Computing Applicability Conditions for Plans with Loops

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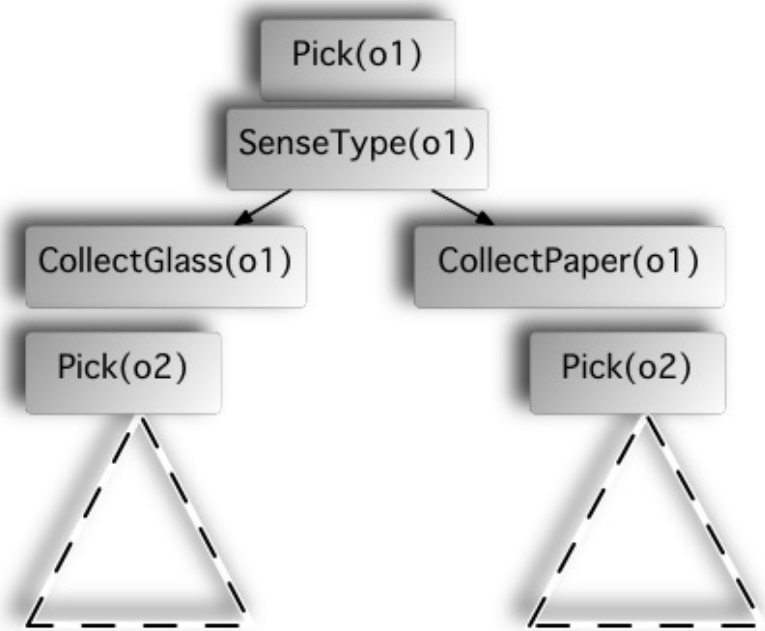
Plans with Loops



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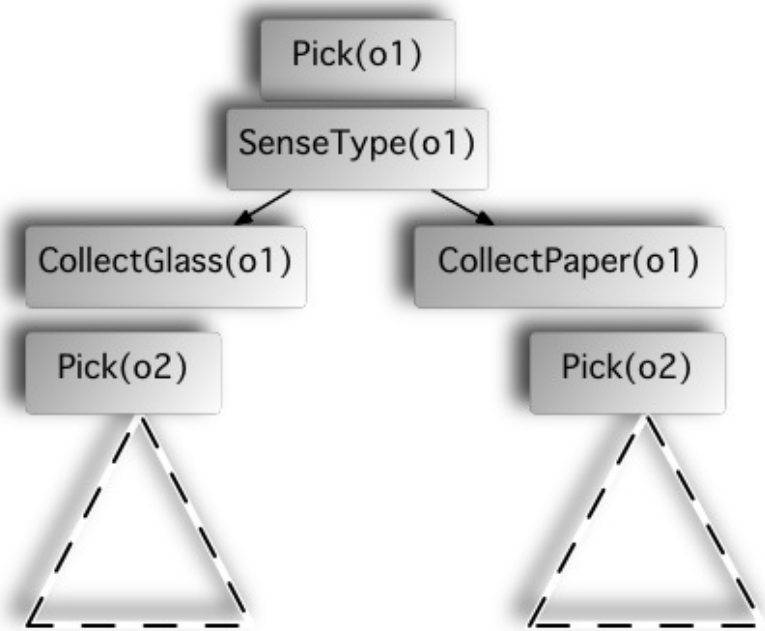
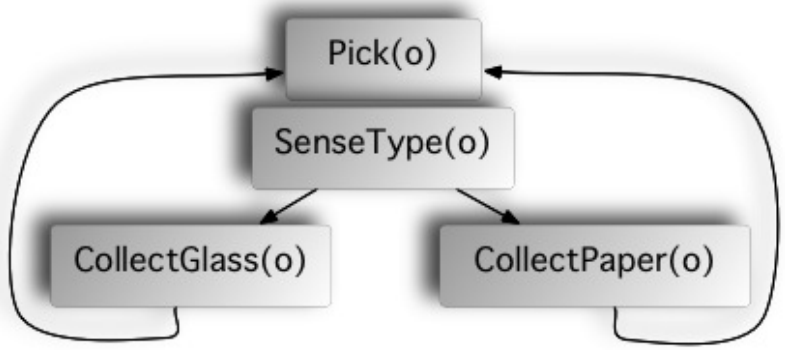
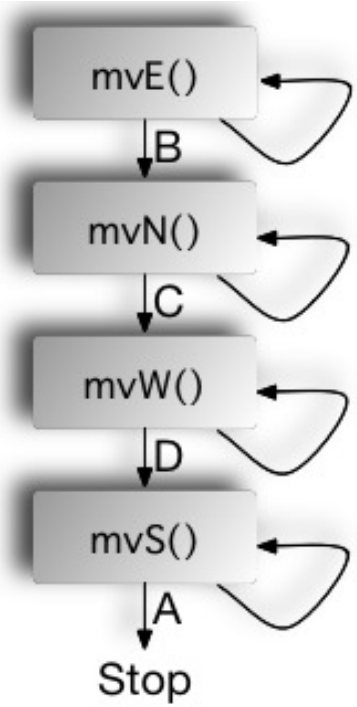


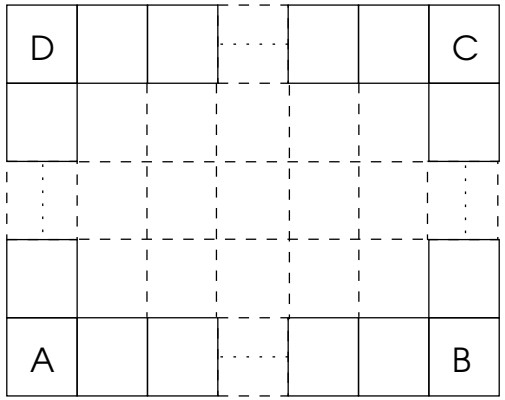


Loops $\Longrightarrow$ smaller, more general plans; allow unknown quantities

Plans with Loops: Power



[Bonet et al., 2009]



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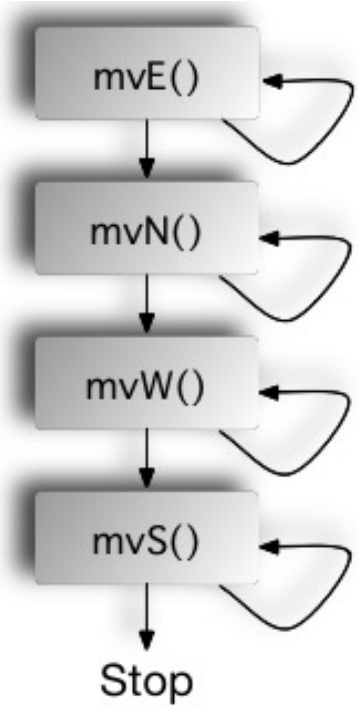
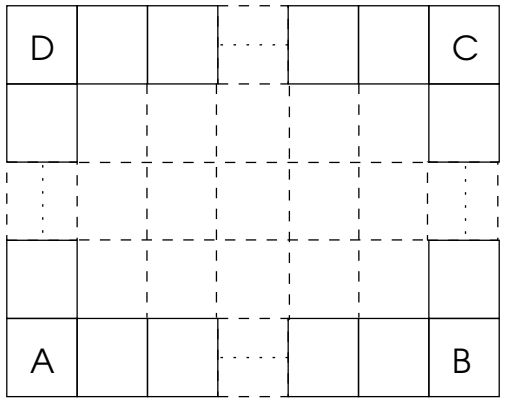
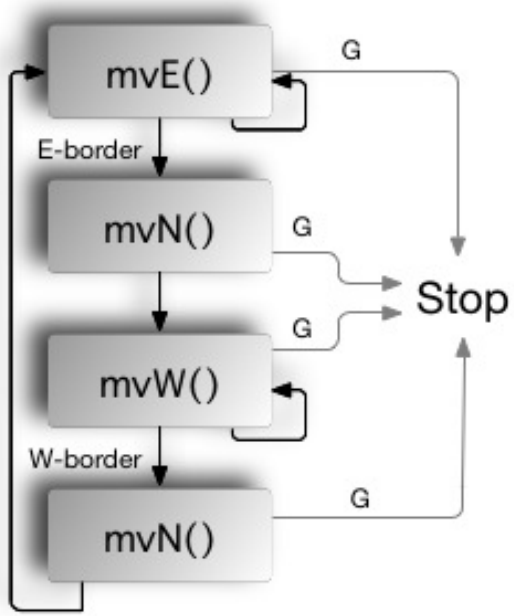
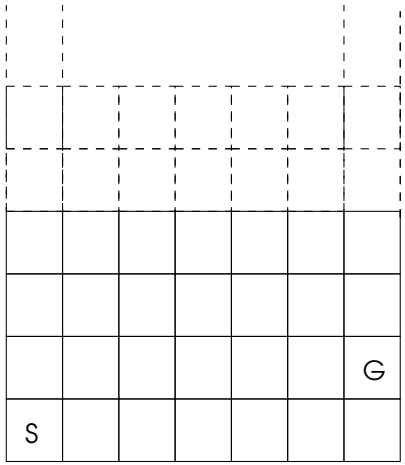




