
Linköping University

# Automated Planning

## Domain-Configurable Planning: Planning with Control Formulas

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# Assumptions



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- Recall the fundamental assumption that we **only** specify
  - Structure: Objects and state variables
  - Initial state and goal
  - **Physical** preconditions and **physical** effects of actions

**We only specify what *can* be done**

**The *planner* should decide what *should* be done**

**But even the most sophisticated heuristics and domain analysis methods lack our intuitions and background knowledge…**

# Domain-Configurable Planners


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**How can we make a planner take advantage of what we know?**

- Planners taking advantage of additional knowledge can be called:
  - **Knowledge-rich**
  - **Domain-configurable**
  - (Sometimes **incorrectly** called "domain-dependent")

# Comparisons (1)



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More effort

Higher performance

## Domain-specific

Must write an entire planner
Can specialize the planner for very high performance

## Domain-configurable

High-level (but sometimes complex) domain definition
Can provide more information for high performance

## "Domain-independent"

Provide minimal information about actions
Less efficient

# Comparisons (2)



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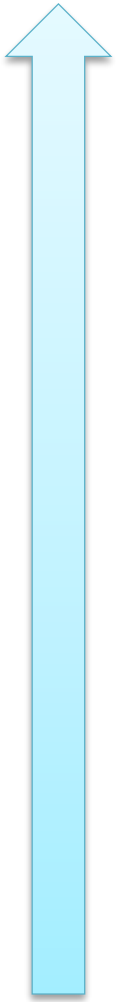
Larger problem classes
can be handled efficiently



**Domain-configurable**

Easier to improve expressivity and efficiency
➔ Often practically useful for a larger set of domains!

**"Domain-independent"**

Should be useful for a wide range of domains

**Domain-specific**

Only works in a single domain

# Domain-Configurable: Prioritization and Pruning

# Two Kinds of Search Guidance (1)



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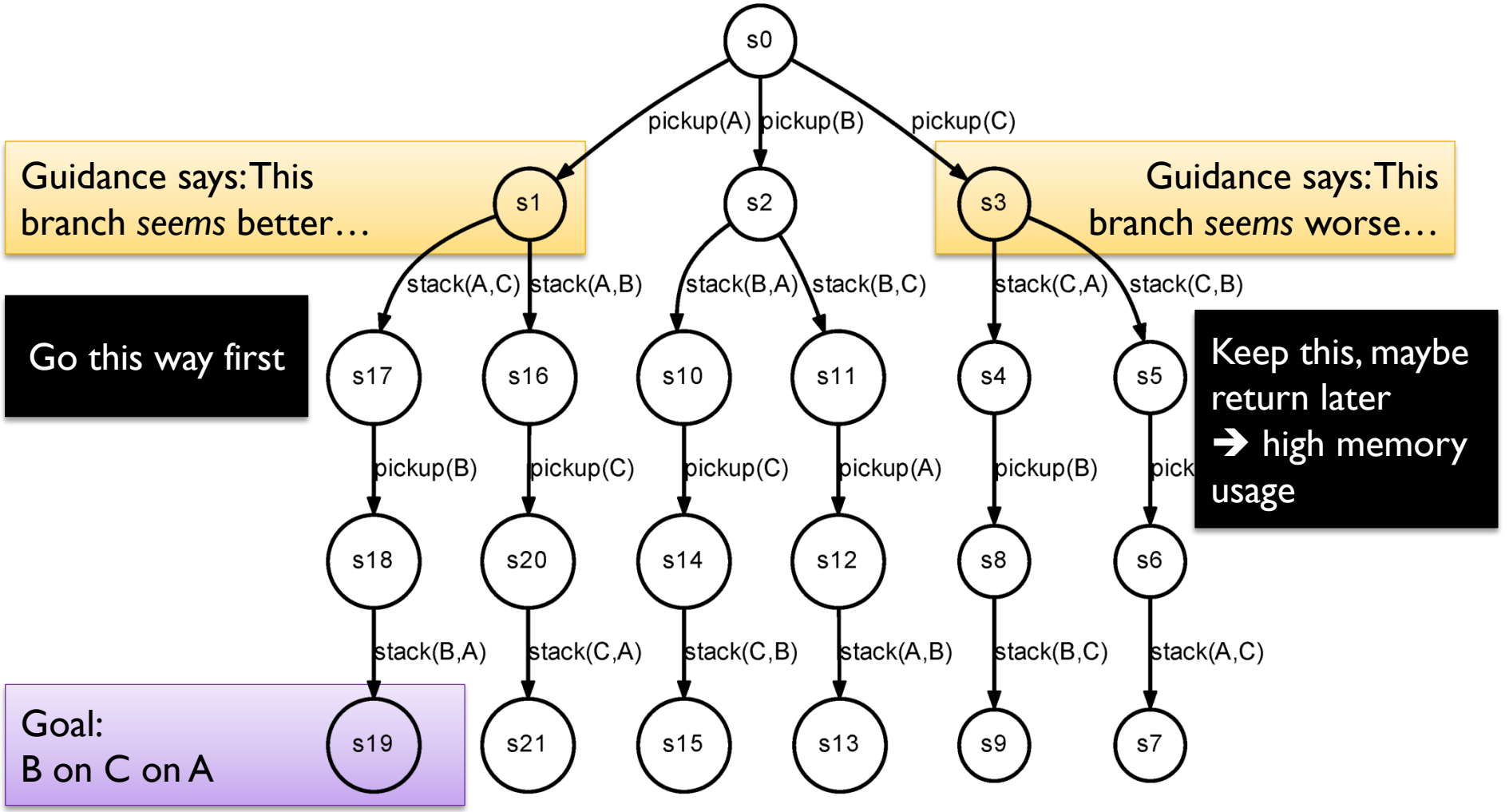
**Prioritization**: Which part of a search tree should be visited **first?**
Could use heuristic functions, could use other methods…



# Prioritization



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- Properties of prioritization:
  - We can always **return** to a node later
  - No need to be **absolutely** certain of your priorities

- **This** is why many domain-independent heuristics work well
  - Provide *reasonable* advice in *most* cases

# Two Kinds of Search Guidance (2)



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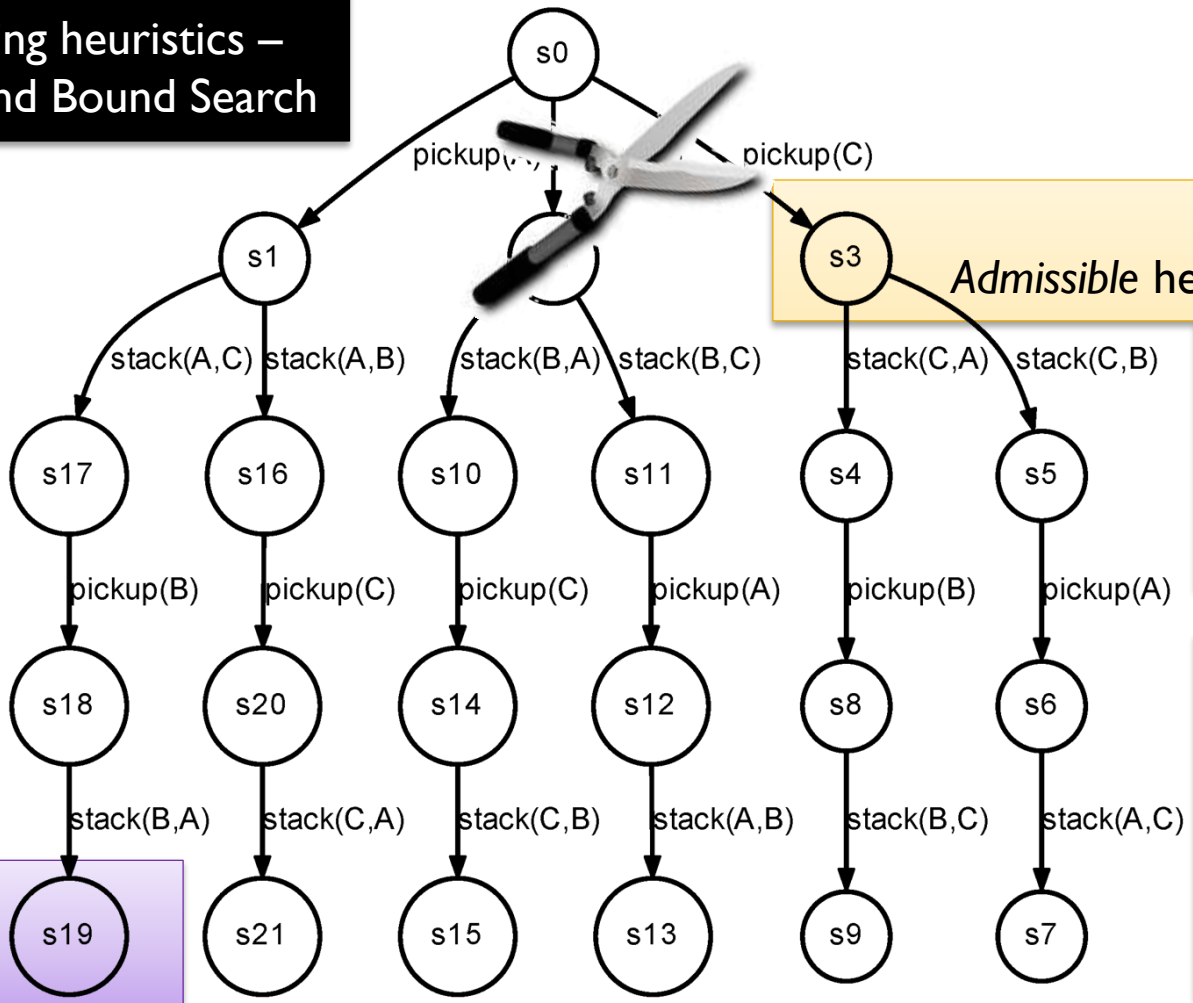
**Pruning**: Which part of a search tree are **definitely useless**?
**Prune** them!

