Directed Search for Generalized Plans Using Classical Planners

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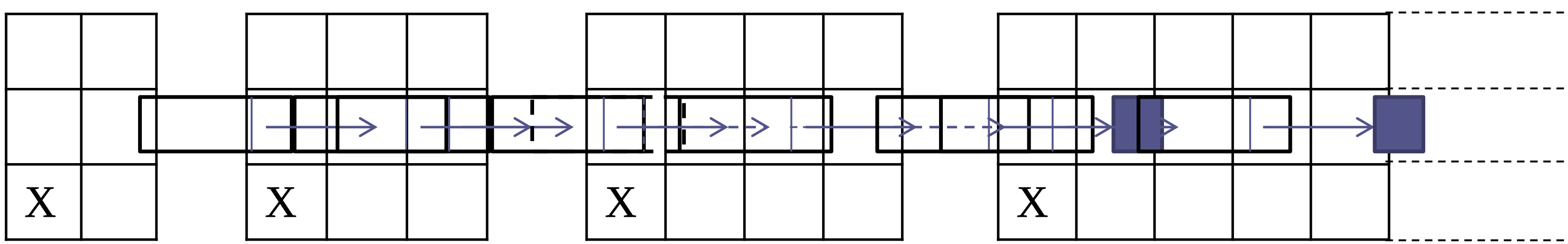
What is Generalized Planning?

- Given: a *domain*, *set of initial states* from potentially different state spaces, goal formula
- Find: A *generalized plan* that *solves* all of the initial states



Reversing a singly linked list Grid Traversal algorithm synthesis problems

Existing Approaches

- Plan reuse [Fikes et al. ’72, Hammond ’86]
- Plans with loops
  - Recognize repetitive patterns in plans [Hu and Levesque ’10, Winner and Veloso ’07, Levesque ’05]
  - Search for cyclic controllers for a partially observable instance [Bonet et al., ’09]
- Our objectives:
  - Guarantees of termination & correctness; directed generalization
  - Not addressed by these approaches

Framework

States

States = logical structures in a domain’s FO(TC) vocabulary

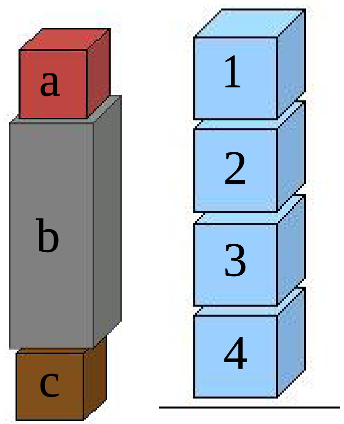
$$V = \{on, onTable, clear, on^{+}\}$$

Define:
Role of an element = set of unary predicates it satisfies

a={*clear*}

b={}

c={*onTable*}



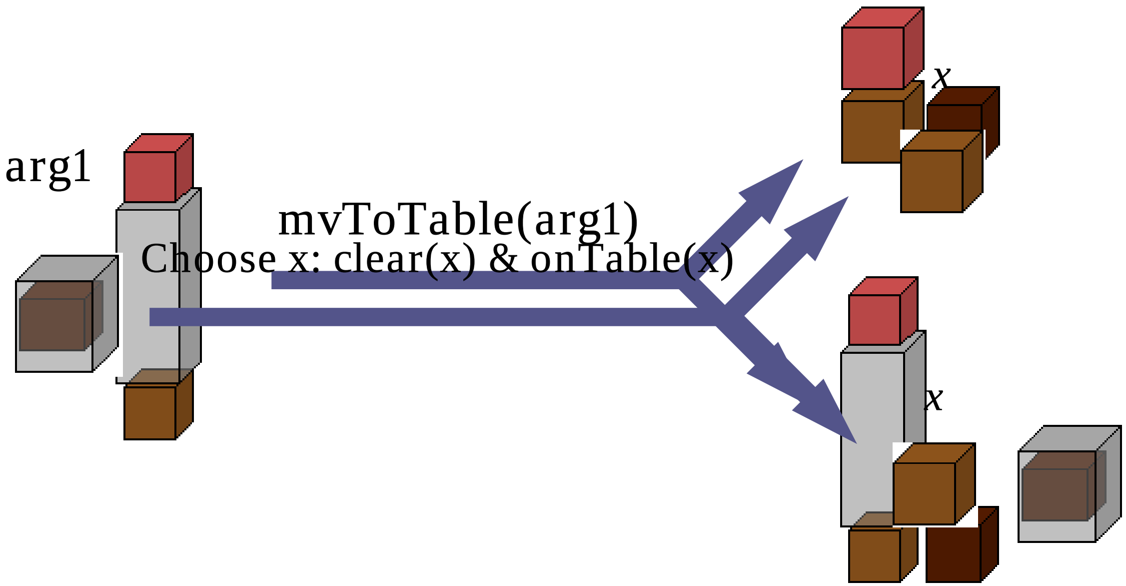
on	a	b	c	4
a	0	½	0	0
b	0	½	½	0 1/2
c	0	0	0	1
4	0	0 0	0	0

on^{+}	a	b	c
	0	1	1
	0	½	1
	0	0	0

- Transitive closure preserves some relationships
- Integrity constraints clarify the sets of states represented by abstract states

