Non-Deterministic Planning

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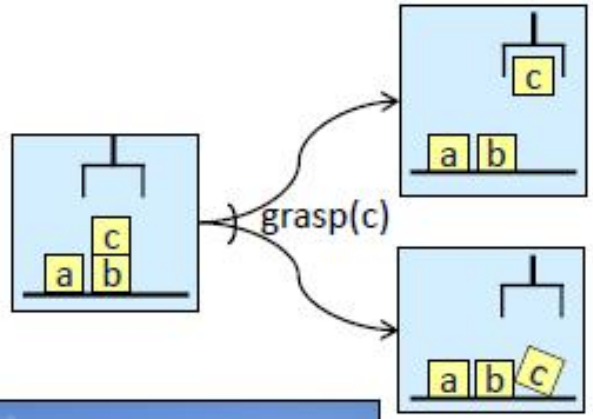
Motivation

- We've assumed action a in state s has just one possible outcome
  - $\gamma(s,a)$



- Often more than one possible outcome
  - Unintended outcomes
  - Exogenous events
  - Inherent uncertainty

Stefan Edelkamp (cf. Book Automated Planning and Acting)

Nondeterministic Planning Domains

- 3-tuple (S, A, γ)
  - S and A – finite sets of states and actions
  - $\gamma: S \times A \rightarrow 2^S$
- $\gamma(s,a)$ = {all possible "next states" after applying action a in state s}
  - a is applicable in state s iff $\gamma(s,a) \neq \emptyset$
- Applicable(s) = {all actions applicable in s} = $\{a \in A \mid \gamma(s,a) \neq \emptyset\}$
- One action representation: n mutually exclusive "effects" lists

$a(z_1, \ldots, z_k)$
pre: $p_1, \ldots, p_m$
eff_1: $e_{11}, e_{12}, \ldots$
eff_2: $e_{21}, e_{22}, \ldots$
…
eff_n: $e_{n1}, e_{n2}, \ldots$

- Problem: n may be combinatorially large
  - Suppose a can cause any possible combination of effects $e_1, e_2, \ldots, e_k$
  - Need $\text{eff}_1, \text{eff}_2, \ldots, \text{eff}_{2^k}$
    - One for for each combination
- For now, ignore most of that
  - states, actions ⇔ nodes, edges in a graph

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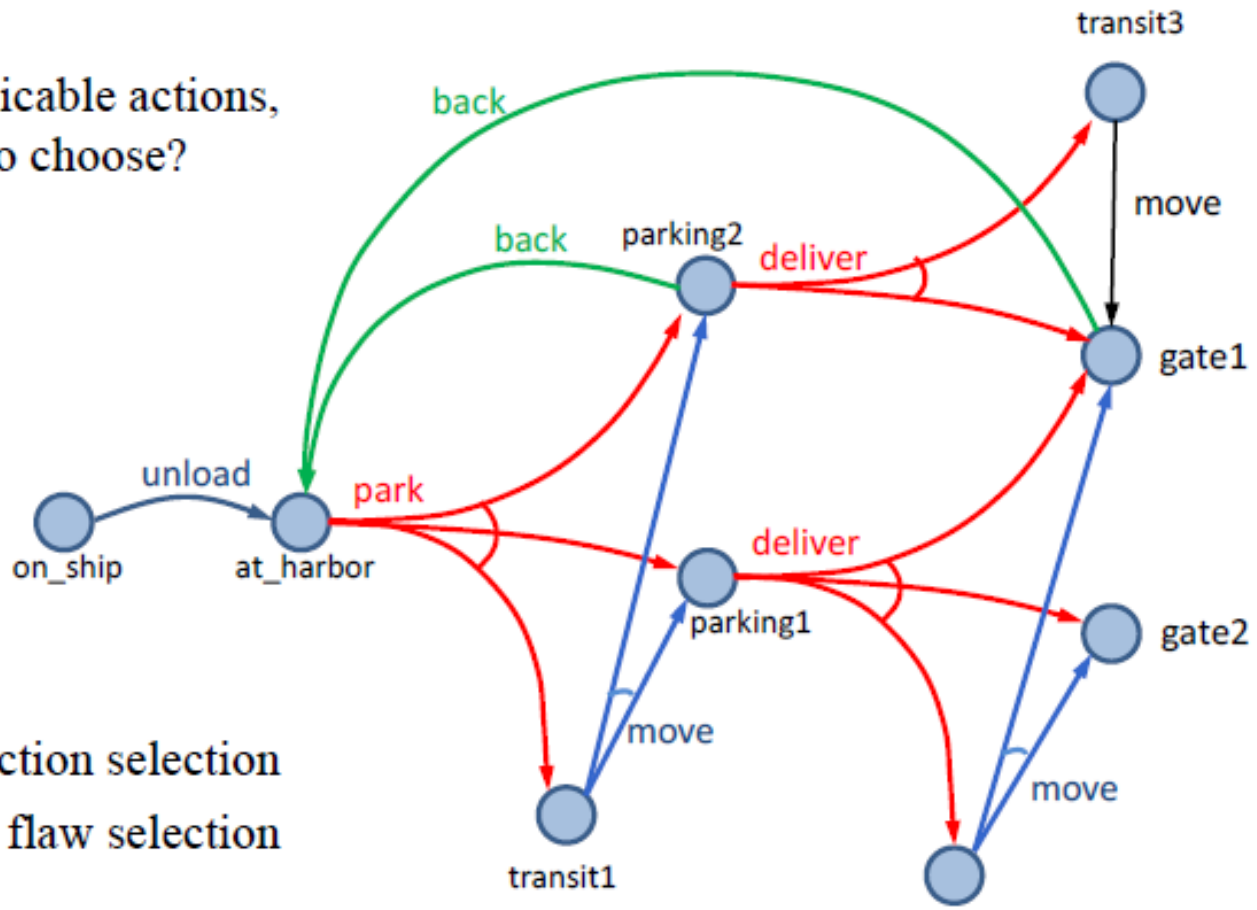
Nondeterministic Planning Domains

- For deterministic planning problems, search space was a graph
- Now it's an AND/OR graph
  - *OR branch*:
    - several applicable actions, which one to choose?
  - *AND branch*:
    - multiple possible outcomes
    - must handle all of them
- Analogy to PSP
  - *OR* branch ⇔ action selection
  - *AND* branch ⇔ flaw selection



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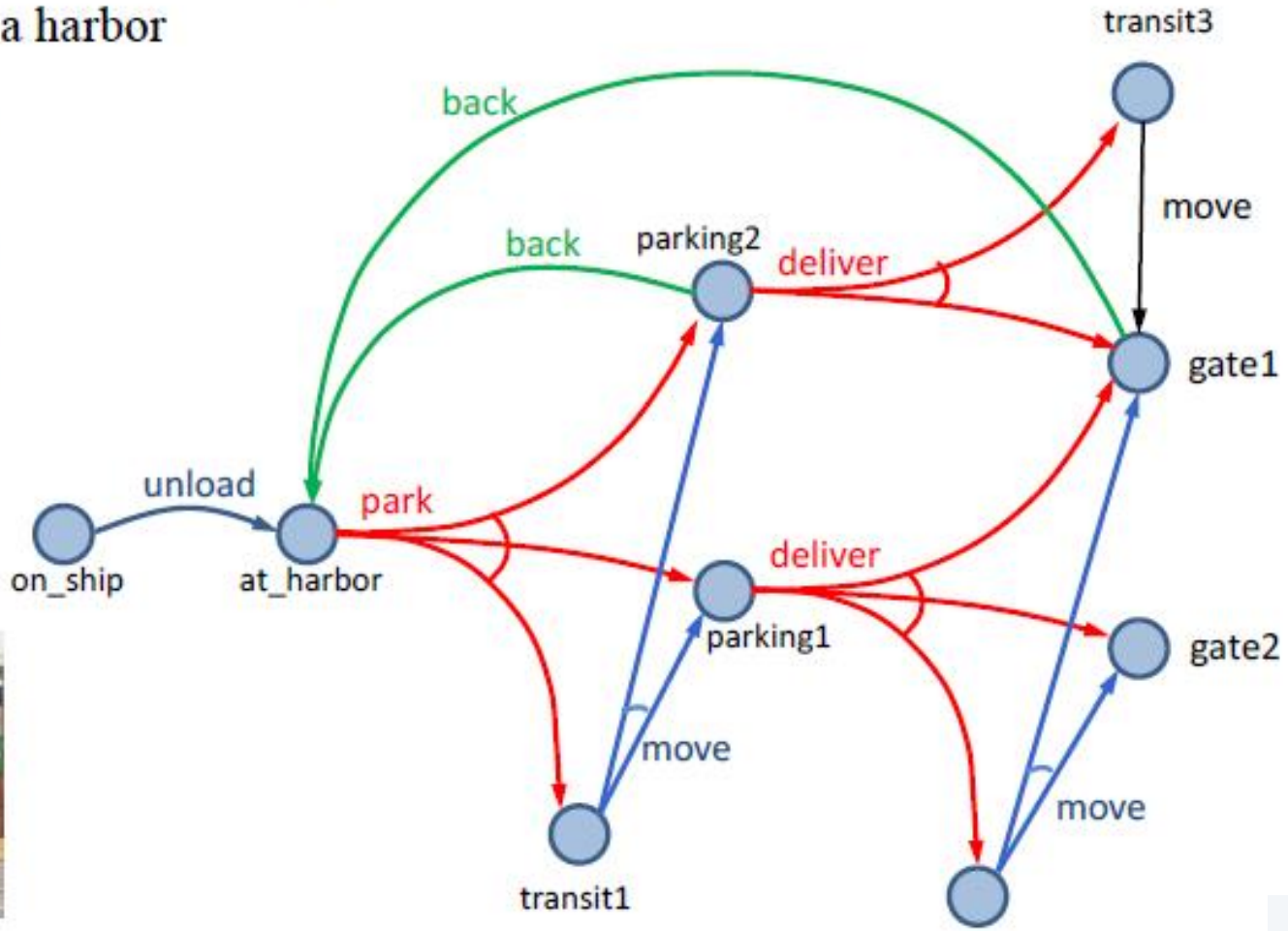
Example

- Very simple harbor management domain
  - Unload a single item from a ship
  - Move it around a harbor



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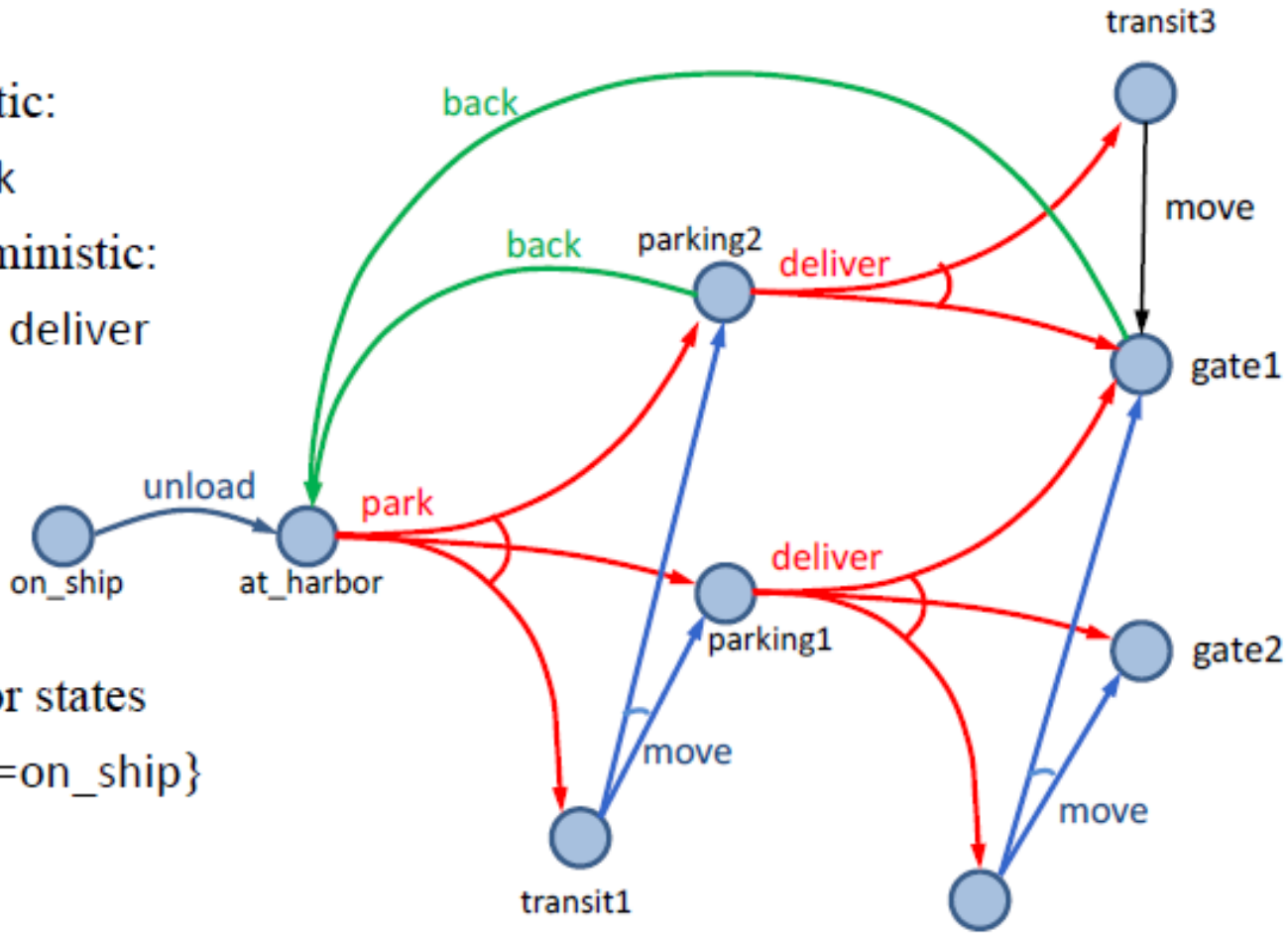
Example

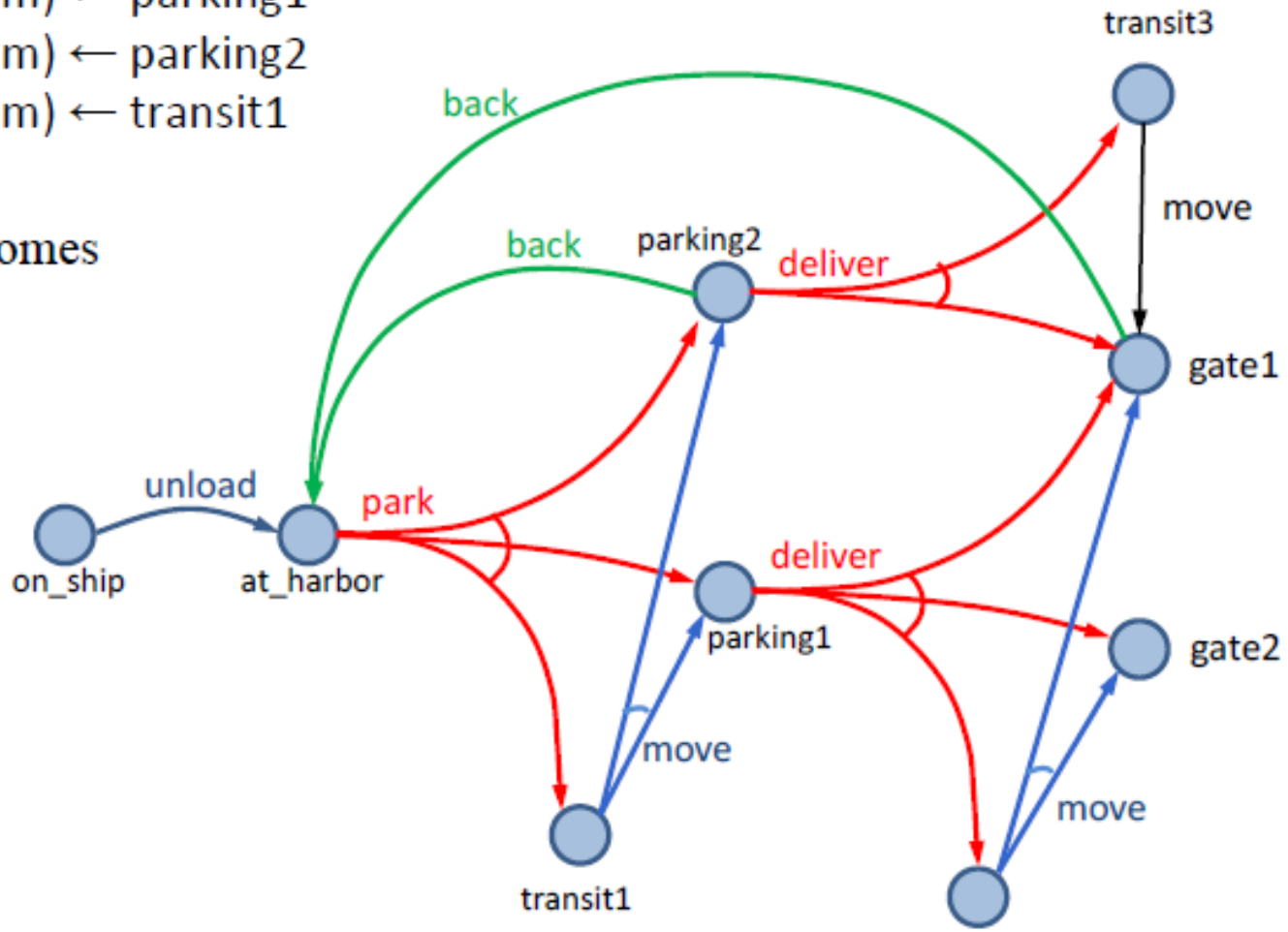
- One state variable: pos(item)
- Five actions
  - Two deterministic:
    - unload, back
  - Three nondeterministic:
    - park, move, deliver
- Simplified names for states
  - For {pos(item)=on_ship} write on_ship



Actions

- park
  - pre: pos(item) = at_harbor
  - eff_1: pos(item) ← parking1
  - eff_2: pos(item) ← parking2
  - eff_3: pos(item) ← transit1

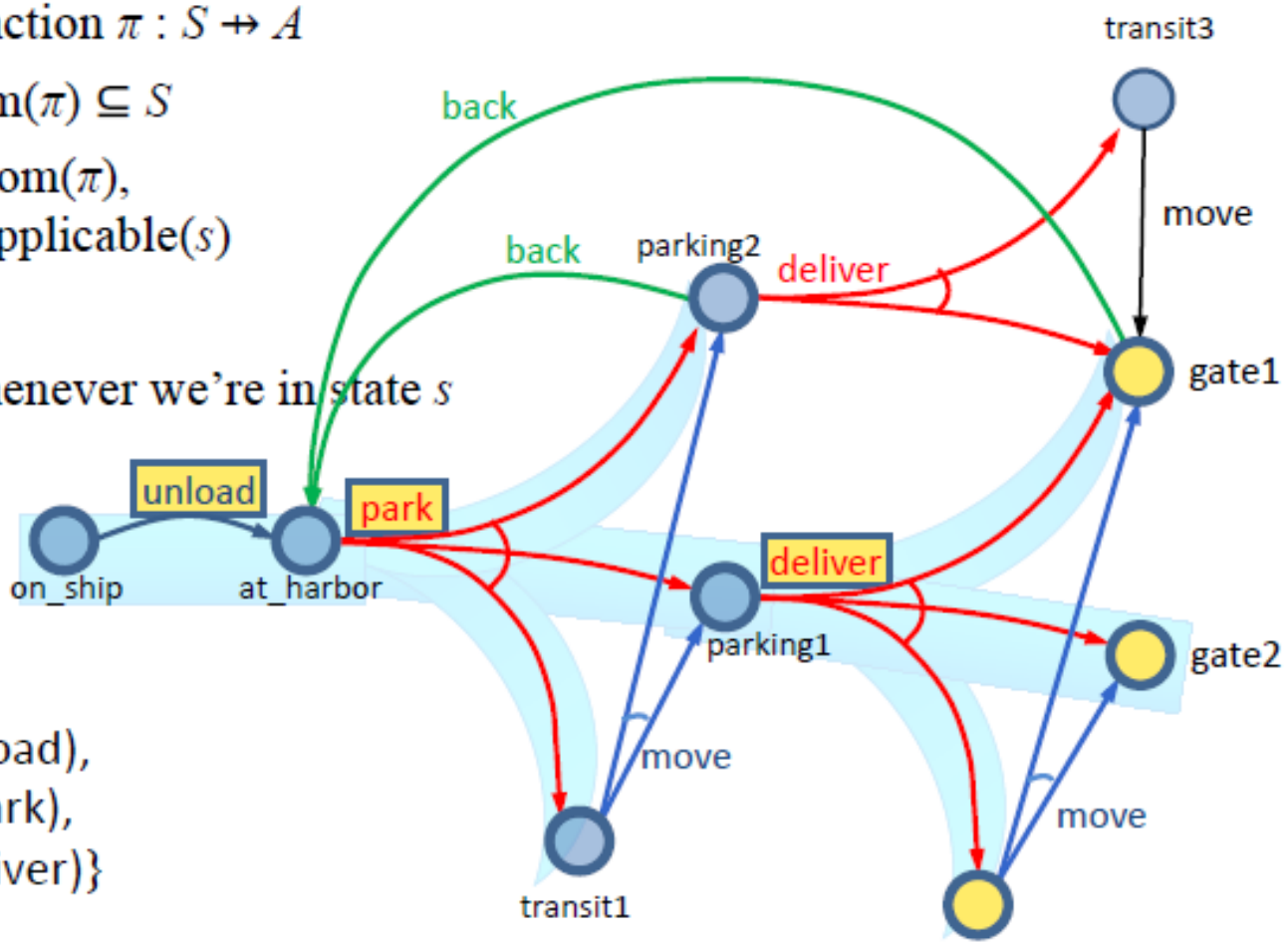
- Three possible outcomes
  - put item in parking1 or parking2 if one of them has space
  - or in transit1 if there's no parking space



~~Plans~~ Policies

- Need something more general than a sequence of actions
  - After park, what do we do next?

- *Policy*: a *partial* function $\pi : S \nrightarrow A$
  - i.e., $\mathrm{Dom}(\pi) \subseteq S$
  - For every $s \in \mathrm{Dom}(\pi)$, require $\pi(s) \in \mathrm{Applicable}(s)$
- Meaning:
  - perform $\pi(s)$ whenever we're in state s



- $\pi_1 = \{(\text{on\_ship}, \text{unload}),$
  $(\text{at\_harbor}, \text{park}),$
  $(\text{parking1}, \text{deliver})\}$

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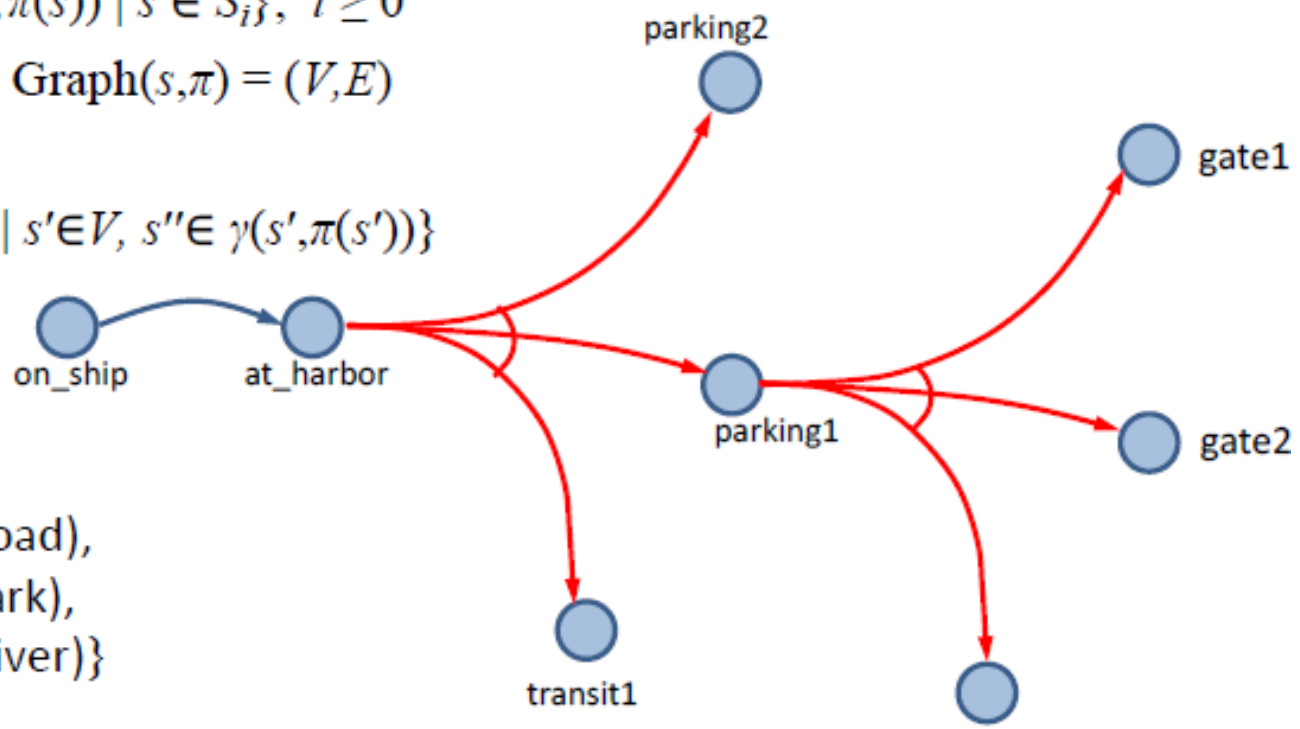
Definitions Over Policies

- *Transitive closure*:
  {all states reachable from s using π}
  - $\hat{\gamma}(s,\pi) = S_0 \cup S_1 \cup S_2 \cup \ldots$
    - $S_0 = \{s\}$
    - $S_{i+1} = \cup\{\gamma(s,\pi(s)) \mid s \in S_i\},\ i \geq 0$
- *Reachability graph*: Graph$(s,\pi) = (V,E)$
  - $V = \hat{\gamma}(s,\pi)$
  - $E = \{(s',s'') \mid s' \in V,\ s'' \in \gamma(s',\pi(s'))\}$
- π_1 = {(on_ship, unload),
  (at_harbor, park),
  (parking1, deliver)}
- *leaves*$(s,\pi) = \hat{\gamma}(s,\pi) \setminus$ Dom(π)
  - may be empty