**Can** be done using heuristics –
example: Branch and Bound Search




Cost g(n)=1
*Admissible* heuristic h(n)=4

Any solution below s3 will cost at least 5

**Prune!**
Never consider the node or its descendants again…

We found a solution of cost 4

# Pruning



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- Can we prune when we search for the **first** solution?
  - A single mistake may *remove all paths to solutions*
  - ➔ Difficult to find good *domain-independent* pruning criteria

# Example: Emergency Services Logistics



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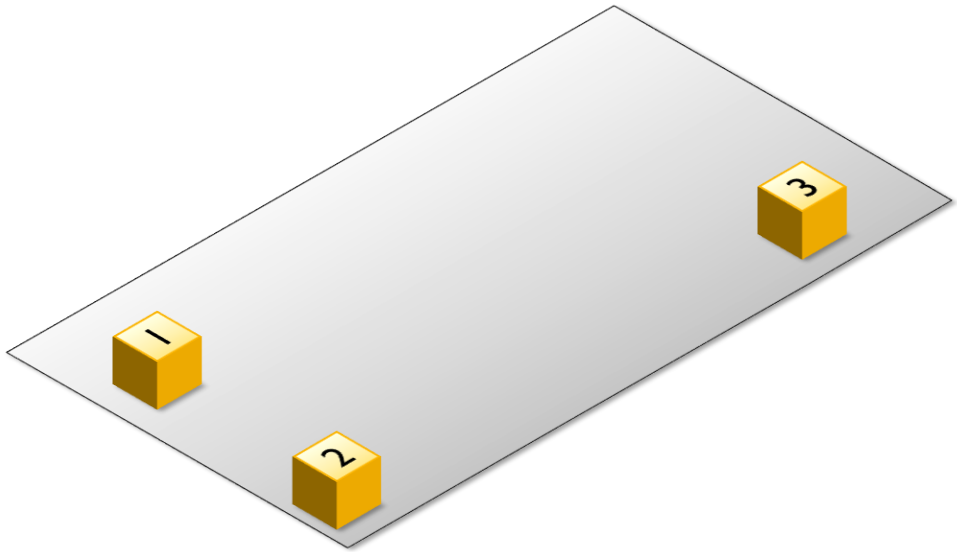
- Emergency Services Logistics
  - Goal: at(crate1, loc1), at(crate2, loc2), at(crate3, loc3)
  - Now: at(crate1, loc1), at(crate2, loc2)




  - Picking up crate1 again is **physically possible**
  - It "destroys" at(crate1, loc1), which is a goal – **obviously stupid!**

The **branch** beginning with pickup(crate1) could be **pruned** from the tree!
How do we **detect** this in a domain-independent way?

# Example: Towers of Hanoi



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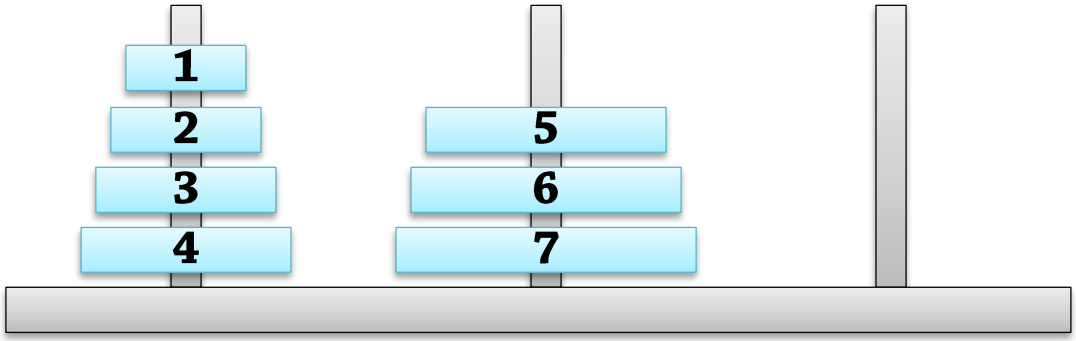
**Should we <u>always</u> prevent the destruction of achieved goals?**

- Goal: on(1,2), on(2,3), on(3,4), on(4,5), on(5,6), on(6,7)
- Now: on(1,2), on(2,3), on(3,4), on(5,6), on(6,7)




- Moving disk 1 to the third peg is **<u>possible</u>** but "destroys" a goal fact: on(1,2)
  - Is this also **<u>obviously stupid</u>**?
  - No, it is **<u>necessary</u>**! Disk 1 is blocking us from moving disk 4…

# Heuristics



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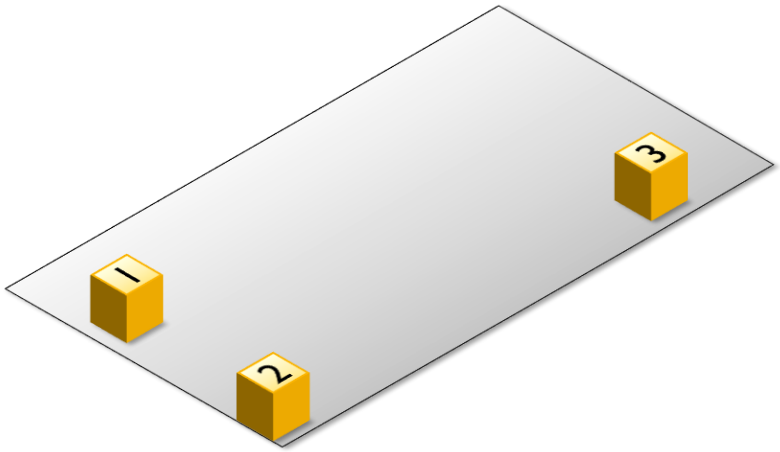
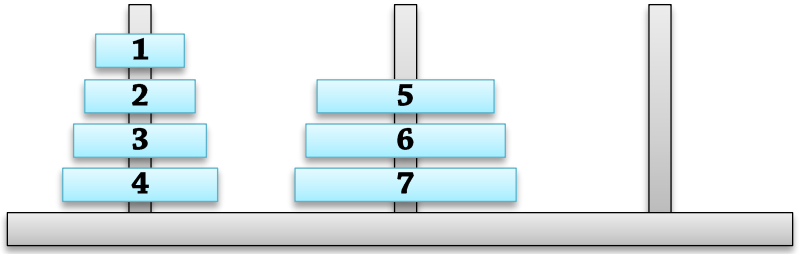
➔ Heuristics **may or may not** detect:

| Picking up crate1 is bad | Moving disk1 is good |
| --- | --- |




Will generally depend on **the entire state**
+ which **alternative states** exist,
not just the fact that you "destroy goal achievement"

Might **delay** investigating either alternative for a while,
return to try this later

# Pruning



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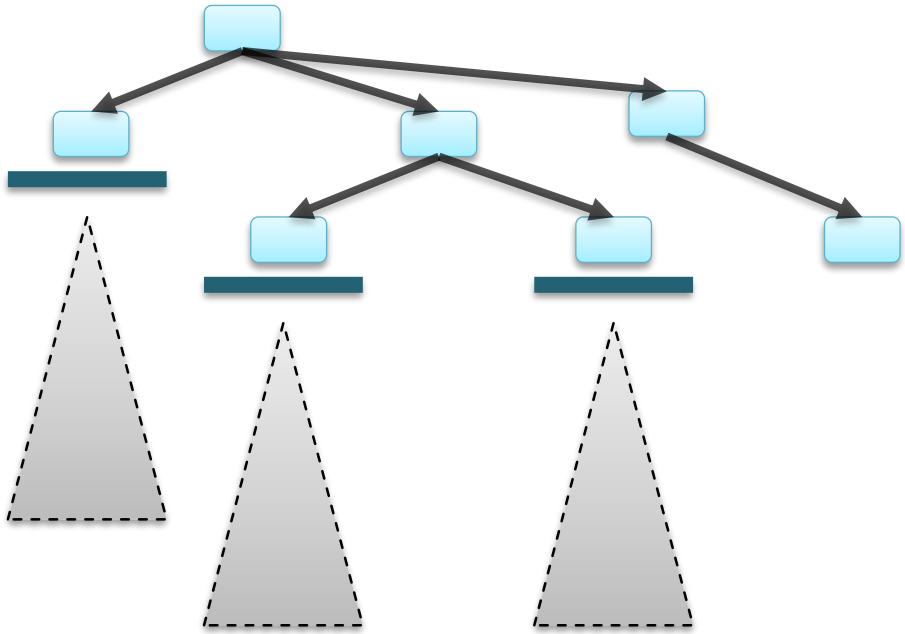
- With a **domain-configurable planner**:
  - We *could* provide *domain-specific heuristics*
    - Strongly discouraging the destruction of goals in Emergency Services Logistics
    - Would keep the *option* to investigate such actions later (not necessary!)
  - We can directly provide stronger domain-specific **pruning criteria**



# Planning with Control Formulas

# Control Formulas



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- **Control formulas**: One way of specifying **when** to prune
  - Motivation
  - Examples
  - Formalism
  - Evaluation of control formulas

# Precondition Control



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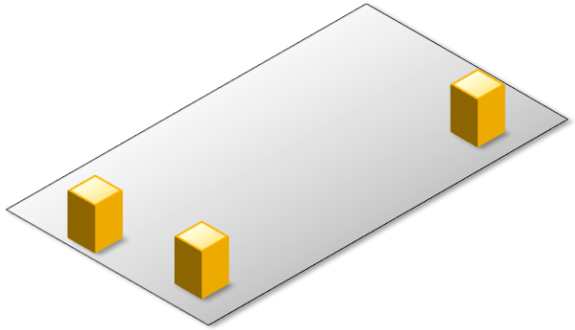
## Simplest control information: **Precondition Control**

- **operator** pickup(*robot*, *crate*, *location*)
  - **precond**:
    - at(*robot*, *location*), at(*crate*, *location*)
    - handempty(*robot*)
    - …and **the goal doesn't require that *crate* should end up at *location***!



How to express this, given that the goal requires at(*crate*,*loc*)?

