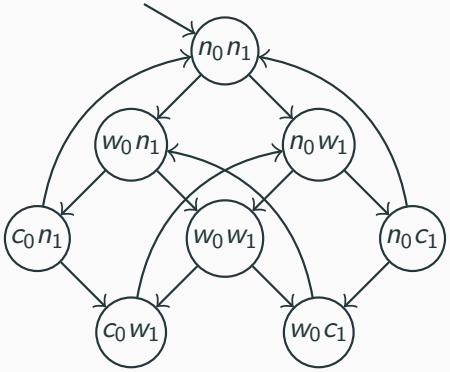

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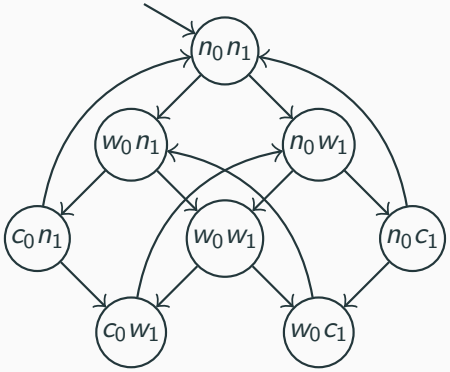

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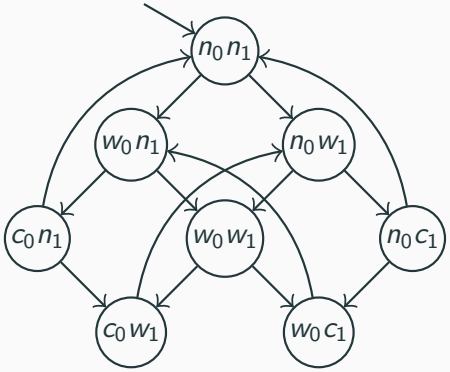

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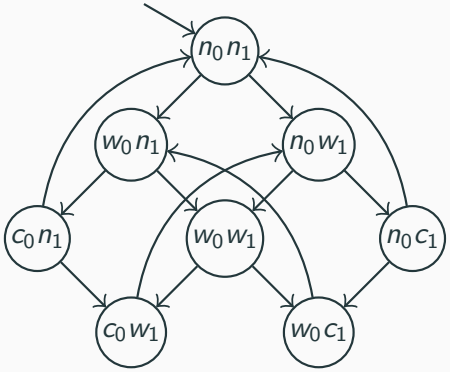

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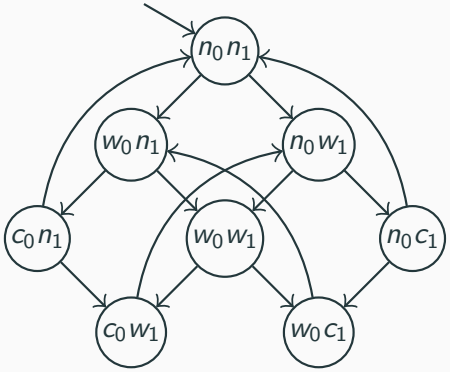

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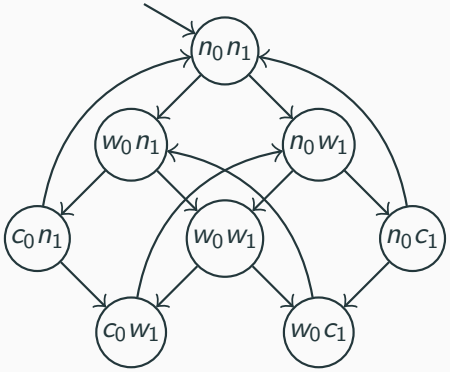

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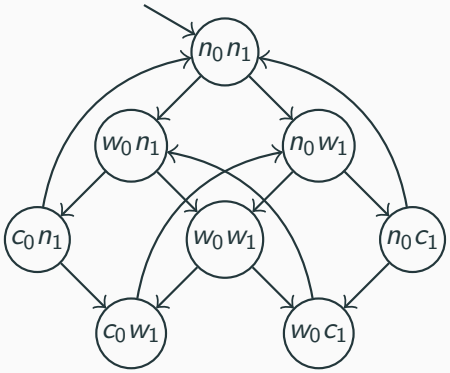

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- $\mathsf{G}\ \psi$ for propositional formula ψ is safety property

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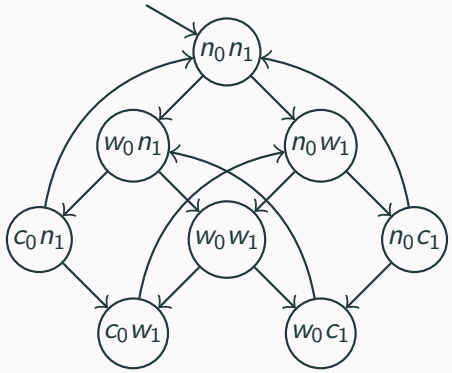

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- $\mathsf{G}\,\psi$ for propositional formula ψ is safety property
- $\mathsf{G}\,(\psi \rightarrow \mathsf{F}\chi)$ for propositional formulas ψ,χ is liveness property

Example: Can This Program Cause An Overflow? (1)

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1 void main() {
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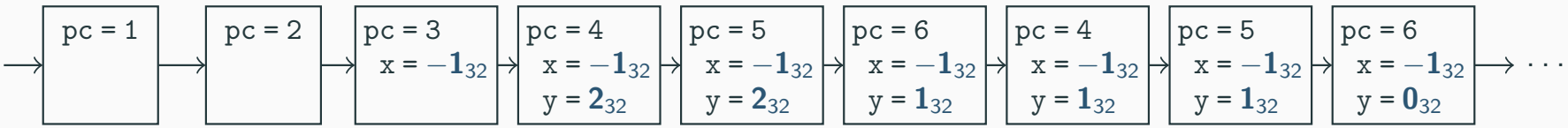