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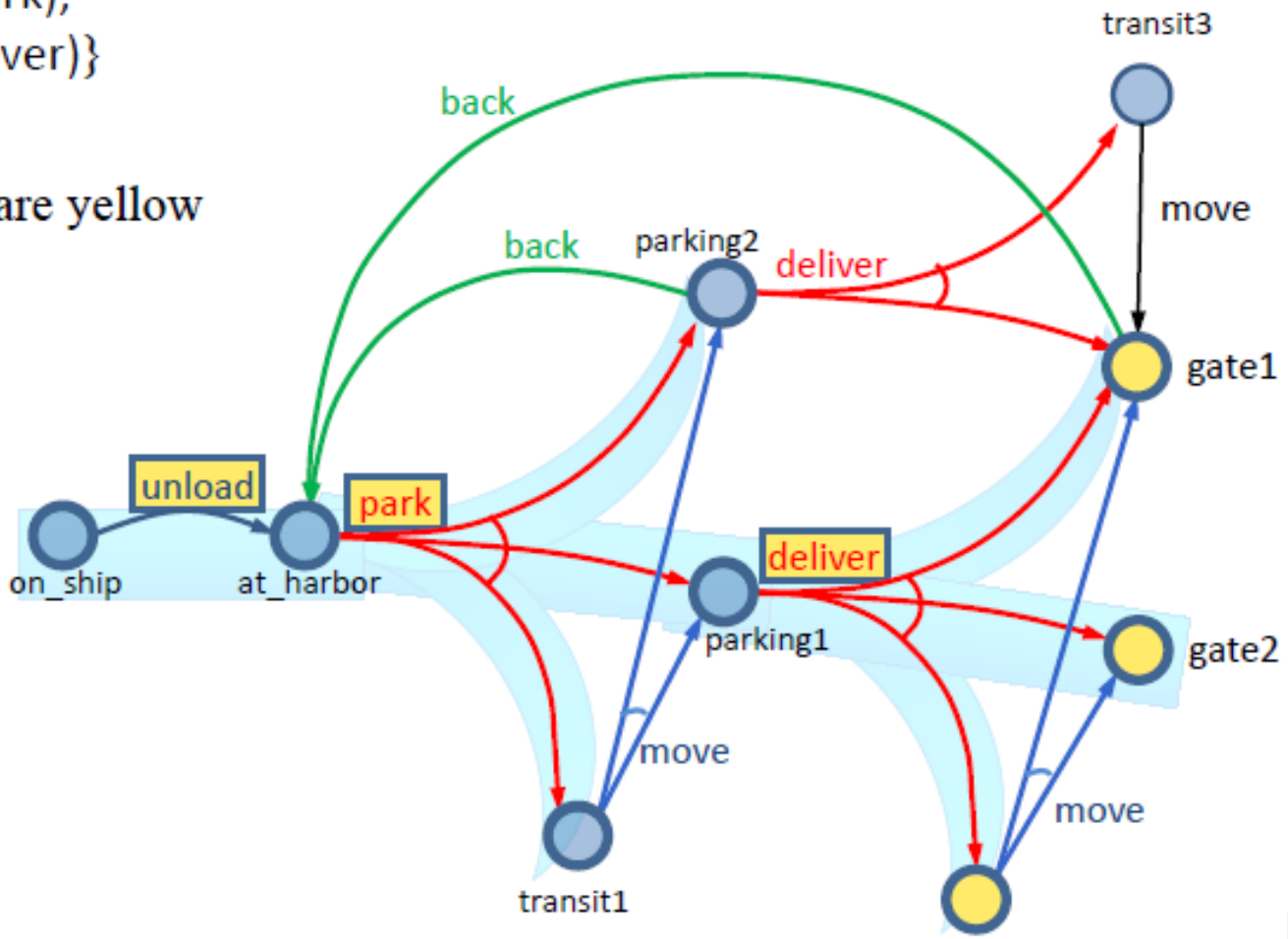
Definitions Over Policies

- π_1 = {(on_ship, unload),
  (at_harbor, park),
  (parking1, deliver)}

- *leaves*(on_ship, π_1) are yellow

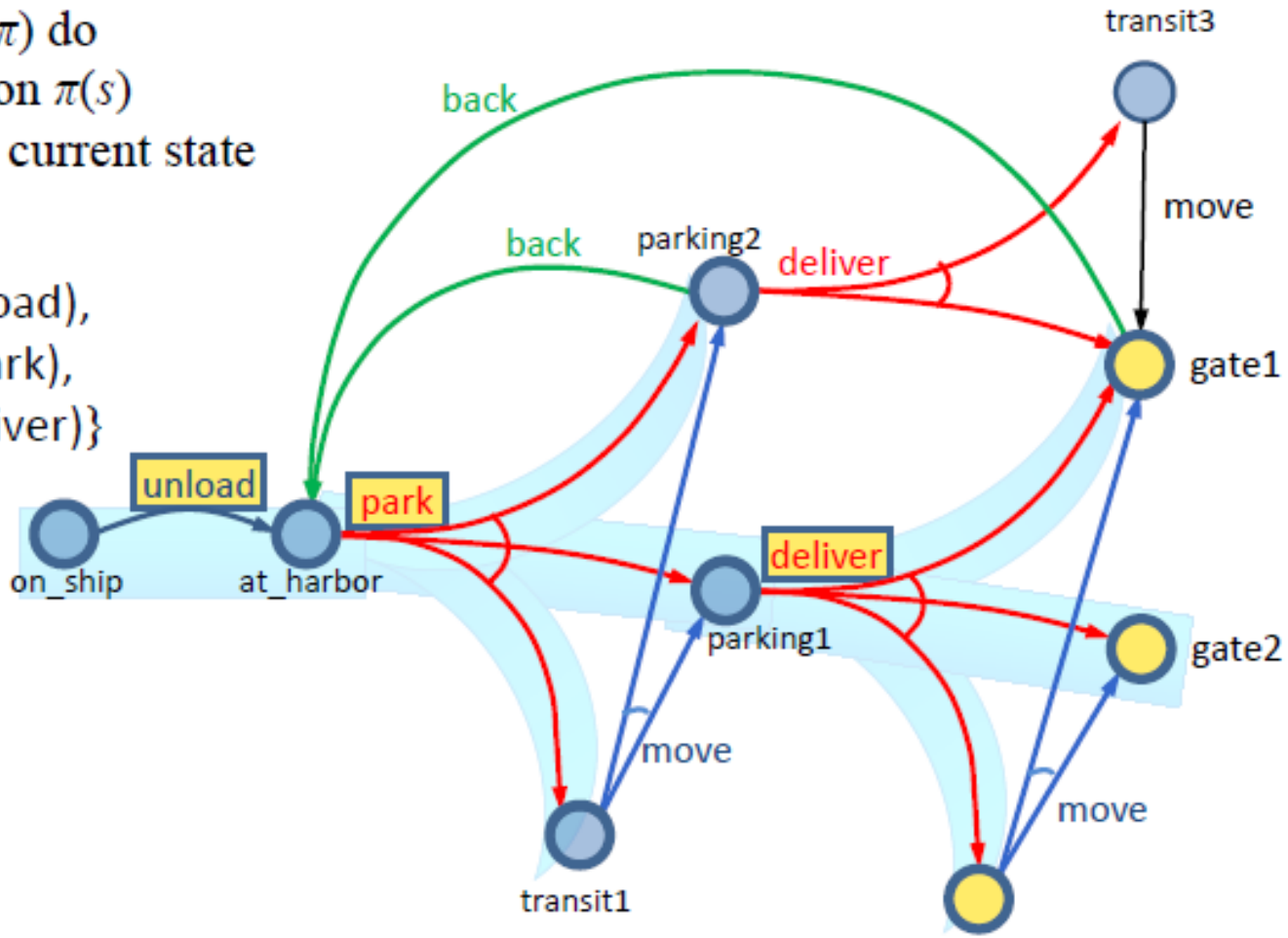
- $leaves(s,\pi) = \hat{\gamma}(s, \pi) \setminus \mathrm{Dom}(\pi)$
  - may be empty



Performing a Policy

- PerformPolicy(π)
  $s \leftarrow$ observe current state
  while $s \in$ Dom(π) do
    perform action $\pi(s)$
    $s \leftarrow$ observe current state

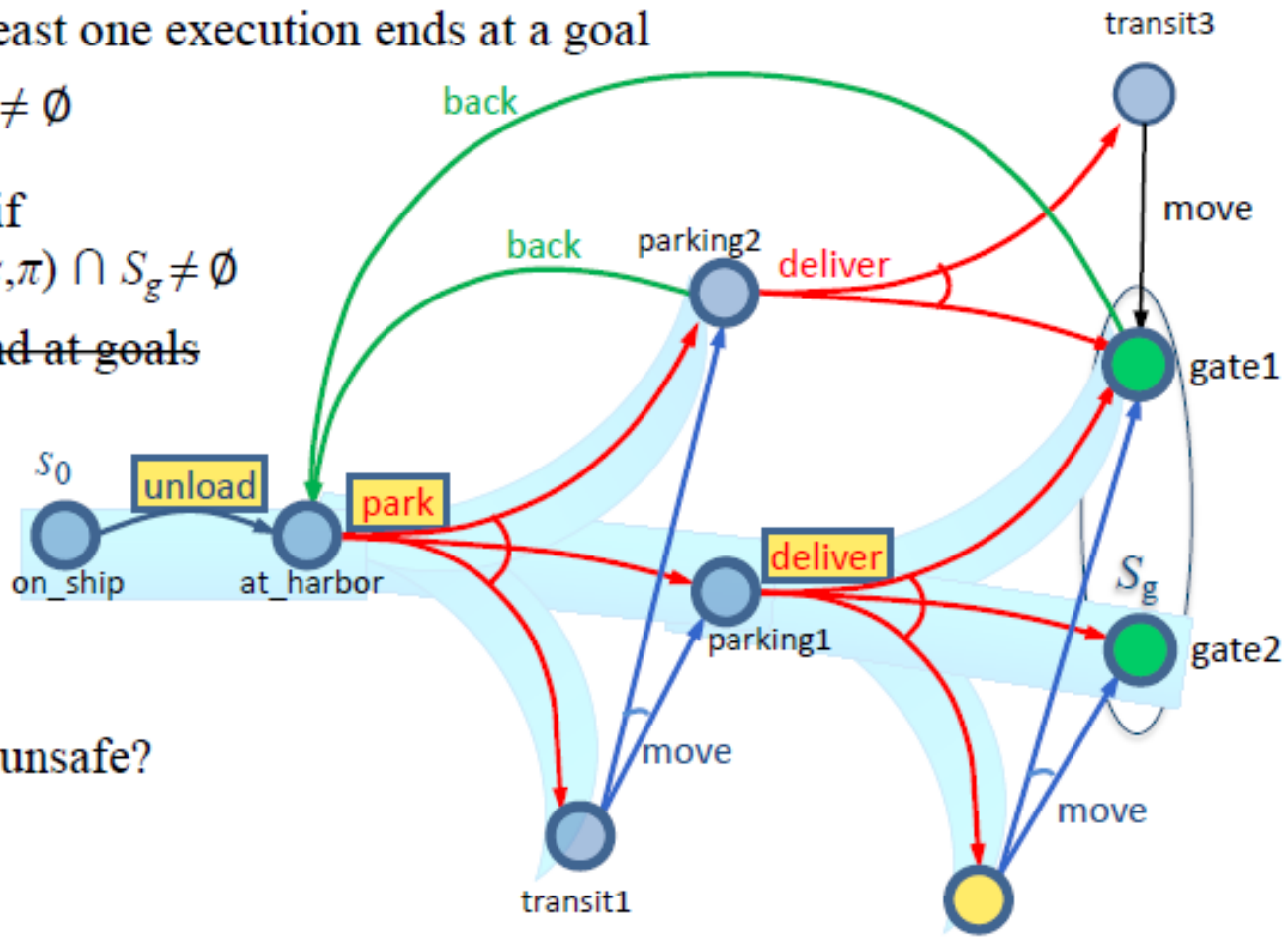
- π_1 = {(on_ship, unload),
  (at_harbor, park),
  (parking1, deliver)}



Planning Problems and Solutions

- Planning problem $P = (\Sigma, s_0, S_g)$
  - planning domain $\Sigma = (S, A, \gamma)$, initial state $s_0 \in S$, set of goal states $S_g \subseteq S$ (shown in green)
- π is a *solution* if at least one execution ends at a goal
  - $leaves(s,\pi) \cap S_g \neq \emptyset$
- A solution π is *safe* if $\forall s \in \hat{\gamma}(s_0,\pi)$, $leaves(s,\pi) \cap S_g \neq \emptyset$
  - ~~all executions end at goals~~
  - at every node of Graph(s_0,π), the goal is reachable
- Otherwise, *unsafe*
  - Is π_1 safe or unsafe?

π_1 = {(on_ship, unload), (at_harbor, park), (parking1, deliver)}



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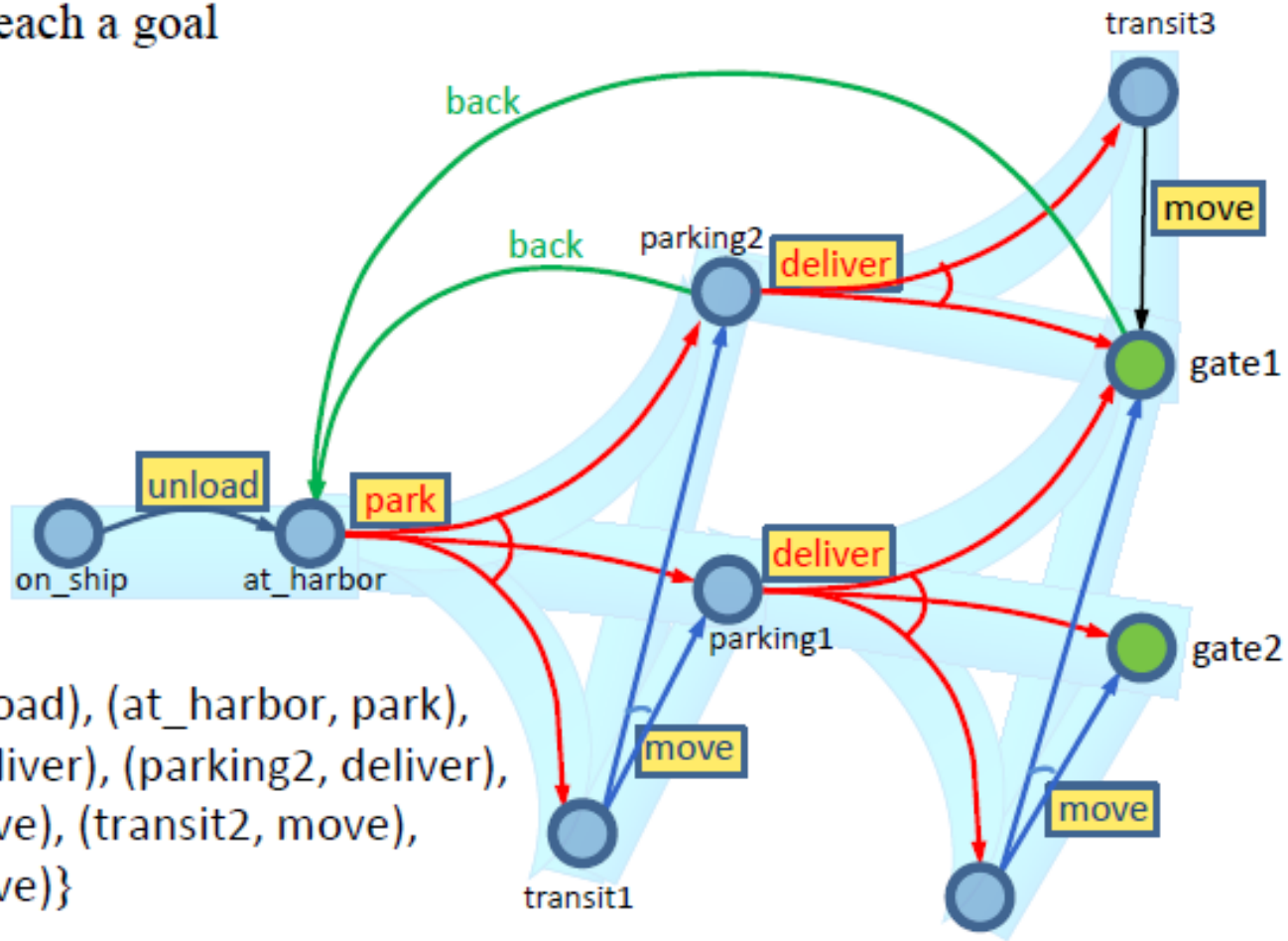
Safe Solutions

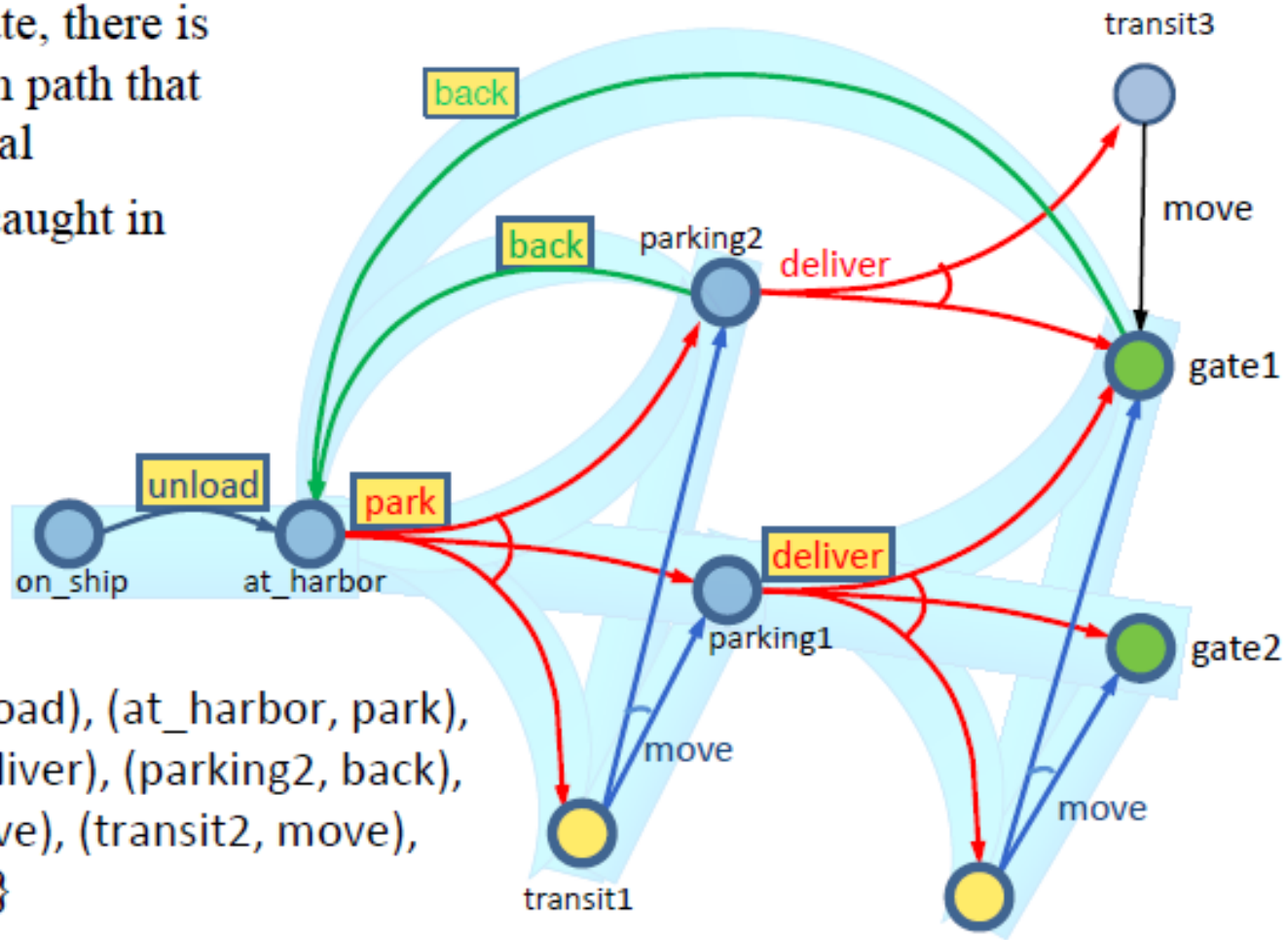
- *Acyclic* safe solution
  - Graph(s_0,π) is acyclic, and $leaves(s,\pi) \subseteq S_g$
  - Guaranteed to reach a goal



- π_2 = {(on_ship, unload), (at_harbor, park),
  (parking1, deliver), (parking2, deliver),
  (transit1, move), (transit2, move),
  (transit3, move)}

Safe Solutions

- *Cyclic* safe solution
  - Graph(s_0, π) is cyclic, $leaves(s,\pi) \subseteq S_g$, $\forall s \in \hat{\gamma}(s_0,\pi)$, $leaves(s,\pi) \cap S_g \neq \emptyset$
    - At every state, there is an execution path that ends at a goal
  - Will never get caught in a dead end



- π_3 = {(on_ship, unload), (at_harbor, park), (parking1, deliver), (parking2, back), (transit1, move), (transit2, move), (gate1, back)}

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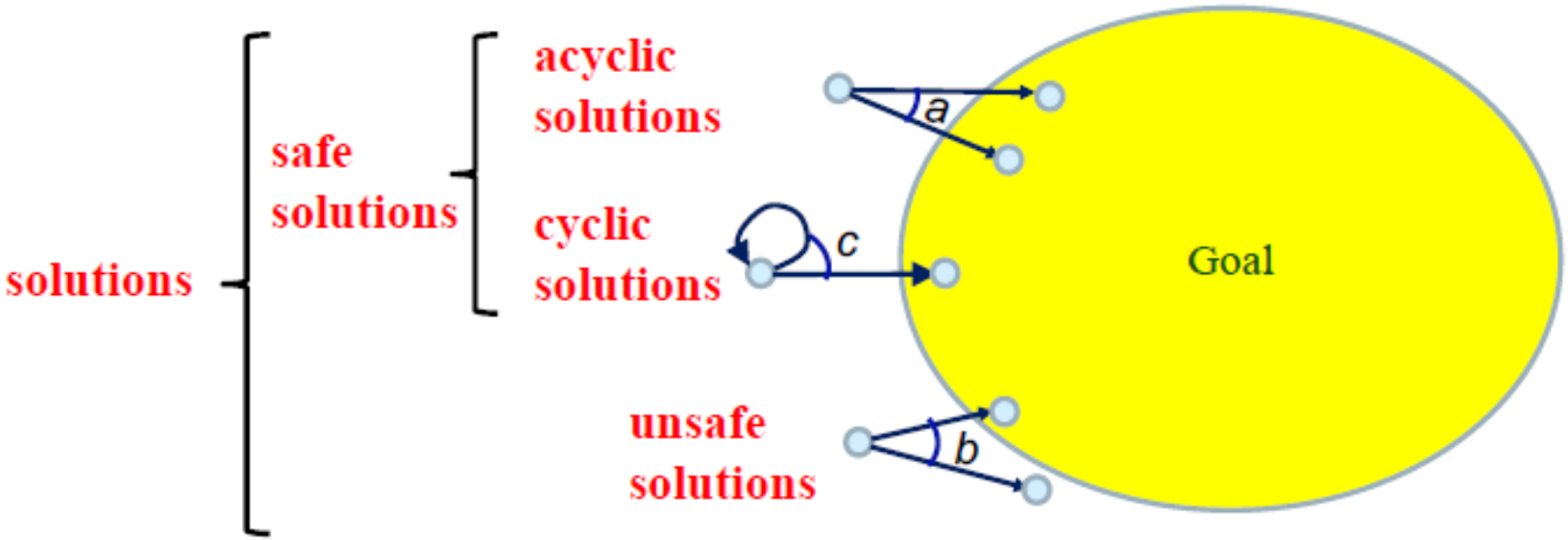
Kinds of Solutions



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Finding (Unsafe) Solutions

For comparison:

Forward-search (Σ, s_0, g)
  $s \leftarrow s_0$; $\pi \leftarrow \langle\rangle$
  loop
    if s satisfies g then return π
    $A' \leftarrow \{a \in A \mid a$ is applicable in $s\}$
    if $A' = \emptyset$ then return failure
    nondeterministically choose $a \in A'$
    $s \leftarrow \gamma(s,a)$; $\pi \leftarrow \pi.a$

Find-Solution (Σ, s_0, S_g)
  $\pi \leftarrow \varnothing$; $s \leftarrow s_0$; $Visited \leftarrow \{s_0\}$
  loop
    if $s \in S_g$ then return π
    $A' \leftarrow$ Applicable(s)
    if $A' = \varnothing$ then return failure
    nondeterministically choose $a \in A'$
(*) nondeterministically choose $s' \in \gamma(s,a)$ ← Decide which state to plan for
    if $s' \in Visited$ then return failure ← Cycle-checking
    $\pi(s) \leftarrow a$; $Visited \leftarrow Visited \cup \{s'\}$; $s \leftarrow s'$

Poll: which should (*) be?
1. nondeterministically choose
2. arbitrarily choose

Example

Find-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$; $s \leftarrow s_0$; $Visited \leftarrow \{s_0\}$

loop

  if $s \in S_g$ then return π

  $A' \leftarrow \text{Applicable}(s)$

  if $A' = \varnothing$ then return failure

  nondeterministically choose $a \in A'$

  nondeterministically choose $s' \in \gamma(s, a)$

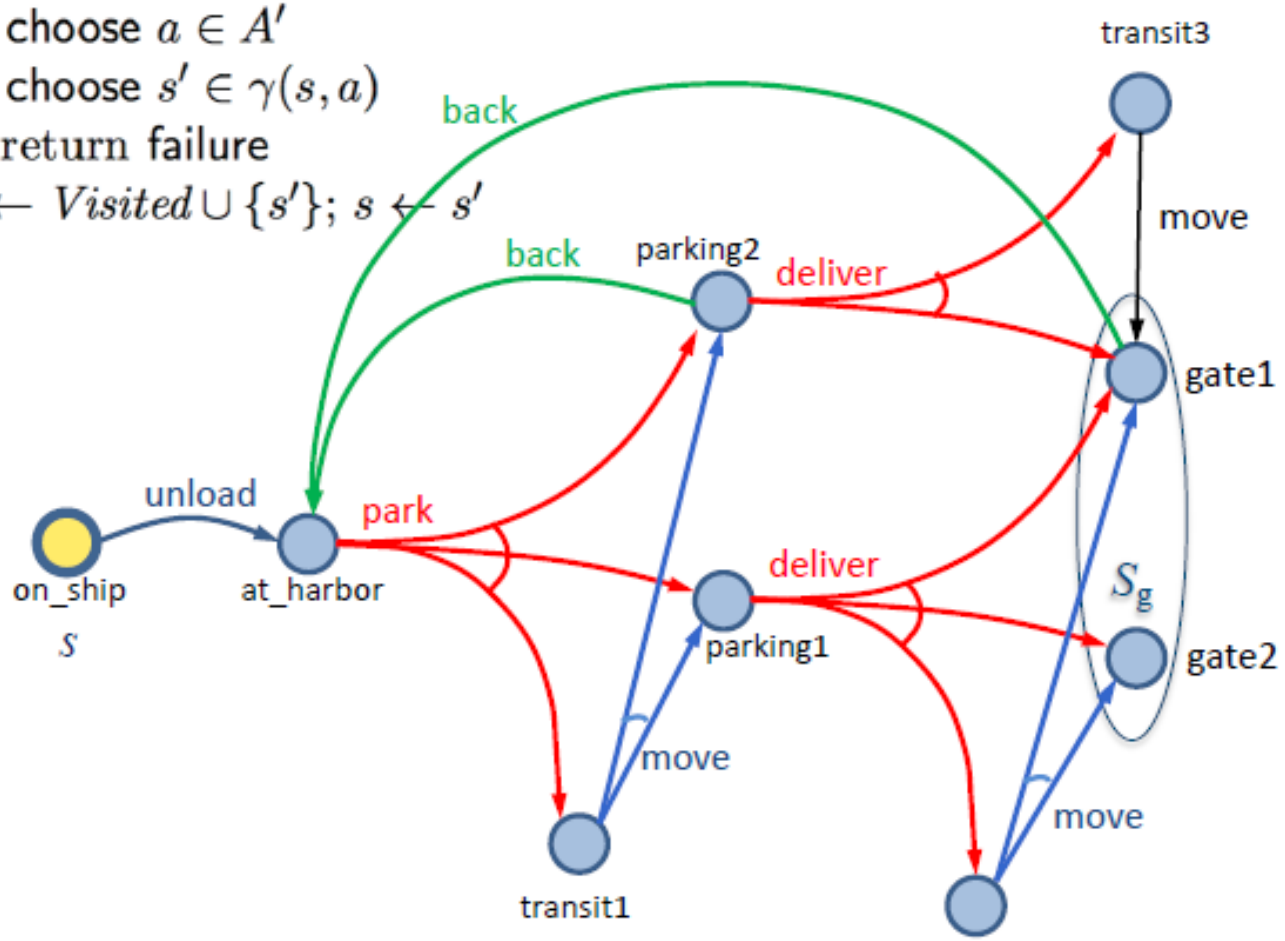
  if $s' \in Visited$ then return failure