- Alternative 1: **New predicate** "destination(*crate*, *loc*)"
  - *Duplicates* the information already specified in the goal
  - **precond**: ¬destination(*crate*, *location*)

Supported by all planners

- Alternative 2: **New language extension** "goal(ϕ)"
  - Evaluated in the set of goal states, not in the current state
  - **precond**: ¬**goal**(at(*crate*, *location*))

Requires extensions, but more convenient

# State Constraints



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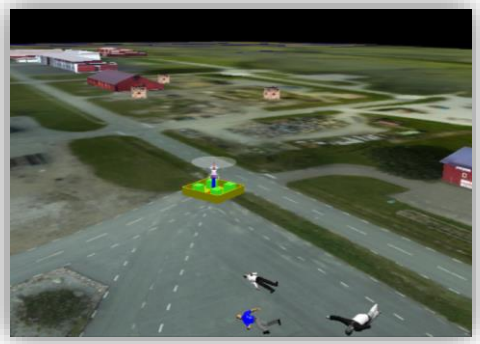
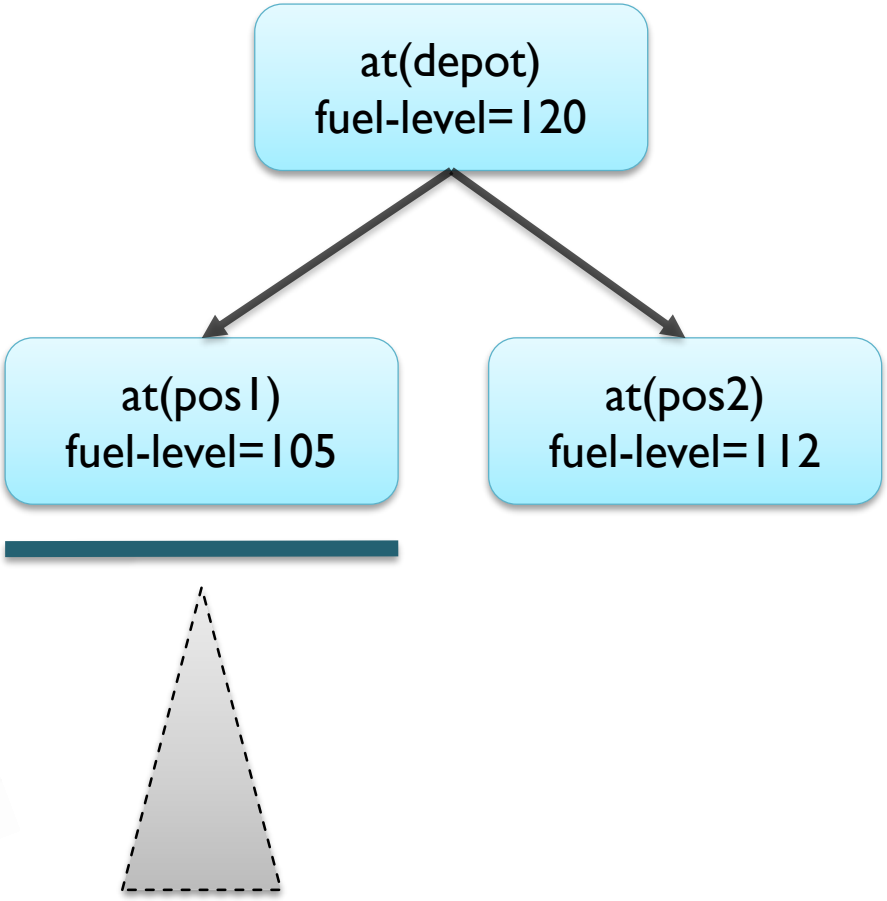
- A UAV should never be where it **can't reach** a refueling point
  - Can't possibly extend such plans into solutions






Reaching nearest refueling point requires 108 fuel

# State Constraints



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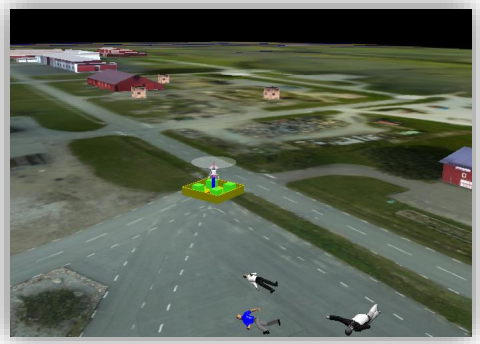
- A UAV should never be where it **can't reach** a refueling point
  - If this happens in a plan, we can't possibly extend it into a solution satisfying the goal
- How to express this?



## Using **preconditions** again?

Must be verified for **every** action:
fly, scan-area, take-off, …

Must be checked even when the UAV is idle, hovering

Inconvenient!

## Using **state constraints**?

Defined **once**,
applied to **every generated state**

$\forall(u:\text{uav})$ [
  $\exists(rp:\text{refueling-point})$ [
    dist(u,rp) * fuel-usage(u) < fuel-avail(u)
  ]
]

Comparatively simple extension!

# Testing State Constraints



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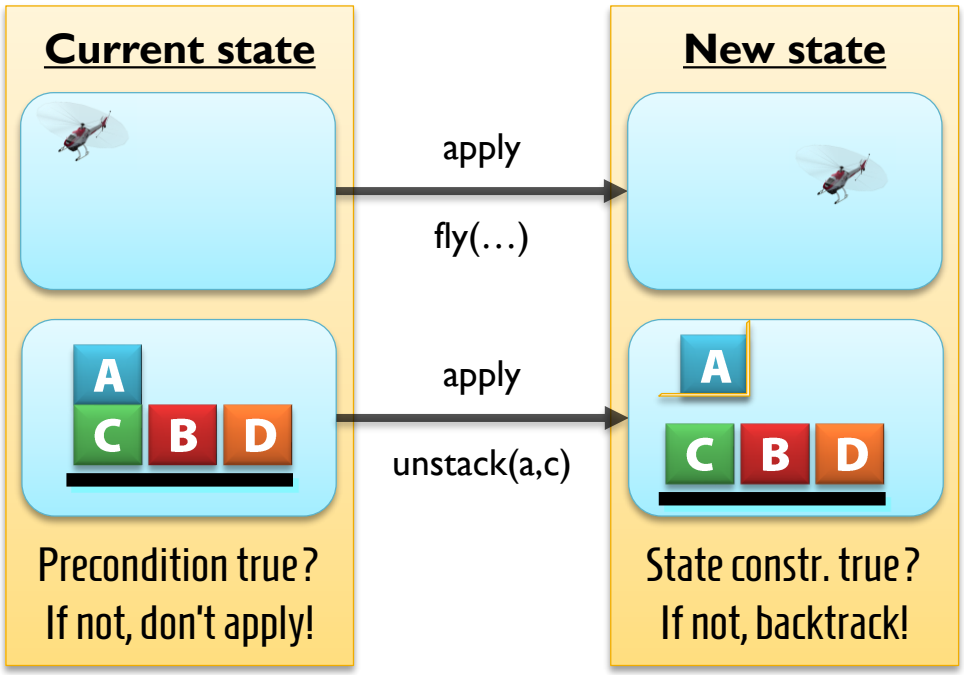
- Testing such **state constraints** is simple
  - Apply an action ➔ new state is generated
    - Formula false in that state ➔ Prune!
  - Similar to preconditions
    - But tested in the state **after** an action is applied, not **before**!



# Temporal Conditions (1)



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- A package on a carrier should **remain there** until it reaches its destination
  - For any plan $\pi$ where we move it prematurely, there is a more efficient plan $\pi'$ where we don't

How to express this as a single formula?

# Temporal Conditions (2)



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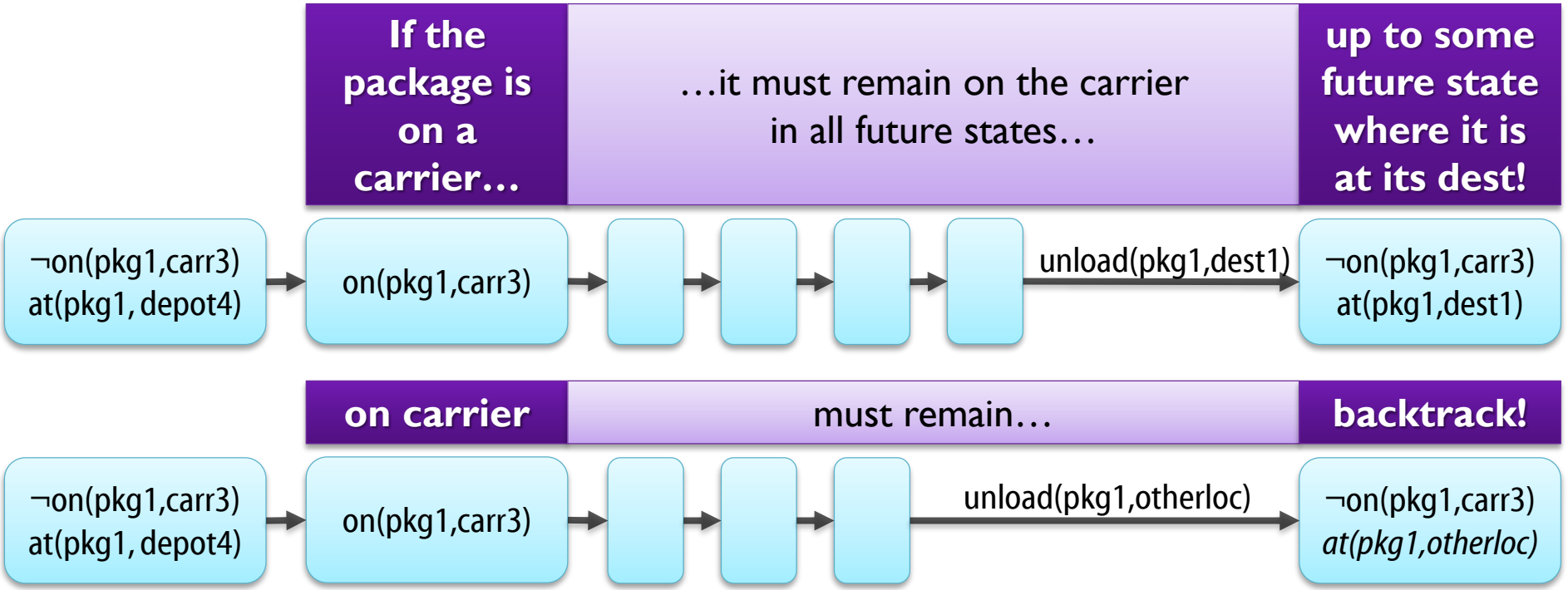
- "A package on a carrier should **remain** there **until** it reaches its destination"




We need a formula constraining an entire **state sequence**, not a single state!