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  - property $\mathsf{G}\,(\mathsf{pc} = 5 \rightarrow ((x > \mathbf{0}_{32} \wedge x + y > y) \vee (x \leqslant \mathbf{0}_{32} \wedge x + y \leqslant y)))$
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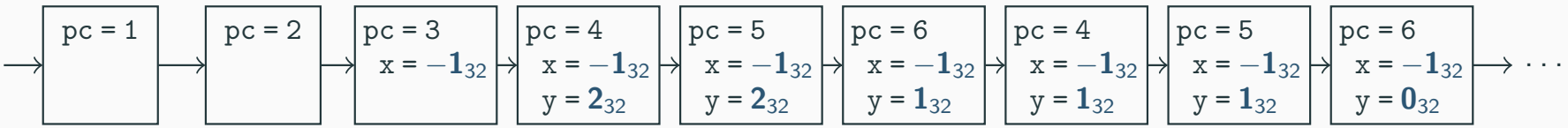
addition $x + y$ in line 5 does not over/underflow



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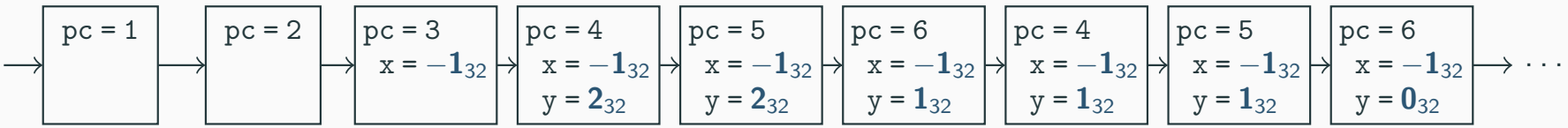

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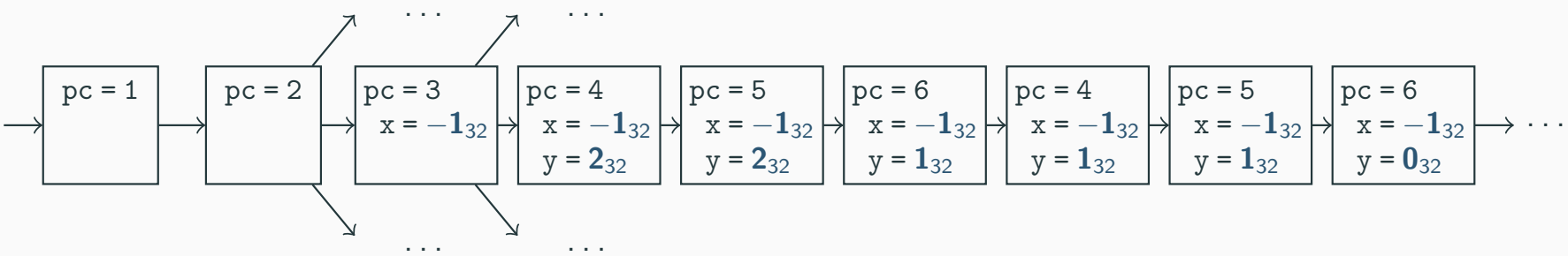

- but state space is very large: $(2^{32})^2 \cdot 7$ for bit width 32

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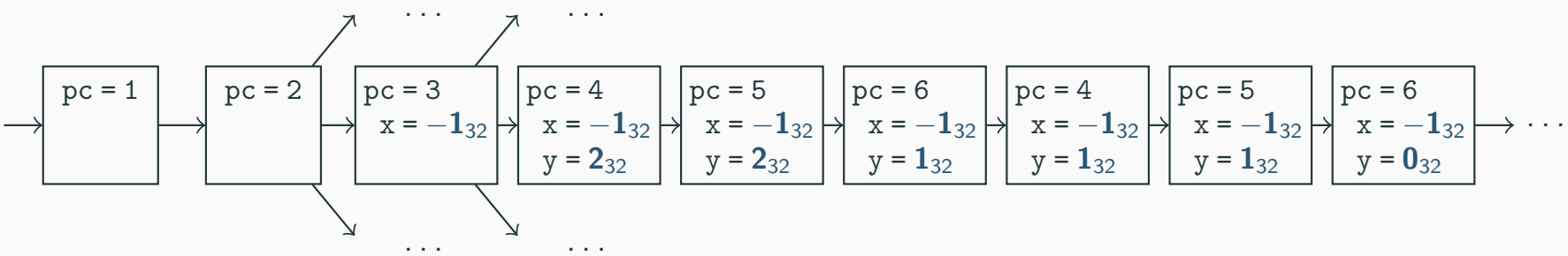

- but state space is very large: $(2^{32})^2 \cdot 7$ for bit width 32
- cannot check all possible values

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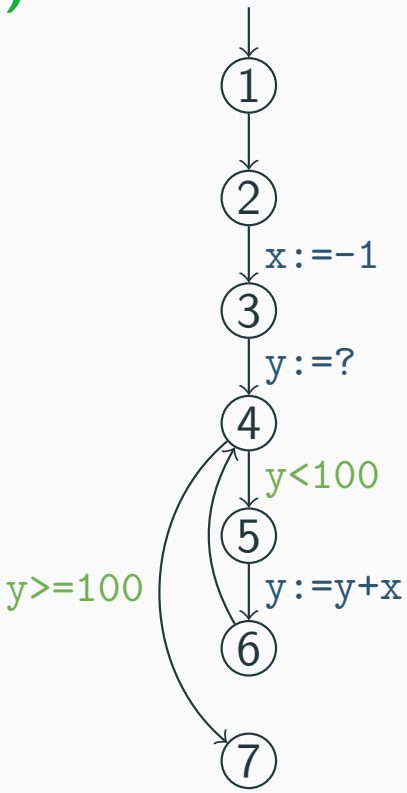

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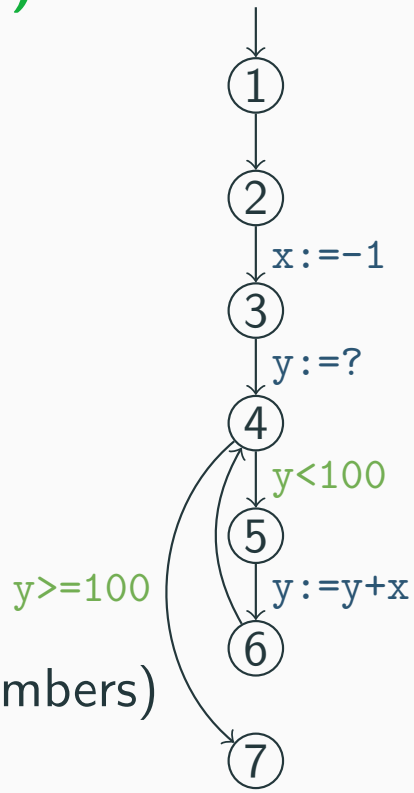