  $\pi(s) \leftarrow a$; $Visited \leftarrow Visited \cup \{s'\}$; $s \leftarrow s'$

s = on_ship

$\pi = \{\}$

$Visited = \{\text{on\_ship}\}$



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Example

Find-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$; $s \leftarrow s_0$; $Visited \leftarrow \{s_0\}$

loop

if $s \in S_g$ then return π

$A' \leftarrow$ Applicable(s)

if $A' = \varnothing$ then return failure

nondeterministically choose $a \in A'$

nondeterministically choose $s' \in \gamma(s, a)$

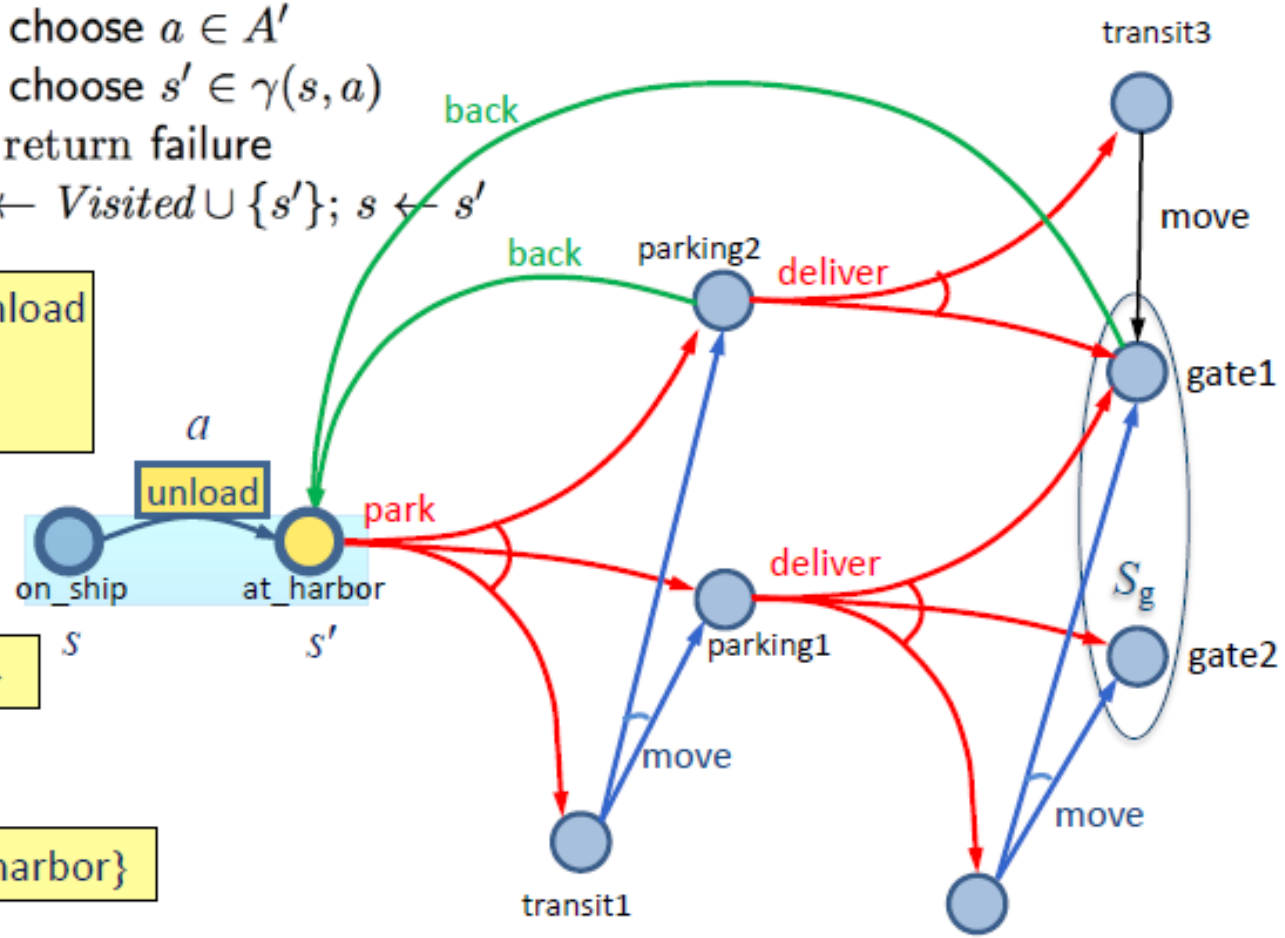
if $s' \in Visited$ then return failure

$\pi(s) \leftarrow a$; $Visited \leftarrow Visited \cup \{s'\}$; $s \leftarrow s'$

s = on_ship, a = unload
$\gamma(s,a)$ = {at_harbor}
s' = at_harbor

π = {(on_ship, unload)}

Visited = {on_ship, at_harbor}



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Example

Find-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$; $s \leftarrow s_0$; $Visited \leftarrow \{s_0\}$

loop

if $s \in S_g$ then return π

$A' \leftarrow \text{Applicable}(s)$

if $A' = \varnothing$ then return failure

nondeterministically choose $a \in A'$

nondeterministically choose $s' \in \gamma(s, a)$

if $s' \in Visited$ then return failure

$\pi(s) \leftarrow a$; $Visited \leftarrow Visited \cup \{s'\}$; $s \leftarrow s'$

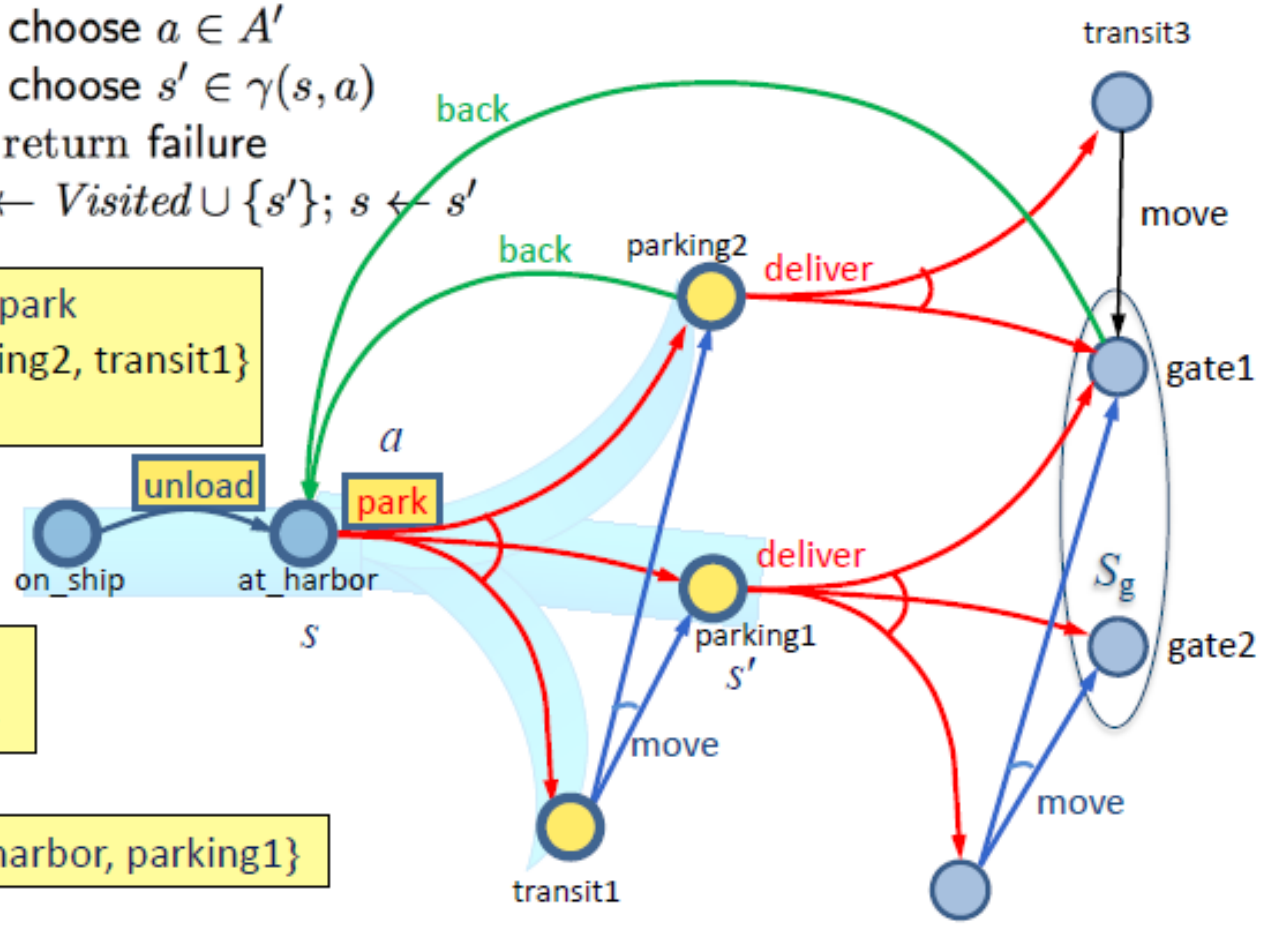
s = at_harbor, a = park

$\gamma(s,a)$ = {parking1, parking2, transit1}

s' = parking1

π = {(on_ship, unload), (at_harbor, park)}

$Visited$ = {on_ship, at_harbor, parking1}



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Example

Find-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$; $s \leftarrow s_0$; $Visited \leftarrow \{s_0\}$

loop

  if $s \in S_g$ then return π

  $A' \leftarrow$ Applicable(s)

  if $A' = \varnothing$ then return failure

  nondeterministically choose $a \in A'$

  nondeterministically choose $s' \in \gamma(s, a)$

  if $s' \in Visited$ then return failure

  $\pi(s) \leftarrow a$; $Visited \leftarrow Visited \cup \{s'\}$; $s \leftarrow s'$

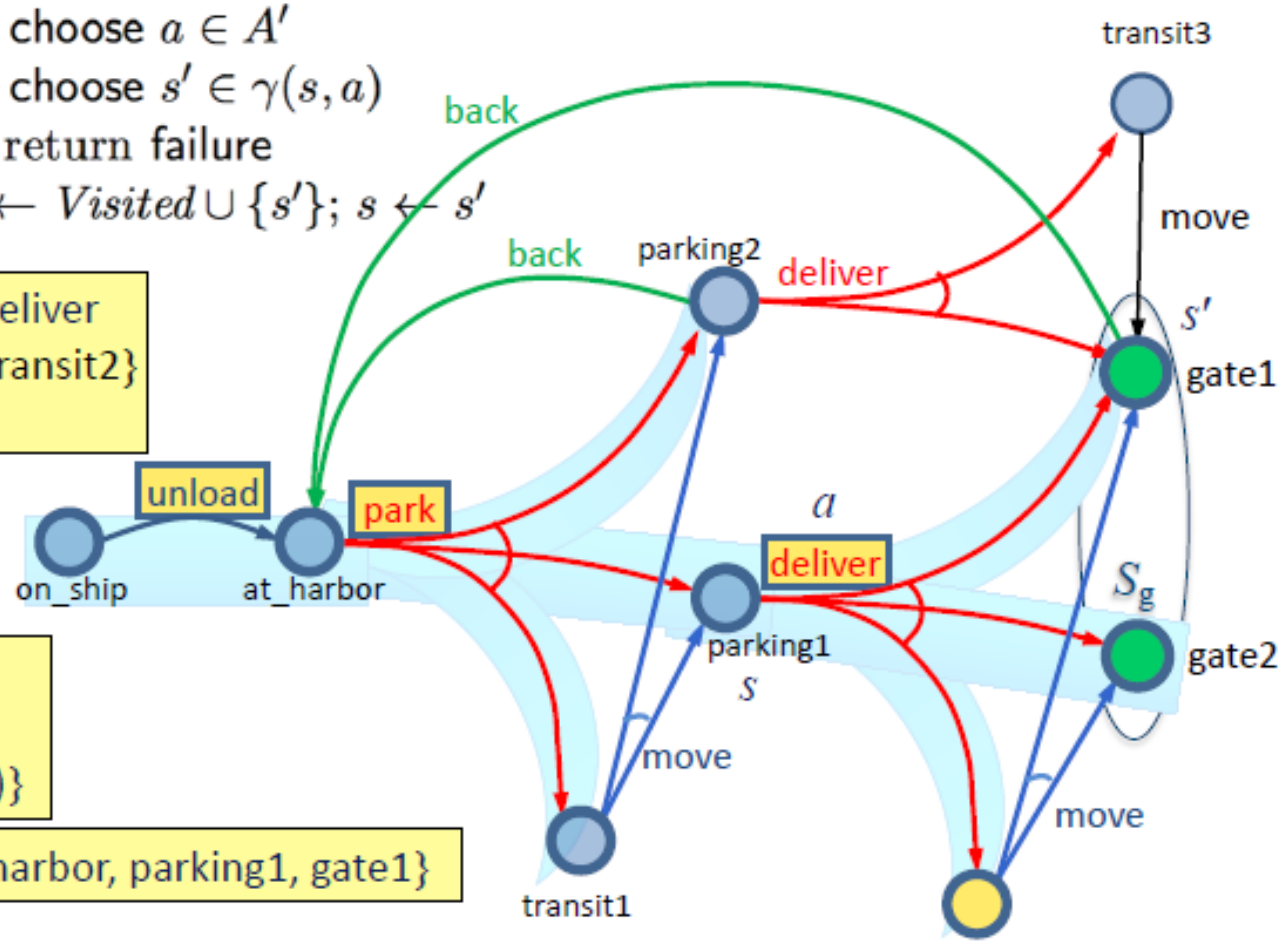
s = parking1, a = deliver

$\gamma(s,a)$ = {gate1, gate2, transit2}

s' = gate1

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver)}

Visited = {on_ship, at_harbor, parking1, gate1}



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Example

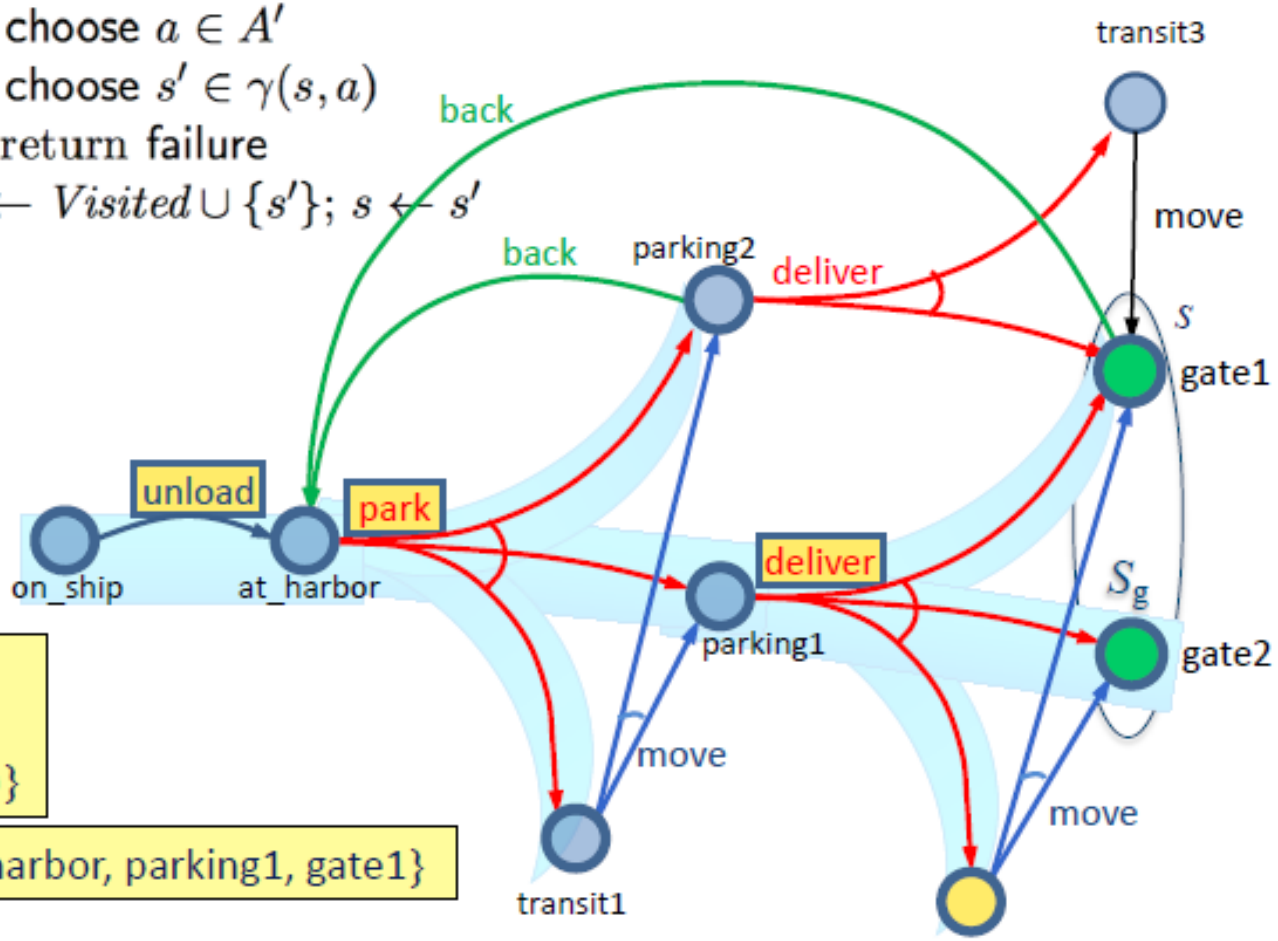
Find-Solution (Σ, s_0, S_g)
  $\pi \leftarrow \varnothing$; $s \leftarrow s_0$; $Visited \leftarrow \{s_0\}$
  loop
    if $s \in S_g$ then return π
    $A' \leftarrow$ Applicable(s)
    if $A' = \varnothing$ then return failure
    nondeterministically choose $a \in A'$
    nondeterministically choose $s' \in \gamma(s, a)$
    if $s' \in Visited$ then return failure
    $\pi(s) \leftarrow a$; $Visited \leftarrow Visited \cup \{s'\}$; $s \leftarrow s'$

s = gate1

gate1 is a goal,
so return π

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver)}

Visited = {on_ship, at_harbor, parking1, gate1}



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Finding Acyclic Safe Solutions

Find-Acyclic-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

$Frontier \leftarrow Frontier \setminus \{s\}$

if Applicable$(s) = \varnothing$ then return failure

nondeterministically choose $a \in$ Applicable(s)

$\pi \leftarrow \pi \cup (s, a)$

$Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

if has-loops$(\pi, a, Frontier)$ then return failure

return π

Check for cycles:

For each $s' \in \gamma(s,a) \cap \text{Dom}(\pi)$, is $s \in \hat{\gamma}(s', \pi)$?

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Example

Find-Acyclic-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

  $Frontier \leftarrow Frontier \setminus \{s\}$

  if Applicable$(s) = \varnothing$ then return failure

  nondeterministically choose $a \in$ Applicable(s)

  $\pi \leftarrow \pi \cup (s, a)$

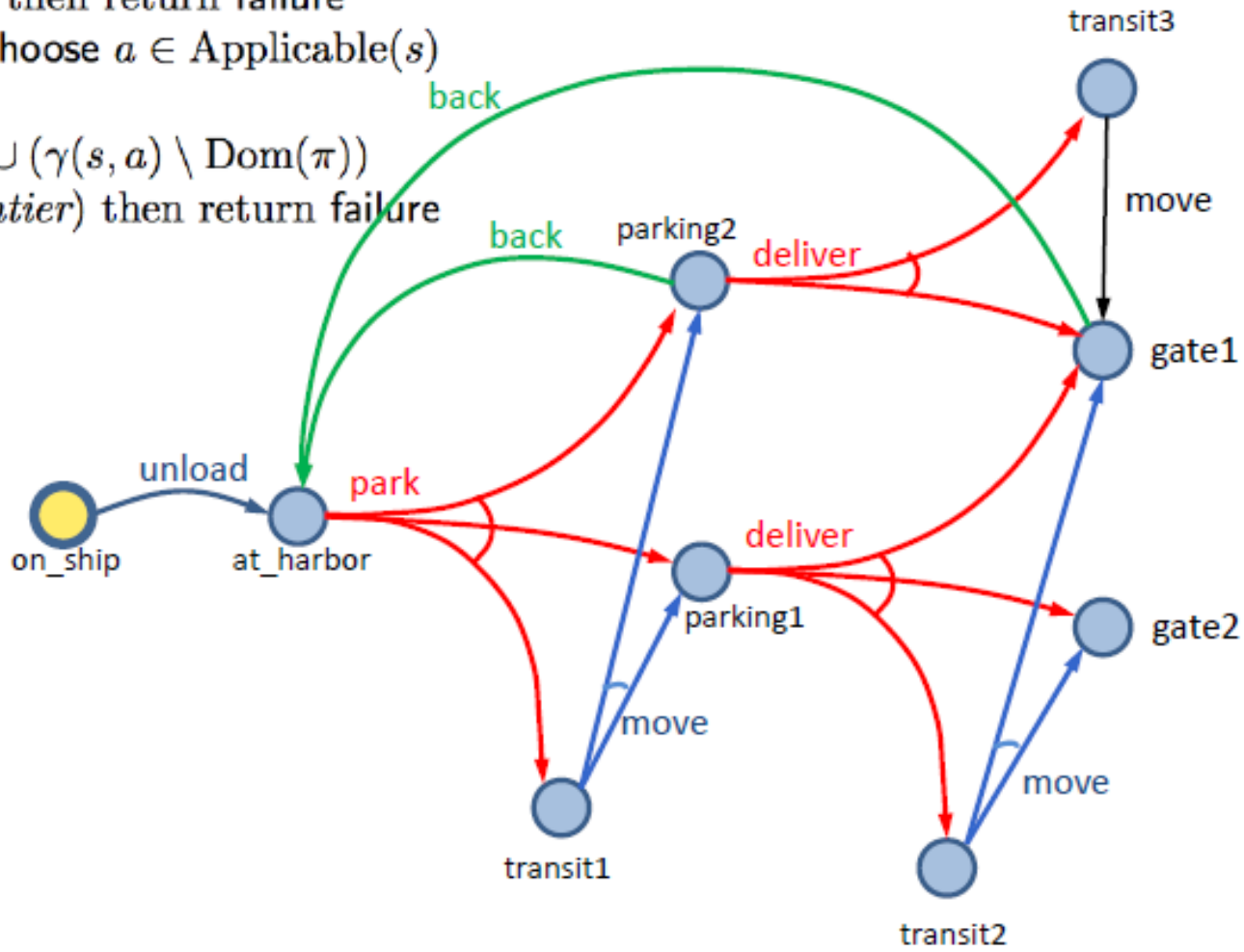
  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

  if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier \setminus S_g = \{\text{on\_ship}\}$

$\pi = \{\}$



Example

Find-Acyclic-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

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  if Applicable$(s) = \varnothing$ then return failure

  nondeterministically choose $a \in$ Applicable(s)

  $\pi \leftarrow \pi \cup (s, a)$

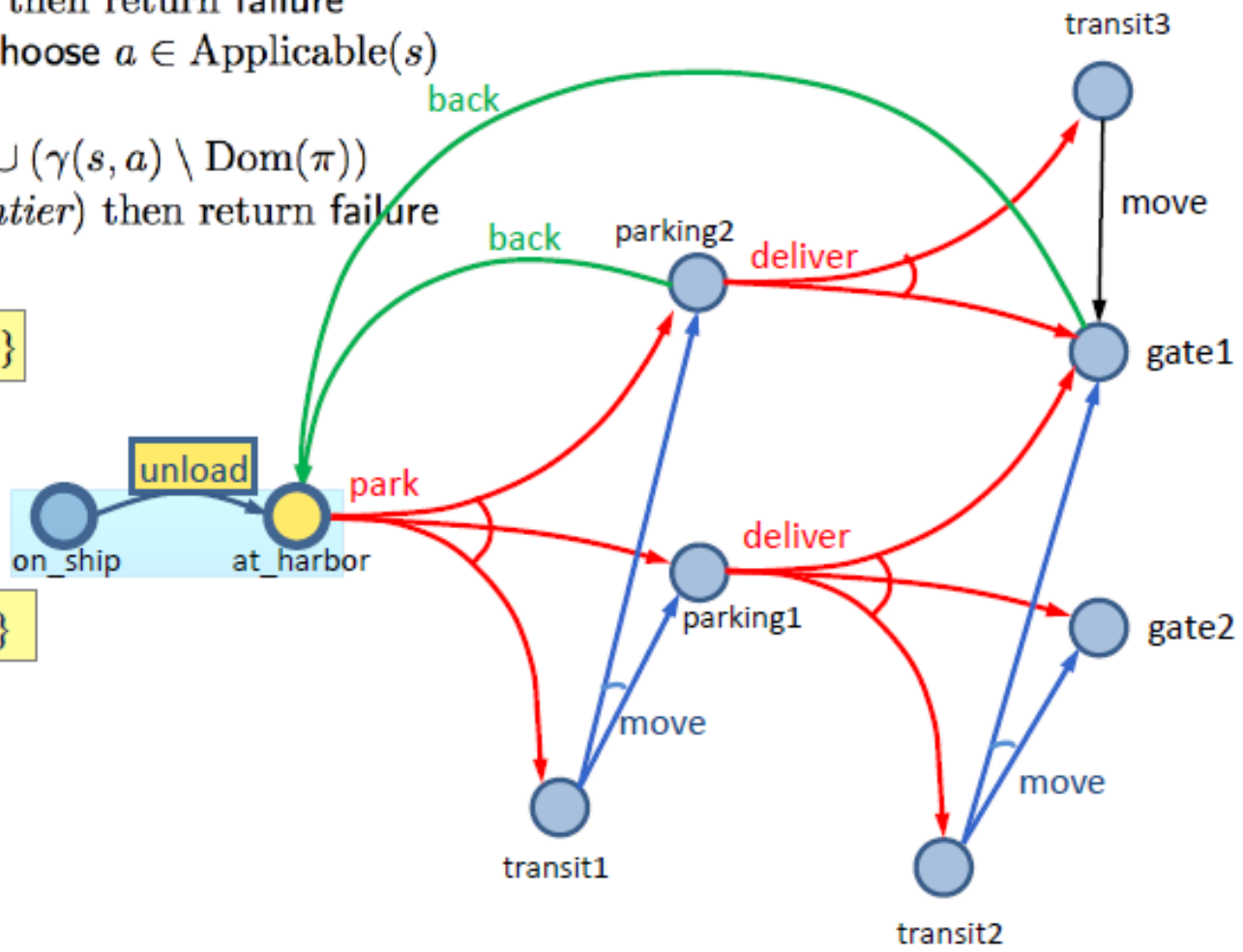
  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

  if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier \setminus S_g$ = {at_harbor}