In planning, this is called a **control formula** or **control rule**

# Linear Temporal Logic



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**We need to extend the logical language!**

- One possibility: Use **Linear Temporal Logic** (as in TLplan)
  - All formulas evaluated relative to a *state sequence* and a *current state*
  - Assuming that $f$ is a formula:
    - $\bigcirc f$ – (**next** $f$) — $f$ is true in the next state
    - $\Diamond f$ – (**eventually** $f$) — $f$ is true either now **or** in some future state
    - $\Box f$ – (**always** $f$) — $f$ is true now **and** in all future states
    - $f_1 \, U \, f_2$ – (**until** $f_1$ $f_2$) — ($f_2$ is true now), **or** ($f_2$ is true in some future state s' and $f_1$ is true in all states until/before then)


Formulas true in <**s0**,s1,s2>:
(on A C)
(**next** (holding A))
(**next** (**next** (on A B))
(**until** (clear B) (on A B))

Formulas true in <**s1**,s2>:
(ontable B)
(holding A)
(**next** (on A B)
(**until** (clear B) (on A B))

# Control Formula



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- "A package on a carrier should **remain** there **until** it reaches its destination"

(forall (?var) (type-predicate ?var) ϕ):
$\forall v.\, \text{type-predicate}(v) \rightarrow \phi$
For all values of ?var that satisfy type-predicate, ϕ must be true

  - (**always**
    (**forall** (?c) (carrier ?c) ;; For all carriers
    (**forall** (?p) (package ?p) ;; For all packages
    (**implies**
    (on-carrier ?p ?c) ;; If the package is on the carrier
    (**until** (on-carrier ?p ?c) ;; ...then it remains on the carrier
    (**exists** (?loc) ;; until there exists a location
    (at ?p ?loc) ;; where it is, and
    (**goal** (at ?p ?loc)))) ;; where the goal says it should be
    ))))

  - Should be true **starting in the initial state**

# Control Formula



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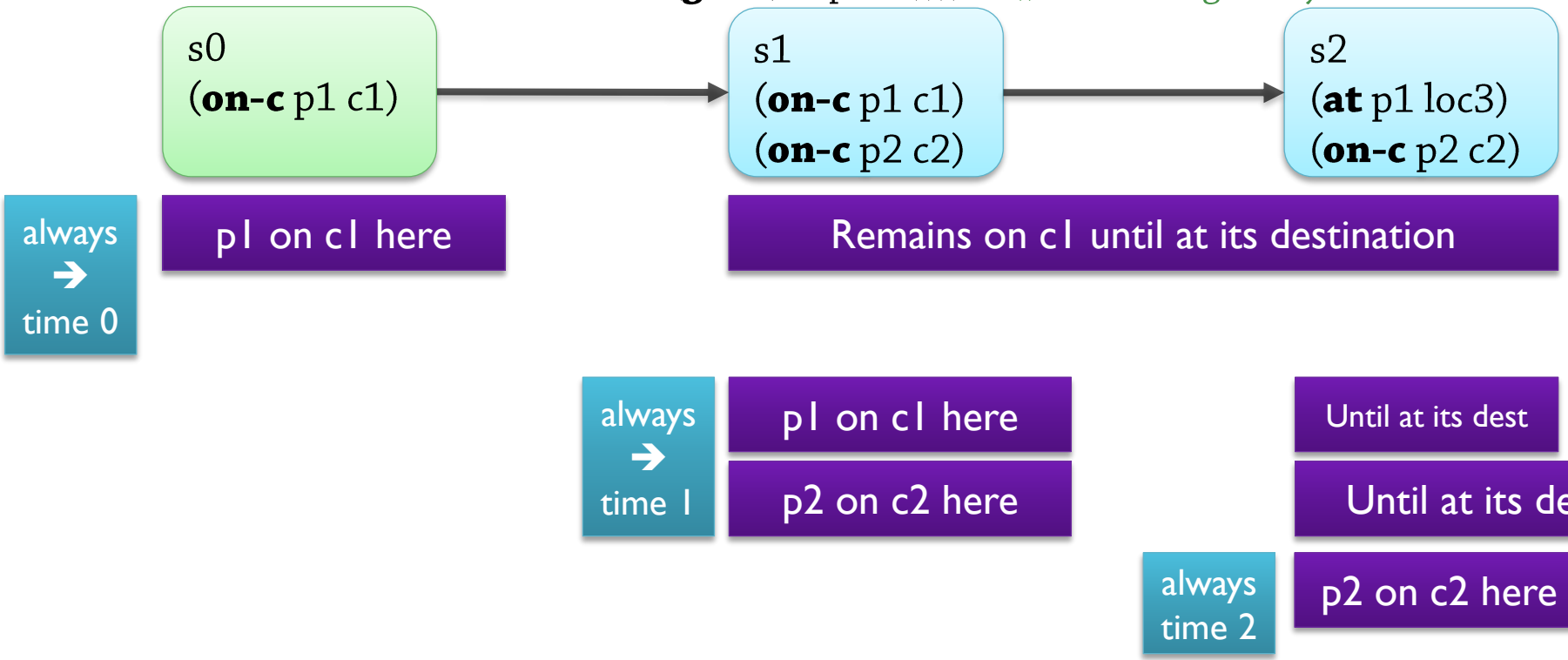
- (**always**
  (**forall** (?c) (carrier ?c)  ;; For all carriers
    (**forall** (?p) (package ?p)  ;; For all packages
      (**implies**
        (on-carrier ?p ?c)  ;; If the package is on the carrier
        (**until** (on-carrier ?p ?c)  ;; …then it remains on the carrier
          (**exists** (?loc)  ;; until there exists a location
            (at ?p ?loc) ;; where it is, and
            (**goal** (at ?p ?loc))))  ;; where the goal says it should be



# Finding Control Formulas

# Blocks World



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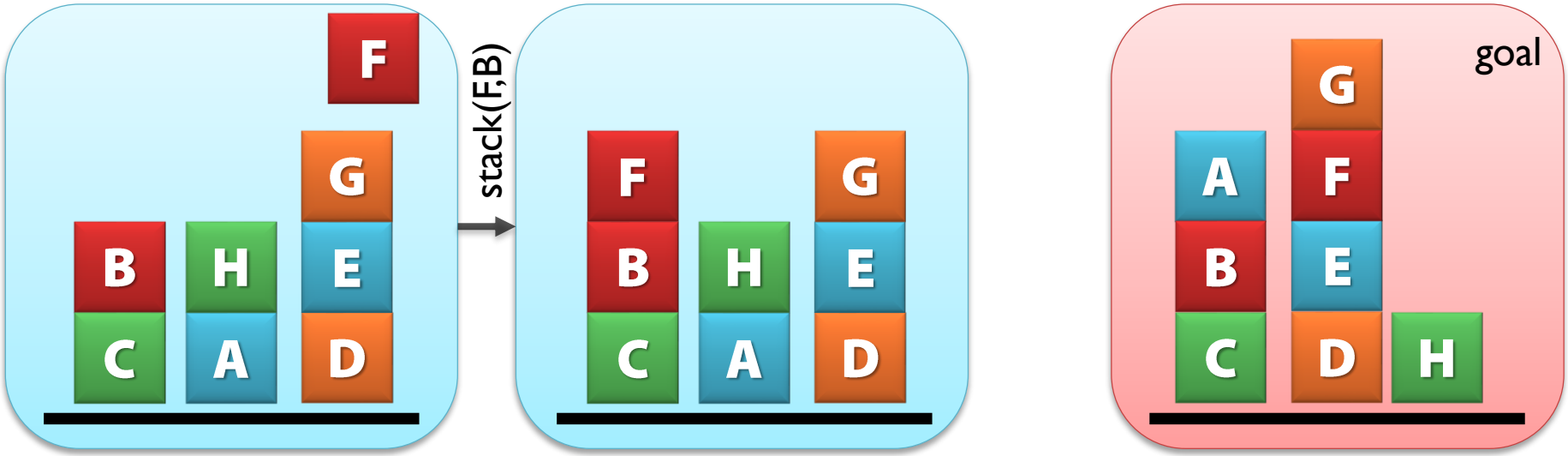
- How do we come up with **good control rules**?
  - Good starting point: "**Don't be stupid!**"
  - **Trace** the search process – suppose the planner tries this:




  - Placing **F on top of B** is stupid, because we'll have to remove it later
    - Would have been better to put F on the table!
  - Conclusion: Should not **extend** a **good tower** the wrong way
    - *Good tower*: a tower of blocks that will never need to be moved

# Blocks World Example (continued)



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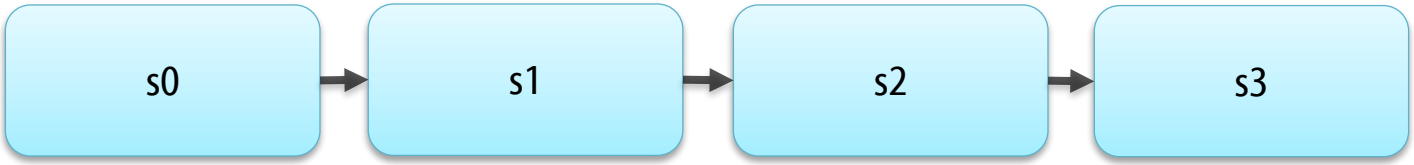
- Rule 1: Every goodtower must always **remain a goodtower**
  - (**forall** (?x) (clear ?x) ;; For all blocks that are clear (at the top of a tower)
    (**implies**
    (goodtower ?x) ;; If the tower is good (no need to move any blocks)
    (**next** (or ;; …then in the next state, either:
    (clear ?x) ;; ?x remains clear (didn't extend the tower)
    (**exists** (?y) (on ?y ?x) ;; or there is a block ?y which is on ?x
    (goodtower ?y)) ;; which is a goodtower
    )))




goodtower(x)? ➔ clear(x) or goodtower(y)

**What about the rest?**

# Blocks World Example (continued)



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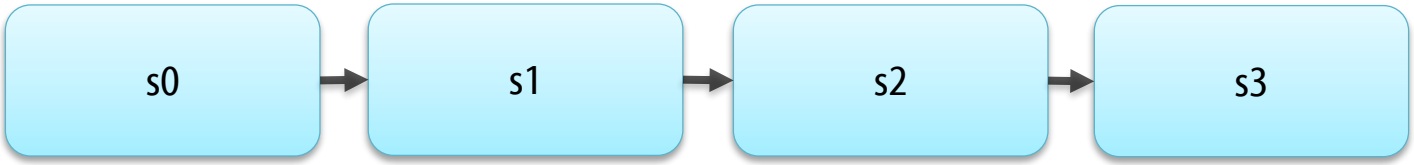
- Rule 1, second attempt:
  - (**always**
    (**forall** (?x) (clear ?x) ;; For all blocks that are clear (at the top of a tower)
    (**implies**
    (goodtower ?x) ;; If the tower is good (no need to move any blocks)
    (**next** (or ;; …then in the next state, either:
    (clear ?x) ;; ?x remains clear (didn't extend the tower)
    (**exists** (?y) (on ?y ?x) ;; or there is a block ?y which is on ?x
    (goodtower ?y)) ;; which is a goodtower
    ))))




goodtower(x)? ➔ clear(x) or goodtower(y)

goodtower(x)? ➔ clear(x) or goodtower(y)

goodtower(x)? ➔ clear(x) or

# Supporting Predicates



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- Some planners allow us to **define** a predicate recursively
  - **goodtowerbelow**(x) means we **will not have to move** x
    - $goodtowerbelow(x) \Leftrightarrow$