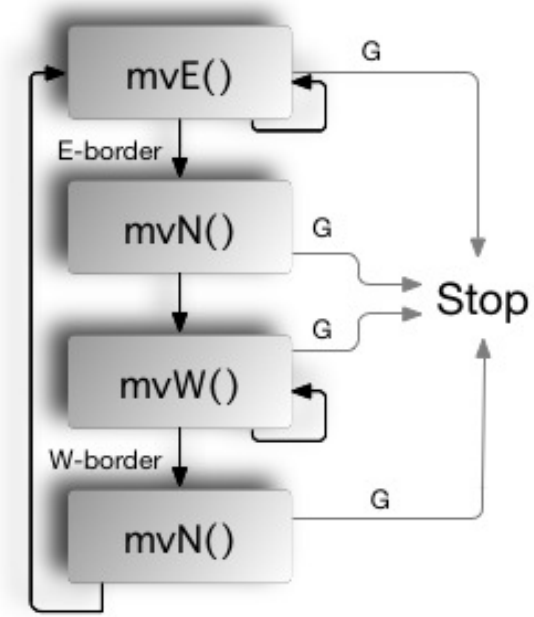
Correct numbers of iterations can reach any point in the interior

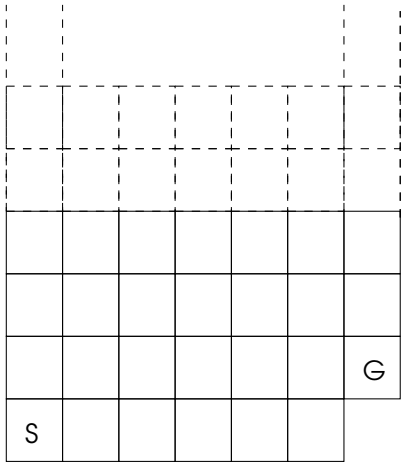
Plans with Loops: Risk





Plans with Loops: Risk





Never reaches G!

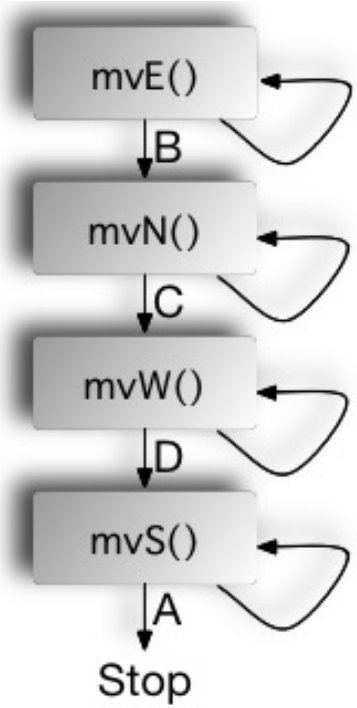
A plan with loops may traverse almost the entire state space – without solving the problem

Loop Effects and Preconditions

Why analyze loops of actions?

- During construction: utility, safety of potential loops
- After construction: will plan Π solve problem instance x?
- Longstanding issues of plan reuse

  Triangle tables, macro operators: linear sequences [Fikes et al., 1972]



Existing Approaches

[Levesque, 2005, Winner and Veloso, 2007, Bonet et al., 2009]

Plan Generation

- Observe working plans
- Extract repetitive patterns and make loops
- Loop utility justified largely by prior experience

Plan Execution

- Apply on any problem instance
- No preconditions; instantiation may traverse the entire state space! (EX: [Levesque, 2005])

Fundamental problems behind these limitations: termination, reachability in plans with loops.

Overview

- Abacus Programs
  - Linear Abacus Programs
  - Abacus Programs with Simple Loops
  - Abacus Programs with Complex Loops
  - Theoretical Results
- Translating Plans to Abacus Programs
- Empirical Results

Abacus Programs

Definition

$\mathcal{R}$ finite set of registers

$\mathcal{S}$ finite set of states

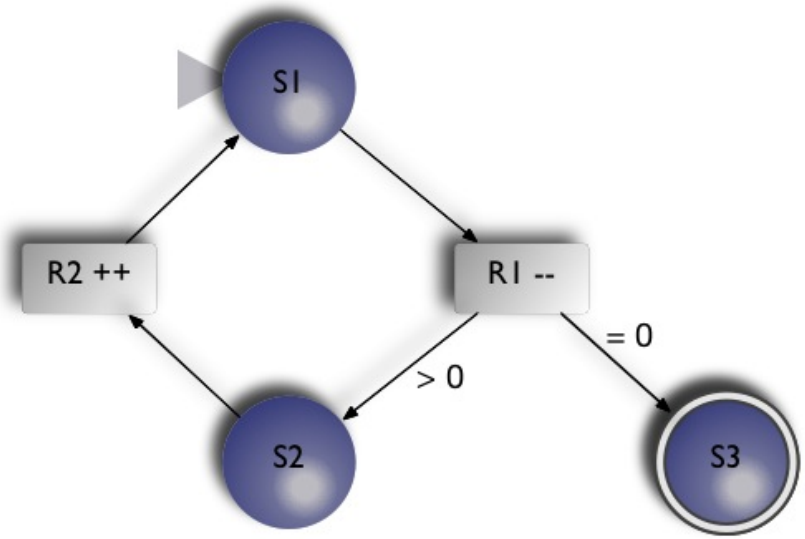
s_0 initial state

s_h halt state

ℓ $\mathcal{S} \rightarrow A$

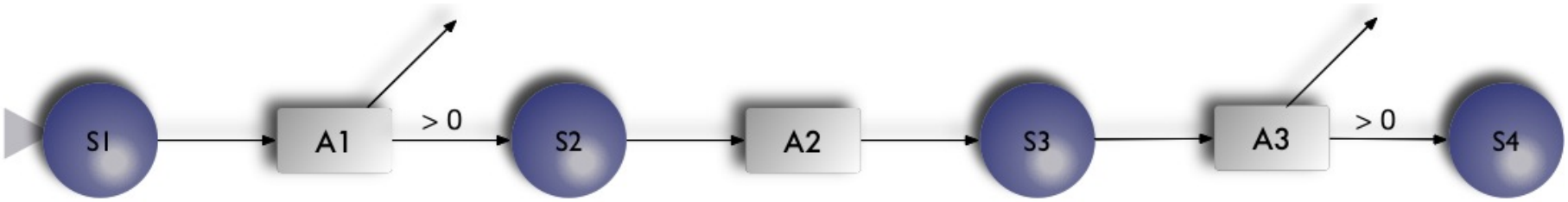
Actions (A):

- $Inc(r, s)$: $r++$; goto s
- $Dec(r, s_1, s_2)$: if $r = 0$ goto s_1
  else $r--$; goto s_2