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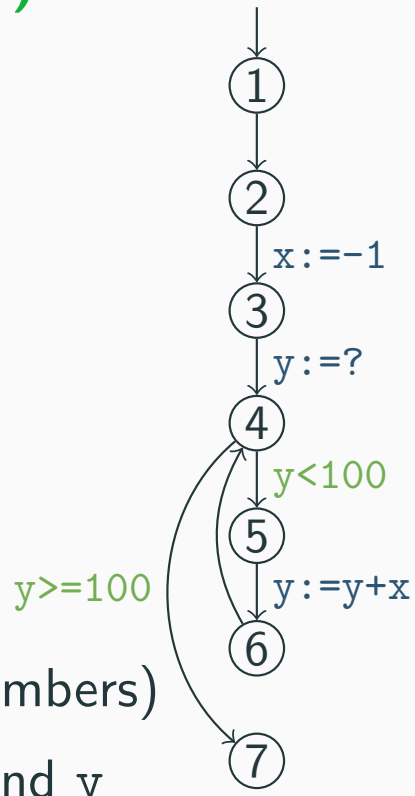

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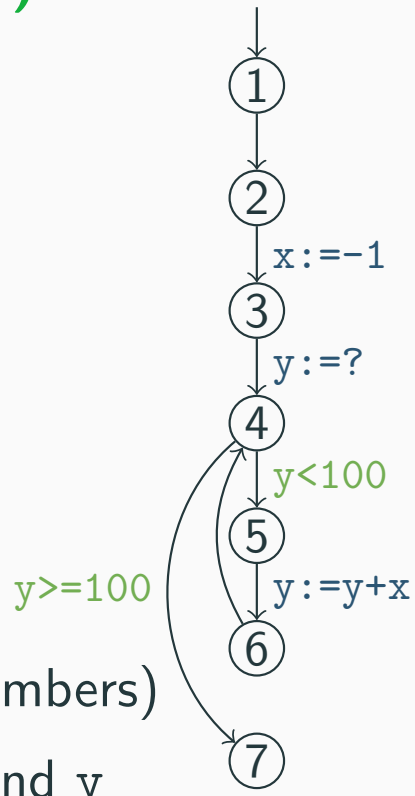

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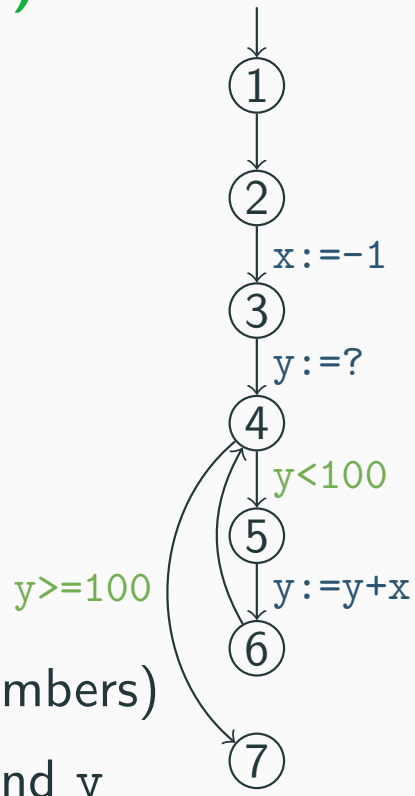

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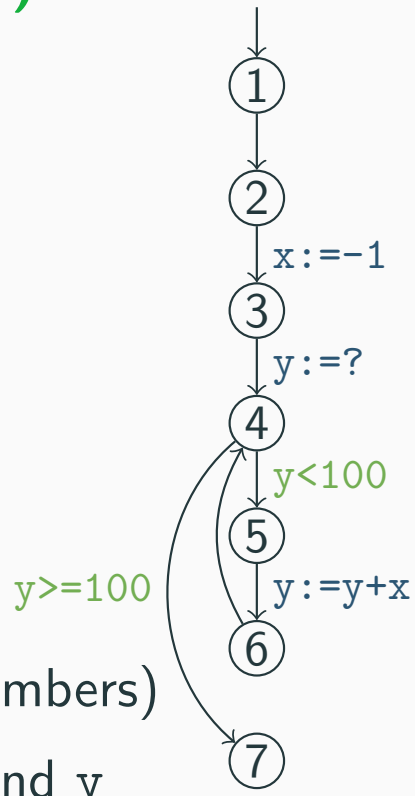

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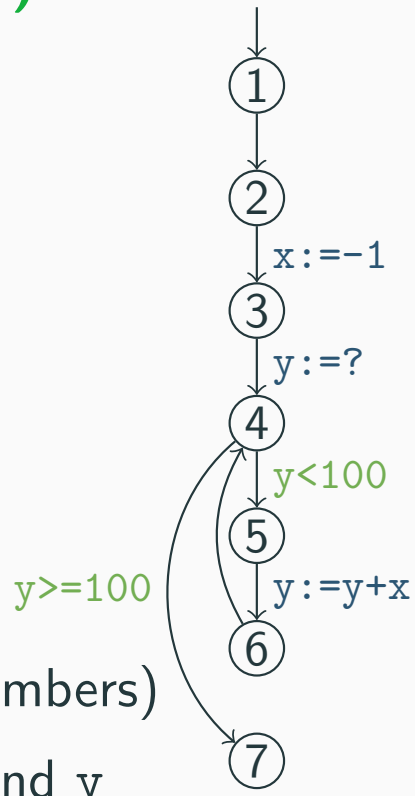

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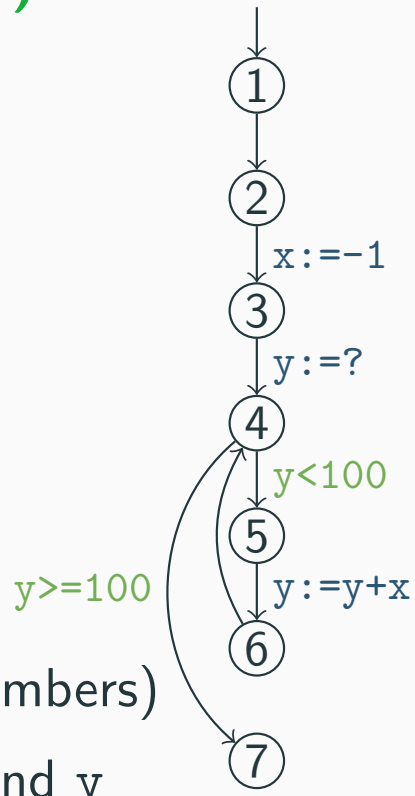