      $[ontable(x) \wedge \neg\exists[y{:}\mathbf{GOAL}(on(x,y)]]$

      $\vee$

      $\exists[y{:}on(x,y)]\ \{$

      $\neg\mathbf{GOAL}(ontable(x)) \wedge$

      $\neg\mathbf{GOAL}(holding(y)) \wedge$

      $\neg\mathbf{GOAL}(clear(y)) \wedge$

      $\forall[z{:}\mathbf{GOAL}(on(x,z))]\ (z = y) \wedge$

      $\forall[z{:}\mathbf{GOAL}(on(z,y))]\ (z = x) \wedge$

      $goodtowerbelow(y)$

      $\}$

X is on the table, and shouldn't be on anything else

X is on something else

Shouldn't be on the table, shouldn't be holding it, shouldn't be clear

If x should be on z, then it *is* (z is y)

If z should be on y, then it *is* (z is x)

The remainder of the tower is also good


**goodtowerbelow: B, C, H**

goal

# Supporting Predicates



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- **goodtower**(*x*) means *x* is the block at the top of a good tower
  - *goodtower*(*x*) ⇔ *clear*(x) ∧ ¬ GOAL(*holding*(*x*)) ∧ *goodtowerbelow*(*x*)

- **badtower**(*x*) means *x* is the top of a tower that isn't good
  - *badtower*(*x*) ⇔ *clear*(*x*) ∧ ¬*goodtower*(*x*)


goodtower: B
goodtowerbelow: B, C, H
badtower: G, E
(neither: D, A)

# Blocks World



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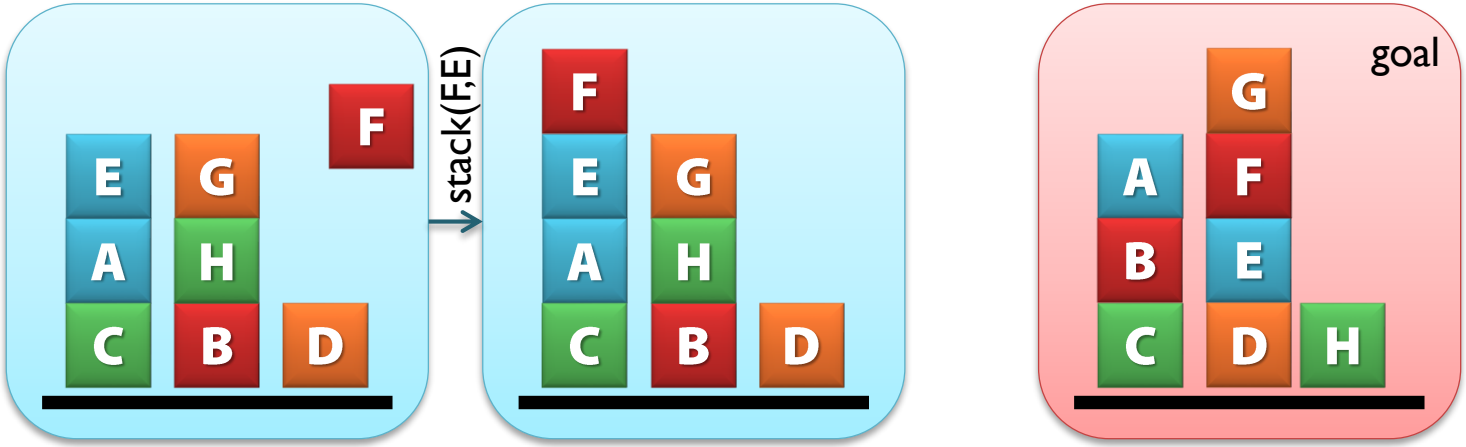
- Step 2: Is this stupid?




- Placing **F on top of E** is stupid, because we have to move E later…
  - Would have been better to put F on the table!
  - But E was not a goodtower, so the previous rule didn't detect the problem
- Never put anything on a badtower!
  - (**always**
    (**forall** (?x) (clear ?x) ;; For all blocks at the top of a tower
    (**implies**
    (badtower ?x) ;; If the tower is bad (must be dismantled)
    (**next** (not (exists (?y) (on ?y ?x)))))))) ;; Don't extend it!

# Blocks World



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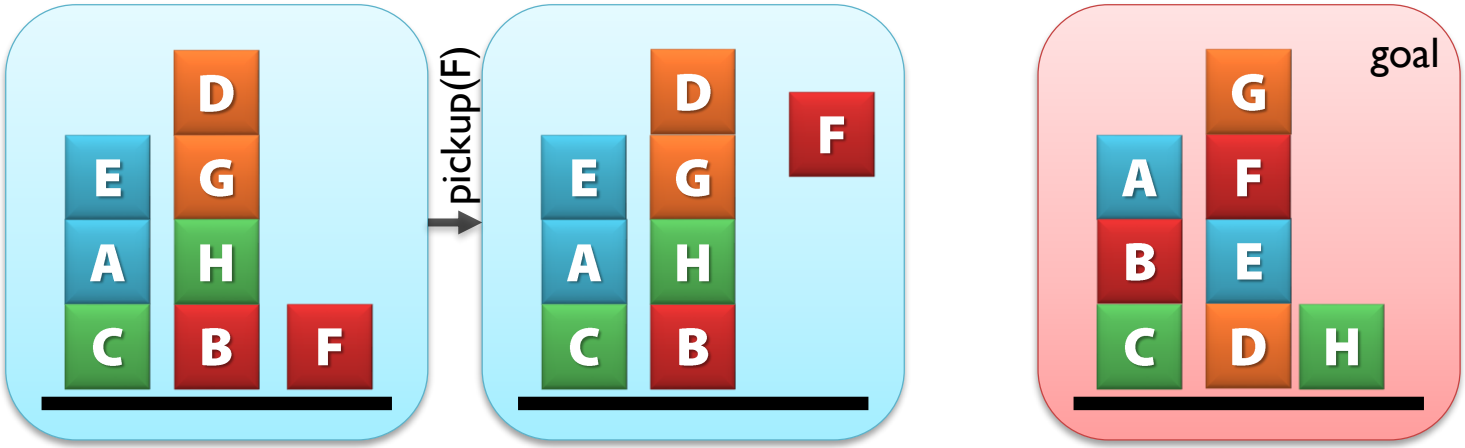
- Step 3: Is this stupid?




  - **Picking up F** is stupid!
    - It is on the table, so we can wait until its destination is ready:


    - (**always**
      (**forall** (?x) (clear ?x)  ;; For all blocks at the top of a tower
        (**implies**
          (**and** (ontable ?x)
            (exists (?y) (goal (on ?x ?y)) (not (goodtower ?y)))
          (**next** (not (holding ?x)))))))

# Pruning using Control Formulas

# Pruning using Control Formulas



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- How do we decide **when to prune** the search tree?
  - Obvious idea:
    - Take the **state sequence** corresponding to the **current action sequence**
    - **Evaluate** the formula over that sequence
    - If it is false: Prune / backtrack!

# Evaluation 1



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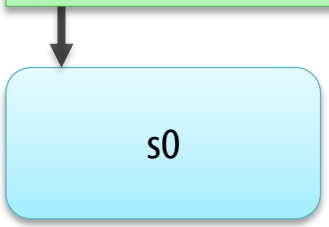
- Problem:
  - (**always**
    (**forall** (?c) (carrier ?c) ;; For all carriers
    (**forall** (?p) (package ?c) ;; For all packages
    (**implies**
    (on-carrier ?p ?c) ;; If the package is on the carrier
    (**until** (on-carrier ?p ?c) ;; …then it remains on the carrier
    (**exists** (?loc) ;; until there exists a location
    (at ?p ?loc) ;; where it is, and
    (**goal** (at ?p ?loc)))) ;; where the goal says it should be
    ))))

No package on a carrier
in the initial state:
Everything is OK




**”Every boat I own
is a billion-dollar yacht
(because I own zero boats)”**

# Evaluation 2



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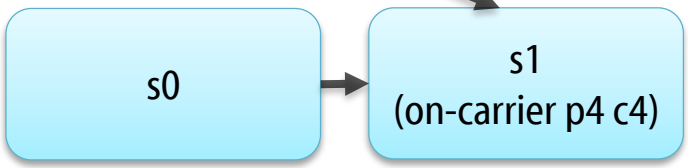
- Problem:
  - (**always**
    (**forall** (?c) (carrier ?c) ;; For all carriers
    (**forall** (?p) (package ?c) ;; For all packages
    (**implies**
    (on-carrier ?p ?c) ;; If the package is on the carrier
    (**until** (on-carrier ?p ?c) ;; …then it remains on the carrier
    (**exists** (?loc) ;; until there exists a location
    (at ?p ?loc) ;; where it is, and
    (**goal** (at ?p ?loc)))) ;; where the goal says it should be
    ))))

**When we add an action placing a package on a carrier…**

**…there is no future state where the package is at its destination!**




The formula is violated,
but only because the solution is not *complete* yet!
We must be allowed to continue,
generating new states…

# Evaluation 3: What's Wrong?



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- We had an **obvious** idea:
  - Take the state sequence corresponding to the current plan
  - Evaluate the formula over that sequence
  - If it is false: Prune / backtrack!