[AI Journal 2011]

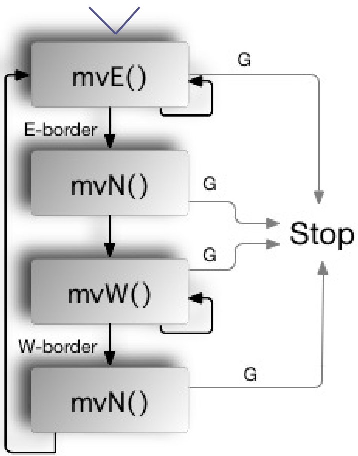
Action Application



- Branch depends on #elements (role-count) in the middle
- May need to draw out representative elements prior to action application
  - Such operations + changing the drawn element's role = TM expressiveness (abacus programs)

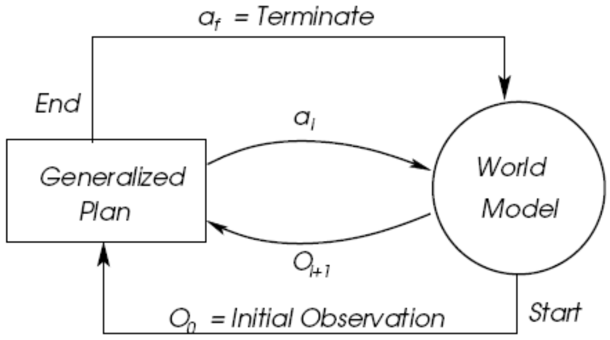
[ICAPS 2010; AI Journal 2011]

Generalized Plans: Definition



- Connected, directed graph
- Nodes = actions
- Edges = conditions/ “abstract” states
    - Will use the dual representation in algorithms
- Start/Terminal nodes

A special class of finite state transducers



Recall: Generalized Planning Problem

- Given: a *domain* (predicate vocabulary + actions + integrity constraints), set of initial states (abstract state S_0), goal formula (FO(TC))
- Find: A generalized plan that *solves* every initial state represented by S_0
- "Solves" an initial state: Every possible execution reaches the goal in a finite number of steps

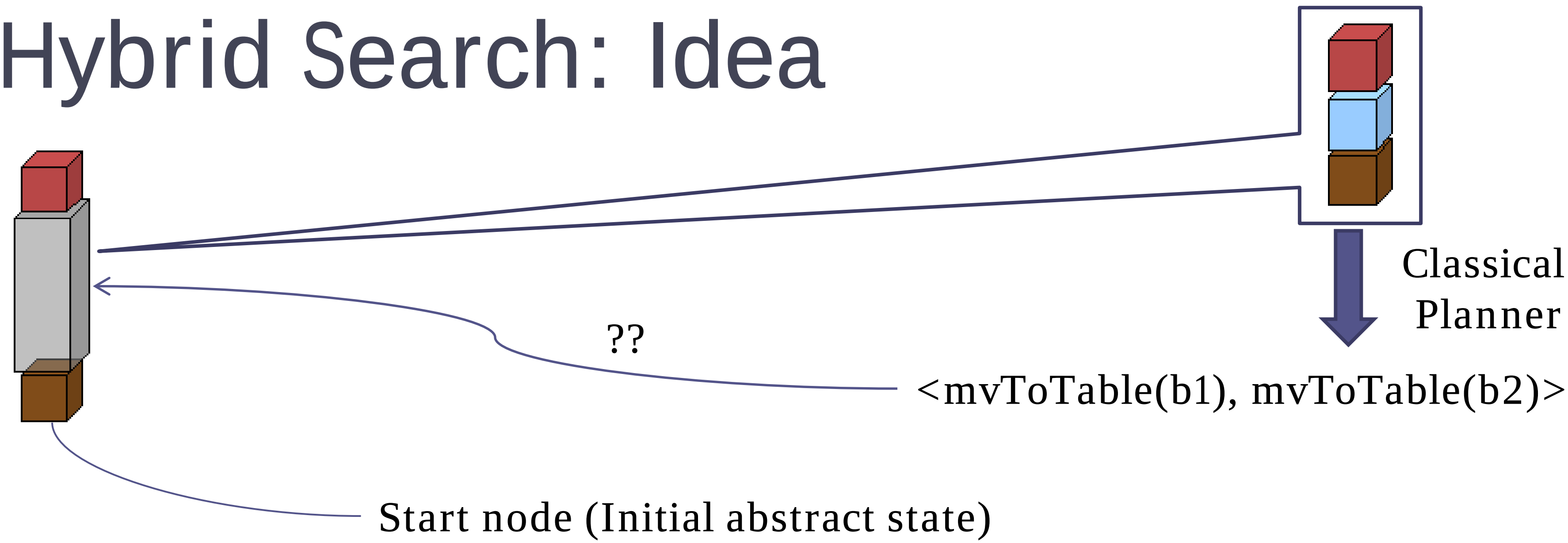
[AI Journal, 2011]