Turing-complete $\Longrightarrow$ reachability is undecidable

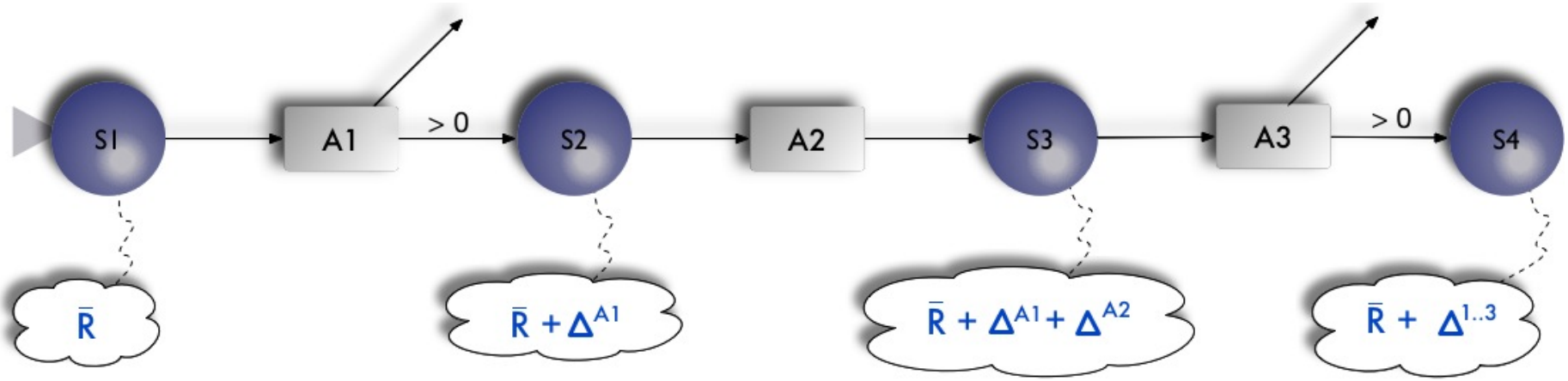
Linear Abacus Programs



Can Efficiently Find

- Cumulative action effects
- Branch Conditions

Linear Abacus Programs



Can Efficiently Find

- Cumulative action effects
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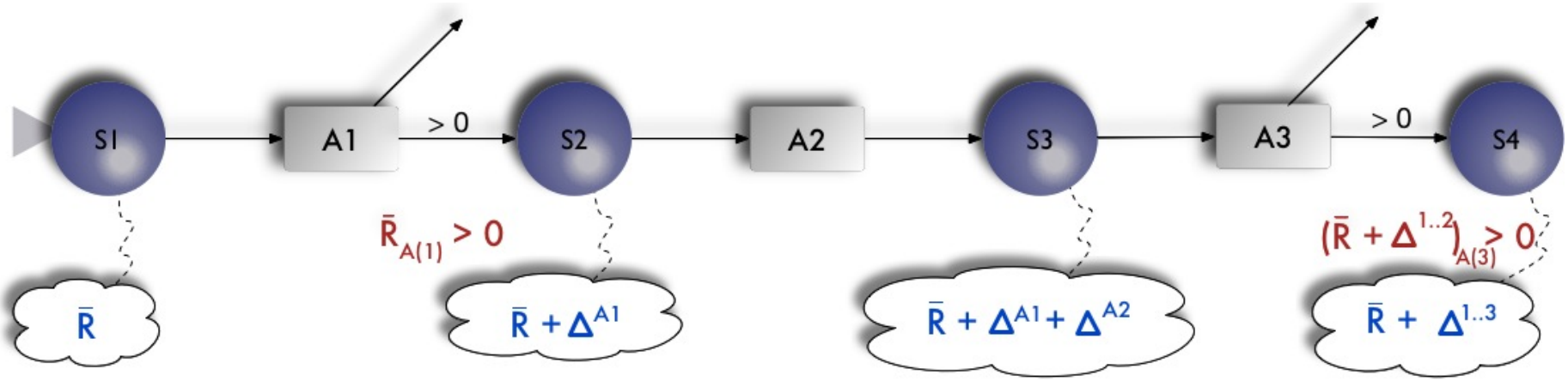
Notation

$\bar{R}$	$\langle R_1, R_2, \ldots R_k \rangle$
Δ^{Ai}	Ai's change vector
$A(i)$	Index of Ai's register
$\bar{R}_i$	R_i
$\Delta^{1\ldots m}$	$\Delta^{A1} + \ldots + \Delta^{Am}$

Linear Abacus Programs



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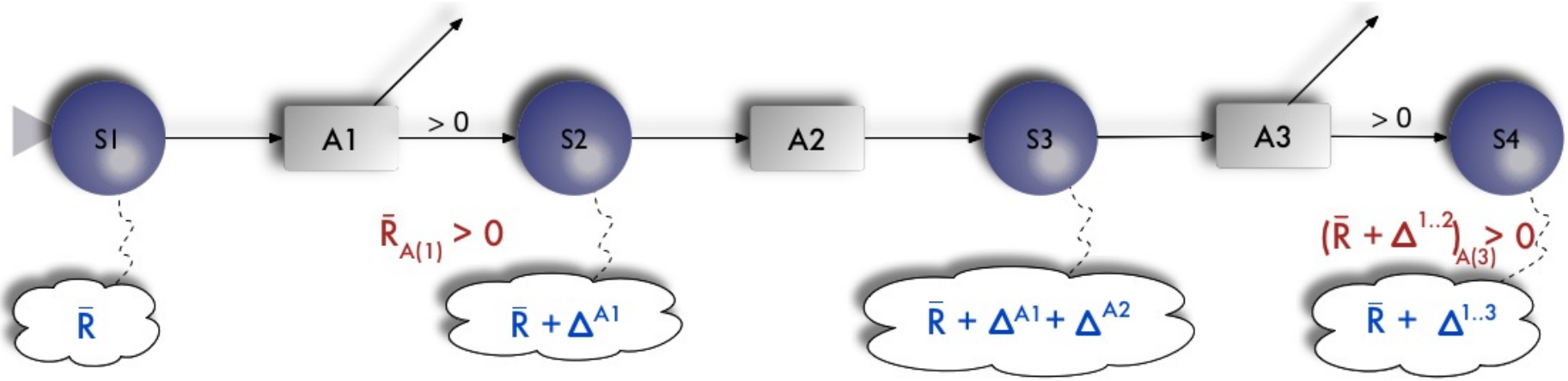
Linear Abacus Programs: Preconditions



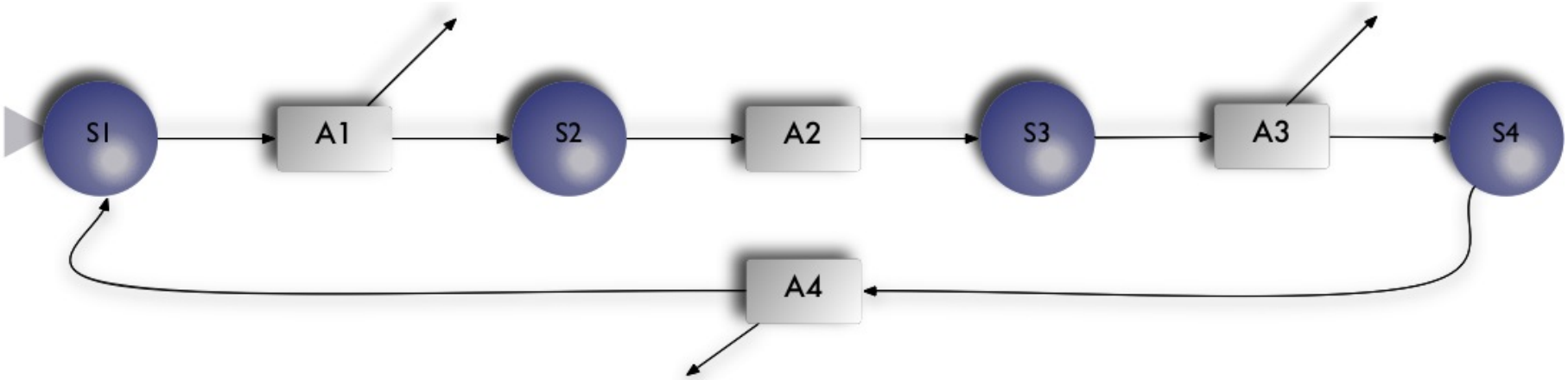
Necessary and Sufficient Conditions

Sequence of n actions; $\bar{F}$ = final register values

$$(\bar{R} + \Delta^{1\ldots i-1})_{A(i)} \quad \circ \quad 0, \qquad i = 1 \ldots n$$