- This is actually **wrong**!
  - Formulas should hold in the state sequence of the **solution**
  - But they don't have to hold in every **intermediate** action sequence…

# Analysis



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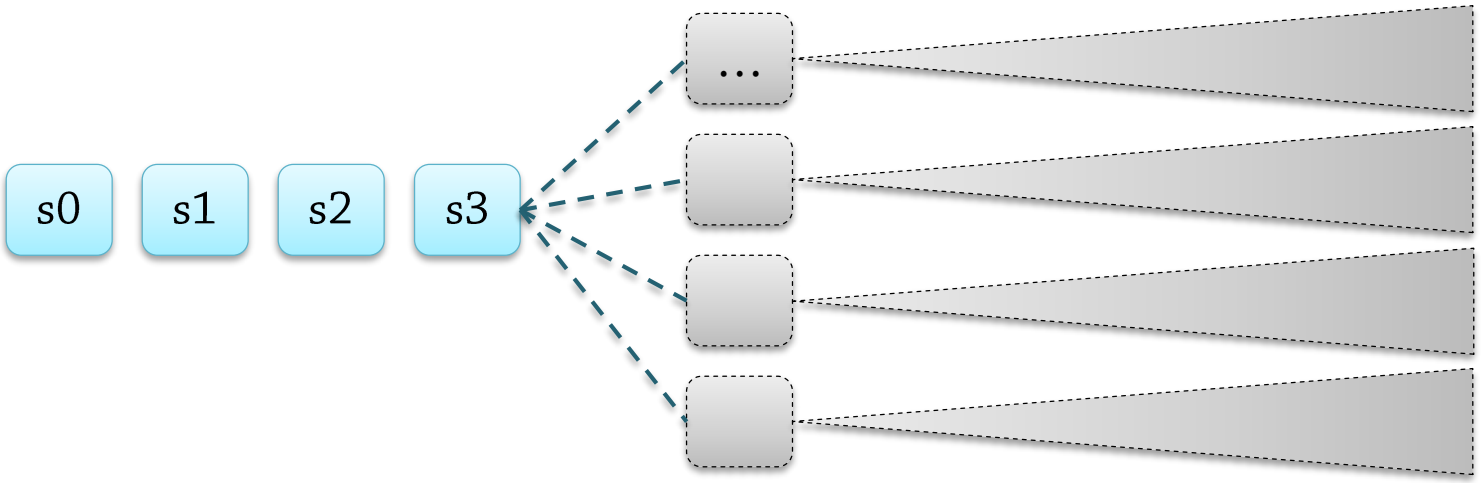
- Analysis:




We have applied some actions, yielding a sequence of states

We intend to generate additional actions and states, but right now we don't know which ones

**The control formula should be satisfied by the entire state sequence corresponding to a solution**

We only know **some** of those states

Should only backtrack if we can prove that you **can't** find **additional** states so that the control formula becomes true

# Analysis 2



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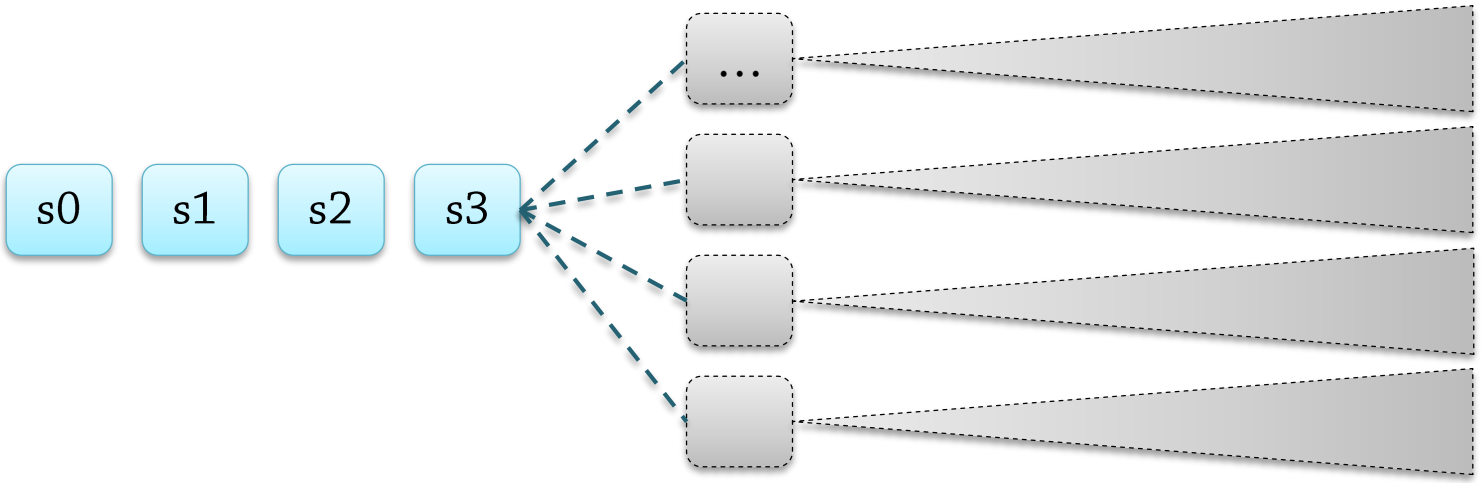
- Analysis 2:




**The control formula should be satisfied by the entire state sequence corresponding to a solution**

Evaluate those **parts** of the formula that refer to known states

**Leave** other parts of the formula to be evaluated later

**If the result can be proven to be FALSE, then backtrack**

# Progressing Temporal Formulas (1)



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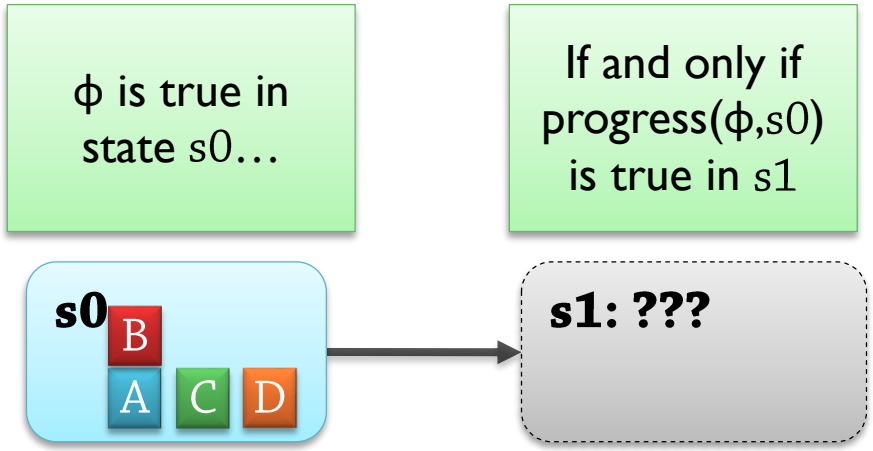
- We use **formula progression**
  - We **progress** a formula Φ through a single **state** *s* at a time
    - First the initial state, then each state generated by adding an action
  - The result is a **new formula**
    - Containing conditions that we must "postpone", evaluate starting in the **next** state



# Progressing Temporal Formulas (2)



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- More intuitions?
  - Suppose you are reading a book. A *page* is analogous to a *state*.

| | | |
|---|---|---|
| "The figure appears 5 pages from here" is true on page 7 | ⟺ | "The figure appears 4 pages from here" is true on page 8 |
| "Fig 1 appears 3 pages from here and fig 2 appears 5 pages from here" is true on page 7 | ⟺ | "Fig 1 appears 2 pages from here and fig 2 appears 4 pages from here" is true on page 8 |
| "Starting where I am now, there's a figure on every page" is true on page 7 | ⟺ | There actually is a figure on page 7, and "Starting where I am now, there's a figure on every page" is true on page 8 |
| "If there's a figure on this page, there is no figure on the next page [otherwise I don't care]" is true on page 7 | ⟺ | Check if there *is* a figure on this page. If so: f="There's no figure on this page". Otherwise: f="true". Check whether f is true on page 8. |

# Progressing Temporal Formulas (3)



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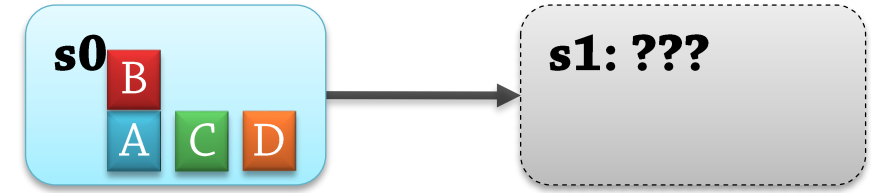
- Base case: Formulas **without** temporal operators ("on(A,B) → on(C,D)")
  - Must be true **here**, in **this** state
  - progress(Φ, s) = TRUE if Φ holds in s (we already know how to test this)
  - progress(Φ, s) = FALSE otherwise




If "f → g" is true in state s0…

Then progress returns TRUE, which is true in s1

If "f → g" is false in state s0…

Then progress returns FALSE, which is false in s1

# Progressing Temporal Formulas (4)



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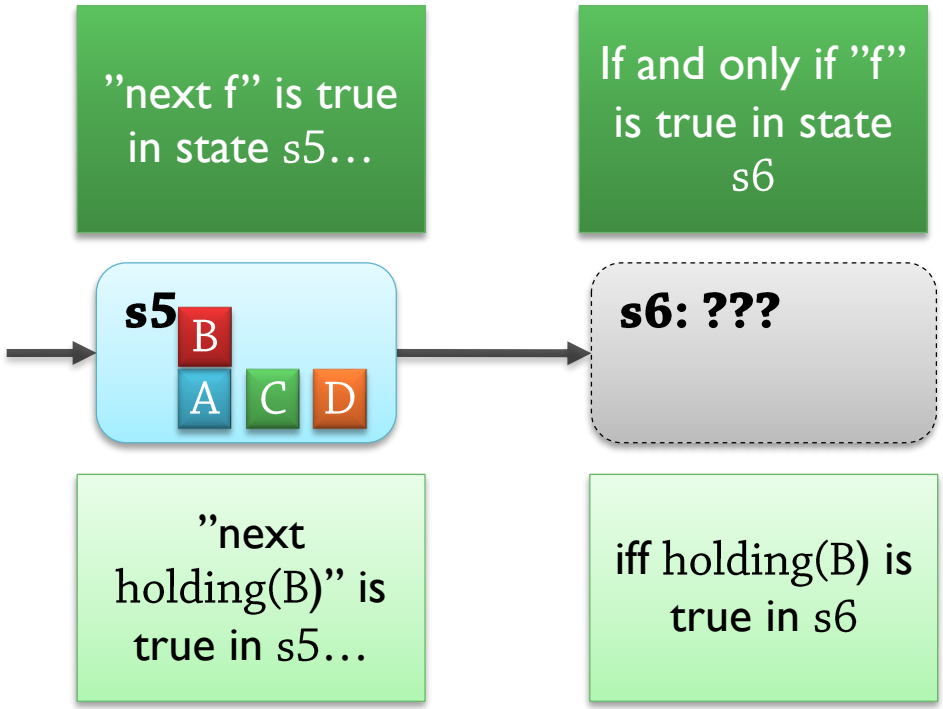
- Simple case: **next**
  - progress(next *f*, s) = f
    - Because ”next f” is true in this state iff f is true in the next state
    - This is by definition what progress() should return!