Generalized Plan Synthesis

Our Approach

- Get an example *unsolved* problem instance
- Get a classical plan for solving this instance
- Generalize and merge this plan
- Repeat

Hybrid Search: Idea

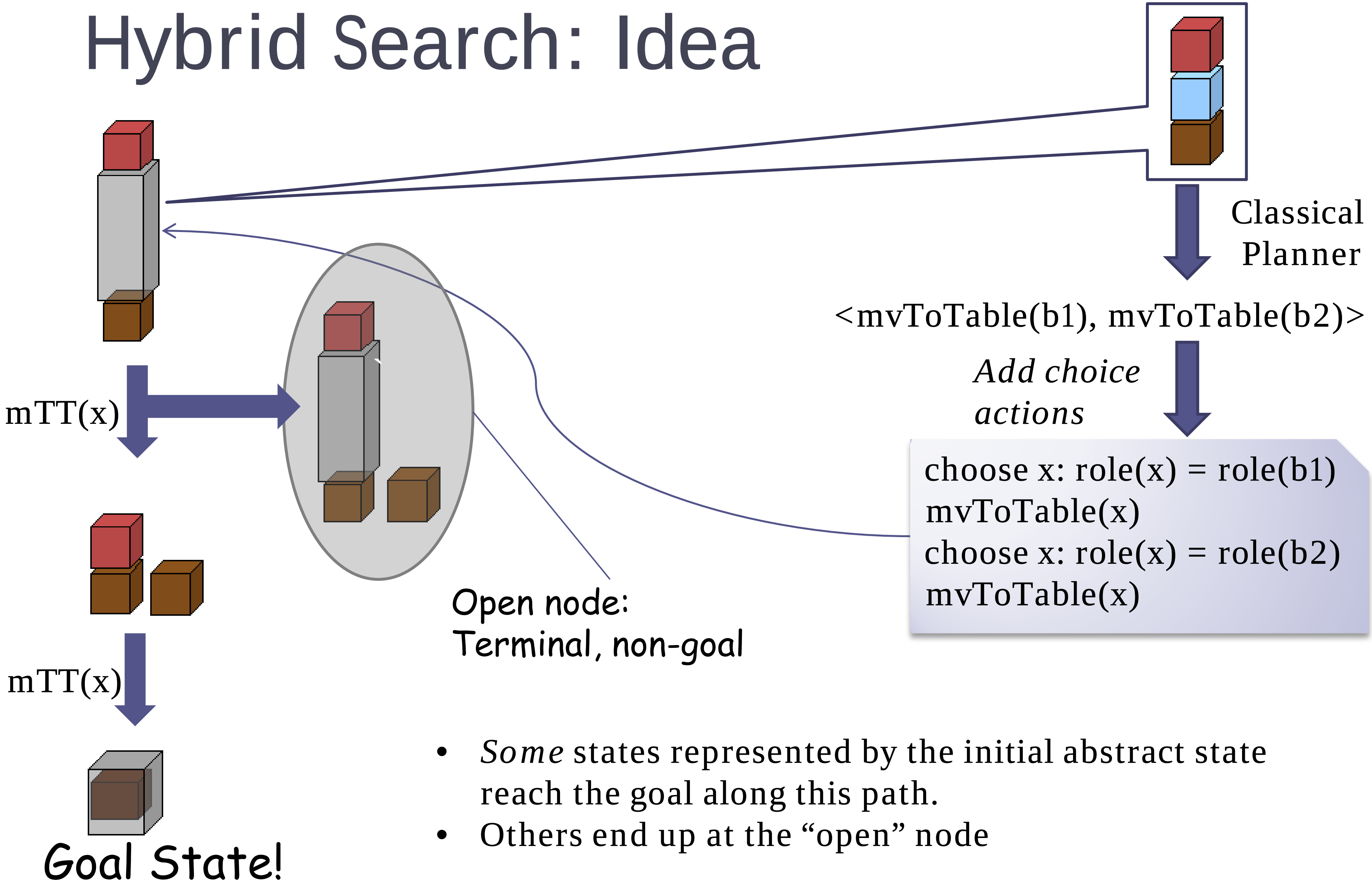


Objects b1 … problem,
or in the ab…

Dual Representation:

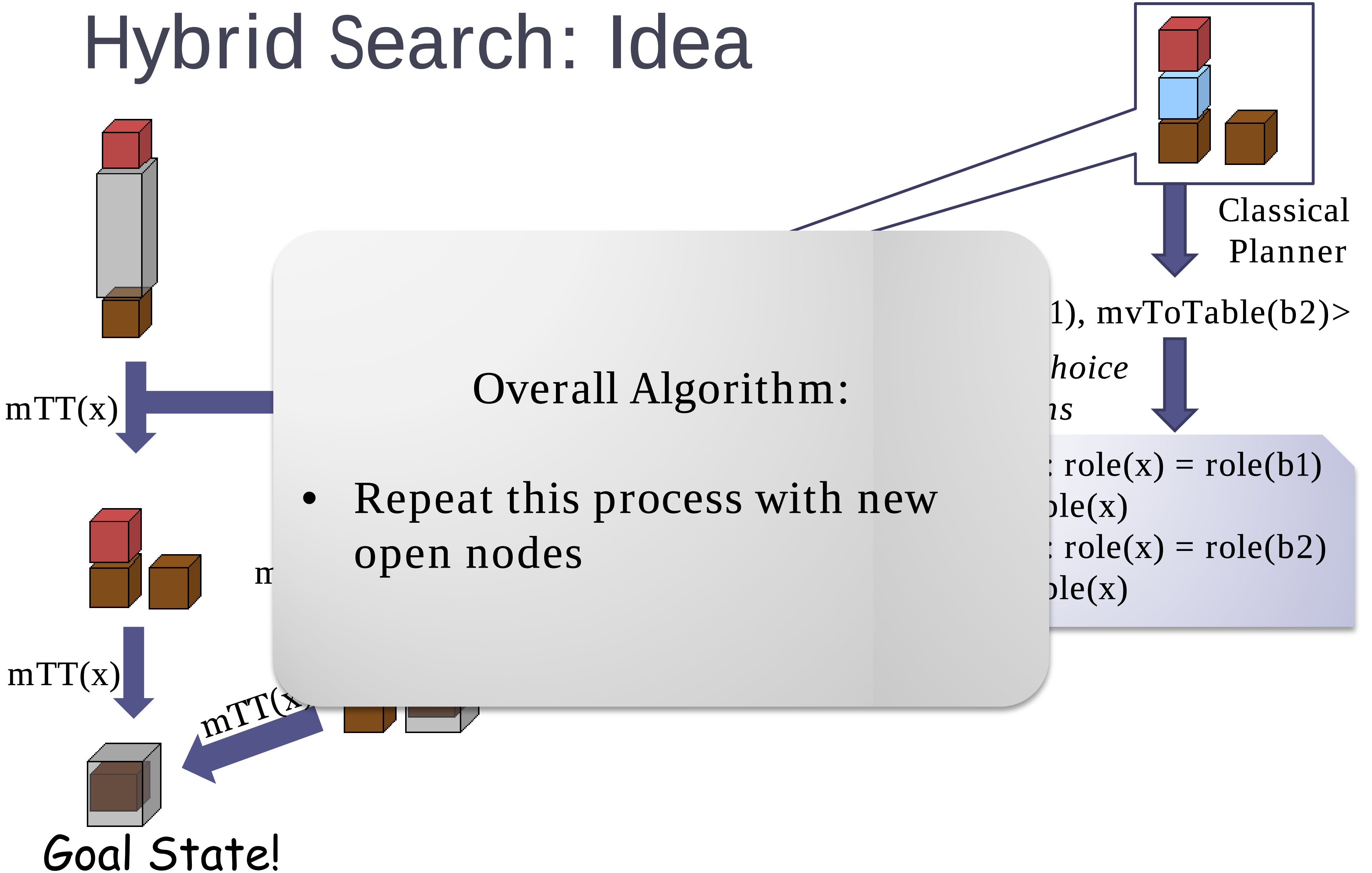
Nodes = Abstract States
Edges = Actions

Hybrid Search: Idea



- *Some* states represented by the initial abstract state reach the goal along this path.
- Others end up at the “open” node