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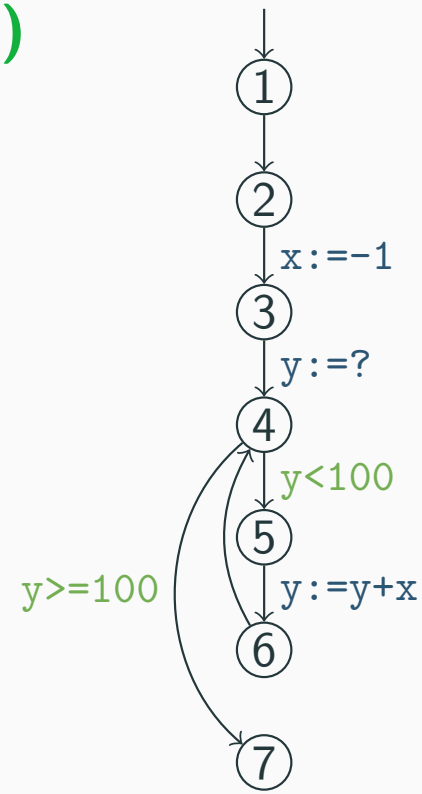

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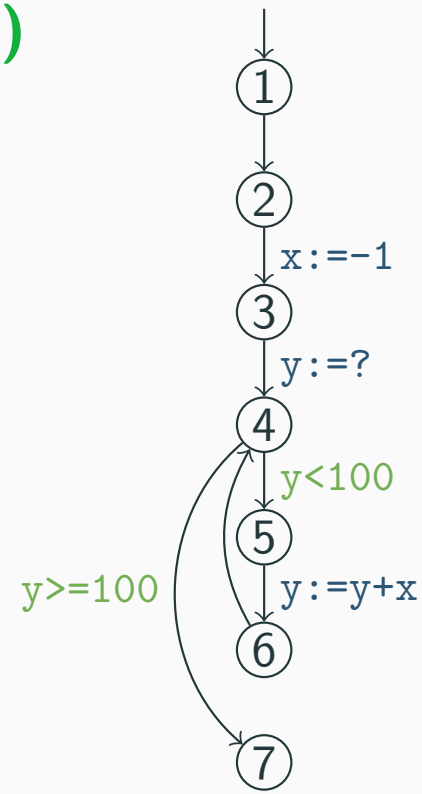

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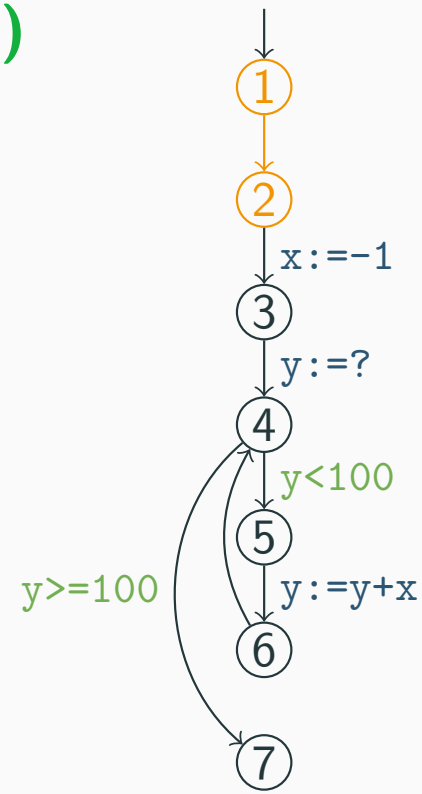

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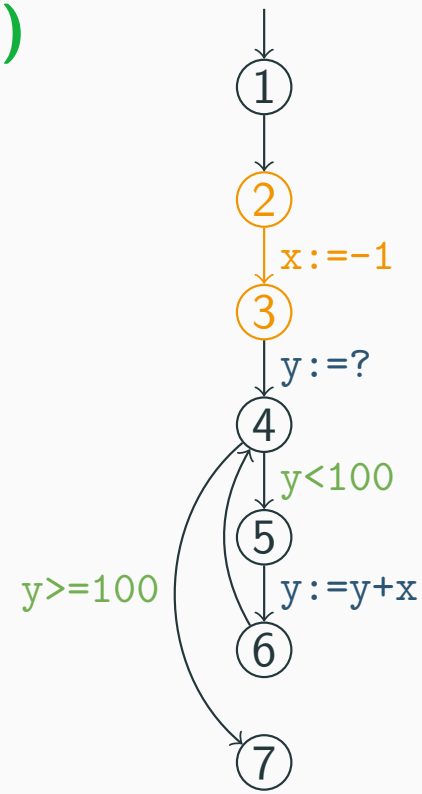

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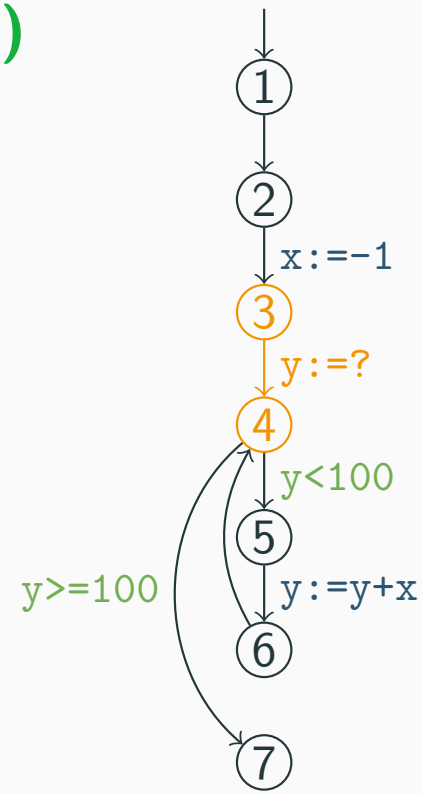