**Additional cases are discussed in the book (always, eventually, until, …)**

# Progression in Depth First Search



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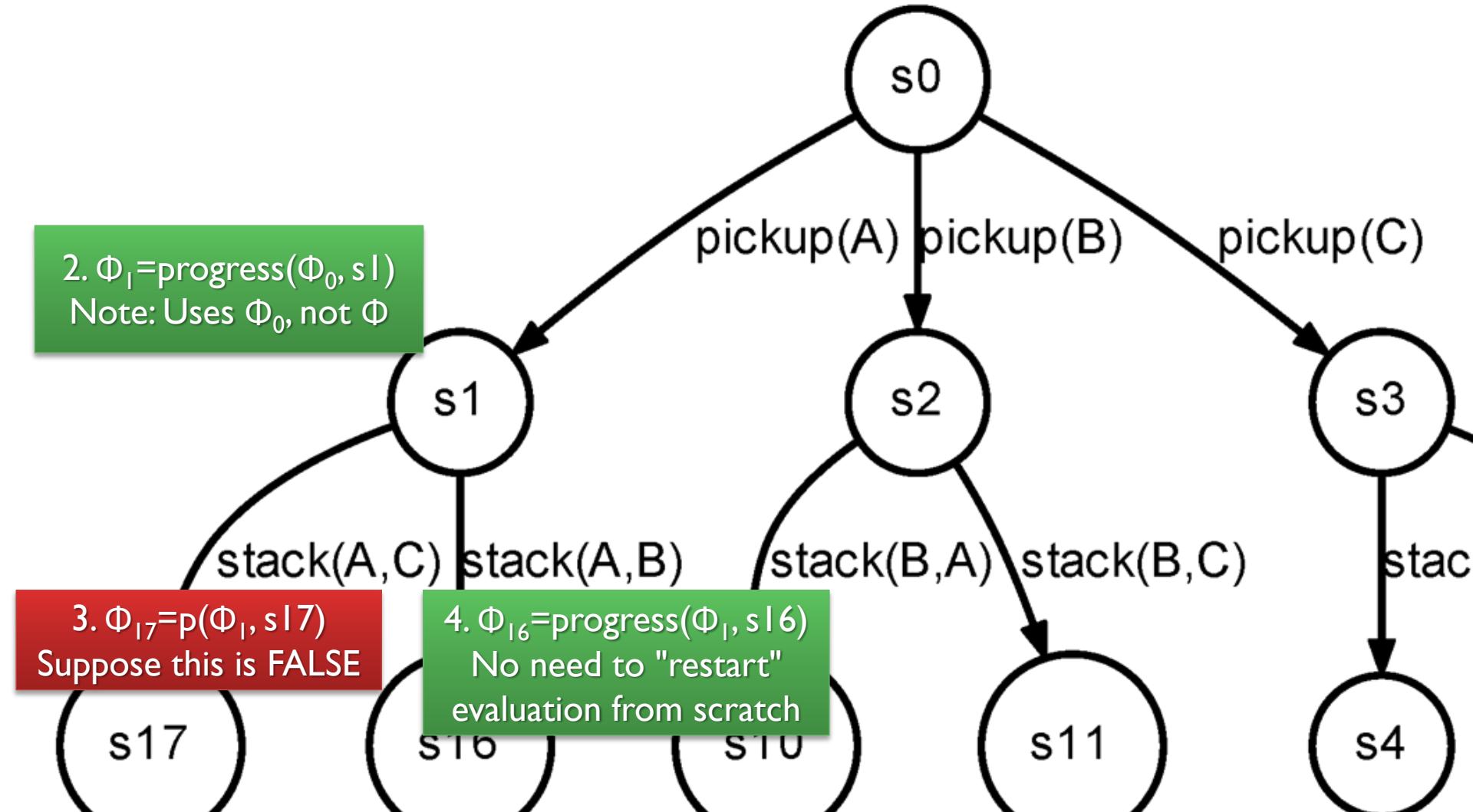
Φ = original control formula

1. Calculate and store $\Phi_0$=progress(Φ, s0)
Resolves all references to values in state s0!




2. $\Phi_1$=progress($\Phi_0$, s1)
Note: Uses $\Phi_0$, not Φ

3. $\Phi_{17}$=p($\Phi_1$, s17)
Suppose this is FALSE

4. $\Phi_{16}$=progress($\Phi_1$, s16)
No need to "restart" evaluation from scratch

# DFS with Pruning



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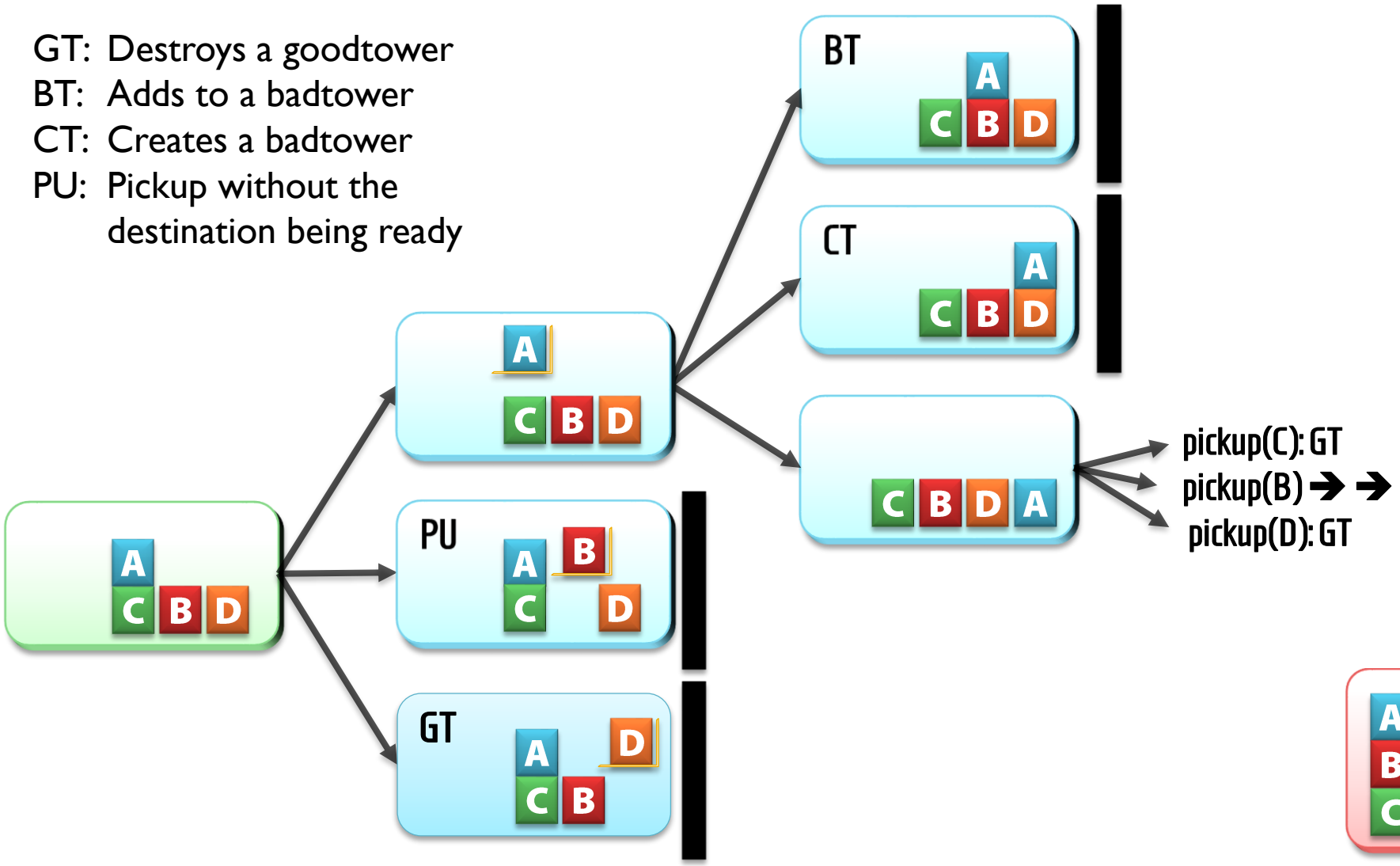
GT: Destroys a goodtower
BT: Adds to a badtower
CT: Creates a badtower
PU: Pickup without the destination being ready



# Performance



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- 2000 International Planning Competition
  - **TALplanner** received the top award for a "hand-tailored" (i.e., domain-configurable) planner
- 2002 International Planning Competition
  - **TLplan** won the same award
- Both of them (as well as SHOP, an HTN planner):
  - Ran **several orders of magnitude** faster than the "fully automated" (i.e., not domain-configurable) planners
    - especially on large problems
  - Solved problems on which other planners ran out of time/memory
  - Required a **considerably greater modeling effort** for each planning domain