π = {(on_ship, unload)}



Example

Find-Acyclic-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

$Frontier \leftarrow Frontier \setminus \{s\}$

if Applicable$(s) = \varnothing$ then return failure

nondeterministically choose $a \in$ Applicable(s)

$\pi \leftarrow \pi \cup (s, a)$

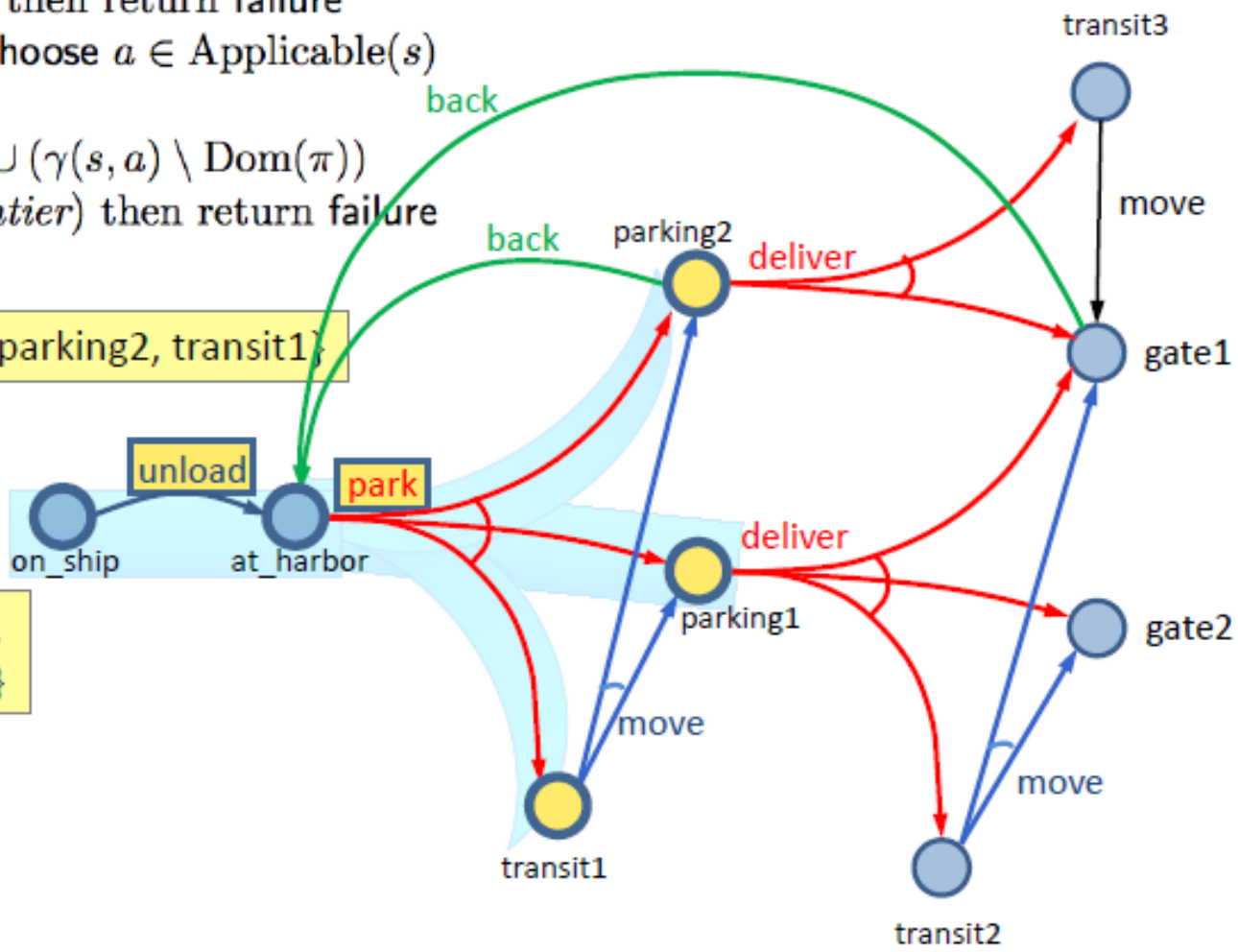
$Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier \setminus S_g$ = {parking1, parking2, transit1}

π = {(on_ship, unload), (at_harbor, park)}



Example

Find-Acyclic-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

  $Frontier \leftarrow Frontier \setminus \{s\}$

  if Applicable$(s) = \varnothing$ then return failure

  nondeterministically choose $a \in$ Applicable(s)

  $\pi \leftarrow \pi \cup (s, a)$

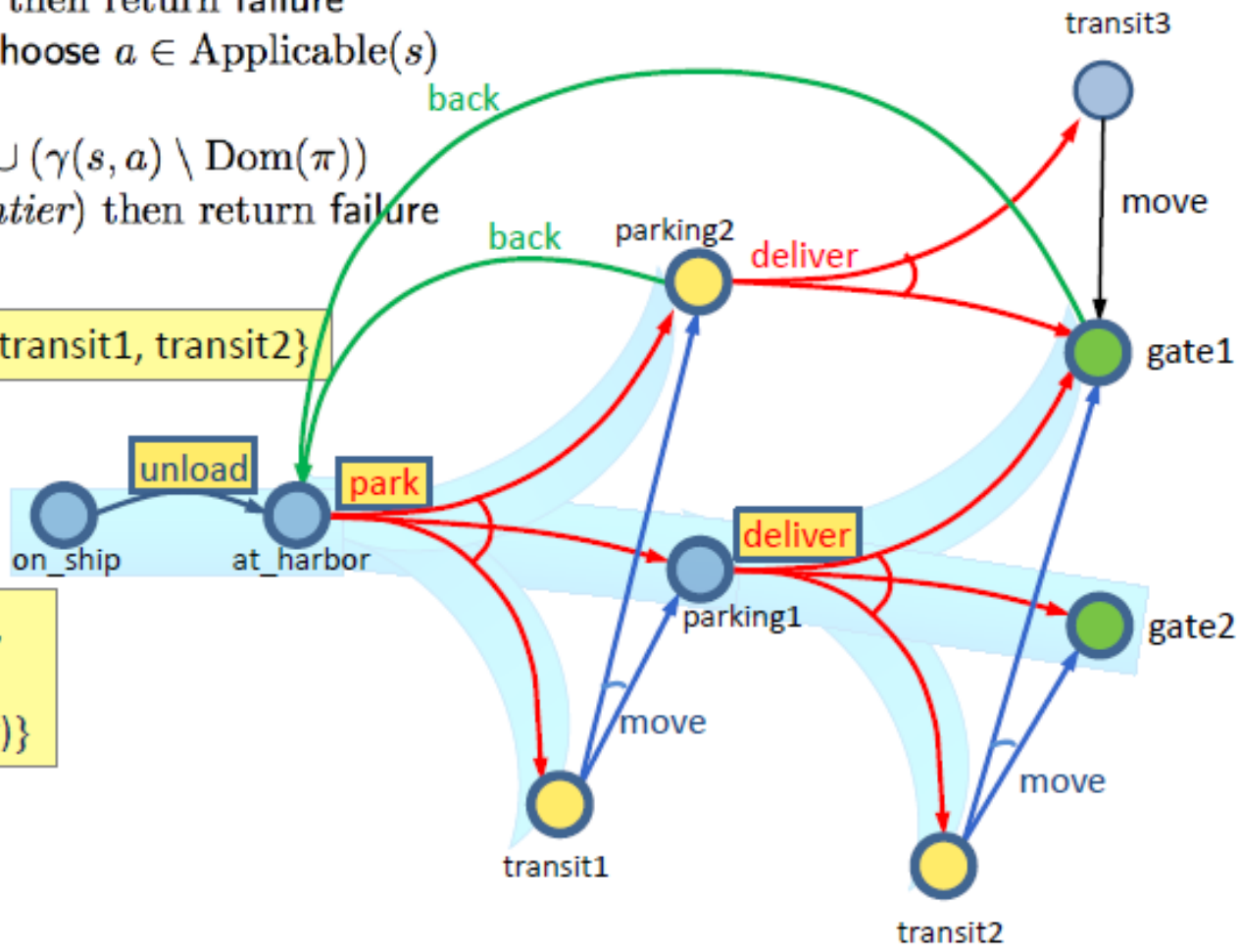
  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

  if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier \setminus S_g$ = {parking2, transit1, transit2}

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver)}



Find-Acyclic-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

  $Frontier \leftarrow Frontier \setminus \{s\}$

  if Applicable$(s) = \varnothing$ then return failure

  nondeterministically choose $a \in$ Applicable(s)

  $\pi \leftarrow \pi \cup (s, a)$

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

  if has-loops$(\pi, a, Frontier)$ then return failure

return π

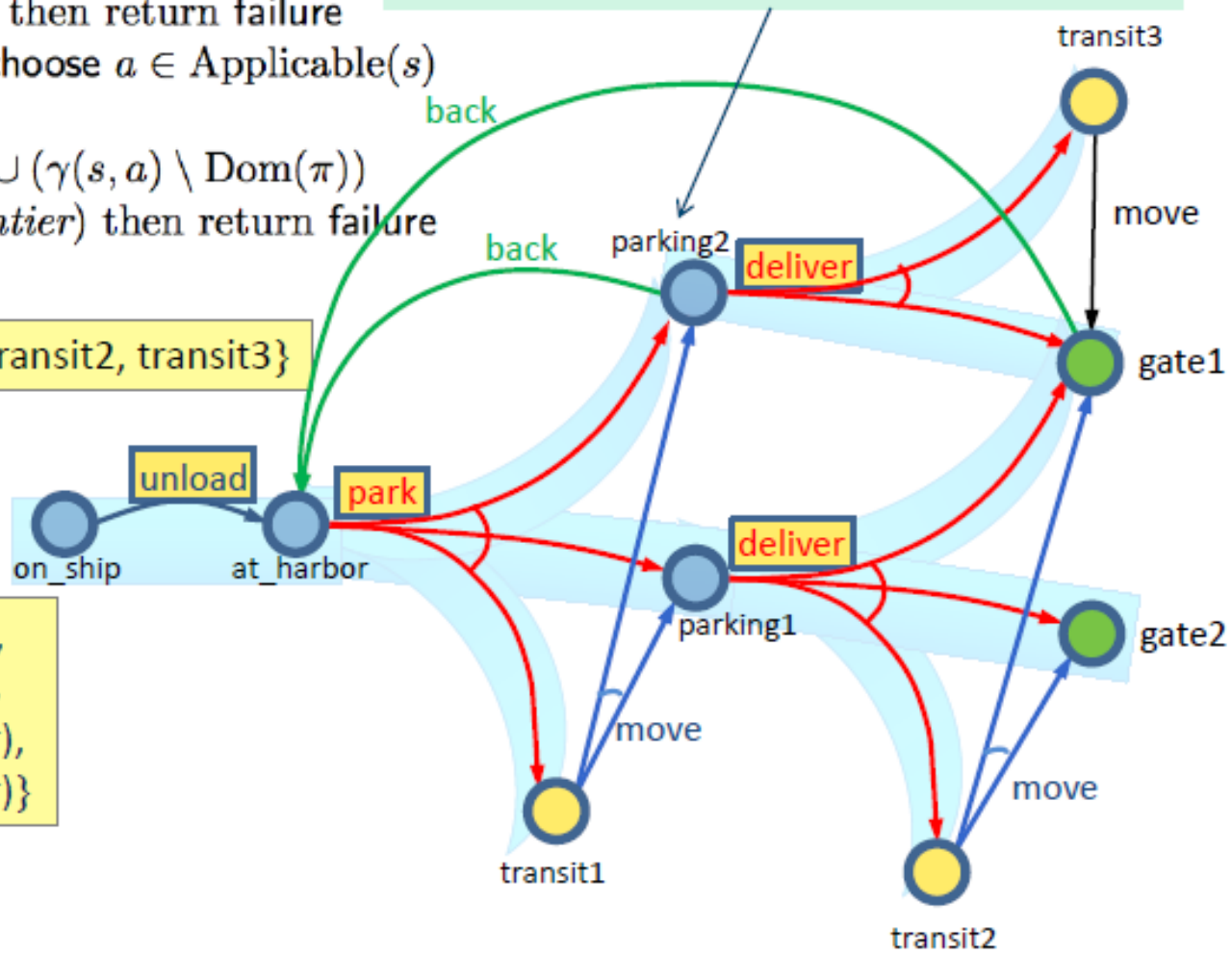
$Frontier \setminus S_g$ = {transit1, transit2, transit3}

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver)}

Example

nondeterministically choose back or deliver

- back ⇒ cycle, so return failure
- deliver ⇒ no cycle, so continue

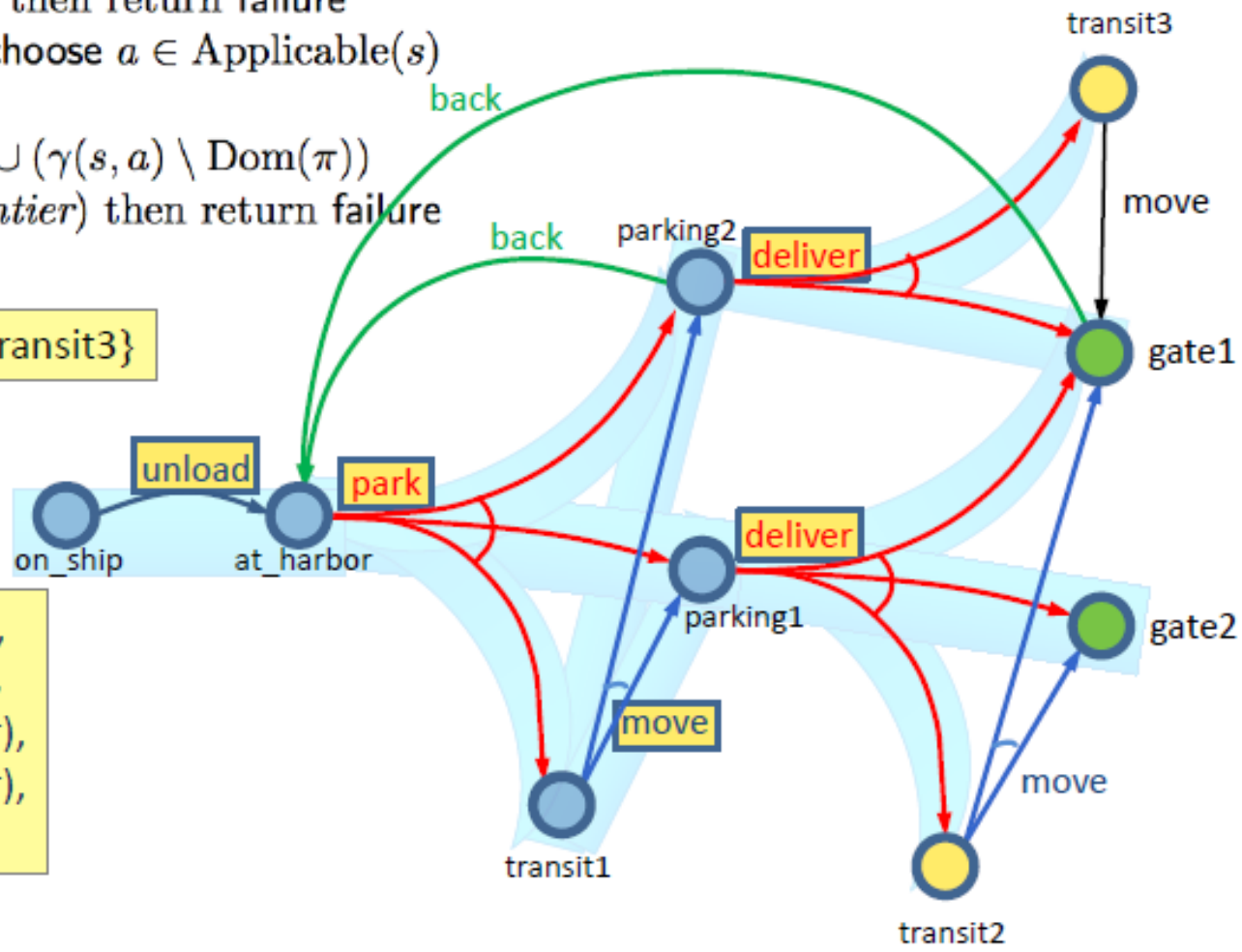


Example

Find-Acyclic-Solution (Σ, s_0, S_g)
- $\pi \leftarrow \varnothing$
- $Frontier \leftarrow \{s_0\}$
- for every $s \in Frontier \setminus S_g$ do
  - $Frontier \leftarrow Frontier \setminus \{s\}$
  - if Applicable$(s) = \varnothing$ then return failure
  - nondeterministically choose $a \in$ Applicable(s)
  - $\pi \leftarrow \pi \cup (s, a)$
  - $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
  - if has-loops$(\pi, a, Frontier)$ then return failure
- return π

$Frontier \setminus S_g$ = {transit2, transit3}

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit1, move)}



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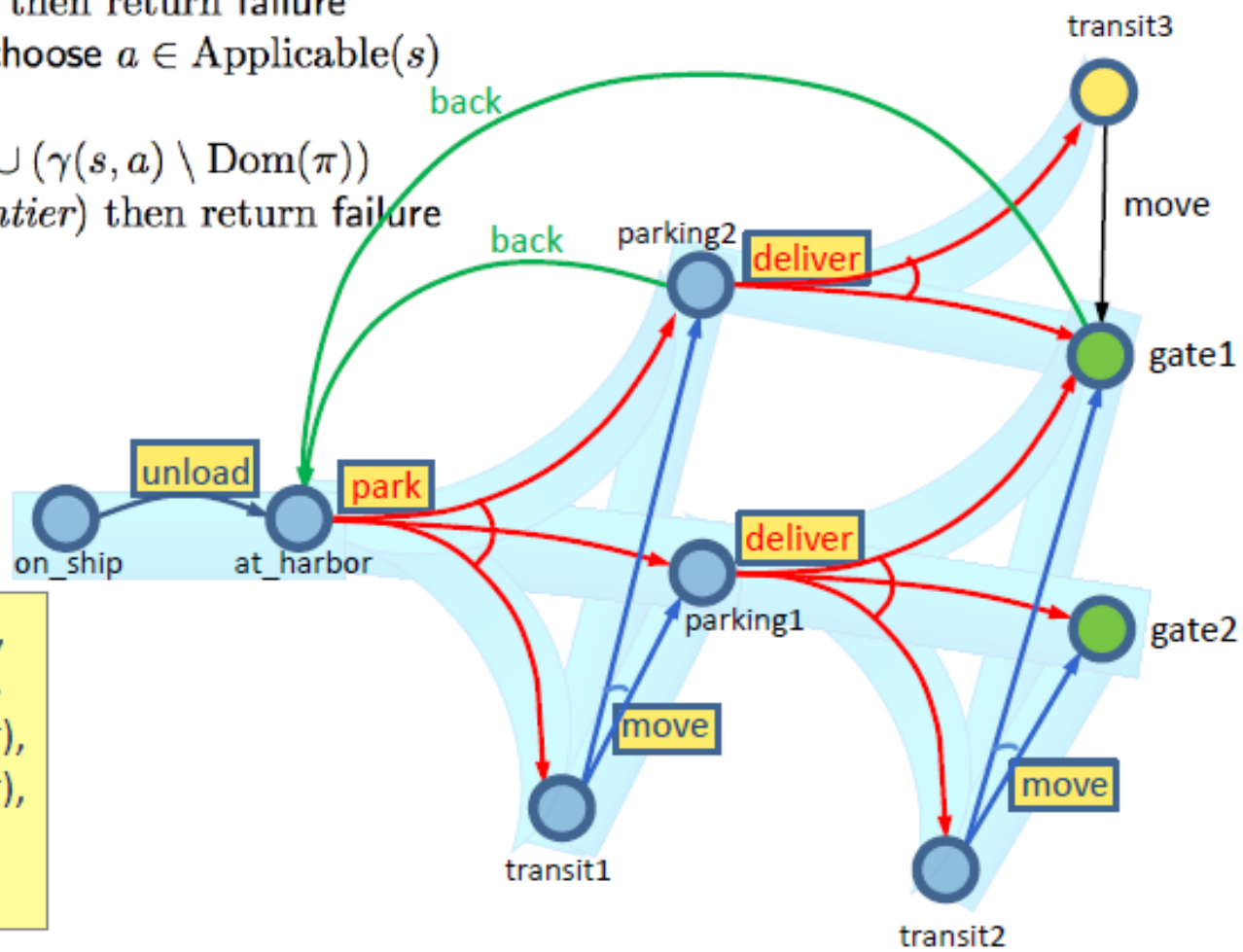
Example

Find-Acyclic-Solution (Σ, s_0, S_g)
- $\pi \leftarrow \varnothing$
- $Frontier \leftarrow \{s_0\}$
- for every $s \in Frontier \setminus S_g$ do
  - $Frontier \leftarrow Frontier \setminus \{s\}$
  - if Applicable$(s) = \varnothing$ then return failure
  - nondeterministically choose $a \in$ Applicable(s)
  - $\pi \leftarrow \pi \cup (s, a)$
  - $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
  - if has-loops$(\pi, a, Frontier)$ then return failure
- return π

$Frontier \setminus S_g = \{\text{transit3}\}$



$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit1, move),
(transit2, move)$\}$

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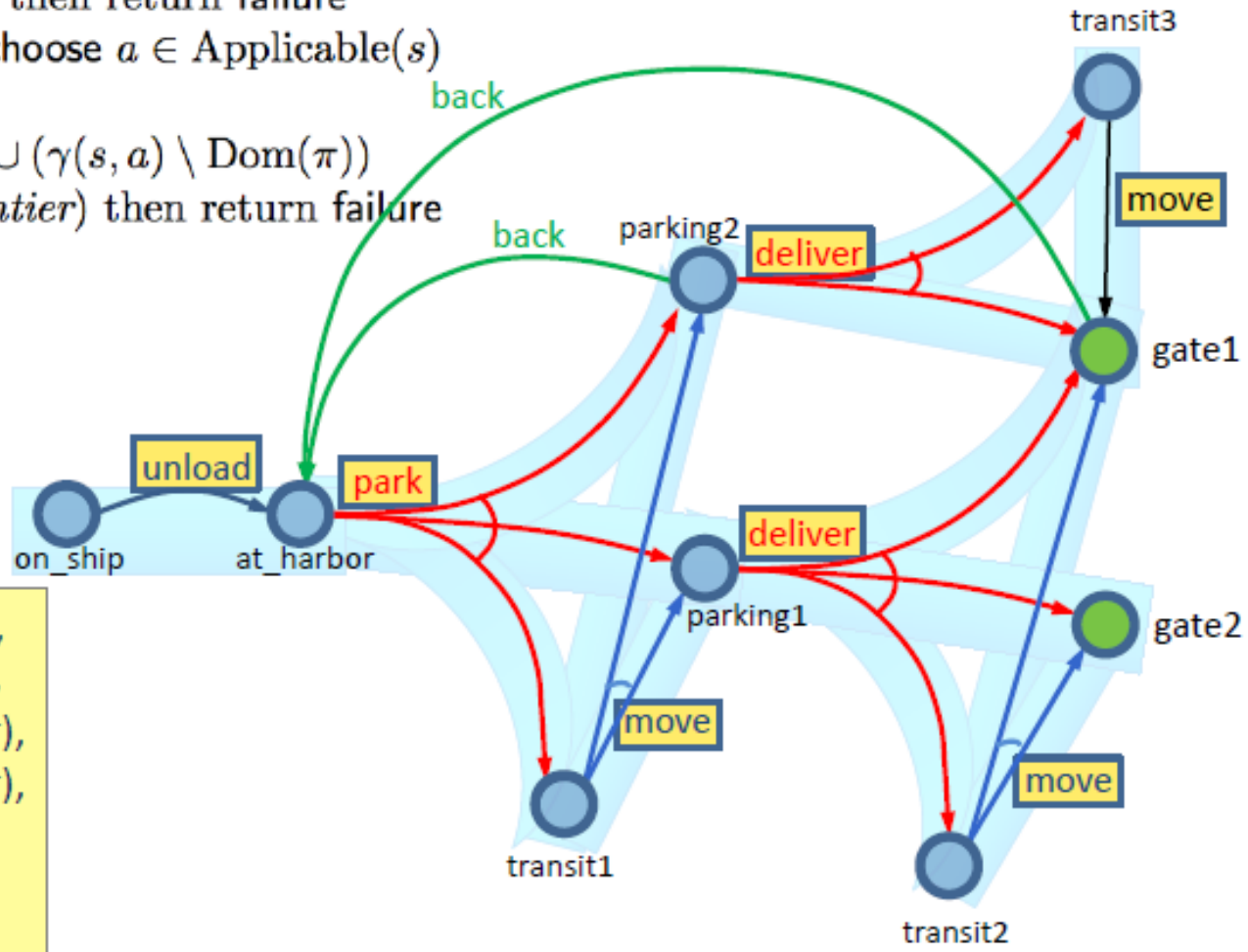
Example

Find-Acyclic-Solution (Σ, s_0, S_g)
- $\pi \leftarrow \varnothing$
- $Frontier \leftarrow \{s_0\}$
- for every $s \in Frontier \setminus S_g$ do
  - $Frontier \leftarrow Frontier \setminus \{s\}$
  - if Applicable$(s) = \varnothing$ then return failure
  - nondeterministically choose $a \in$ Applicable(s)
  - $\pi \leftarrow \pi \cup (s, a)$
  - $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
  - if has-loops$(\pi, a, Frontier)$ then return failure
- return π

$Frontier \setminus S_g = \emptyset$

Found a solution

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit1, move),
(transit2, move),
(transit3, move)}



Stefan Edelkamp (cf. Book Automated Planning and Acting)

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Find-Safe-Solution

Find-Safe-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$ ← *Keep track of unexpanded states, like A**

for every $s \in Frontier \setminus S_g$ do

  $Frontier \leftarrow Frontier \setminus \{s\}$

  if Applicable$(s) = \varnothing$ then return failure

  nondeterministically choose $a \in$ Applicable(s)

  $\pi \leftarrow \pi \cup (s, a)$

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$ ← *Add all outcomes that π doesn't already handle*

  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

- Same as Find-Acyclic-Solution except for one difference:
- has-unsafe-loops instead of has-loops
  - Check whether π contains any cycles that can't be escaped:
  - For each $s' \in \gamma(s,a) \cap \text{Dom}(\pi)$, is $\hat{\gamma}(s',\pi) \cap Frontier = \emptyset$?