$$\bar{F} \quad = \quad \bar{R} + \Delta^{1..n}$$

Abacus Programs with Simple Loops



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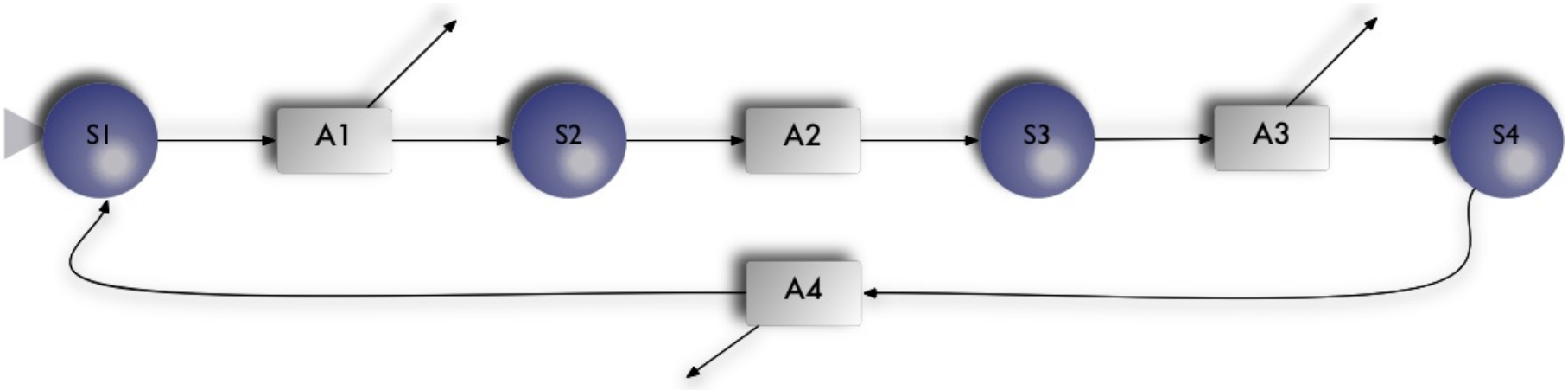

- $LoopIneq(\bar{R}^0) \equiv$
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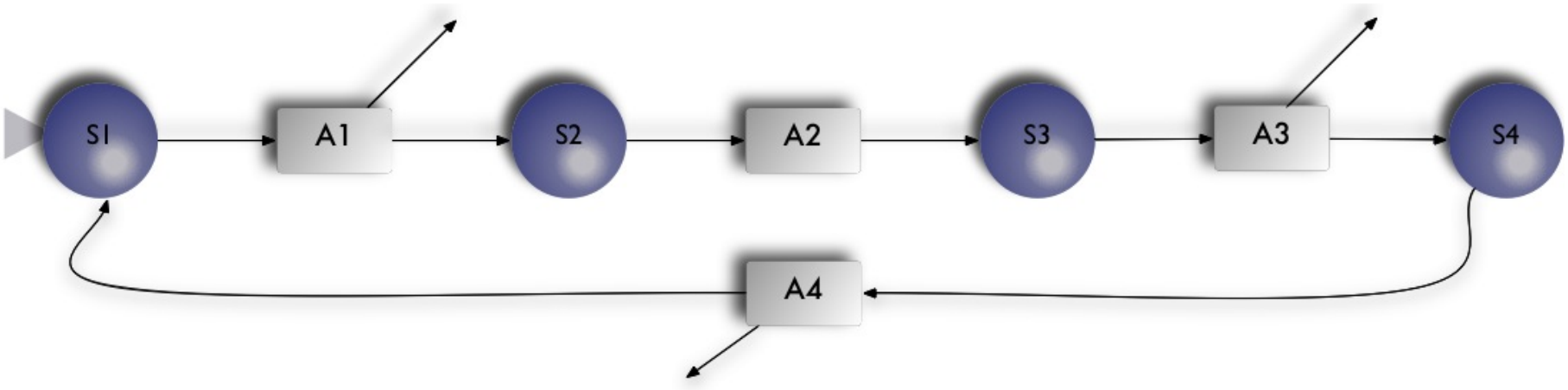
Abacus Programs with Simple Loops



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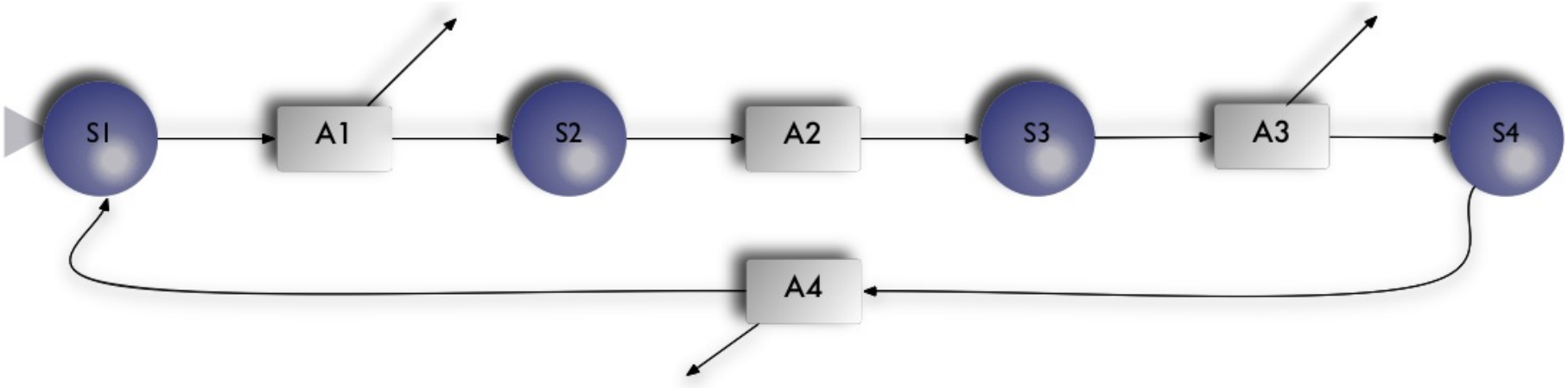

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- $\bar{R}^x = \bar{R}^0 + x \cdot \Delta^{1..n}$
- For l complete iterations:
$$LoopIneq(\bar{R}^0) \wedge LoopIneq(\bar{R}^1) \wedge \cdots \wedge LoopIneq(\bar{R}^{l-1})$$
$$\equiv LoopIneq(\bar{R}^0) \wedge LoopIneq(\bar{R}^{l-1})$$

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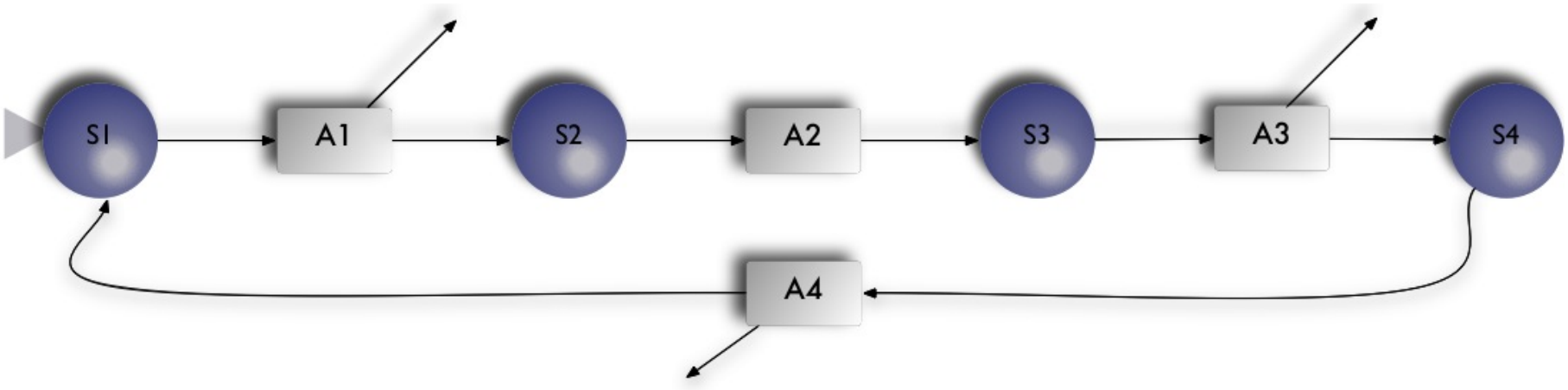