# TALplanner: A demonstration

# TALplanner Example Domain



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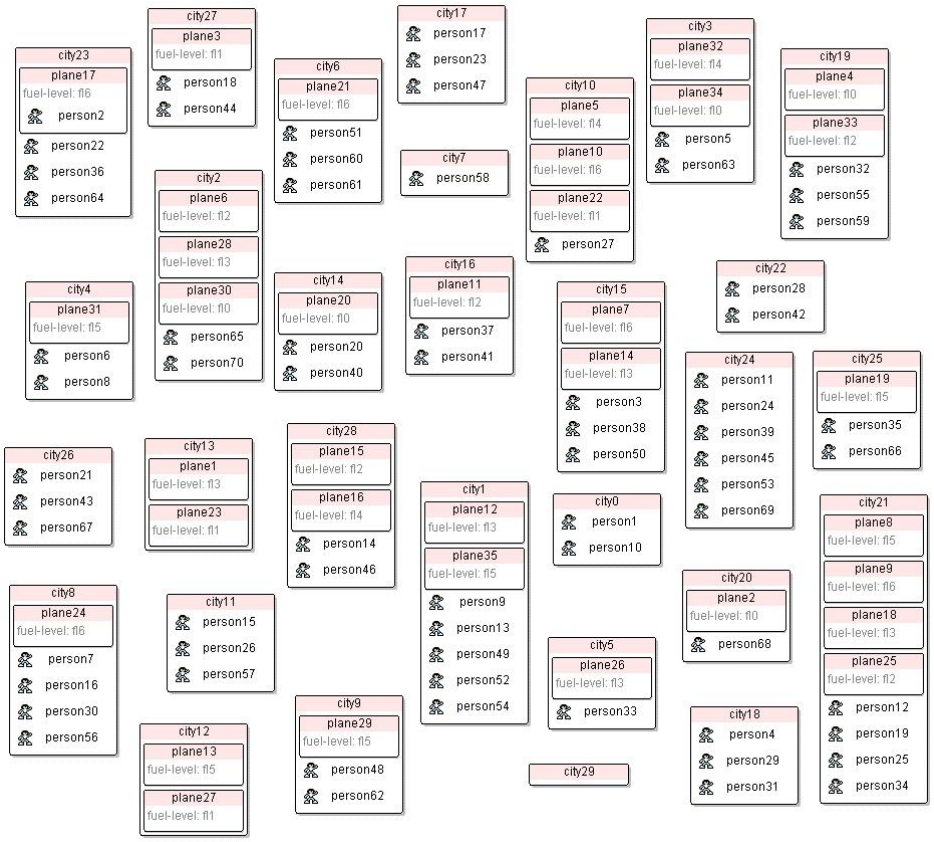
- Example Domain: ZenoTravel
  - Planes move people between cities (**board**, **debark**, **fly**)
  - Planes have limited fuel level; must **refuel**
  - Example instance:
    - 70 people
    - 35 planes
    - 30 cities



# ZenoTravel Problem Instance



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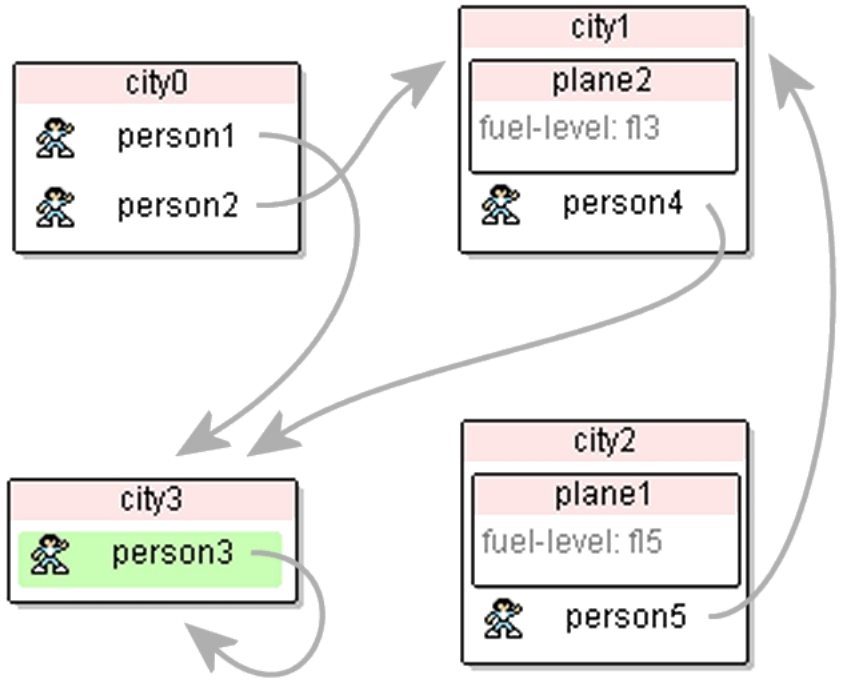
- A smaller problem instance



# What Just Happened?



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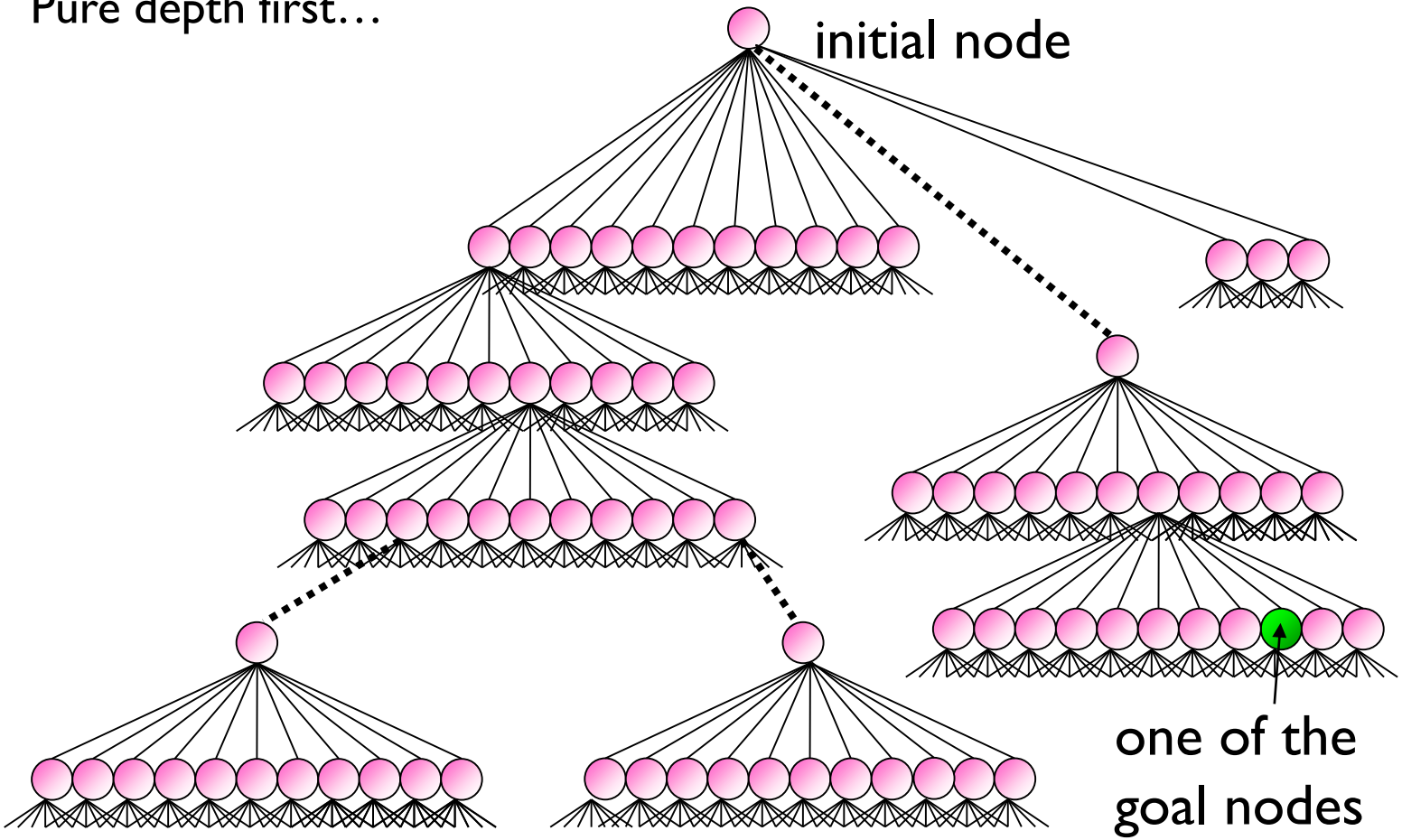
- No additional domain knowledge specified yet!
  - Pure depth first…



# Control Rules



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- **First problem** in the example:
  - Passengers debark whenever possible.
  - Rule: "At any timepoint, if a passenger debarks, he is at his goal."

  - #**control** :name "only-debark-when-in-goal-city"
    **forall** t, *person*, *aircraft* [
    [t] **in**(*person*, *aircraft*) ⟶
    [t+1] **in**(*person*, *aircraft*) ∨
    **exists** city [
    [t] **at**(*aircraft*, *city*) ∧
    **goal**(**at**(*person*, *city*)) ] ]

[t]: ”now”
[t+1]: ”next”

# Control Rules



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- **Second problem** in the example:
  - Passengers board planes, even at their destinations
  - Rule: "At any timepoint, if a passenger boards a plane, he was not at his destination."
  - #**control** :name "only-board-when-necessary"

**forall** t, *person*, *aircraft* [
([t] !**in**(*person*, *aircraft*) ∧
[t+1] **in**(*person*, *aircraft*)) ⟶
**exists** *city1*, *city2* [
[t] **at**(*person*, *city1*) ∧
**goal**(**at**(*person*, *city2*)) ∧
*city1* != *city2* ] ]

# Zeno Travel, second attempt



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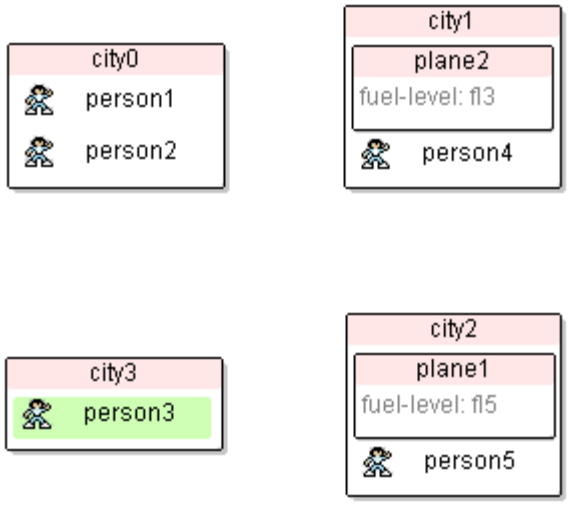

# What's Wrong This Time?



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- Only constrained passengers
- Forgot to constrain airplanes
  - Which cities are reasonable destinations?
  - 1. A passenger's destination
  - 2. A place where a person wants to leave
  - 3. The airplane's destination

# Control Rules



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- #control :name "planes-always-fly-to-goal“
  **forall** t, aircraft, city [
  [t] at(aircraft, city) →
  ([t+1] at(aircraft, city)) |
  **exists** city2 [
  city2 != city &
  ([t+1] at(aircraft, city2)) &
  [t] reasonable-destination(aircraft, city2) ]]
- #**define** [t] reasonable-destination(aircraft, city):
  [t] has-passenger-for(aircraft, city) |
  **exists** person [
  [t] at(person, city) &
  [t] in-wrong-city(person) ] |
  **goal**(at(aircraft, city)) &
  [t] empty(aircraft) &
  [t] all-persons-at-their-destinations-or-in-planes ]

# Zeno Travel, third attempt



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