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Example

Find-Safe-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

$Frontier \leftarrow Frontier \setminus \{s\}$

if Applicable$(s) = \varnothing$ then return failure

nondeterministically choose $a \in$ Applicable(s)

$\pi \leftarrow \pi \cup (s, a)$

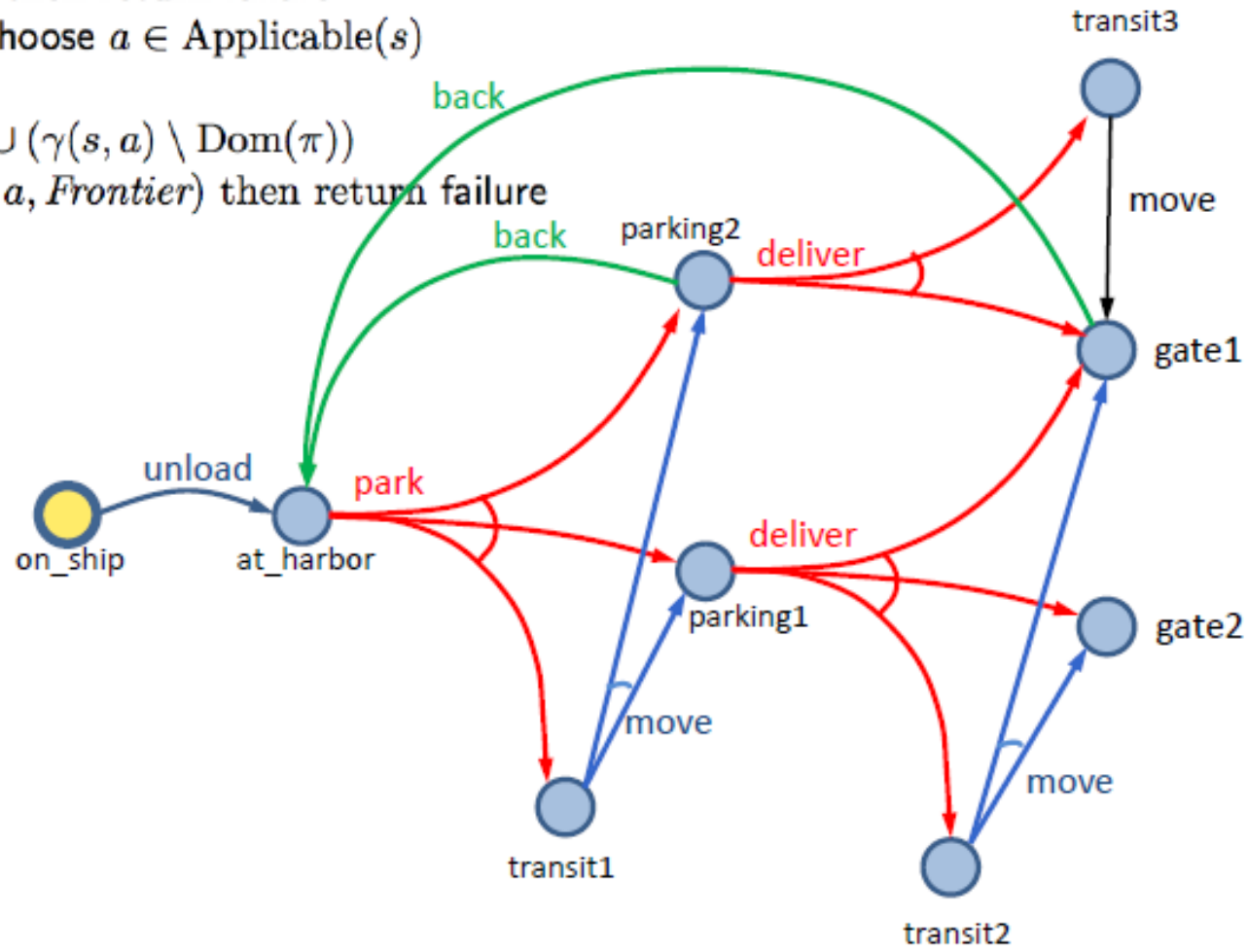
$Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier \setminus S_g = \{\text{on\_ship}\}$

$\pi = \{\}$



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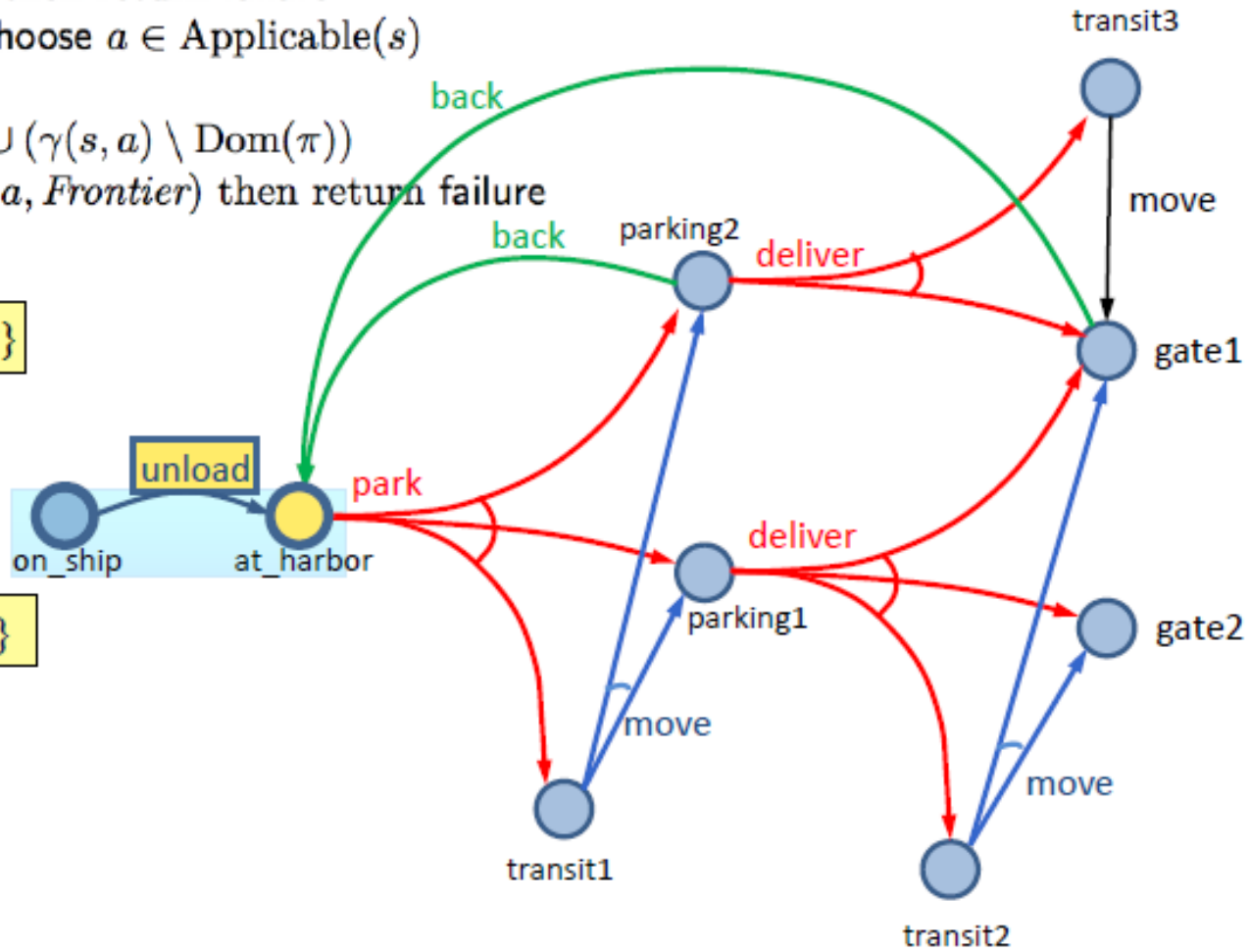
Example

Find-Safe-Solution (Σ, s_0, S_g)
- $\pi \leftarrow \varnothing$
- $Frontier \leftarrow \{s_0\}$
- for every $s \in Frontier \setminus S_g$ do
  - $Frontier \leftarrow Frontier \setminus \{s\}$
  - if Applicable$(s) = \varnothing$ then return failure
  - nondeterministically choose $a \in$ Applicable(s)
  - $\pi \leftarrow \pi \cup (s, a)$
  - $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
  - if has-unsafe-loops$(\pi, a, Frontier)$ then return failure
- return π

$Frontier \setminus S_g$ = {at_harbor}

π = {(on_ship, unload)}



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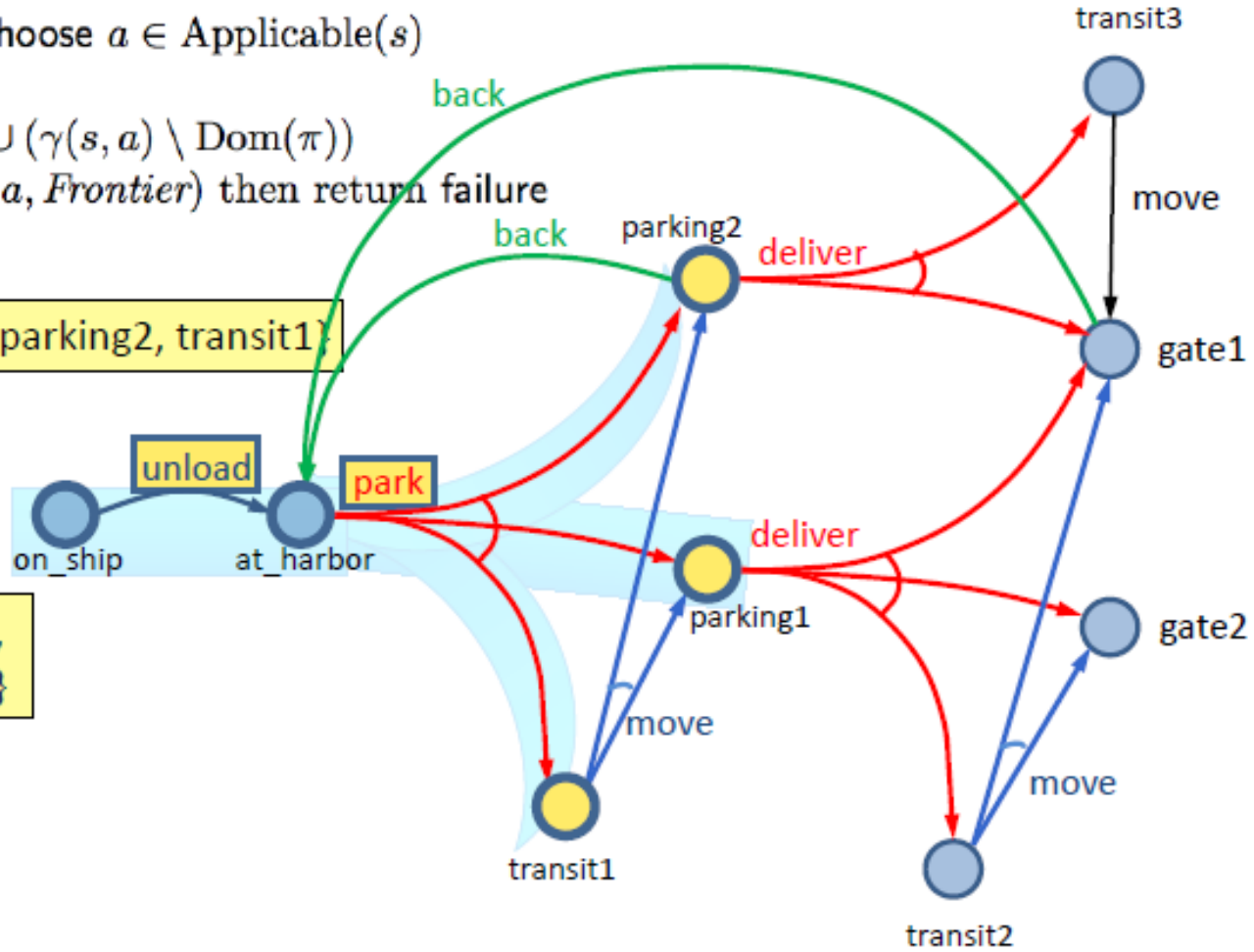
Example

Find-Safe-Solution (Σ, s_0, S_g)
  $\pi \leftarrow \varnothing$
  $Frontier \leftarrow \{s_0\}$
  for every $s \in Frontier \setminus S_g$ do
    $Frontier \leftarrow Frontier \setminus \{s\}$
    if Applicable$(s) = \varnothing$ then return failure
    nondeterministically choose $a \in$ Applicable(s)
    $\pi \leftarrow \pi \cup (s, a)$
    $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
    if has-unsafe-loops$(\pi, a, Frontier)$ then return failure
  return π

$Frontier \setminus S_g$ = {parking1, parking2, transit1}

π = {(on_ship, unload), (at_harbor, park)}

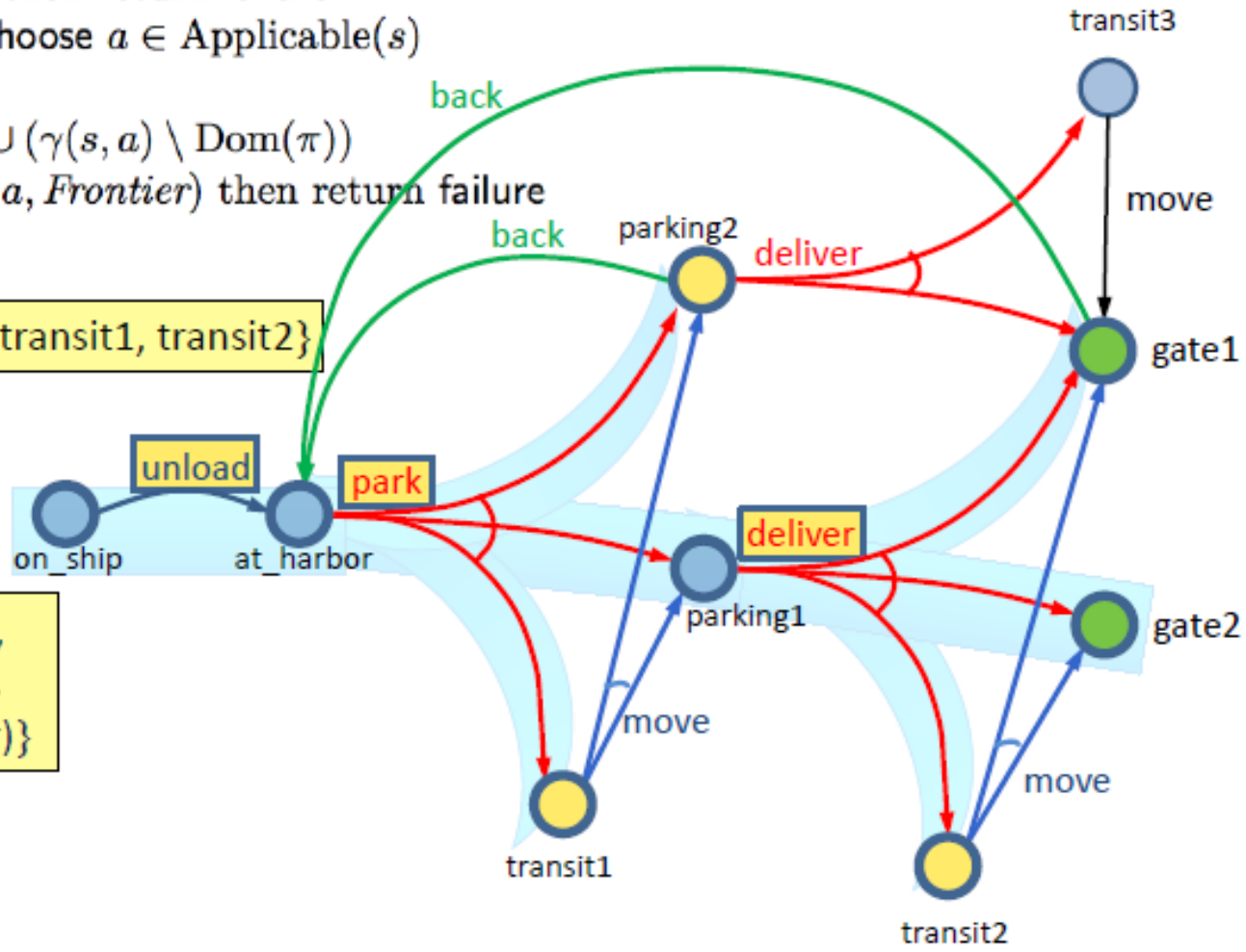


Example

Find-Safe-Solution (Σ, s_0, S_g)
- $\pi \leftarrow \varnothing$
- $Frontier \leftarrow \{s_0\}$
- for every $s \in Frontier \setminus S_g$ do
  - $Frontier \leftarrow Frontier \setminus \{s\}$
  - if Applicable$(s) = \varnothing$ then return failure
  - nondeterministically choose $a \in$ Applicable(s)
  - $\pi \leftarrow \pi \cup (s, a)$
  - $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
  - if has-unsafe-loops$(\pi, a, Frontier)$ then return failure
- return π

$Frontier \setminus S_g$ = {parking2, transit1, transit2}

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver)}



Example

Find-Safe-Solution (Σ, s_0, S_g)

$\pi \leftarrow \varnothing$

$Frontier \leftarrow \{s_0\}$

for every $s \in Frontier \setminus S_g$ do

  $Frontier \leftarrow Frontier \setminus \{s\}$

  if Applicable$(s) = \varnothing$ then return failure

  nondeterministically choose $a \in$ Applicable(s)

  $\pi \leftarrow \pi \cup (s, a)$

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$

  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

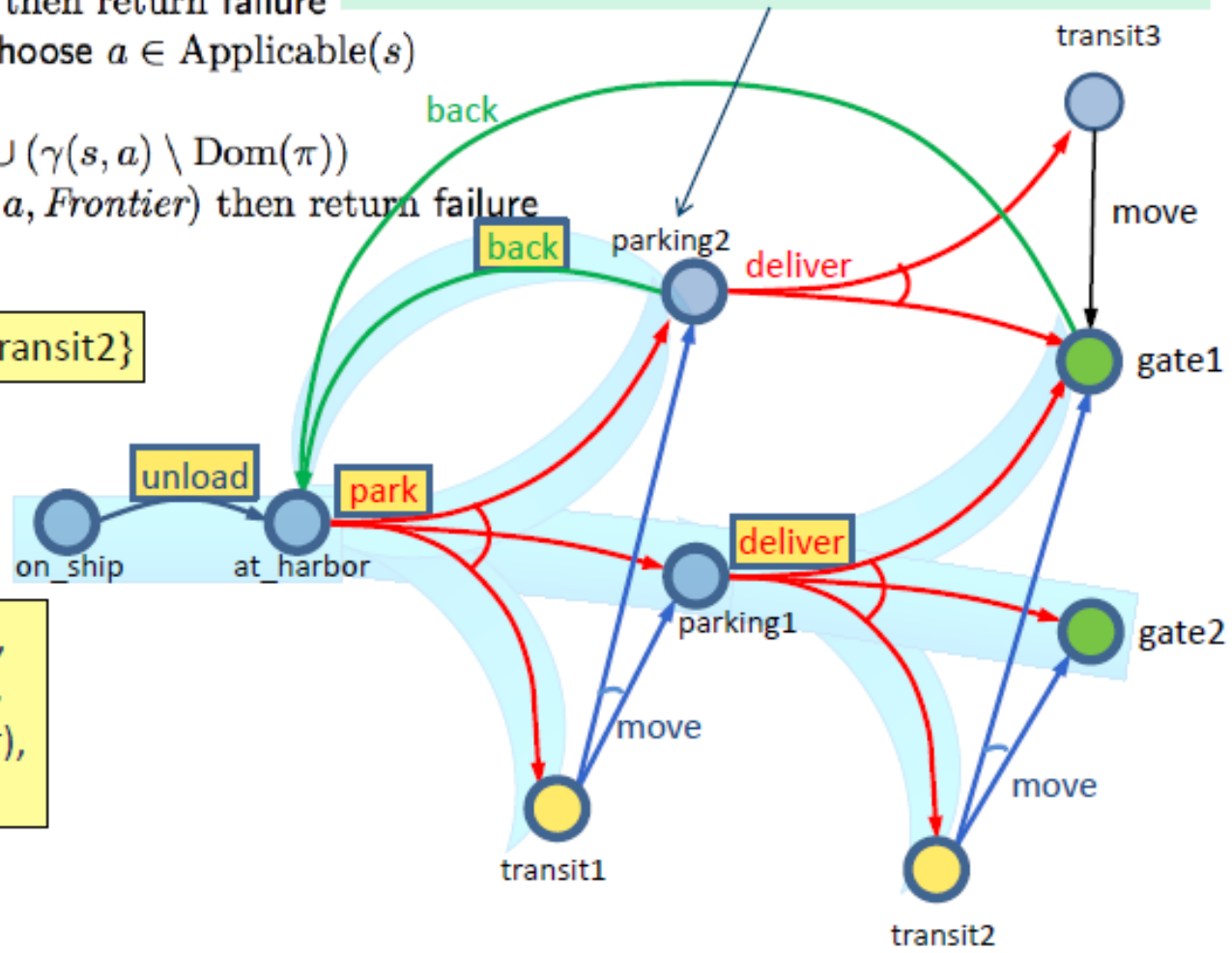
return π

Nondeterministically choose back or deliver

- back is OK: escapable cycle

$Frontier \setminus S_g$ = {transit1, transit2}

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, back)}



Example

Find-Safe-Solution (Σ, s_0, S_g)
  $\pi \leftarrow \varnothing$
  $Frontier \leftarrow \{s_0\}$
  for every $s \in Frontier \setminus S_g$ do
    $Frontier \leftarrow Frontier \setminus \{s\}$
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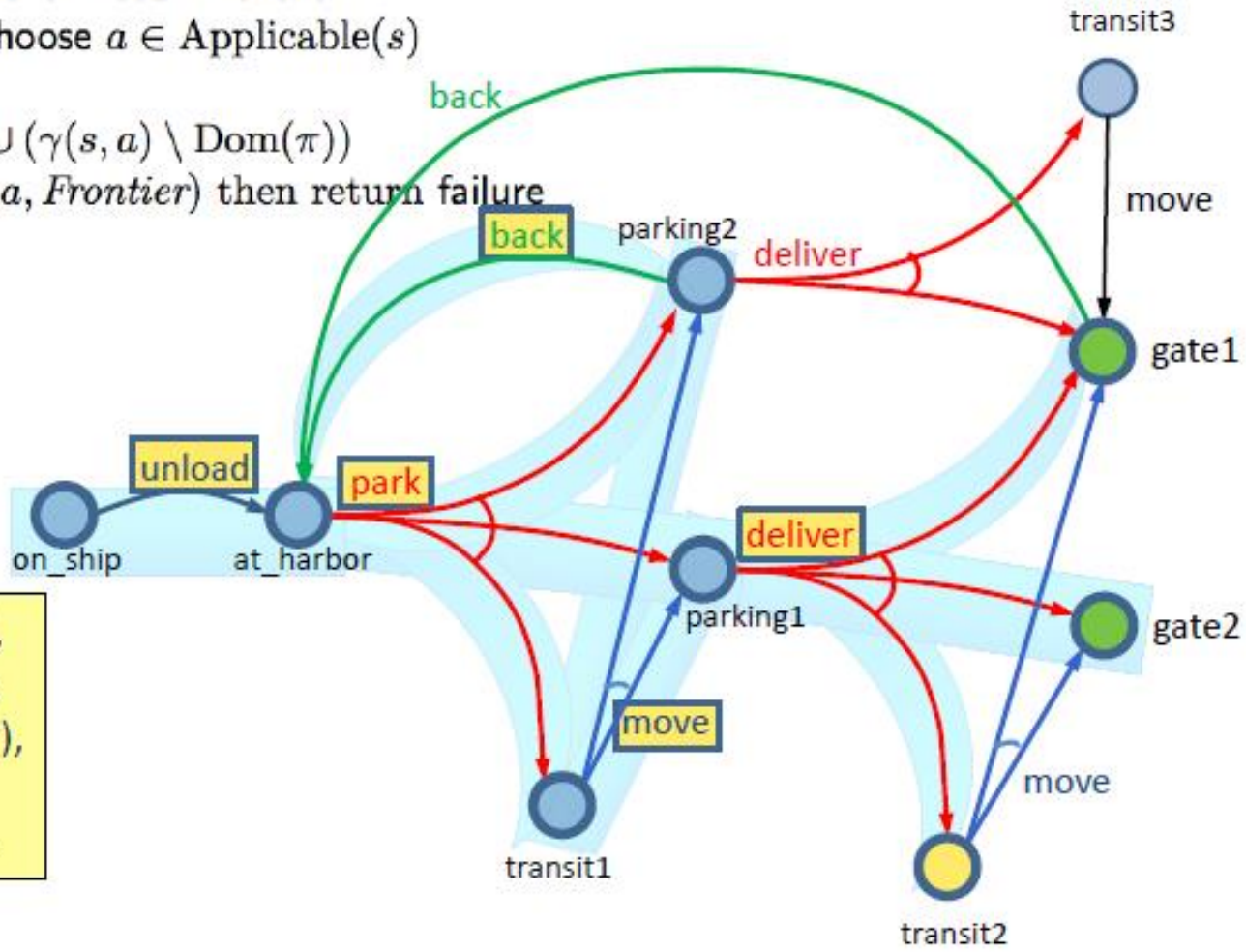
    nondeterministically choose $a \in$ Applicable(s)
    $\pi \leftarrow \pi \cup (s, a)$
    $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
    if has-unsafe-loops$(\pi, a, Frontier)$ then return failure
  return π

$Frontier \setminus S_g$ ={transit2}

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, back),
(transit1, move)}



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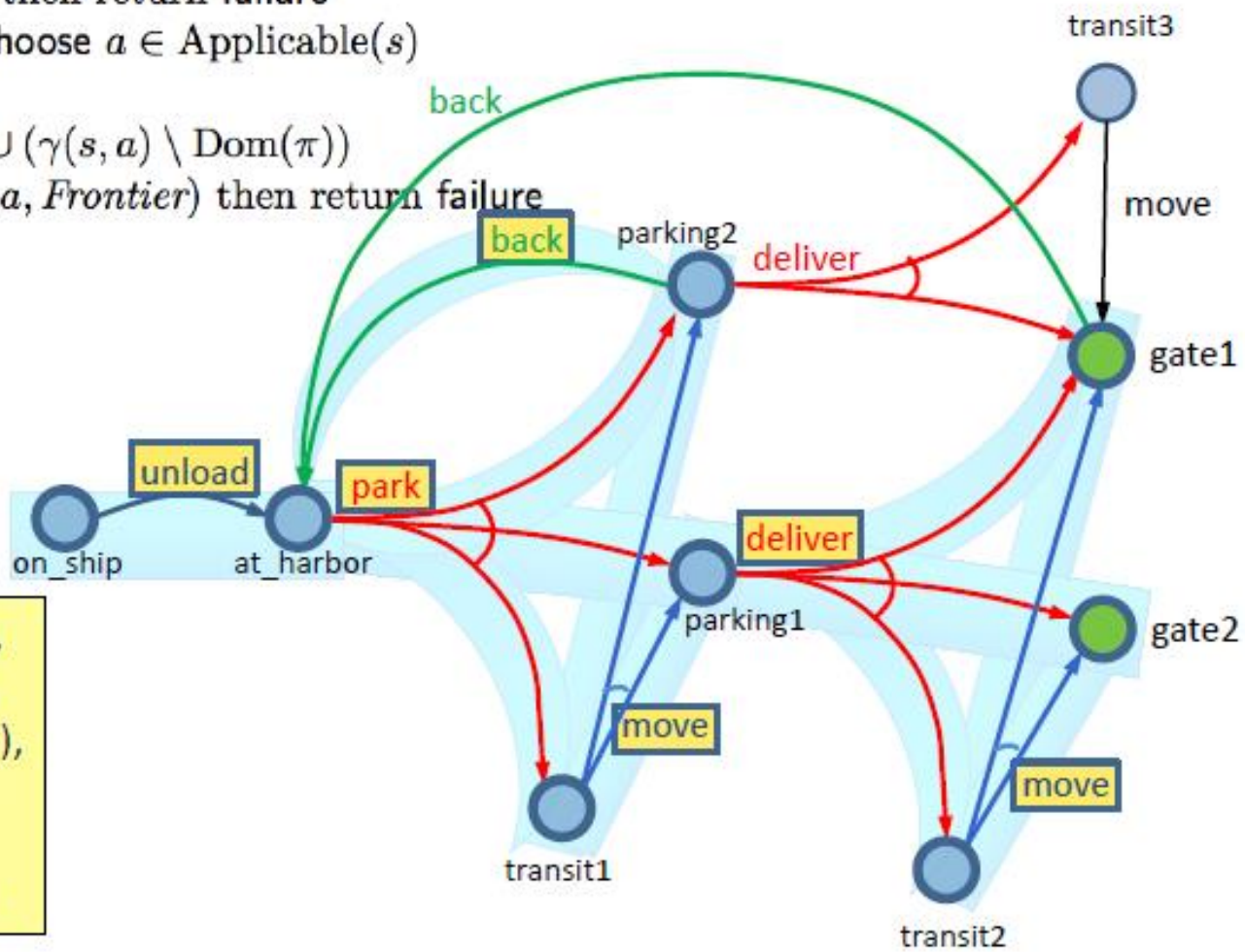
Example

Find-Safe-Solution (Σ, s_0, S_g)
  $\pi \leftarrow \varnothing$
  $Frontier \leftarrow \{s_0\}$
  for every $s \in Frontier \setminus S_g$ do
    $Frontier \leftarrow Frontier \setminus \{s\}$
    if Applicable$(s) = \varnothing$ then return failure
    nondeterministically choose $a \in$ Applicable(s)
    $\pi \leftarrow \pi \cup (s, a)$
    $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \text{Dom}(\pi))$
    if has-unsafe-loops$(\pi, a, Frontier)$ then return failure
  return π

$Frontier \setminus S_g = \emptyset$

π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, back),
(transit1, move),
(transit2, move)}



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Guided-Find-Safe-Solution

- Motivation:
  - Much easier to find solutions if they don't have to be safe
  - Find-Safe-Solution needs plans for all possible outcomes of actions
  - Find-Solution only needs a plan for one of them
- Idea:
  - loop
    - Find a solution π
    - Look at each leaf node of π
      - If the leaf node isn't a goal, find a solution and incorporate it into π

Guided-Find-Safe-Solution

Guided-Find-Safe-Solution (Σ, s_0, S_g)
  if $s_0 \in S_g$ then return$(\varnothing)$
  if $Applicable(s_0) = \varnothing$ then return(failure)
  $\pi \leftarrow \varnothing$
  loop
    $Q \leftarrow leaves(s_0, \pi) \setminus S_g$
    if $Q = \varnothing$ then do
      $\pi \leftarrow \pi \setminus \{(s, a) \in \pi \mid s \notin \widehat{\gamma}(s_0, \pi)\}$
      return(π)
    select arbitrarily $s \in Q$
    $\pi' \leftarrow$ Find-Solution(Σ, s, S_g)
    if $\pi' \neq$ failure then do
      $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin \text{Dom}(\pi)\}$
    else if $s = s_0$ then return failure *(not in book)*
    else for every s' and a such that $s \in \gamma(s', a)$ do
      $\pi \leftarrow \pi \setminus \{(s', a)\}$
      make a not applicable in s'

π is a solution. Return the part that's reachable from s_0.