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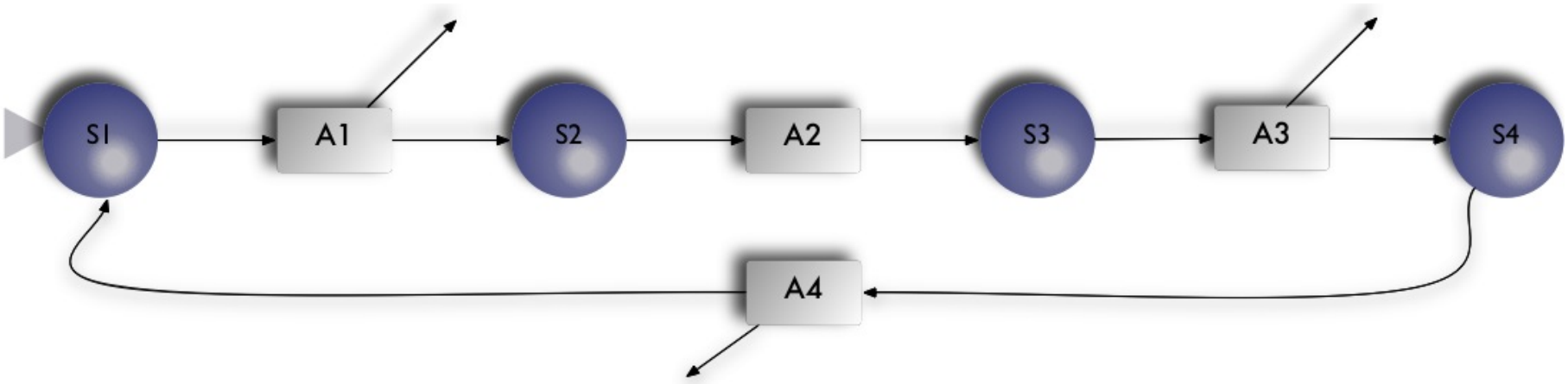
- $\bar{F} = \bar{R}^l = \bar{R}^0 + l \cdot \Delta^{1\ldots n}$

Abacus Programs with Simple Loops: Preconditions



Necessary and Sufficient Conditions

For l complete iterations of a loop with n actions

$$LoopIneq(\bar{R}^0) \wedge LoopIneq(\bar{R}^{l-1})$$
$$\bar{F} = \bar{R}^l = \bar{R}^0 + l \cdot \Delta^{1\ldots n}$$

Recall: Approach

- Translate plans with loops into abacus programs (preserve structure)
- Design algorithms for finding preconditions of classes of abacus programs

Need to represent “sensing” actions.

Non-deterministic Actions

NSet Action

$NSet(r, s_1, s_2)$		set r to 0; goto $s_1 \in S$
	or	set r to 1; goto $s_2 \in S$

Non-deterministic Actions

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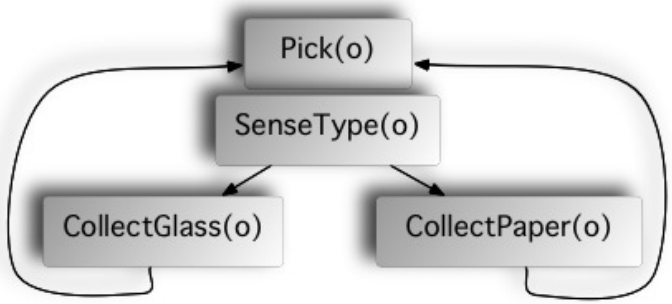
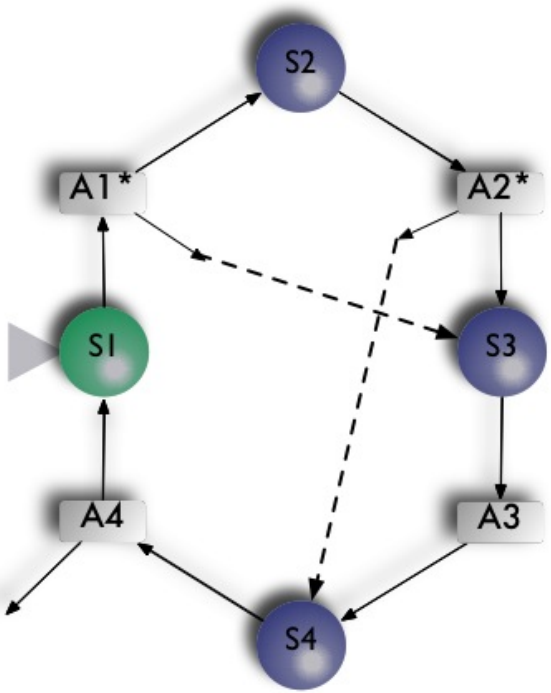
- Abacus programs don't need *NSet* for computational power (Turing-complete).
- *NSet* allows in-place translation of plans with sensing actions.



Find preconditions in terms of effect counts

Simple Loops with Shortcuts



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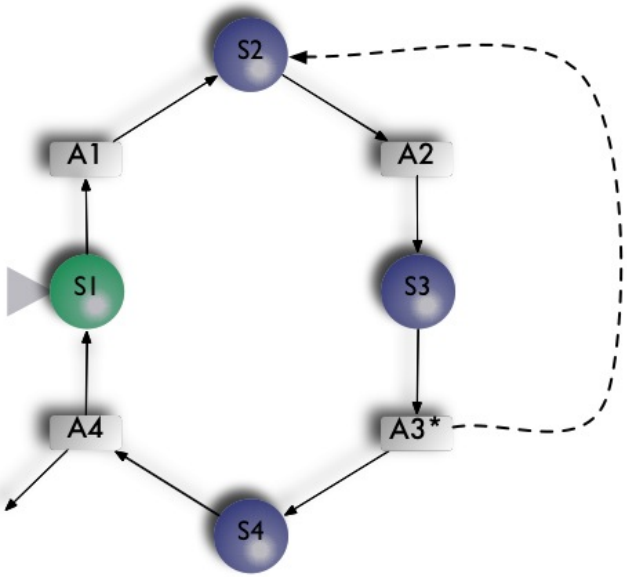
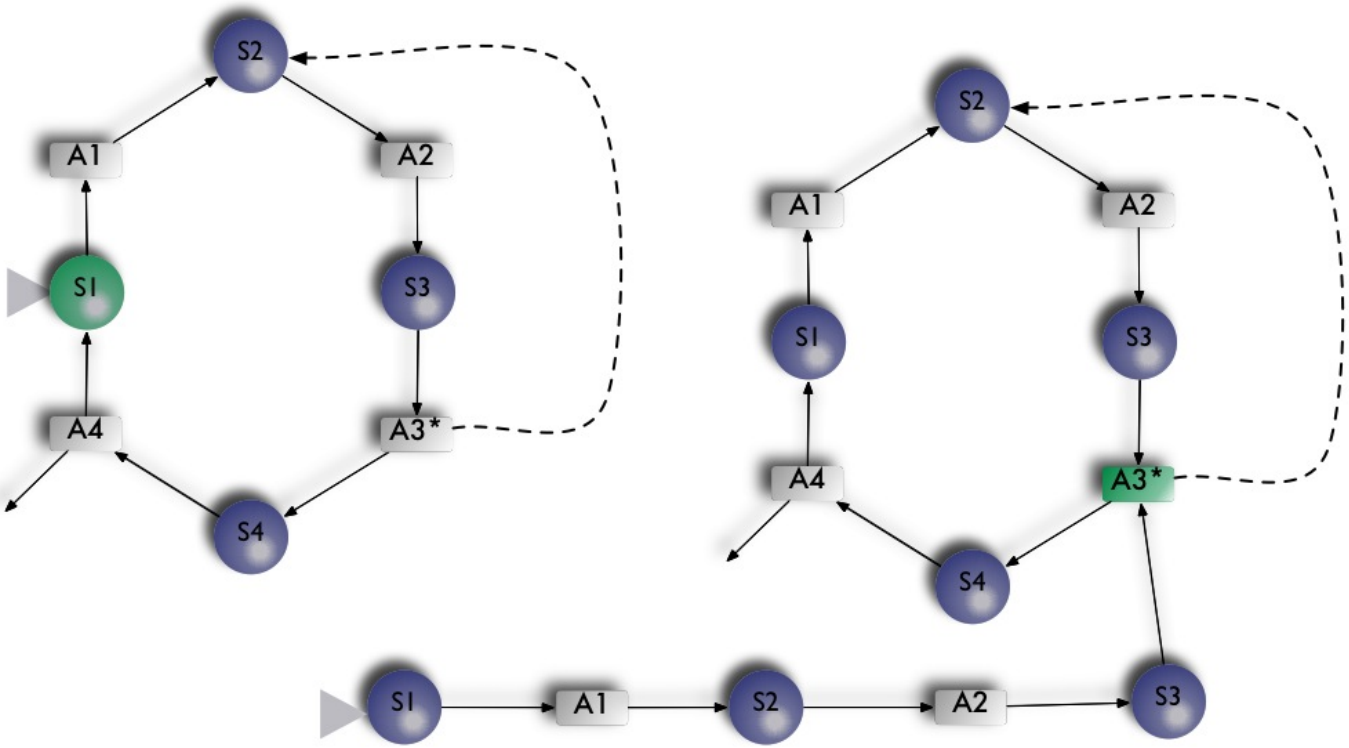