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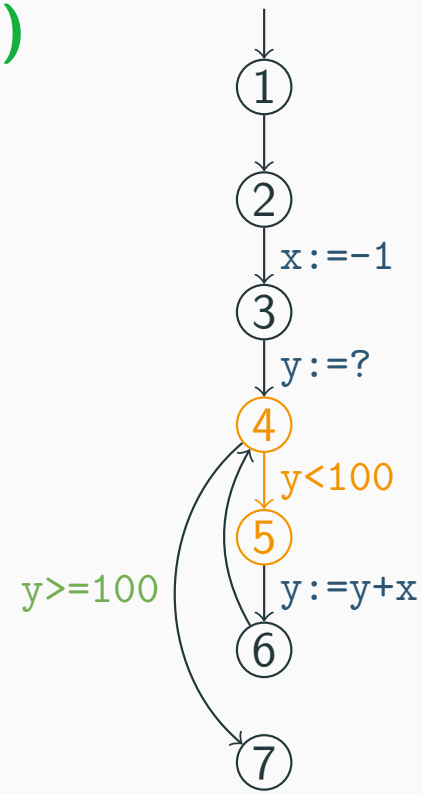

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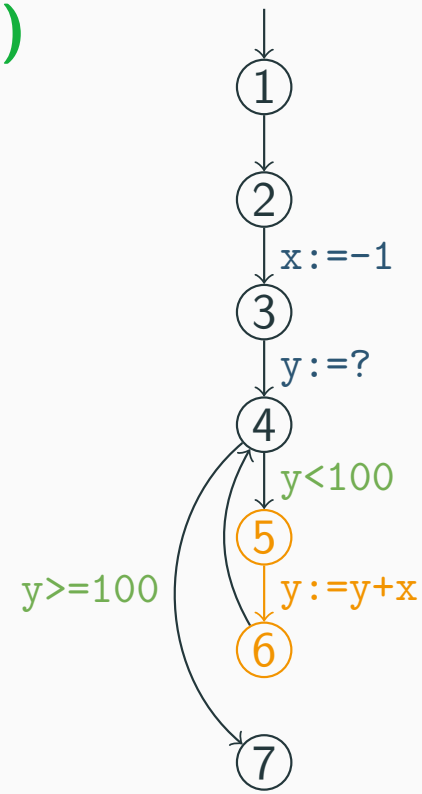

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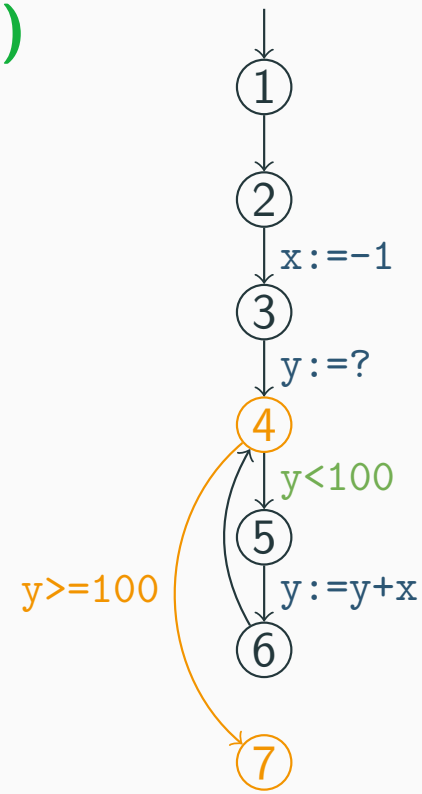

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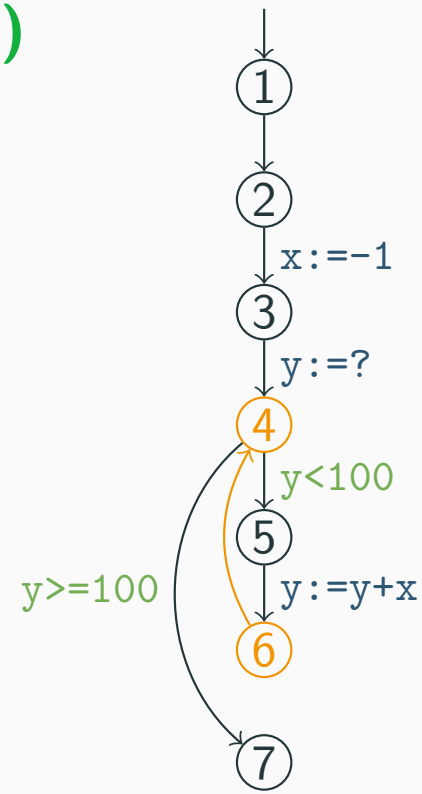

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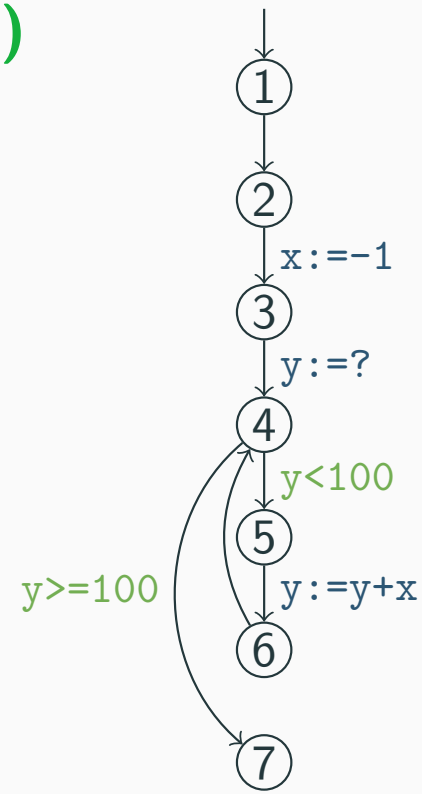