Choose any leaf s that isn't a goal. Find a solution π' for s.

For each (s,a) in π', add to π unless π already has an action at s

s is unsolvable. For each (s',a) that can produce s, modify π and Σ so we'll never use a at s'

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Guided-Find-Safe-Solution (Σ, s_0, S_g)

if $s_0 \in S_g$ then return($\varnothing$)
if $Applicable(s_0) = \varnothing$ then return(failure)
$\pi \leftarrow \varnothing$
loop
  $Q \leftarrow leaves(s_0, \pi) \setminus S_g$
  if $Q = \varnothing$ then do
    $\pi \leftarrow \pi \setminus \{(s, a) \in \pi \mid s \notin \widehat{\gamma}(s_0, \pi)\}$
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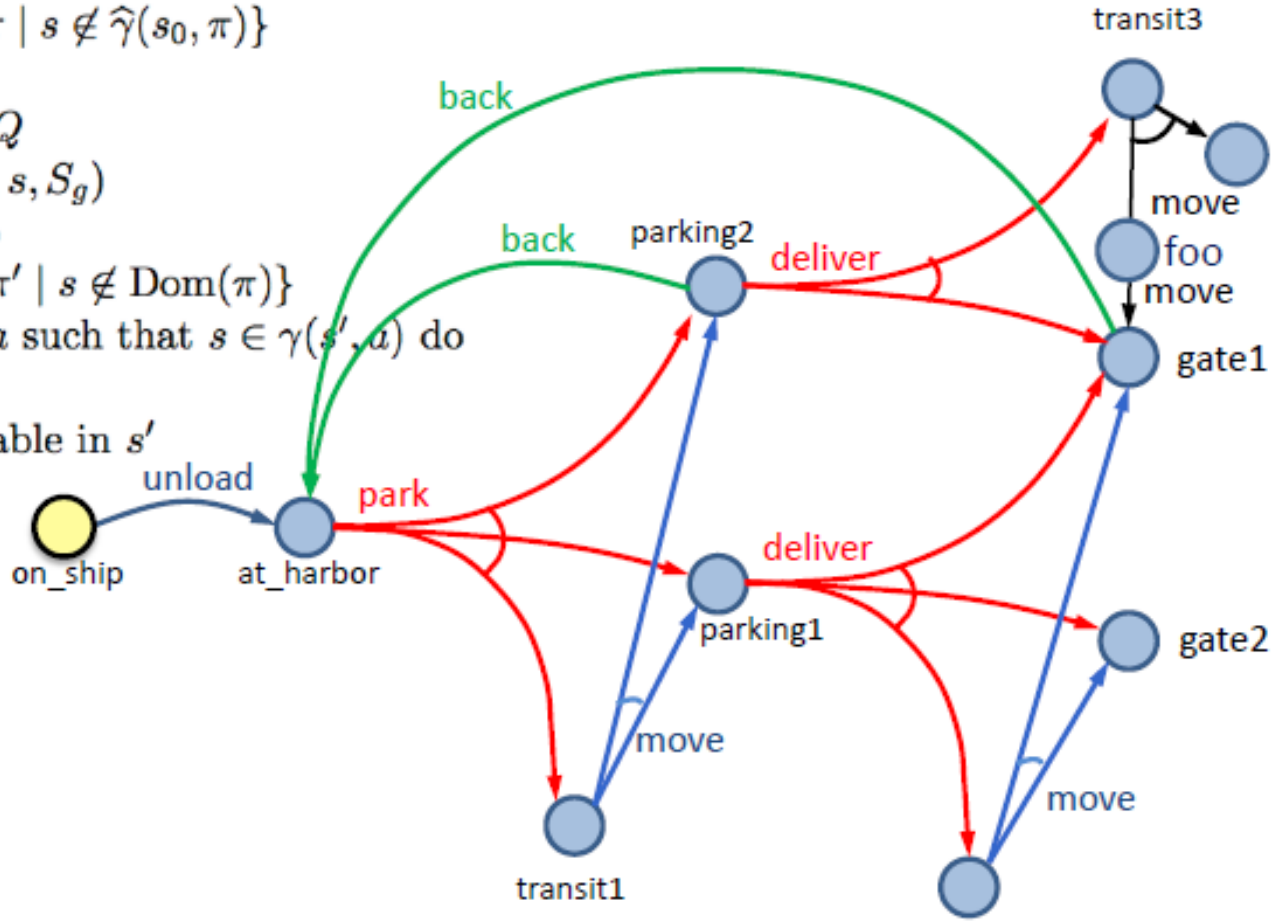
    make a not applicable in s'

Example



Guided-Find-Safe-Solution (Σ, s_0, S_g)

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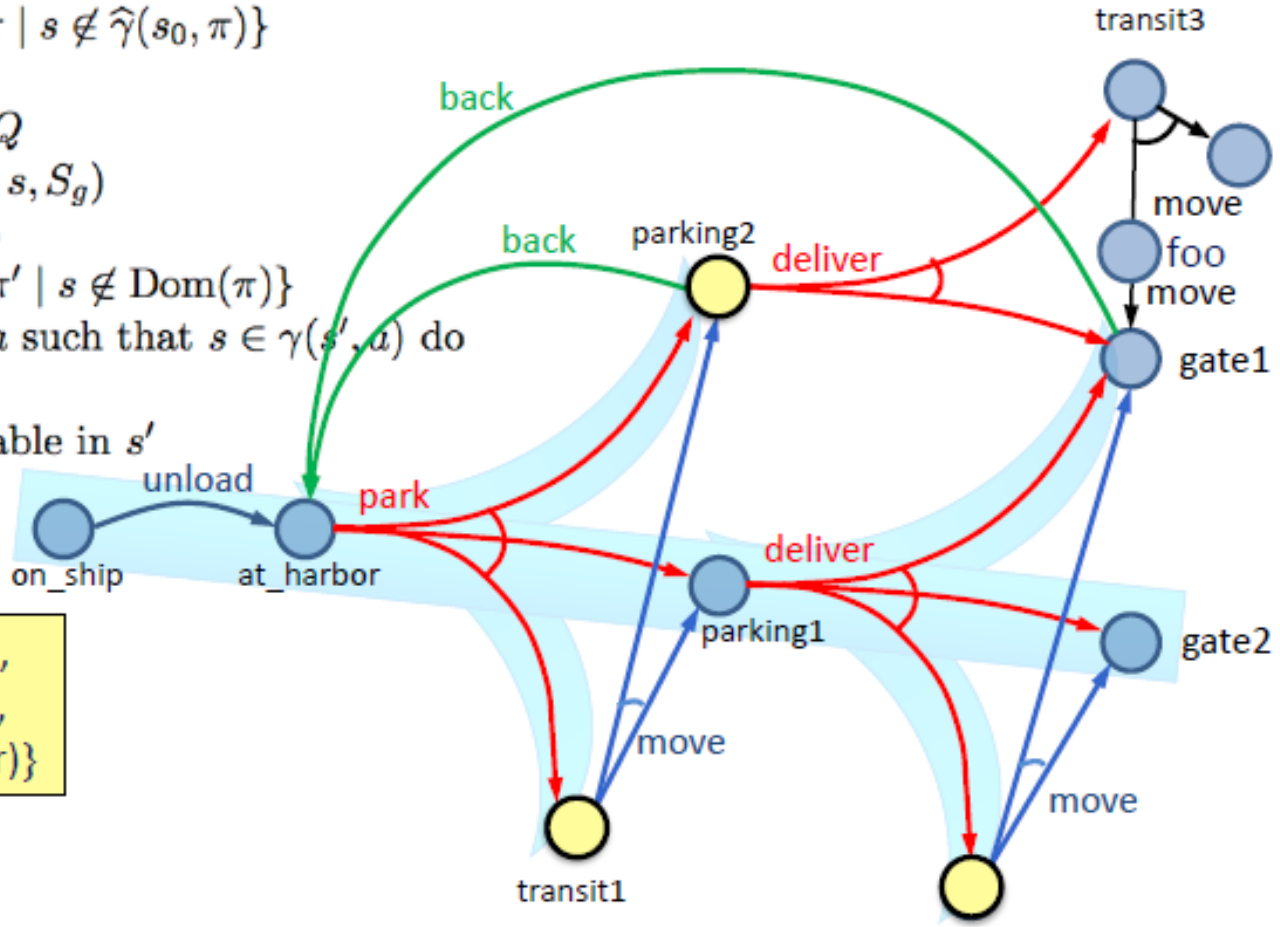
    make a not applicable in s'

Example



π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver)}

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Guided-Find-Safe-Solution (Σ, s_0, S_g)

if $s_0 \in S_g$ then return($\varnothing$)
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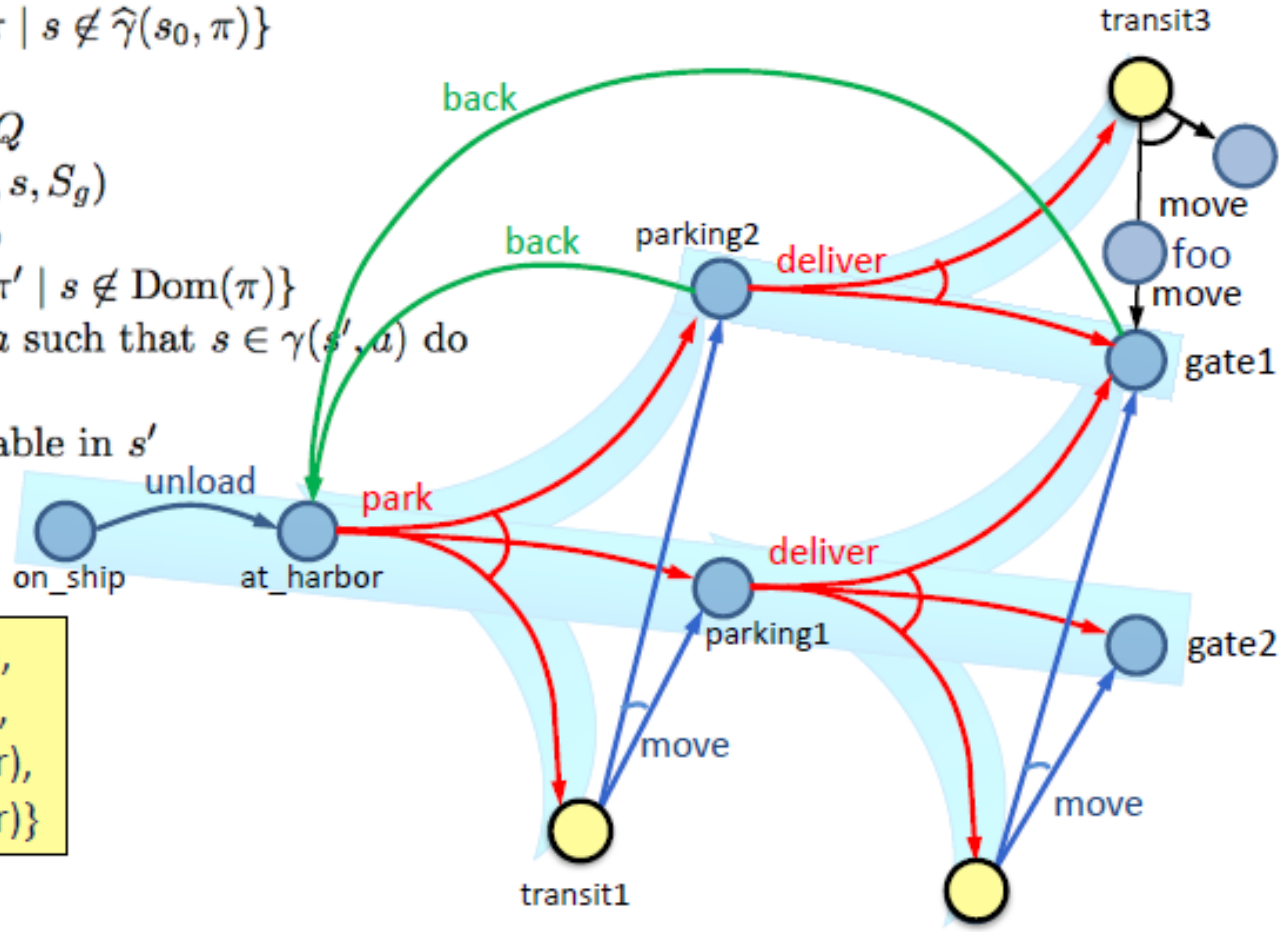
    make a not applicable in s'

Example



π = {(on_ship, unload),
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Guided-Find-Safe-Solution (Σ, s_0, S_g)

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    return(π)
  select arbitrarily $s \in Q$
  $\pi' \leftarrow$ Find-Solution(Σ, s, S_g)
  if $\pi' \neq$ failure then do
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  else for every s' and a such that $s \in \gamma(s', a)$ do
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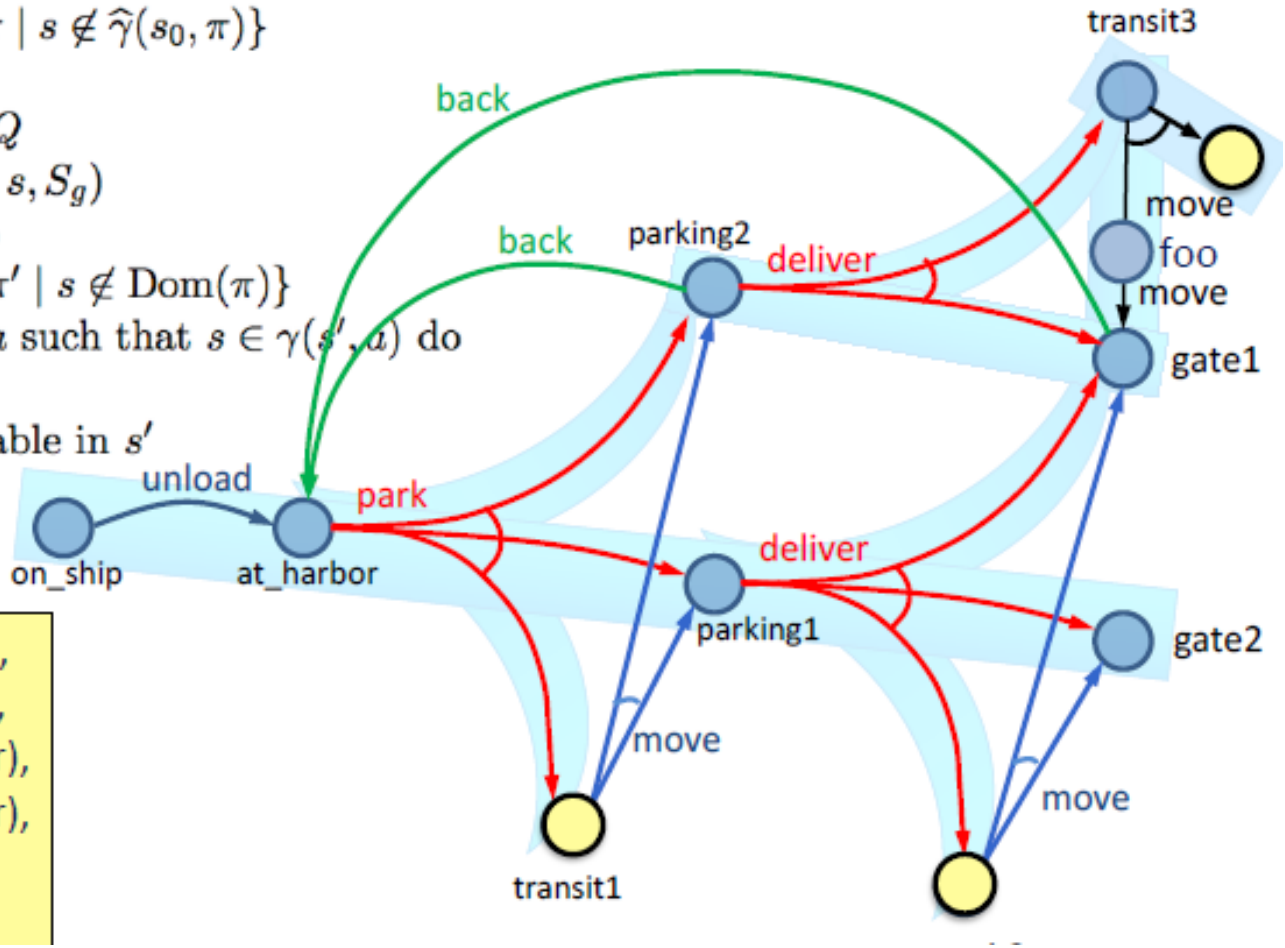
    make a not applicable in s'

Example



π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit3, move),
(foo, move)}

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Guided-Find-Safe-Solution (Σ, s_0, S_g)

if $s_0 \in S_g$ then return($\varnothing$)
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  if $\pi' \neq$ failure then do
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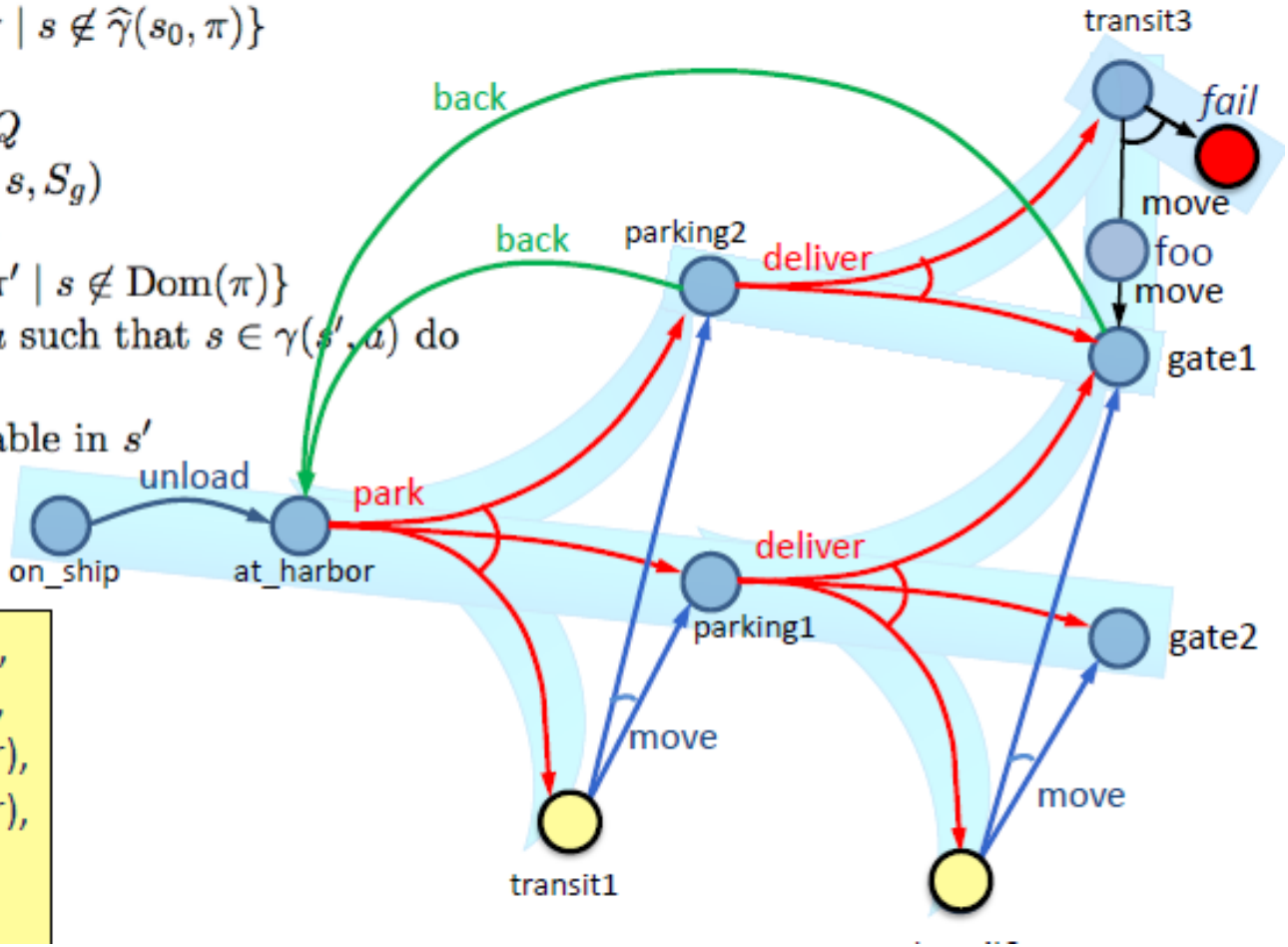
Example



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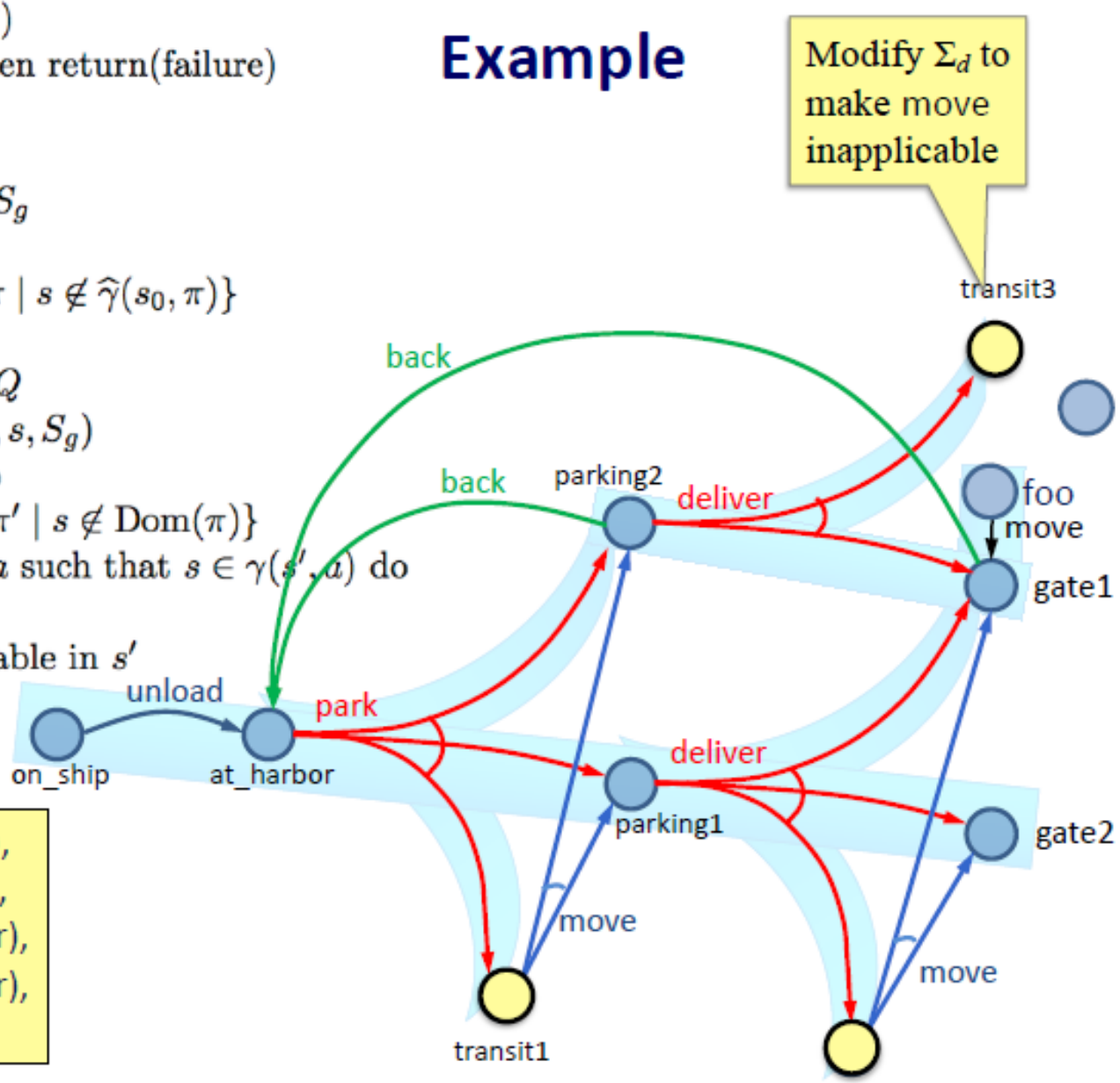
Example