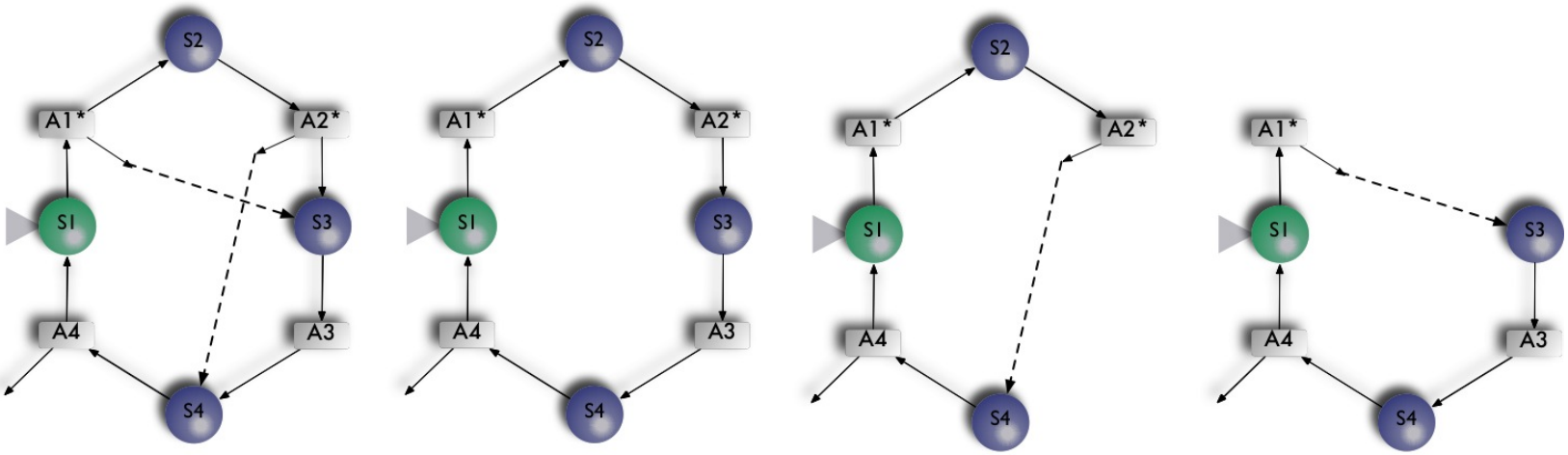
More commonly considered “nested” loops

Simple Loops with Shortcuts

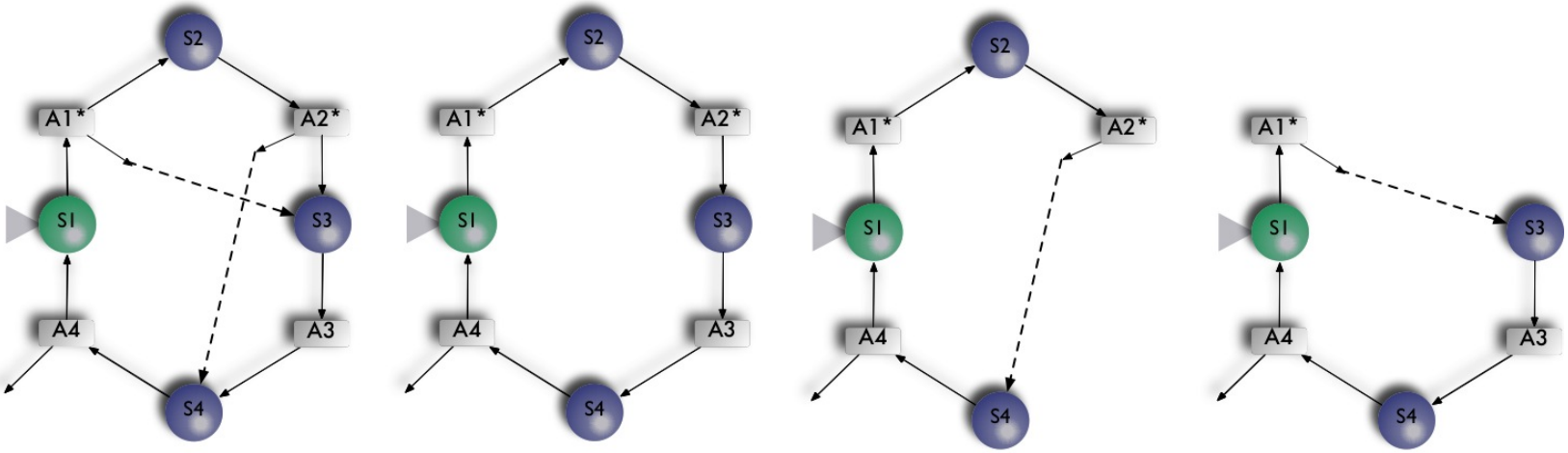


More commonly considered “nested” loops
....can be translated by changing the start node.

Simple Loops with Shortcuts



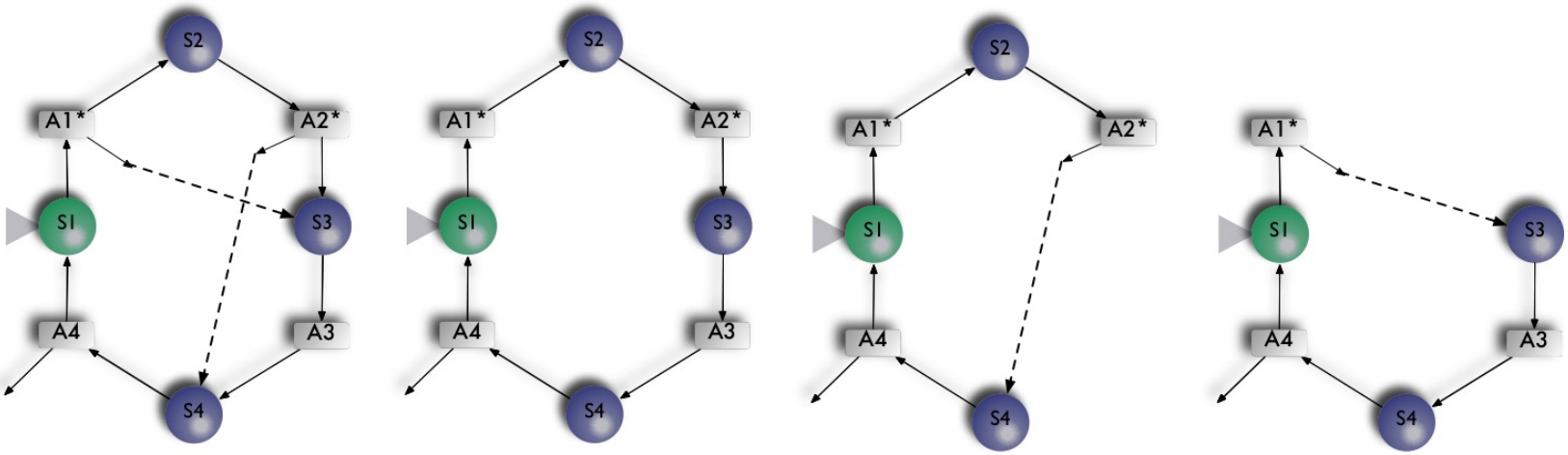
Monotonicity



Monotone Shortcuts

The *net* change on a register due to every simple loop created by shortcuts must be in the same direction (positive/negative).