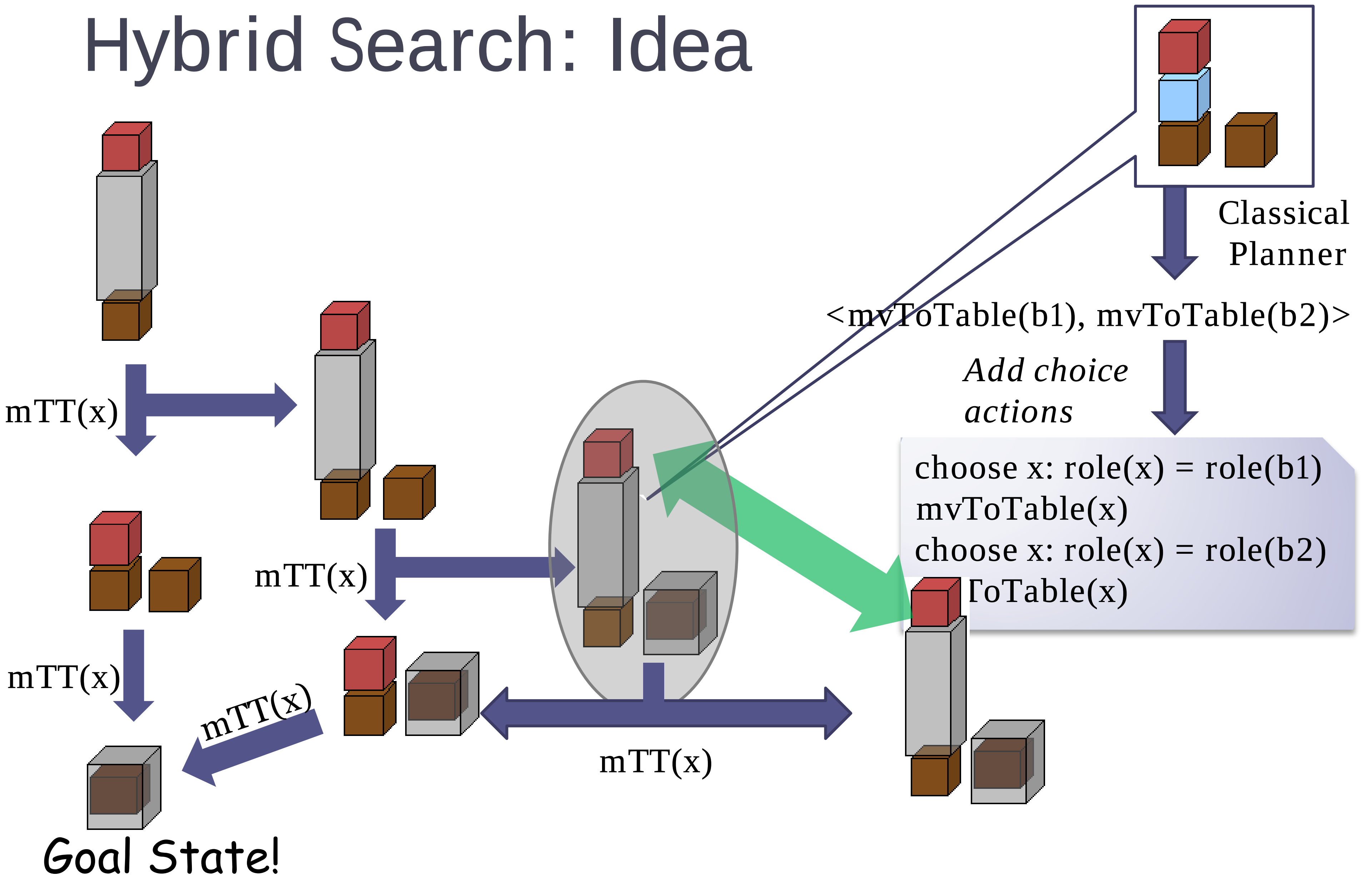
Hybrid Search: Idea



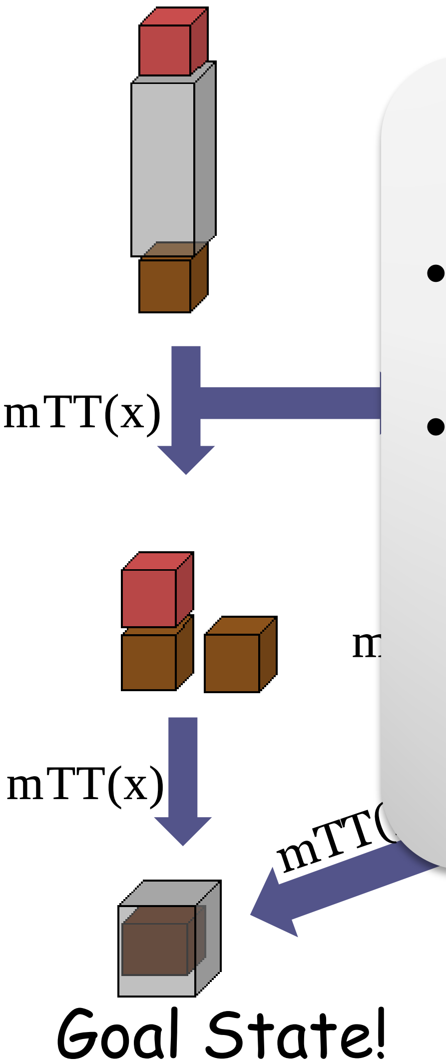
Overall Algorithm:

- Repeat this process with new open nodes

Hybrid Search: Idea



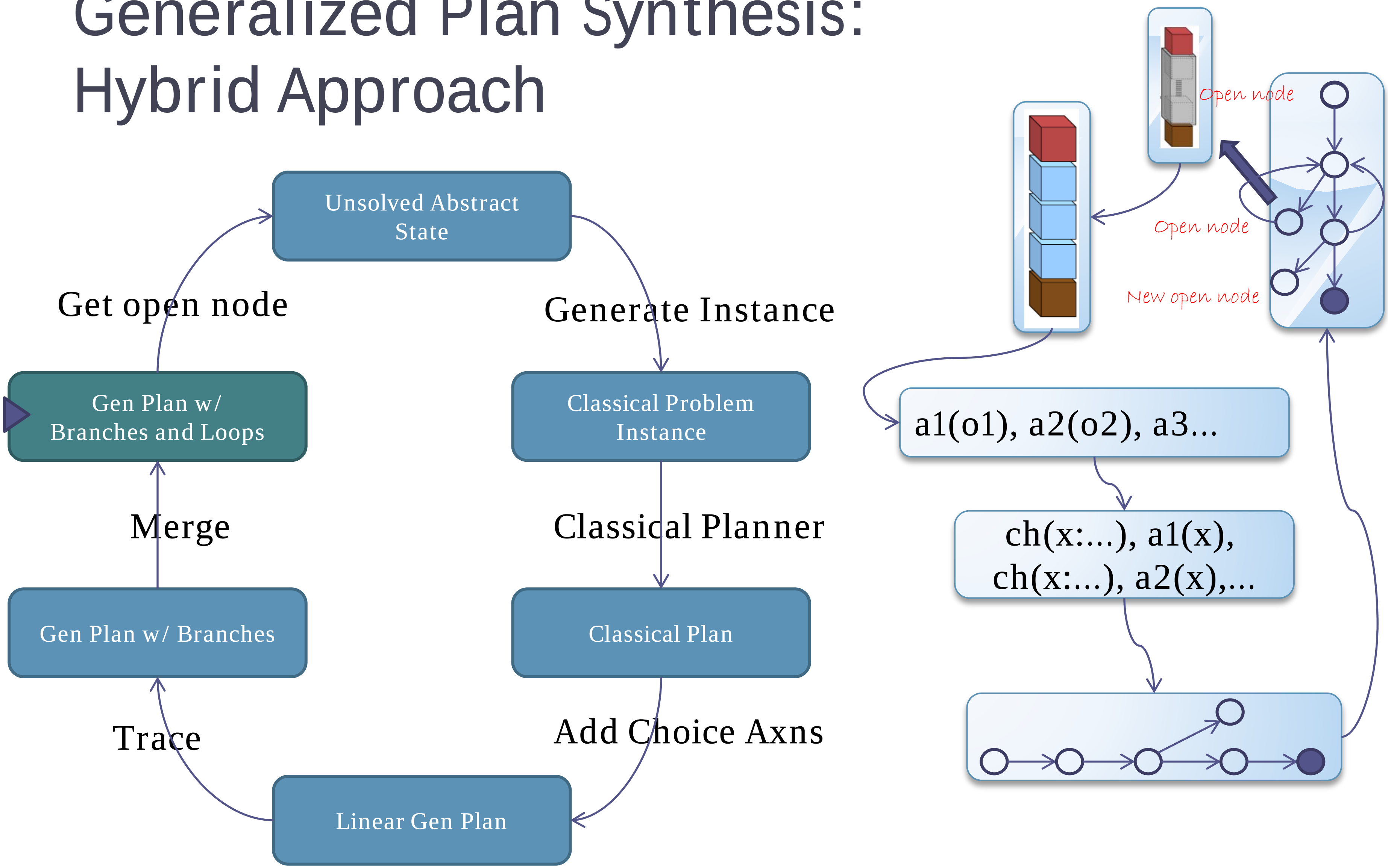
Hybrid Search: Idea



Overall Algorithm:

- Repeat this process with new open nodes
- Merge an abstract state with an existing one that subsumes it:
  - Loops must be guaranteed to terminate: undecidable problem
  - Use methods from [ICAPS 2010]

Generalized Plan Synthesis: Hybrid Approach

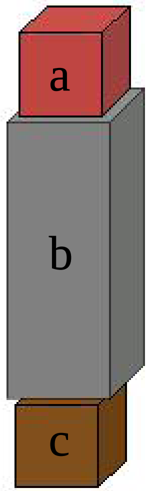


Components of Hybrid Search: Instance Generation

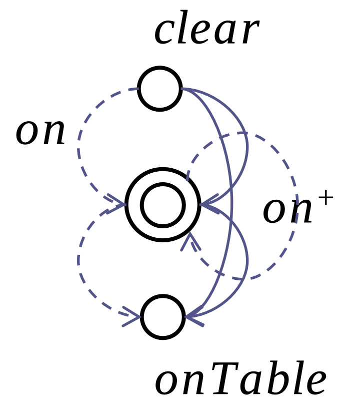
a={*clear*}

b={}

c={*onTable*}



on	**a**	**b**	**c**
a	0	½	0
b	0	½	½
c	0	0	0



Describe the abstract state using FO(TC) formulas capturing:

1. Each role present: e.g. $\exists x$ *clear(x)* &…
2. Each singleton present: e.g. $\forall x, y$ *clear*(x) & *clear*$(y) \rightarrow x{=}y$ &…
3. Each **true** predicate tuple: e.g. *clear(x)* & *onTable(y)* → $on^{+}(x,y)$ &…
4. Each **false** predicate tuple: e.g. *clear(x)* & *onTable(y)* → ¬ *on(x,y)* &…
5. Integrity constraints: e.g. $\forall x, y, z$ *on*(x,z) & *on*$(y,z) \rightarrow x{=}y$&…

½'s remain unspecified

Instance Generation

-
- First-order model generators are available, but our formulas use transitive closure (TC)
- TC cannot be expressed in first-order logic
- Simulate it using:

$$\forall x, y\ p^{tc}(x, y) \leftrightarrow p(x, y) \lor \exists z\ (p(x, z) \land p^{tc}(z, y))$$

This is *accurate* in finite, acyclic models

[Lev Ami et al., 2005, 2009]