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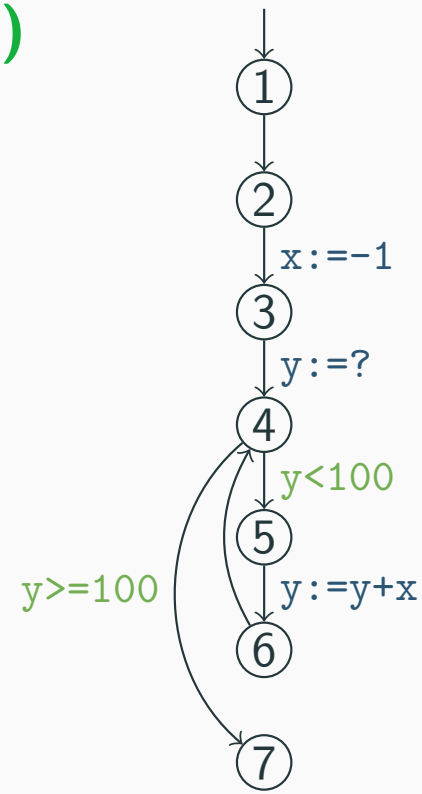

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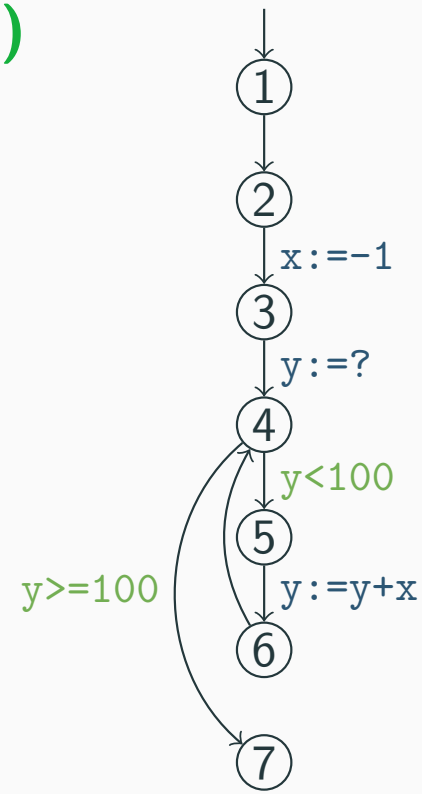

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3. if φ_k satisfiable then overflow can occur within k steps ... ask Z3 🪄

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- find counterexamples to desired property of transition system (bugs)
- counterexamples are bounded in size

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transition system $\mathcal{T} = (S, \rightarrow, S_0, L)$ where

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Remark

S and A may be (countably) infinite

Bounded Model Checking: Safety Properties

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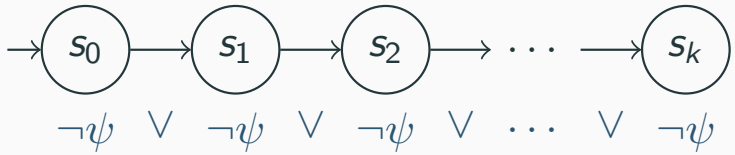
given transition system and property G ψ, look for counterexamples in $\leqslant k$ steps



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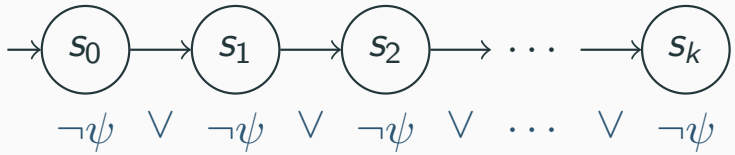

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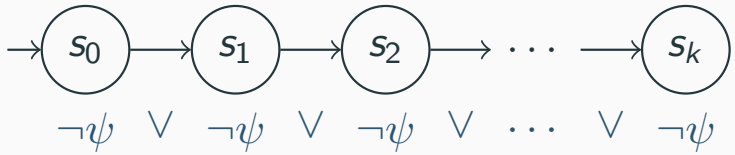

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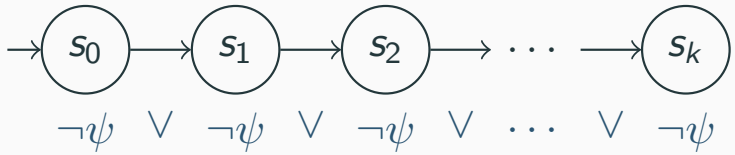

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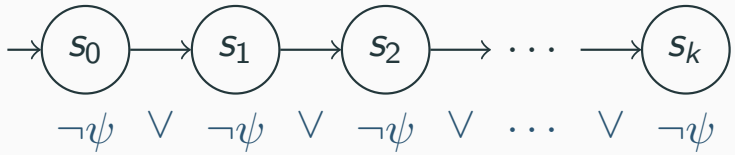

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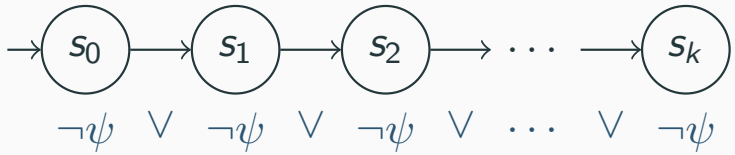

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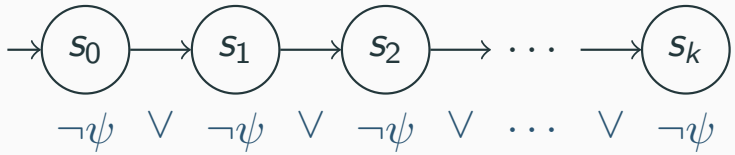

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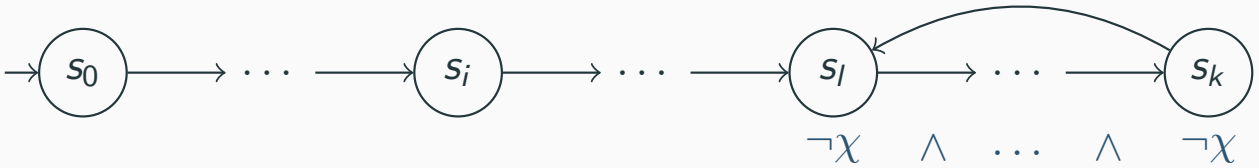