Simple Loops with Shortcuts: Computing Preconditions

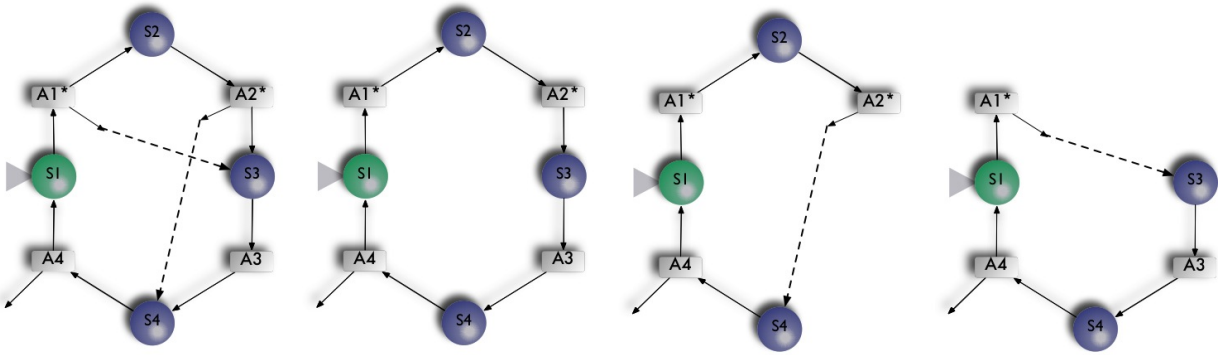


Suppose: m simple loops; $k_1, \ldots, k_m$ iterations

- $\bar{F} = \bar{R}^0 + \sum_{i=0}^{m} k_i \Delta^{loop_i}$
- k_i iterations of loop i: no register can fall below zero.

Need: least intermediate value of every register ≥ 0.

Constraining Minimum Register Values



Constraints on Min Values

m simple loops; $k_1, \ldots, k_m$ iterations

$$R_j \in \mathcal{R}^+ : \quad R_j^0 + \delta_{\widehat{\jmath}} \geq 0$$

$$R_j \in \mathcal{R}^- : \quad R_j^0 + \sum_{i=0}^{m} k_i \Delta^{\text{loop}_i} + \delta_{\widehat{\jmath}} - \Delta^{\text{loop}_{\widehat{\jmath}}} \geq 0$$

Notation

$\mathcal{R}^+$	registers with net positive change
$\mathcal{R}^-$	registers with net negative change
$\widehat{\jmath}$	index of loop with greatest *partial* negative change on R_j.

Order Dependence

Constraints on Minimum Register Values

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Example

loop_1 increase R_1 by 3.

loop_2 decrease R_1 by 2, then increase it by 5.

Efficiently expressing general order dependent constraints: open problem!

Order Dependence

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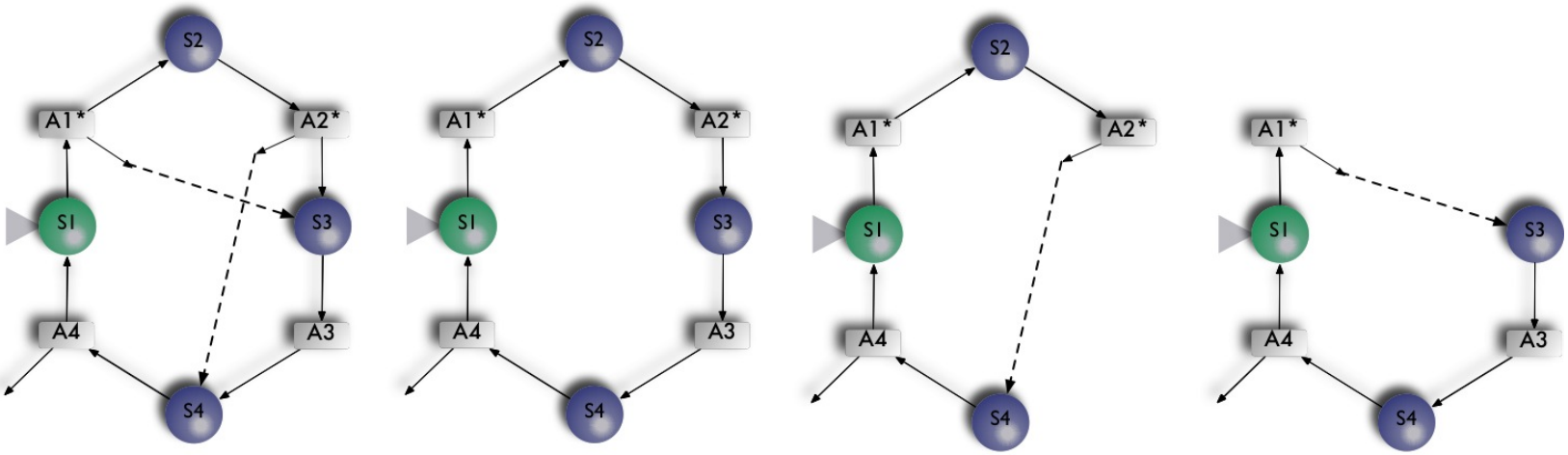
Accurate Conditions Order dependent!

Efficiently expressing general order dependent constraints: open problem!

Equality Constraints, Order Dependence



- Non-spurious equality constraint: inherently order dependent

Equality constraints, $\delta_{\hat{\jmath}} \neq \Delta^{loop_{\hat{\jmath}}}$ induce order dependence (details in paper).

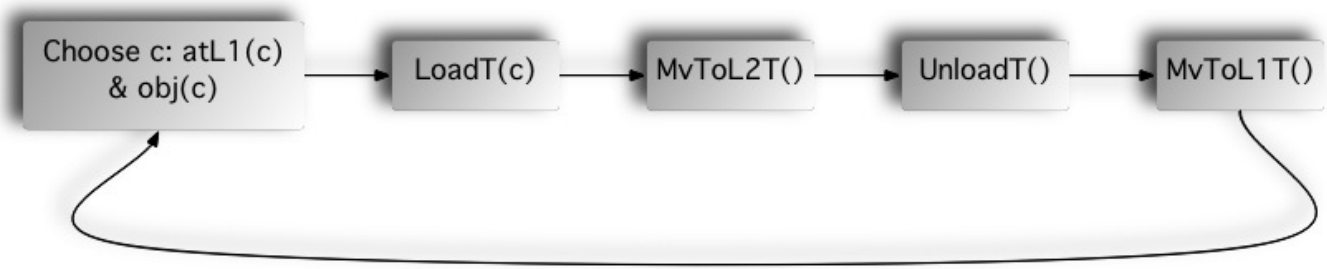
Main Results

Let S be a node in an abacus program Π, all of whose strongly connected components are simple loops or simple loops with monotone shortcuts; $\bar{F}$: a vector of register values.

Theorem

We can compute a disjunction of linear constraints on the initial register values ($\bar{R}^0$) for reaching S with $\bar{F}$. The computed conditions are necessary and sufficient if every simple loop with shortcuts is order independent, and sufficient otherwise.