Formal Guarantees

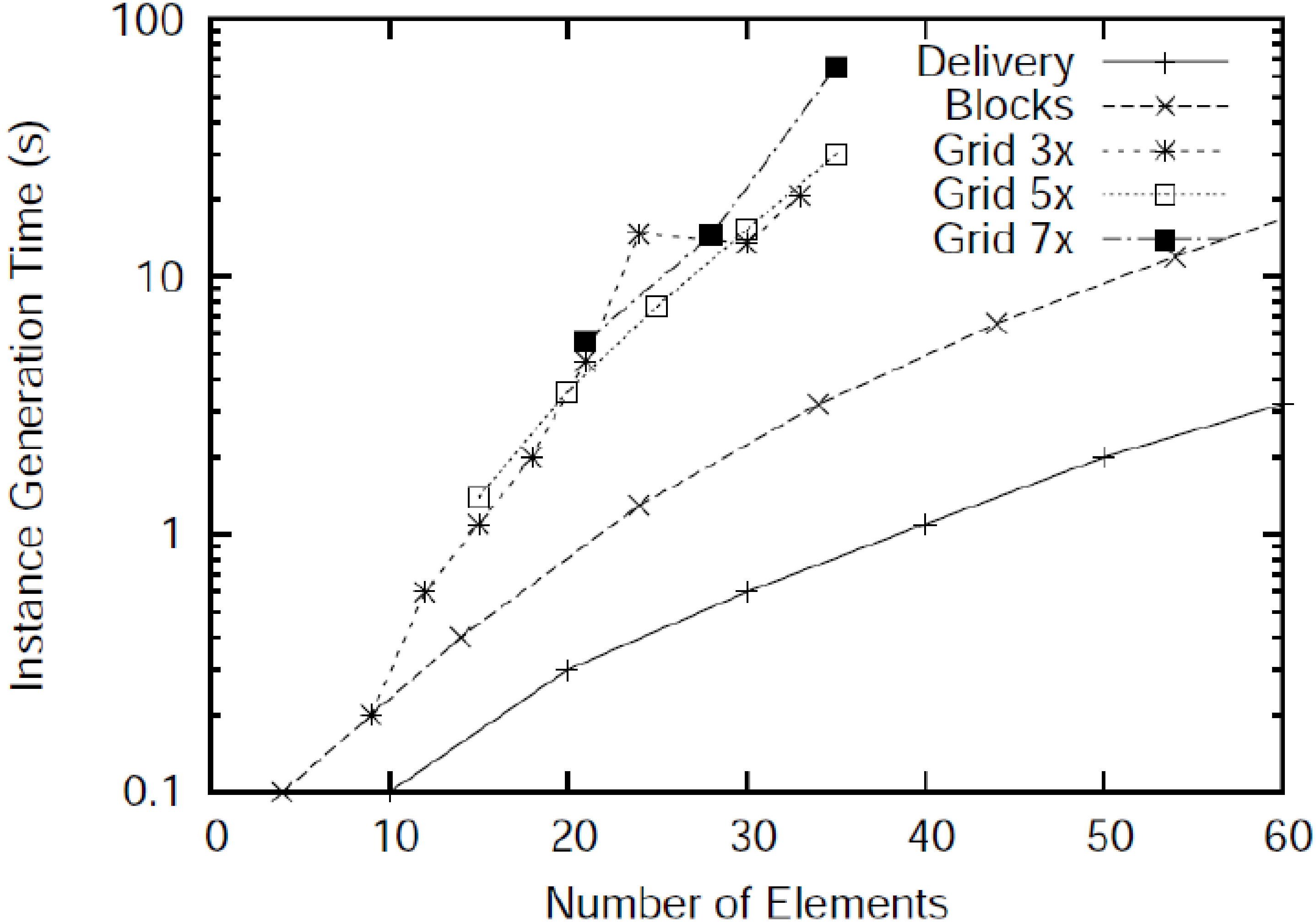
- Action application: sound
  - *States-represented-by*[*axn*(abstract state)] ⊇ *axn*(*states-represented-by*[abstract state])

- If a plan's execution terminates, it must do so at a state represented by an open node

- If plan terminates & all open nodes satisfy the goal condition: plan solves all instances of init. abs. state

Results

Results: Instance Generation



Results

	Initial Role Count = 1					Initial Role Count = 5*				
Problem	N_{calls}	$\|S\|_{max}$	$\|\pi\|_{max}$	Applicability	T(s)	N_{calls}	$\|S\|_{max}$	$\|\pi\|_{max}$	Applicability	T(s)
Delivery	7	**9**	**9**	T, C, P	297	7	14	25	T, C, P	**246**
Grid3x	6	**15**	**12**	T, C, P	166	**3**	21	20	T, C, P	**82**
Grid5x	8	**25**	**22**	T, C, P	631	**4**	35	34	T, C, P	**172**
Grid6x*	10	30	**27**	T, C, P	**1791**	**9**	30	29	T, C, P	1902
Hall-A	7	**10**	**6**	T, C, P	180	**3**	24	18	T, C, P	**70**
Reverse	7	8	**6**	T, C	119	**6**	8	15	**T, C, P**	**128**
Sorting	7	**7**	6	T, C, P	**78**	7	9	6	T, C, P	82
Striped Tower	10	**10**	**11**	T, C, P	831	**5**	14	24	T, C, P	**290**
Y-Transport	9	13	**53**	T, C, P	943	**7**	13	63	T, C, P	**550**