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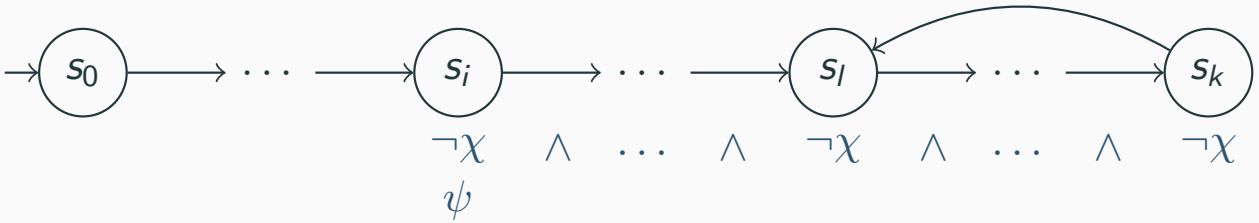

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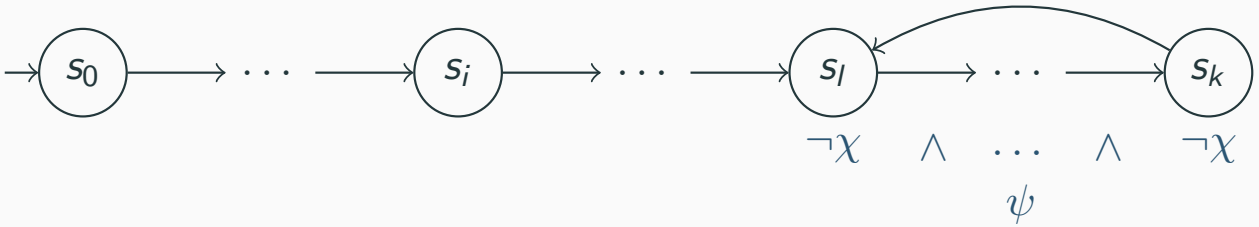

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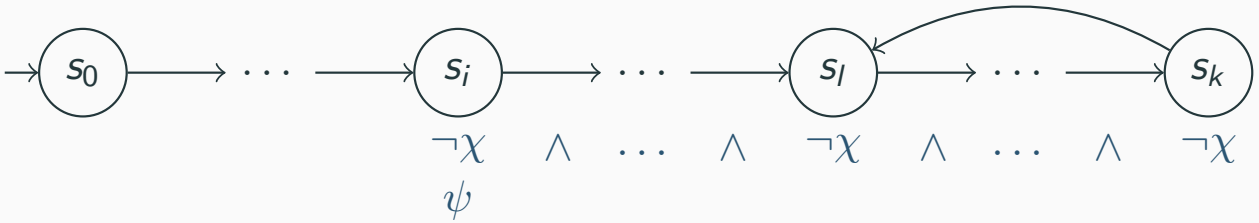

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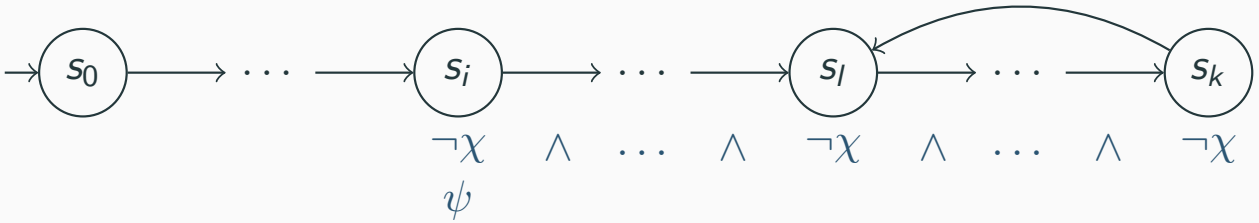

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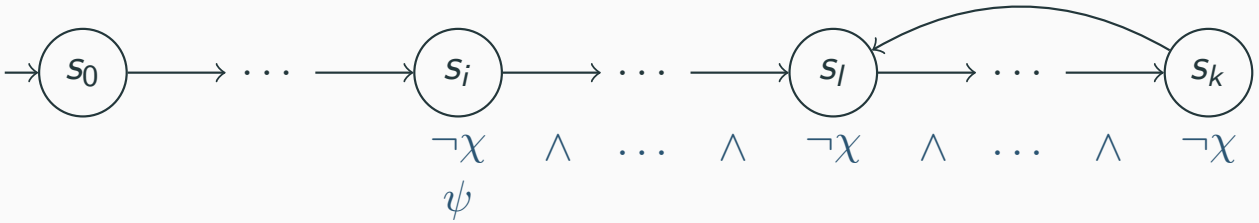

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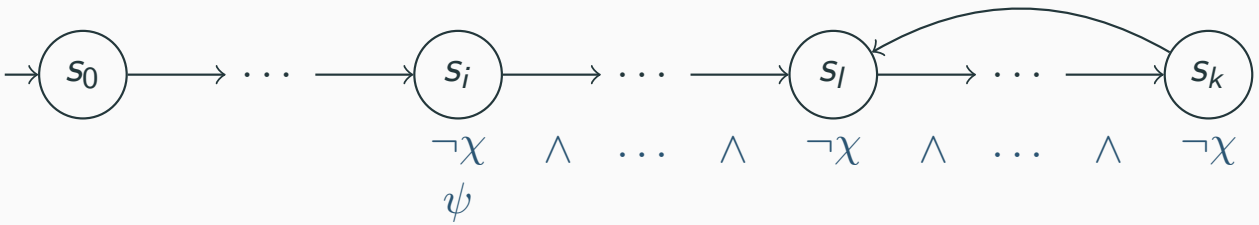

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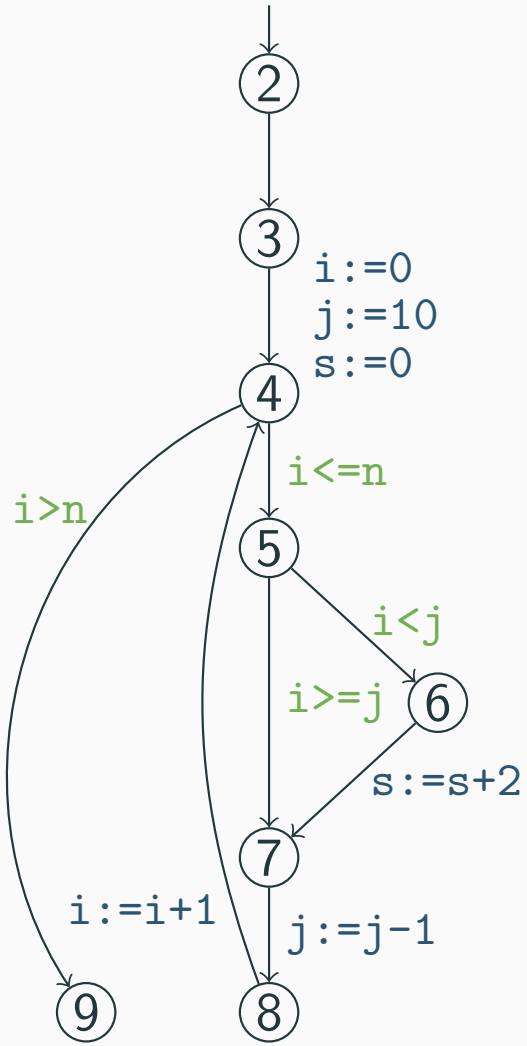