Translating Plans To Abacus Programs



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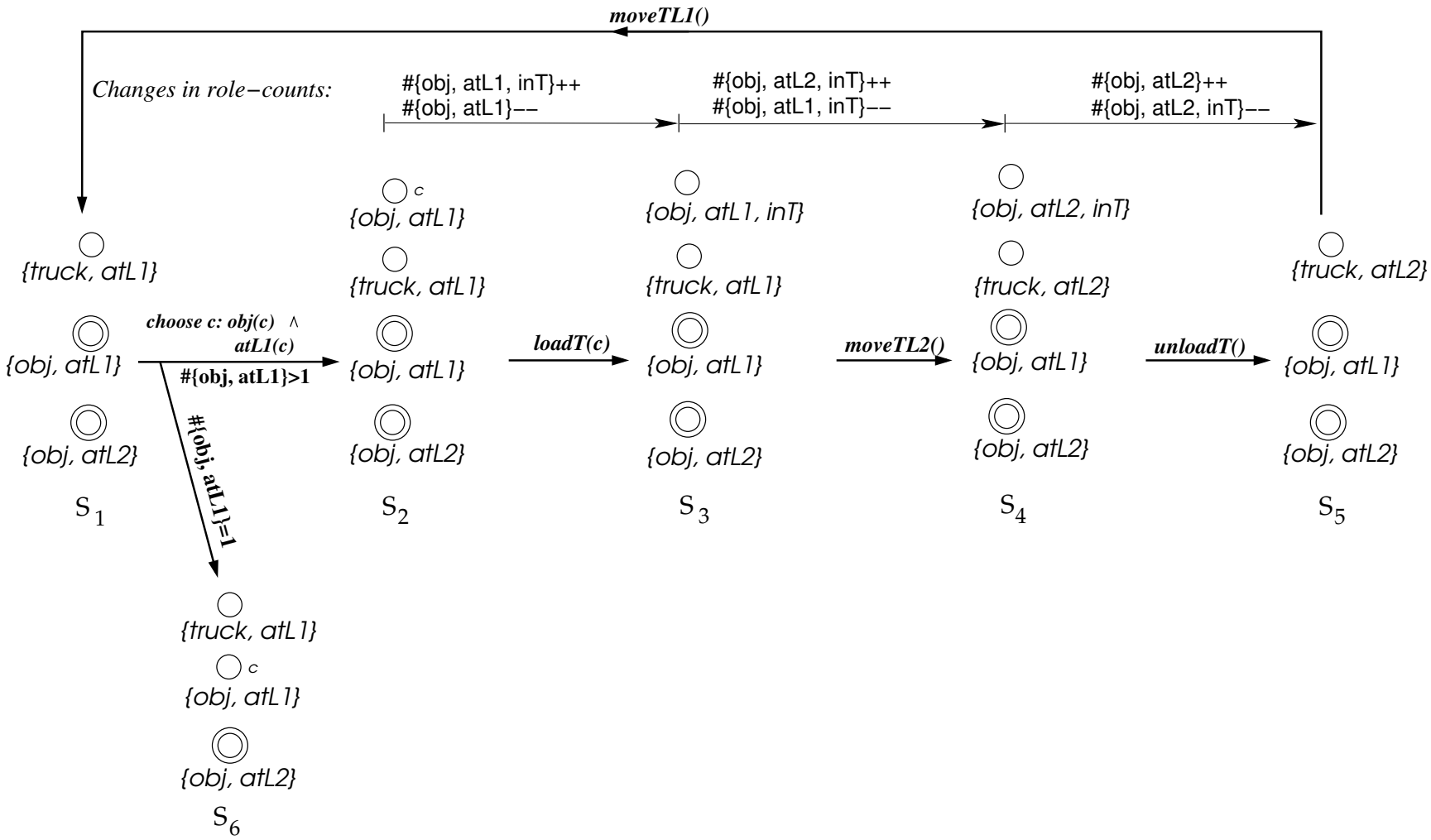
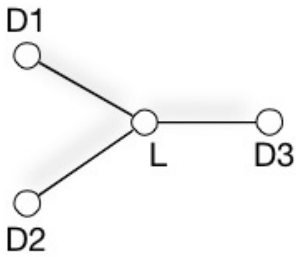
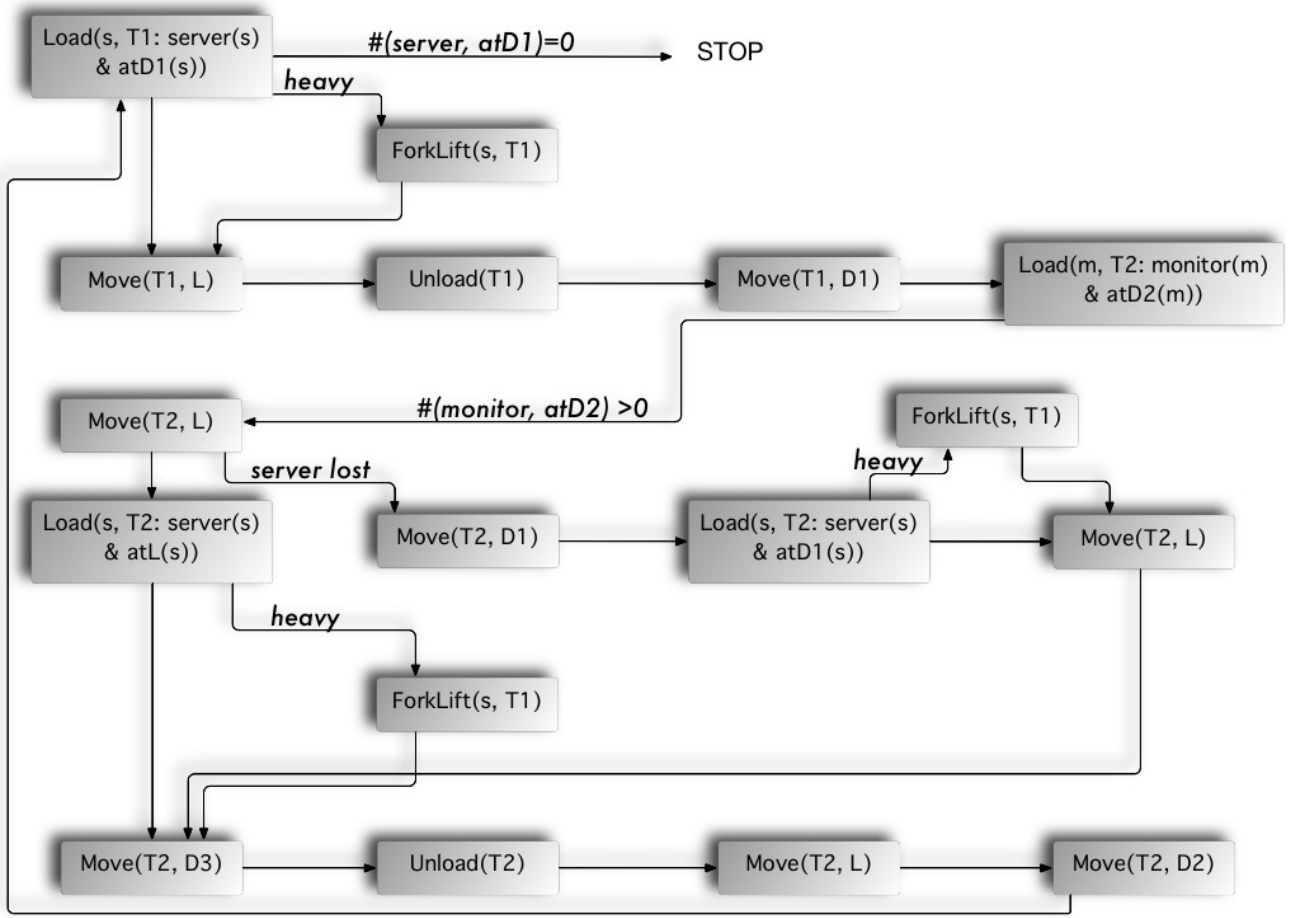


Works for all unary, and a class of binary domains

Empirical Results





$$s_3^f = m_3^f = \sum_{i=0}^{7} k_i;$$
$$s_1^f = s_1^0 - \sum_{i=0}^{7} k_i - k_0 - k_5 - k_6 - k_7 = 0$$

Empirical Results

Time Taken to Compute Preconditions

Problem	Time (s)	Problem	Time(s)
Accumulator	0.01	Prize-A(7)	0.02
Corner-A	0.00	Recycling	0.02
Diagonal	0.01	Striped Tower	0.02
Hall-A	0.01	Transport	0.01
Prize-A(5)	0.01	Transport (conditional)	0.06

Conclusion

- An approach for computing summarized effects of loops of actions
- Use during construction and for precondition evaluation
- Future work:
  - Greater translation to abacus programs (counts of properties)
  - Further categorization of tractable classes
  - Expression of order dependent constraints
  - Use of symbolic precondition evaluation for non-numeric branches.

Complete Preconditions

Preconditions for a Simple Loop with Shortcuts

- $I = \sum_{i=0}^{m} k_i$; $\bar{F} = \bar{R}^0 + \sum_{i=0}^{m} k_i \Delta^{loop_i}$
- $R_j \in \mathcal{R}^- : \quad \bigvee_{x=0_j,\ldots,m_j} \{k_{i<x} = 0; k_x \neq 0;$
  $R_j^0 + \sum_{i \geq x} k_i \Delta^{\text{loop}_i} + \delta_x - \Delta^{\text{loop}_x} \geq 0\}$
- $R_j \in \mathcal{R}^+ : \quad \bigvee_{x=0_j,\ldots,m_j} \{k_{i<x} = 0; k_x \neq 0; R_j^0 + \delta_x \geq 0\}$

References I

Bonet, B., Palacios, H., and Geffner, H. (2009).
Automatic derivation of memoryless policies and finite-state controllers using classical planners.
In *Proc. of the 19th International Conf. on Artificial Intelligence Planning and Scheduling*.

Fikes, R., Hart, P., and Nilsson, N. (1972).
Learning and Executing Generalized Robot Plans.
Technical report, AI Center, SRI International.

Levesque, H. J. (2005).
Planning with loops.
In *Proc. of IJCAI*, pages 509–515.

References II

Winner, E. and Veloso, M. M. (2007).
LoopDISTILL: Learning domain-specific planners from example plans.
In *Workshop on AI Planning and Learning, ICAPS*.