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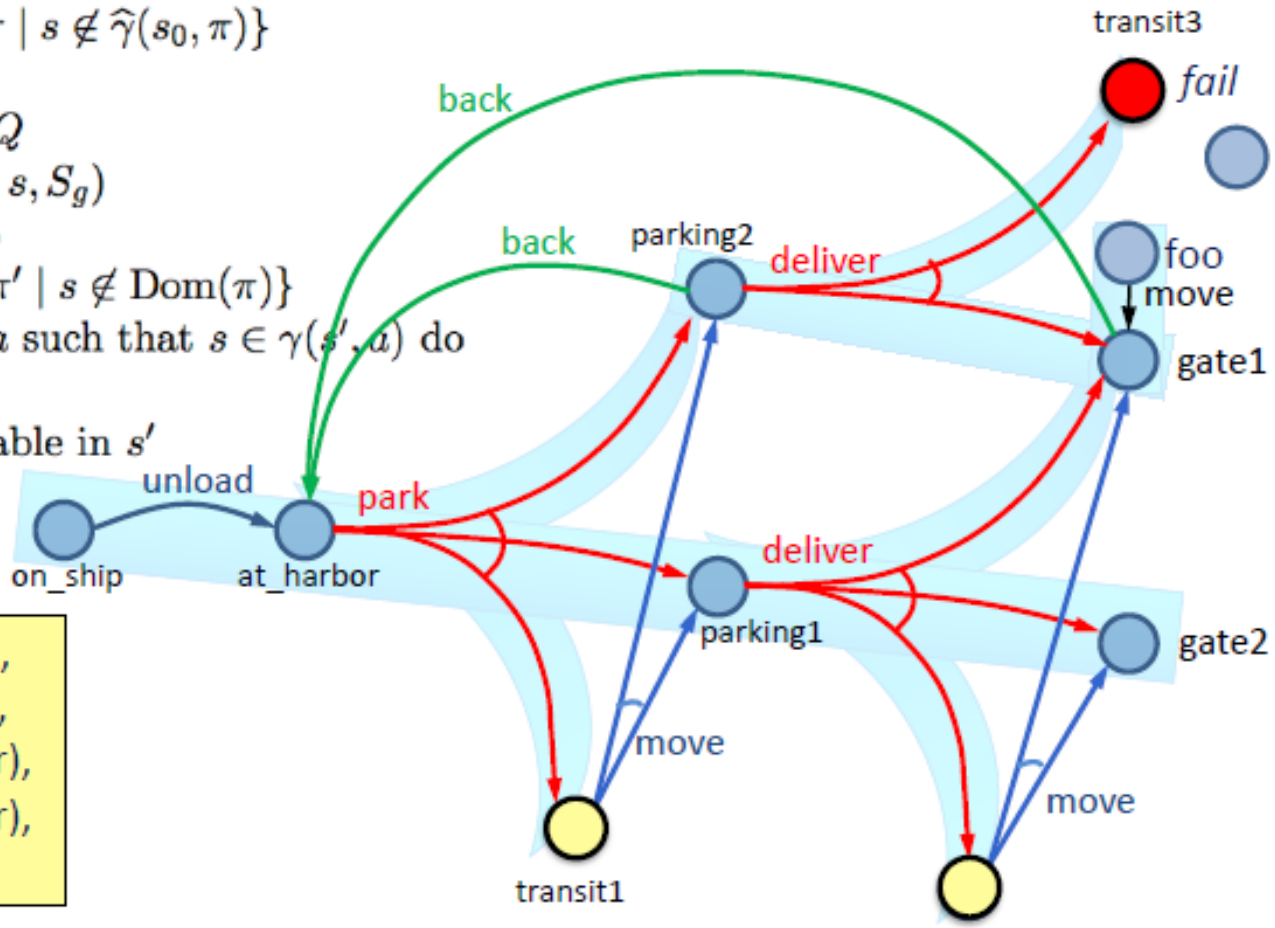
Example



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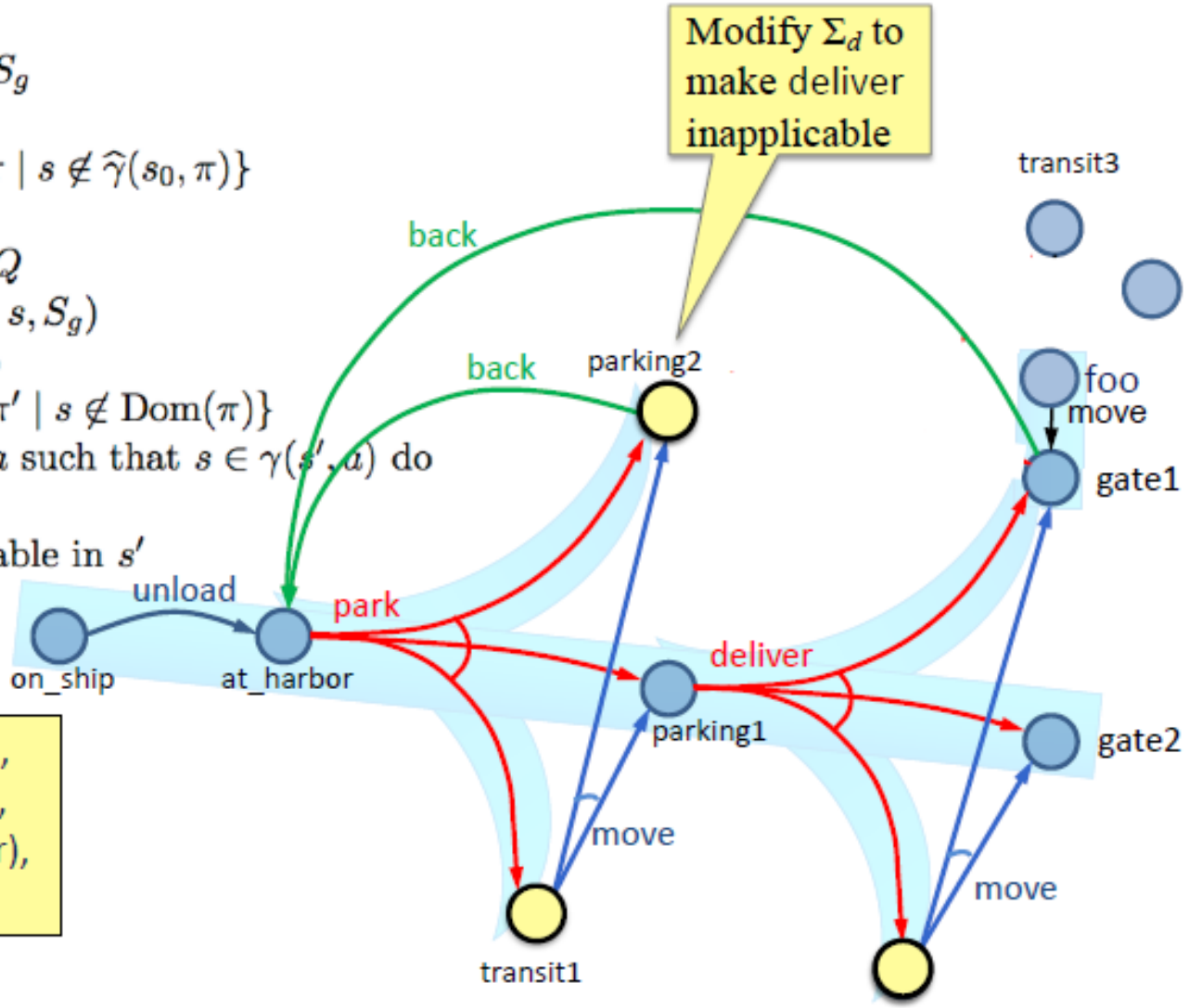
Example



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(foo, move)}

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Guided-Find-Safe-Solution (Σ, s_0, S_g)

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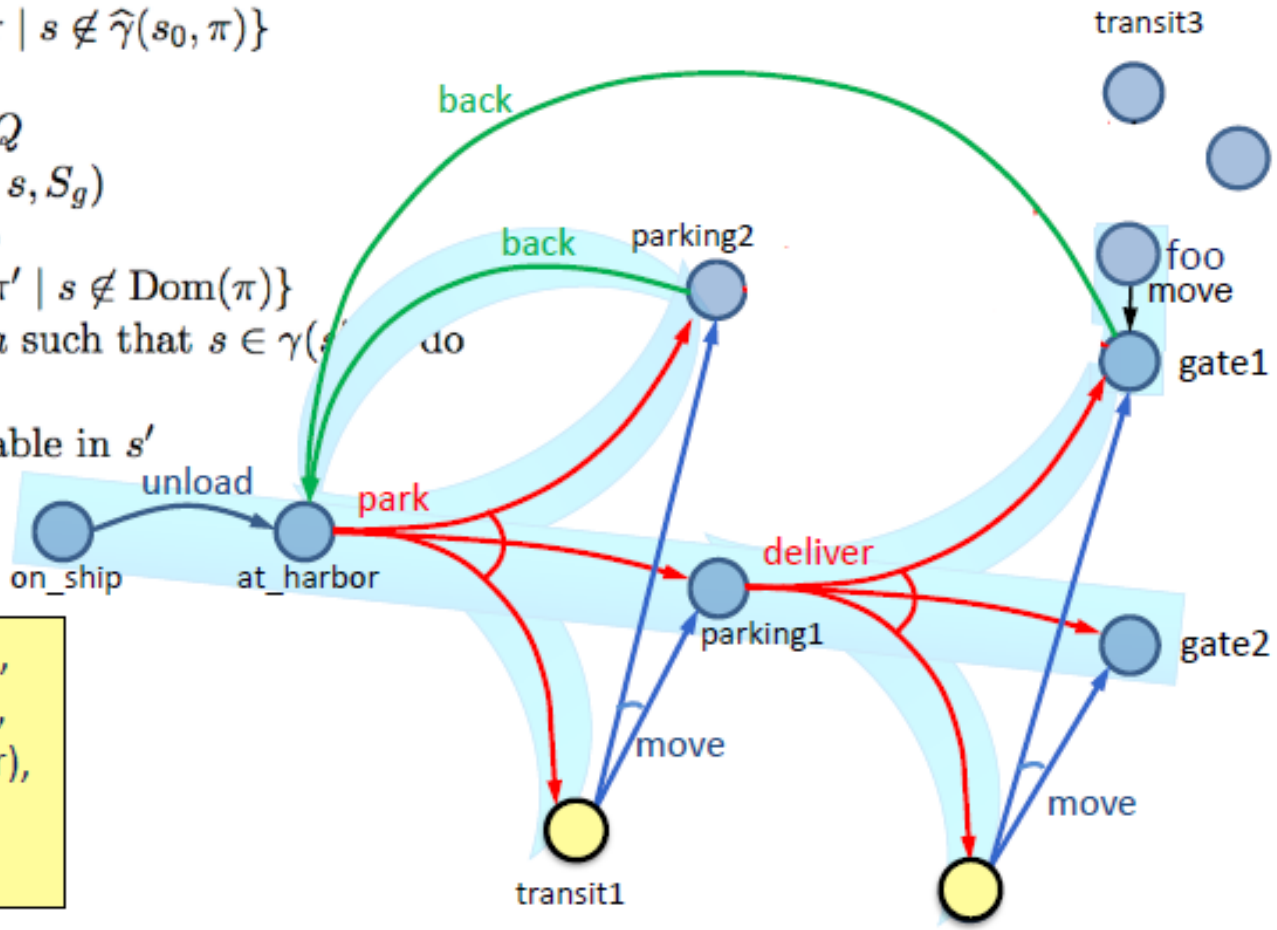

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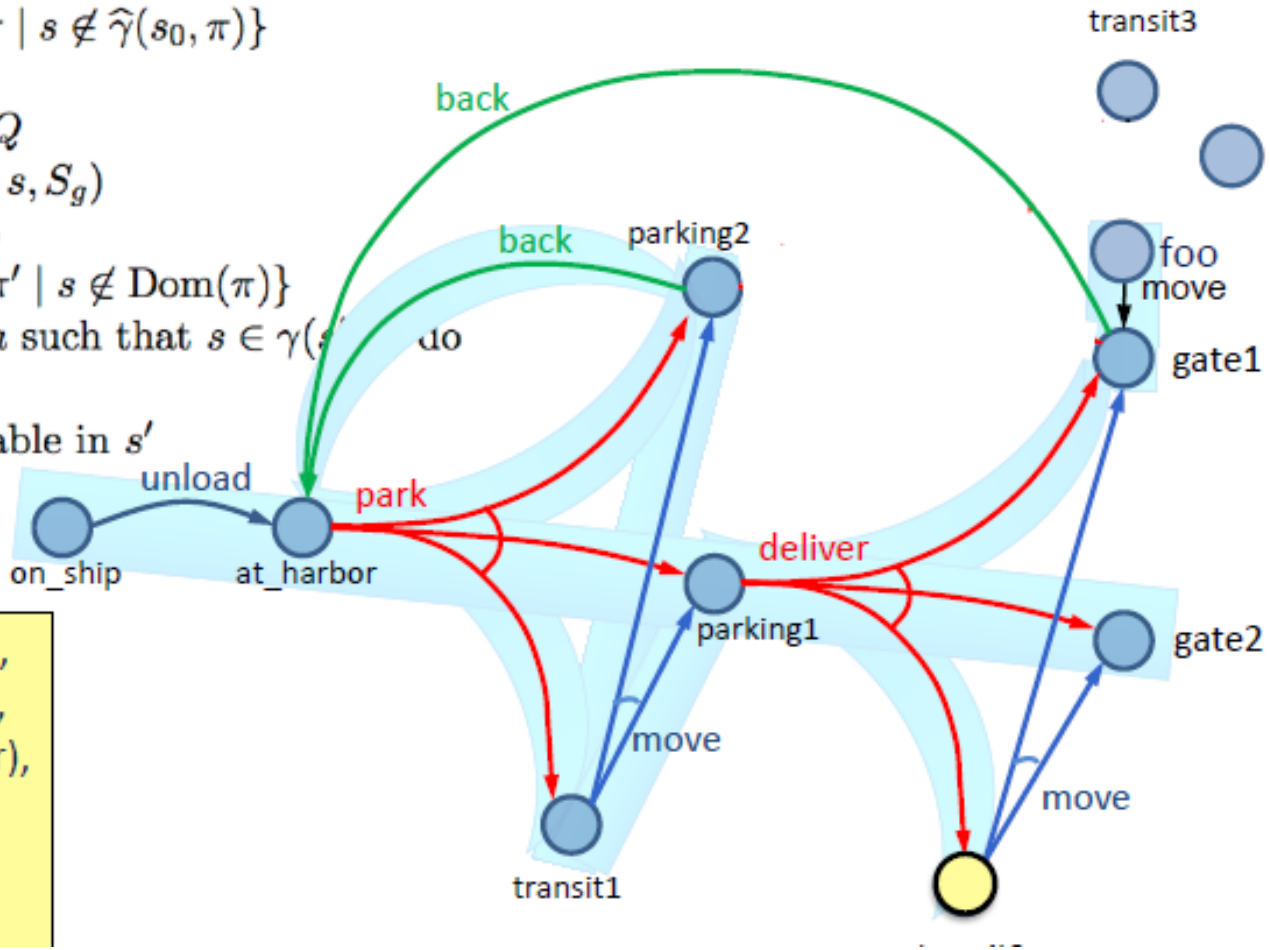

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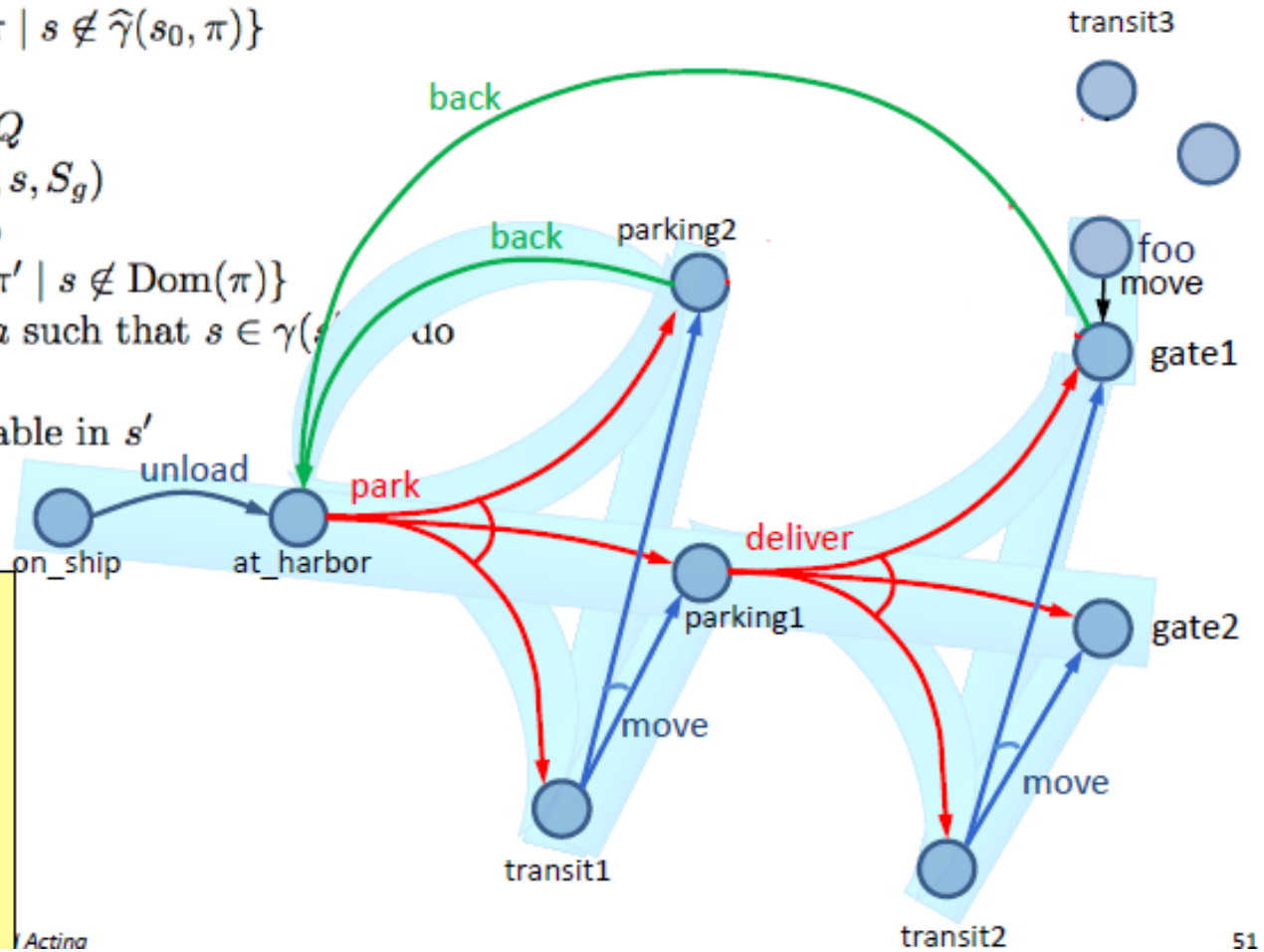

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Stefan Edelkamp (cf. Book Automated Planning and Acting)

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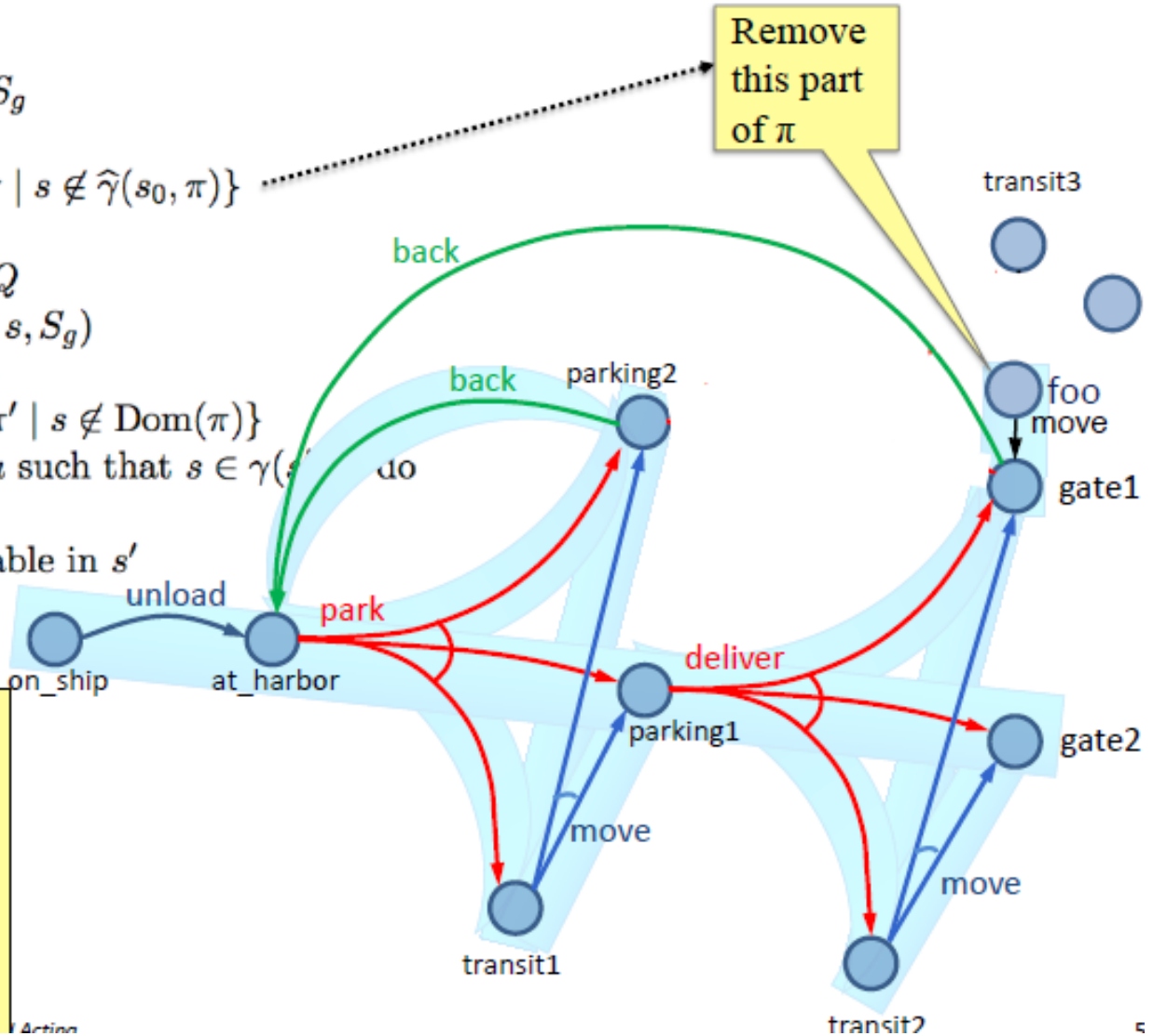

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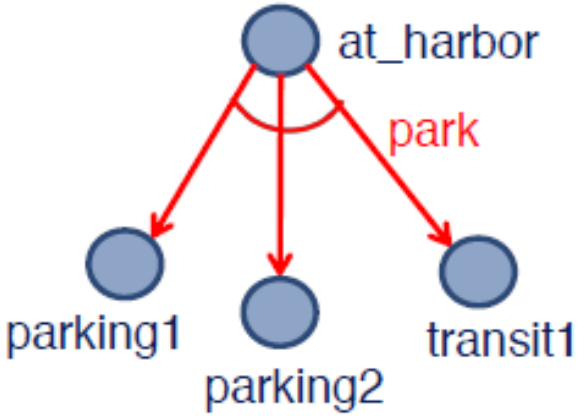
Determinization

- How to implement it?
  - Need implementation of Find-Solution
  - Need it to be very efficient
    - We'll call it many times
- Idea: instead of Find-Solution, use a classical planner

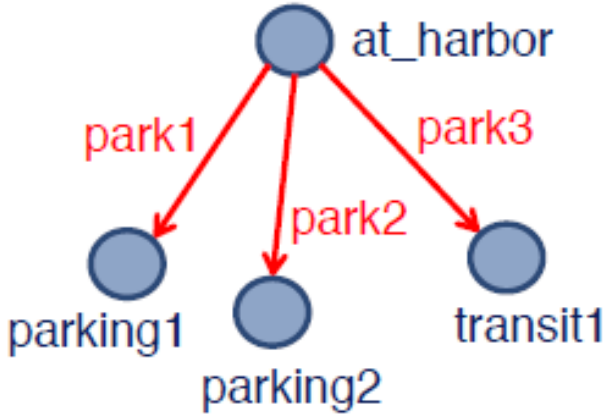
Stefan Edelkamp (cf. Book Automated Planning and Acting)

Determinization

- Convert the nondeterministic actions into something the classical planner can use
- *Determinize*
  - Suppose a_i has n possible outcomes
  - n deterministic actions, one for each outcome



- Classical planner returns a plan $p = \langle a_1, a_2, \ldots, a_n \rangle$
- If p is acyclic, can convert it to a policy
  - (unsafe) solution for P
  - $\{(s_0,\boldsymbol{a}_1), (s_1,\boldsymbol{a}_2), \ldots, (s_{n-1},\boldsymbol{a}_n)\rangle$ where
    - each $\boldsymbol{a}_i$ is the nondeterministic action whose determinization includes a_i
    - $s_i \in \gamma(s_{i-1},\boldsymbol{a}_i)$



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Determinization

- Nondeterministic planning problem $P = (\Sigma, s_0, S_g)$
- Determinization $P_d = (\Sigma_d, s_0, S_g)$
- Classical planner returns a solution for P
  - a plan $p = \langle a_1, a_2, \ldots, a_n \rangle$
- If p is acyclic, can convert it to an (unsafe) solution for P
  - $\{(s_0, \boldsymbol{a}_1), (s_1, \boldsymbol{a}_2), \ldots, (s_{n-1}, \boldsymbol{a}_n)\}$
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  - each $s_i \in \gamma(s_{i-1}, \boldsymbol{a}_i)$

Plan2policy$(p = \langle a_1, \ldots, a_n \rangle, s)$
  $\pi \leftarrow \varnothing$
  loop for i from 1 to n do
    $\pi \leftarrow \pi \cup (s, \text{det2nondet}(a_i))$
    $s \leftarrow \gamma_d(s, a_i)$
  return π