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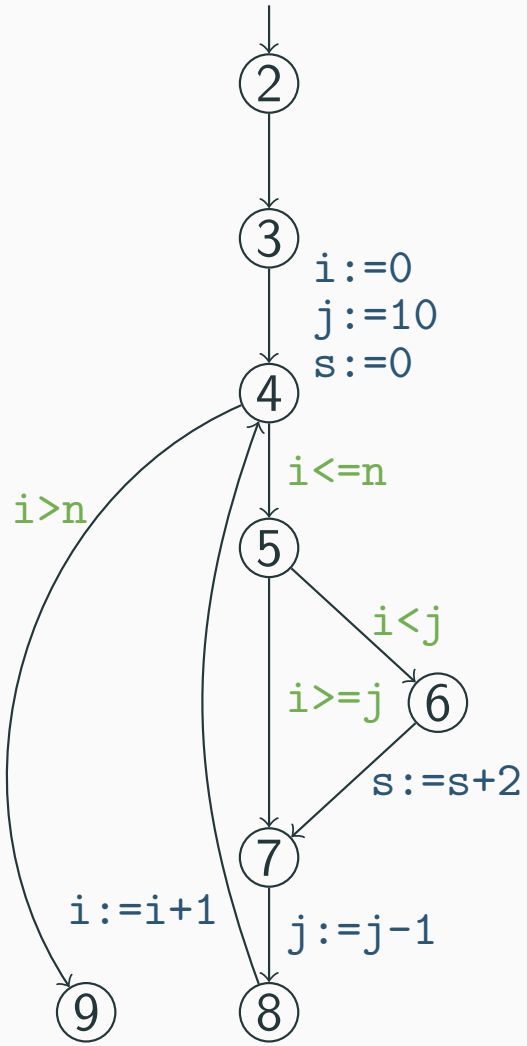

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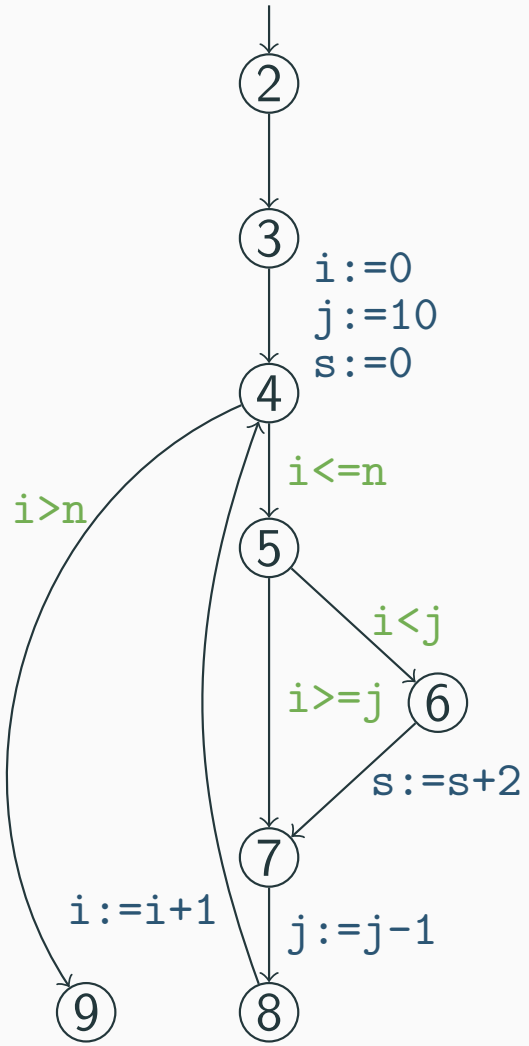

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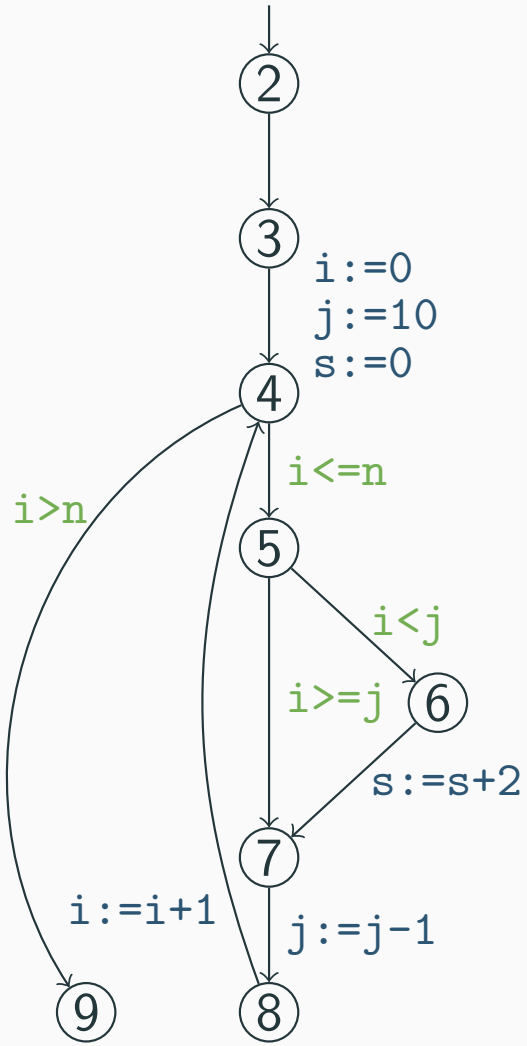

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Bibliography

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