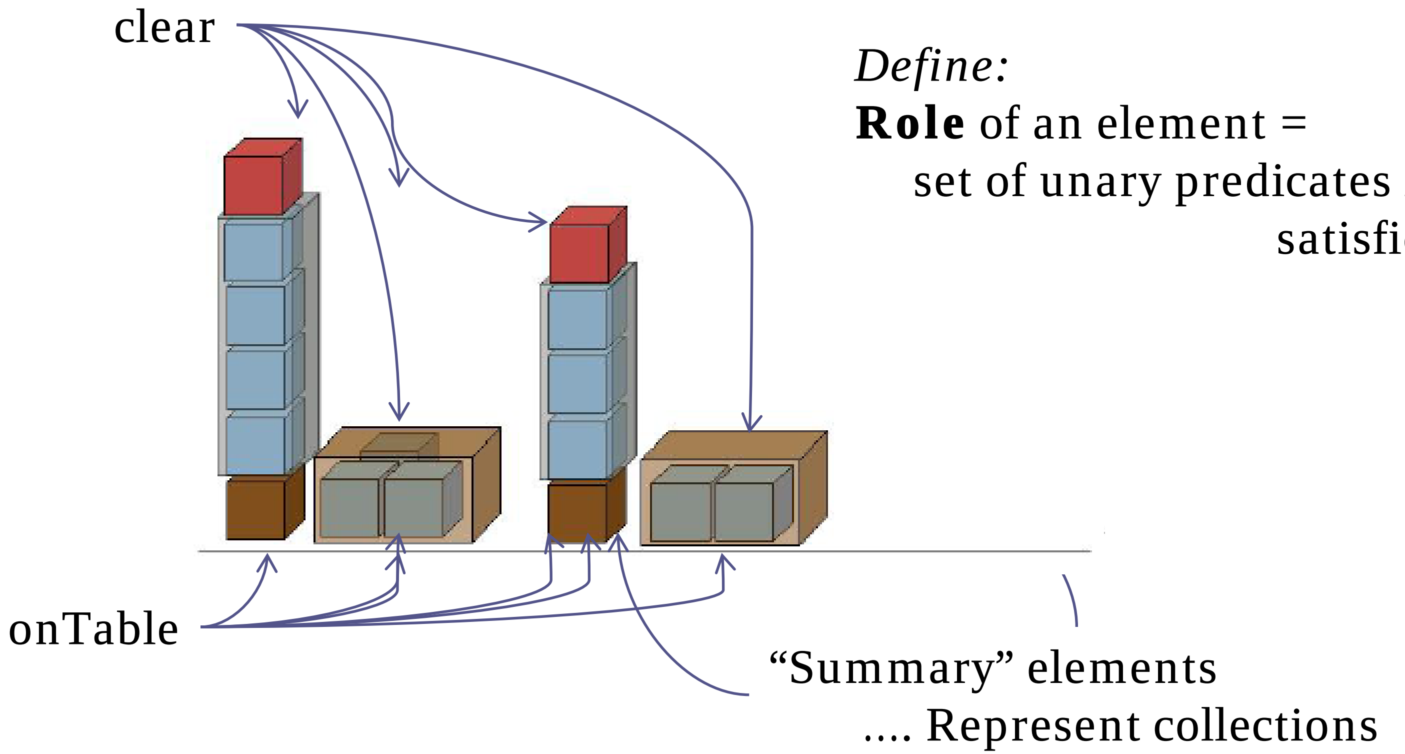
- At most 10 planning problems required to generate generalized plans for unbounded instances
- Problem instances to be solved by classical planners are “small” and deterministic
- Unified approach for algorithm and generalized plan synthesis

Conclusions

- An approach for utilizing the powerful heuristic search capabilities of classical planners for:
  - Simultaneous exploration of infinitely many state spaces using abstraction
  - Generation of potentially useful paths of actions in the abstract state space
- Future Work:
  - More robust termination tests
  - Identification of unreachable/unsolvable open nodes

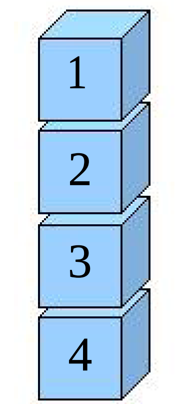
Thank you!

Sets of States as Abstract States

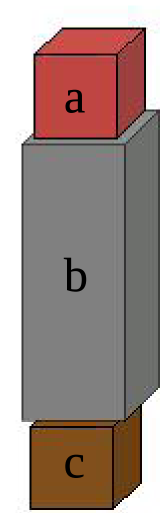


Define:
Role of an element =
set of unary predicates it satisfies

Abstract States: Truth values



on	1	2	3	4
1	0	1 1/2	0	0
2	0 0	0 1/2	1	0 1/2
3	0	0	0	1
4	0	0 0	0	0



on	a	b	c
a	0	½	0
b	0	½	½
c	0	0	0

- Binary relationships with summary elements may become imprecise
- Represented using the truth value ½ , denoting “unknown”
- Integrity constraints clarify the sets of states represented by abstract states

[AI Journal 2011]