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Determinization

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      return(π)
    select $s \in Q$
    $p' \leftarrow$ Forward-search(Σ_d, s, S_g)
    if $p' \neq fail$ then do
      $\pi' \leftarrow$ Plan2policy(p', s)
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      $\pi \leftarrow \pi \setminus \{(s', a)\}$
      make the actions in the determinization of a not applicable in s'

Same as Guided-Find-Safe-Solution

Any classical planner that doesn't return cyclic plans

Convert p' to a policy. Add each (s,a) to π unless π already has an action at s

s is unsolvable. For each (s',a) that can produce s, modify π and Σ_d so we'll never use a at s'

Stefan Edelkamp (cf. Book Automated Planning and Acting)

Example

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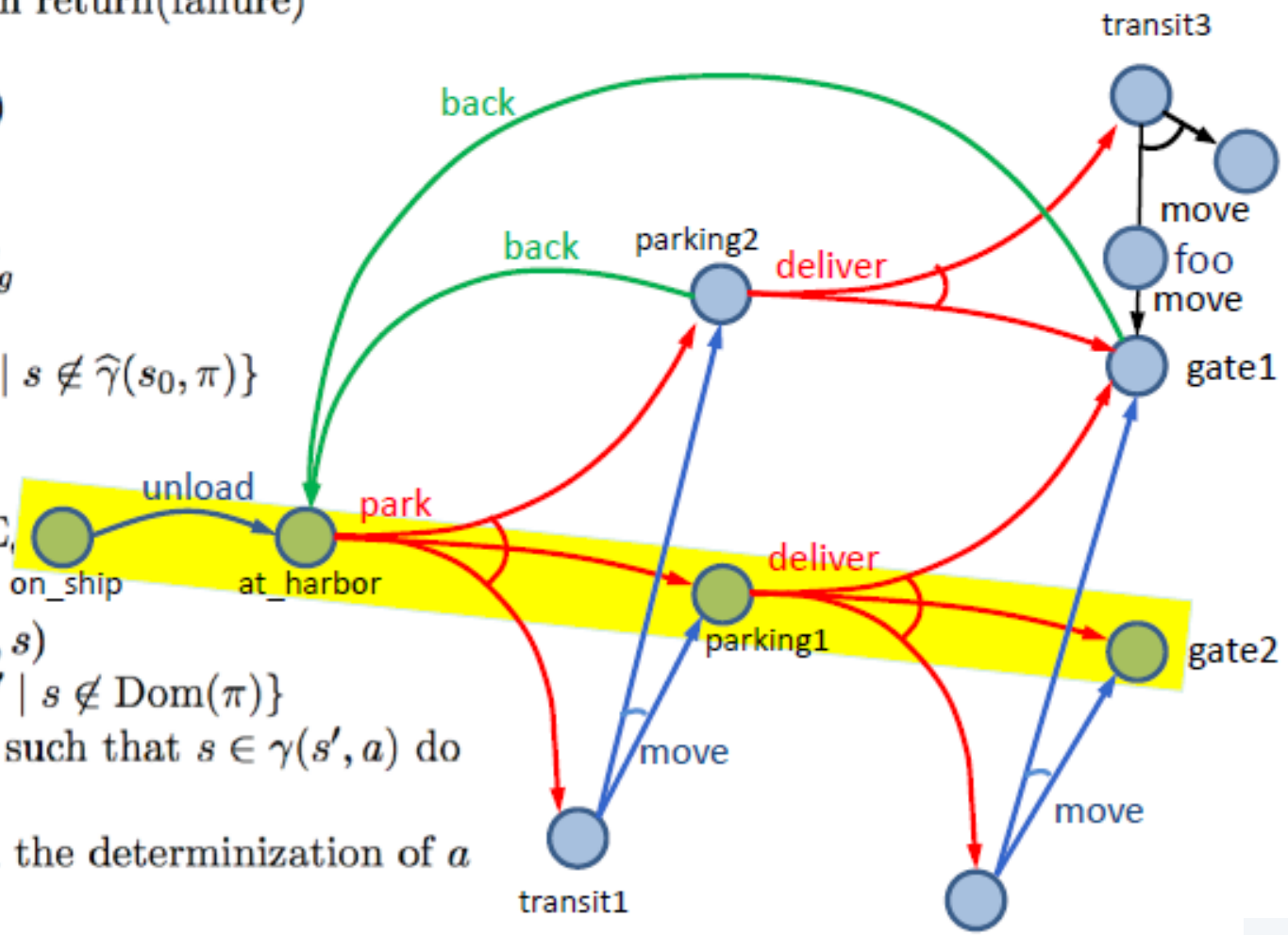

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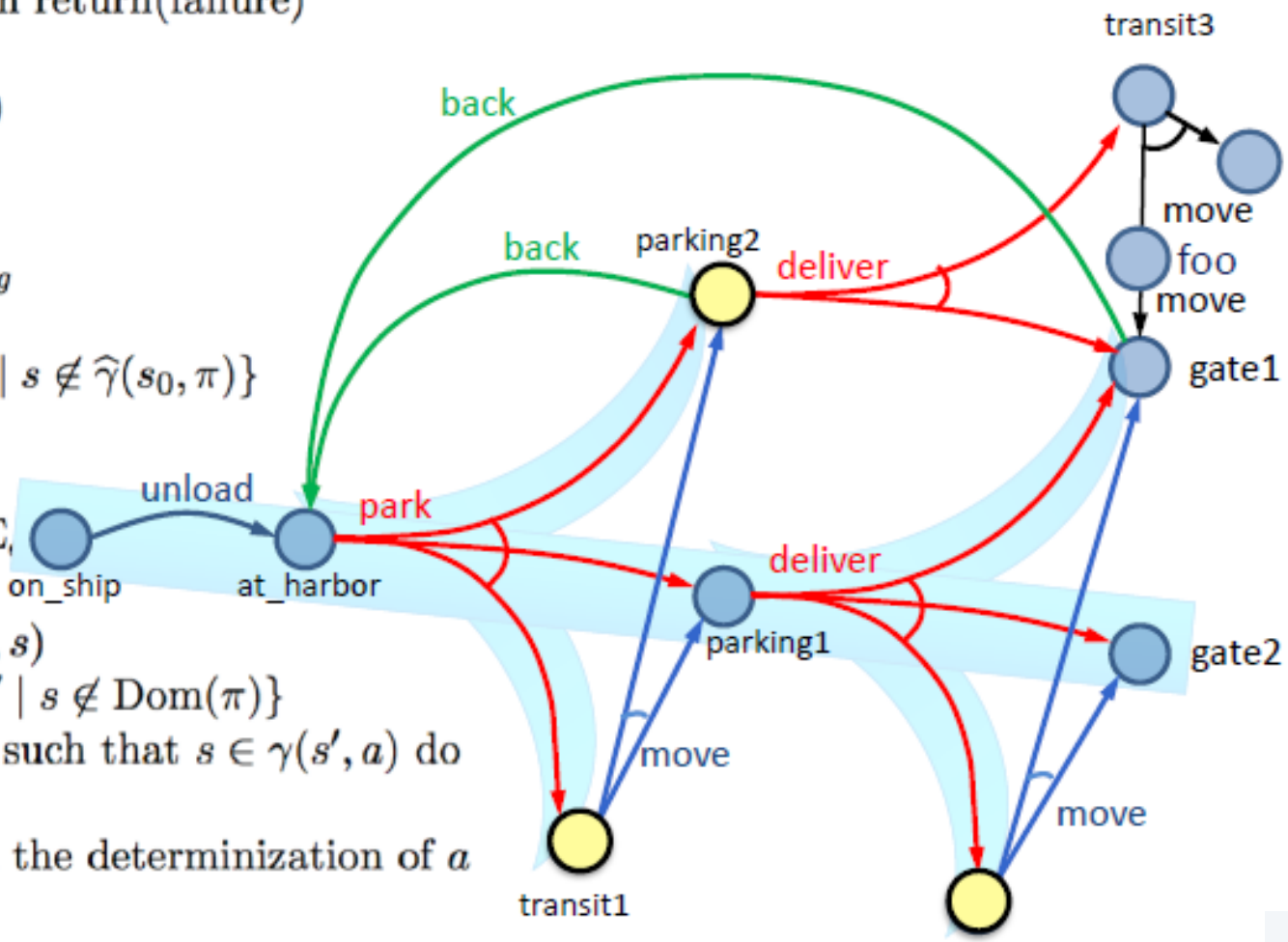

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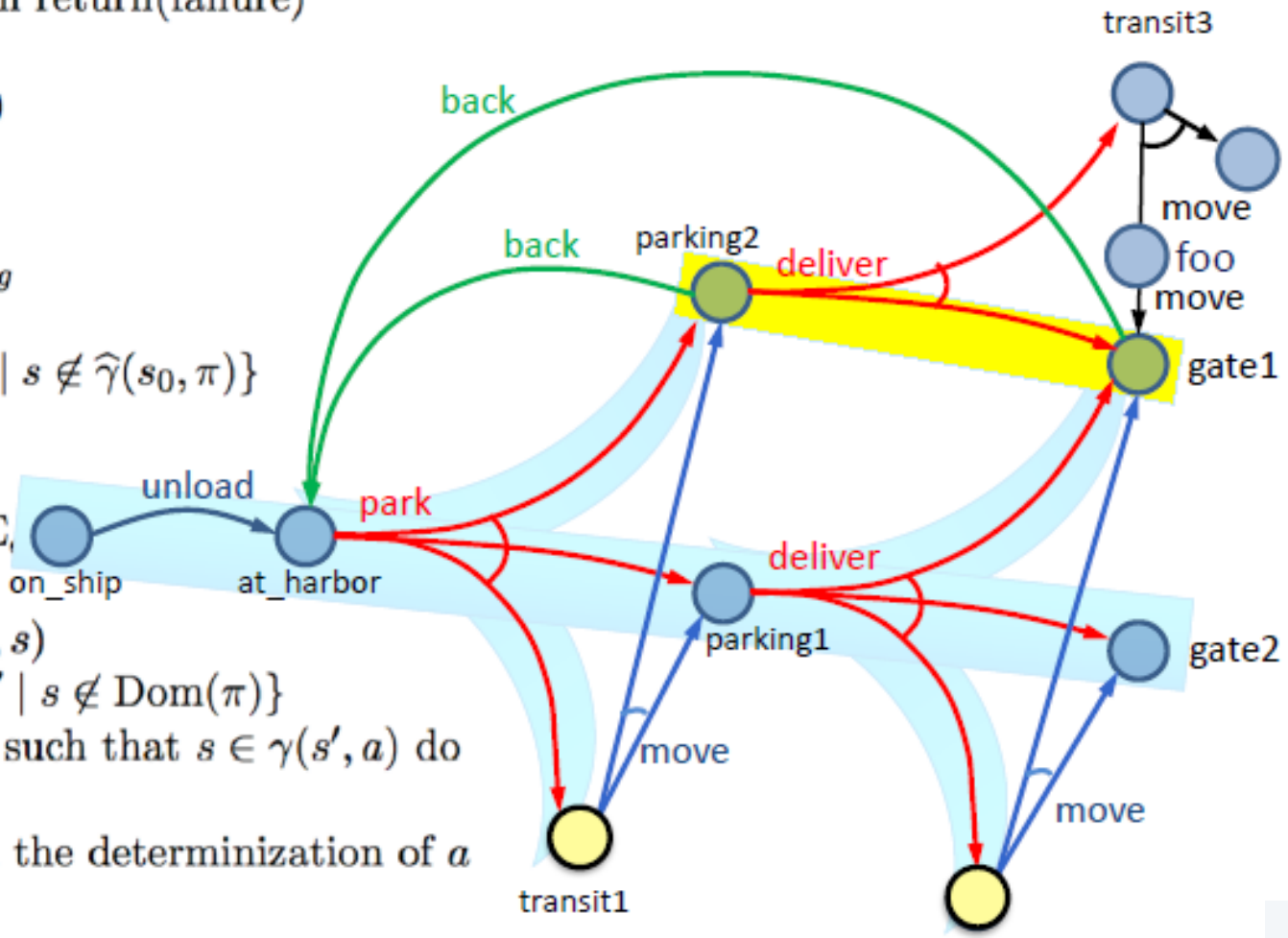

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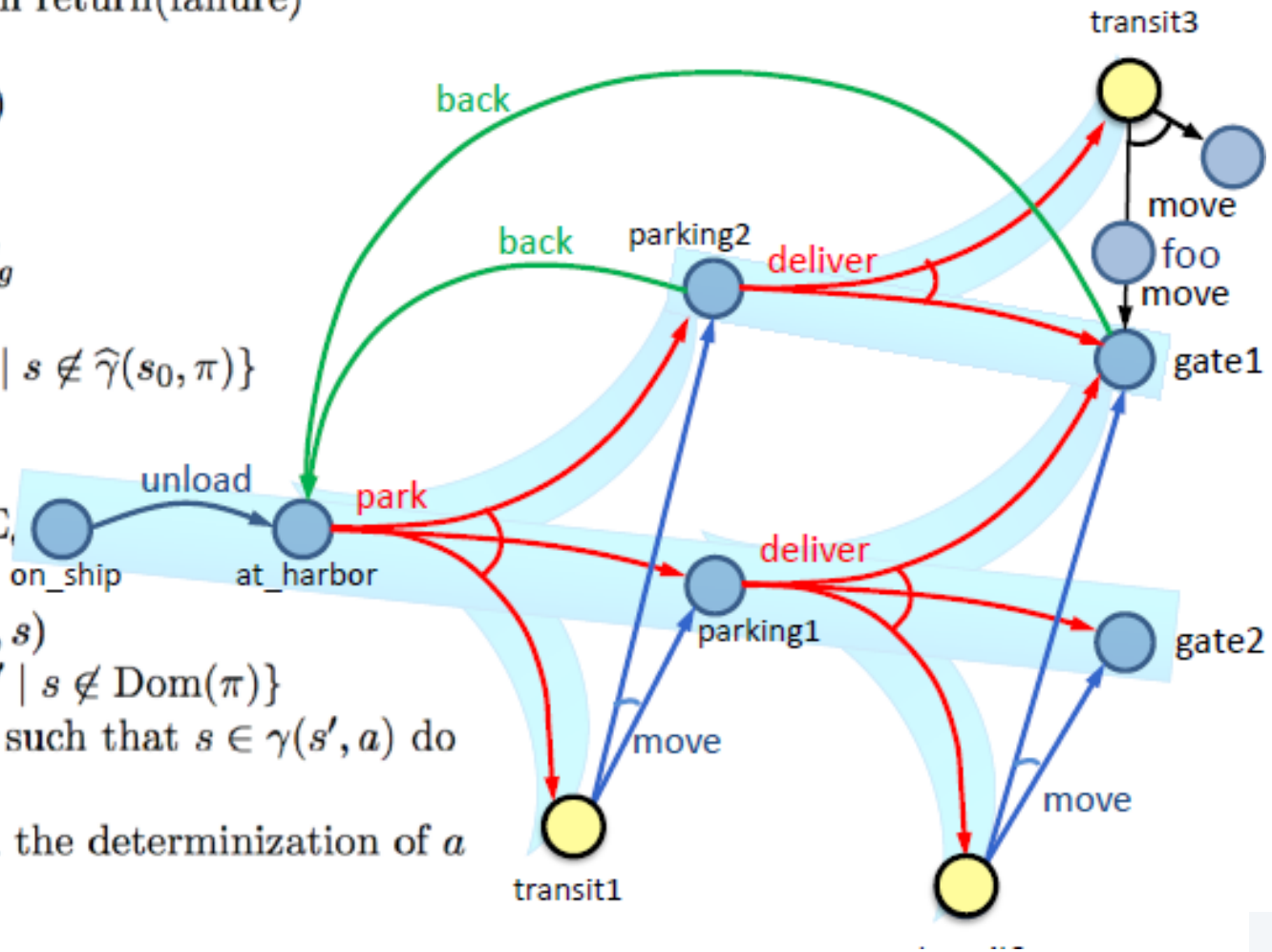

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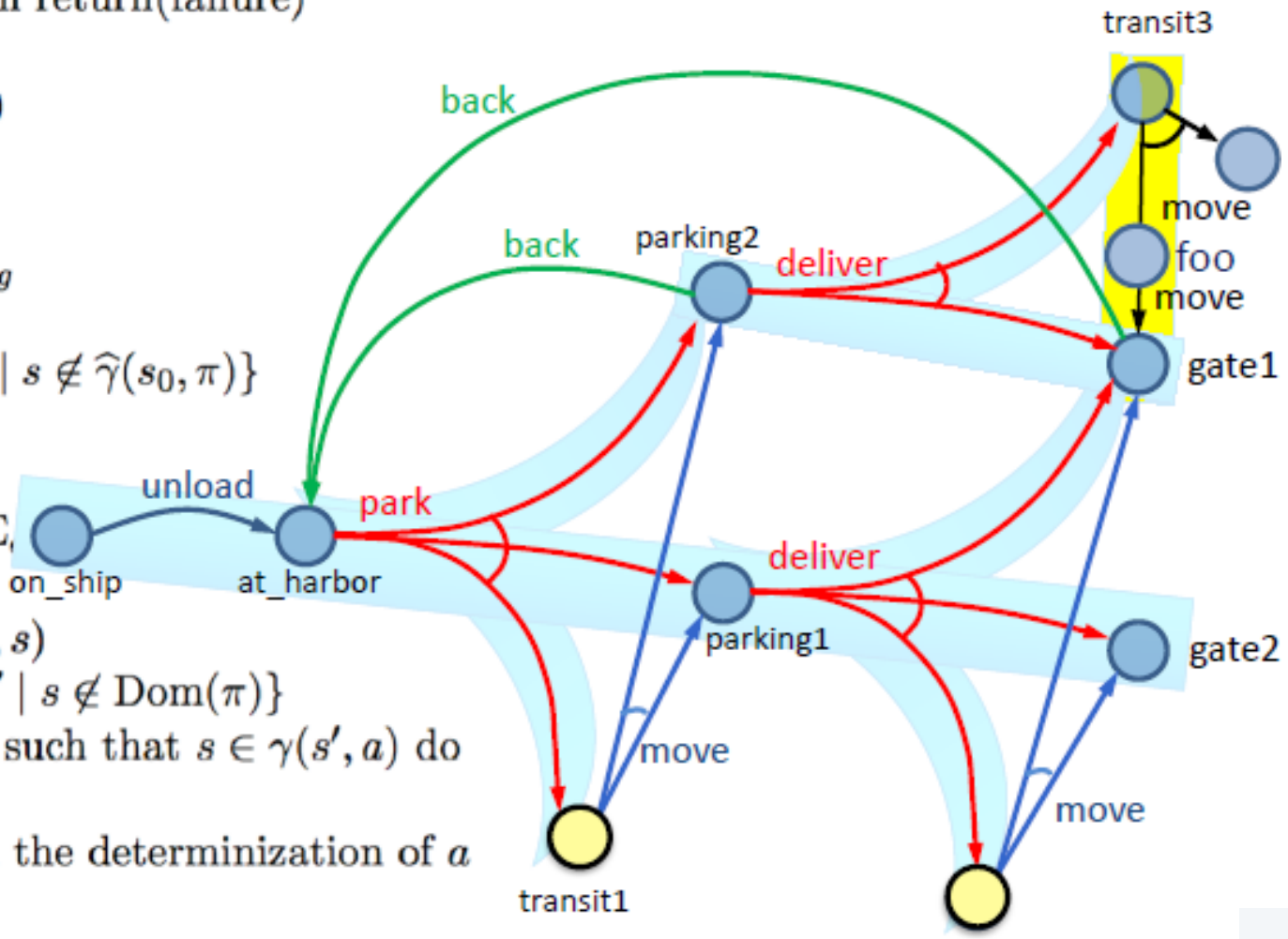

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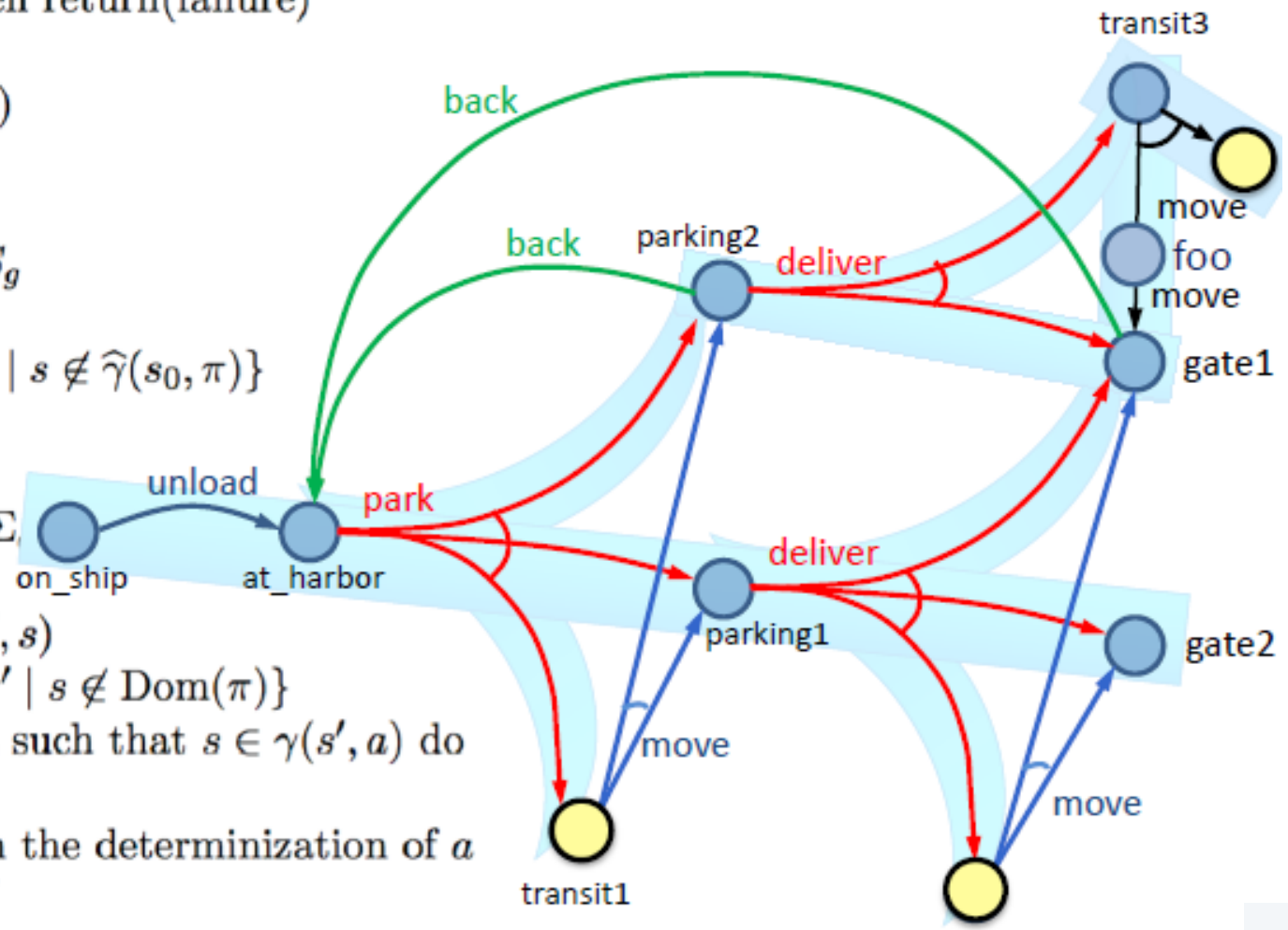

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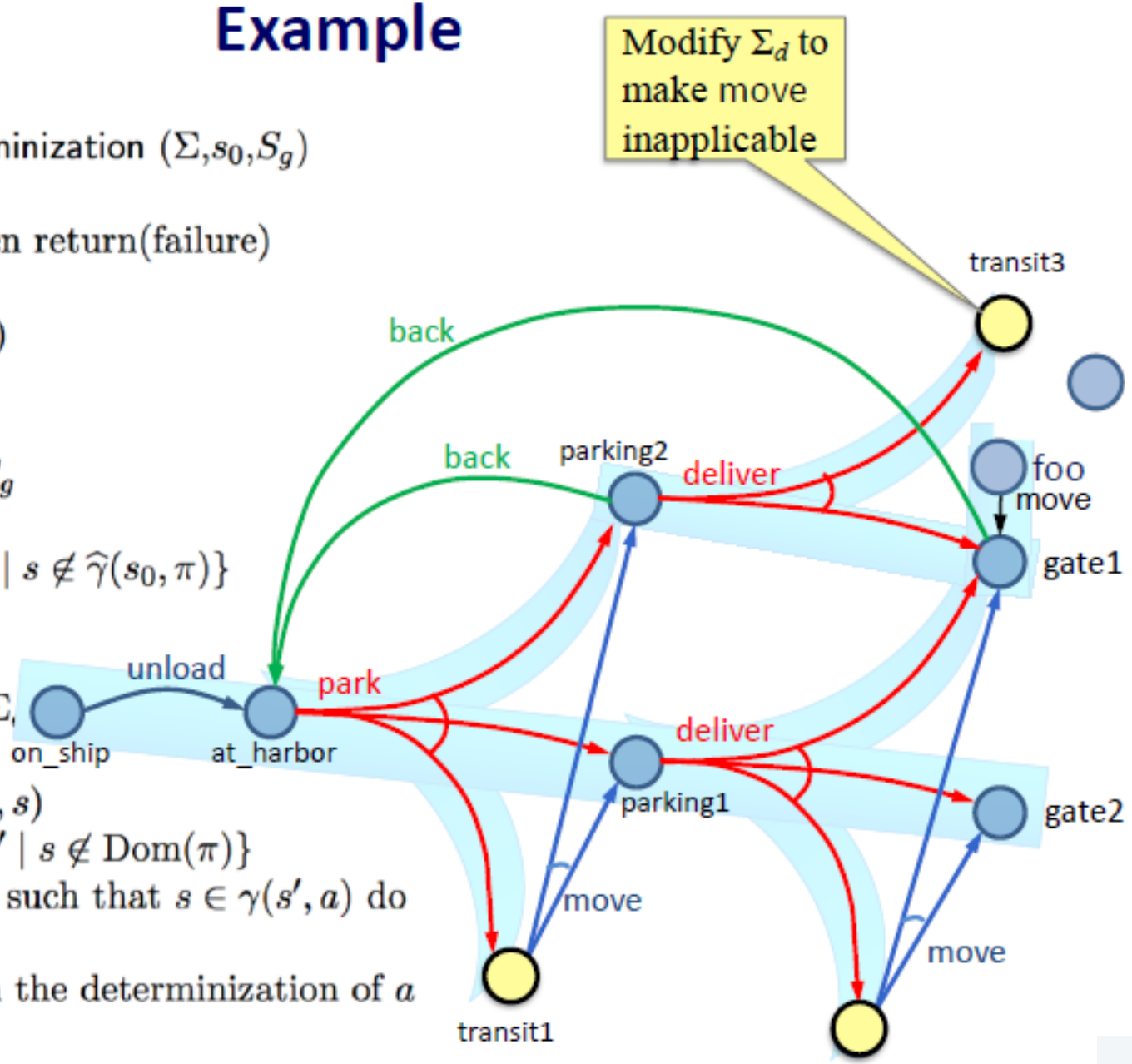

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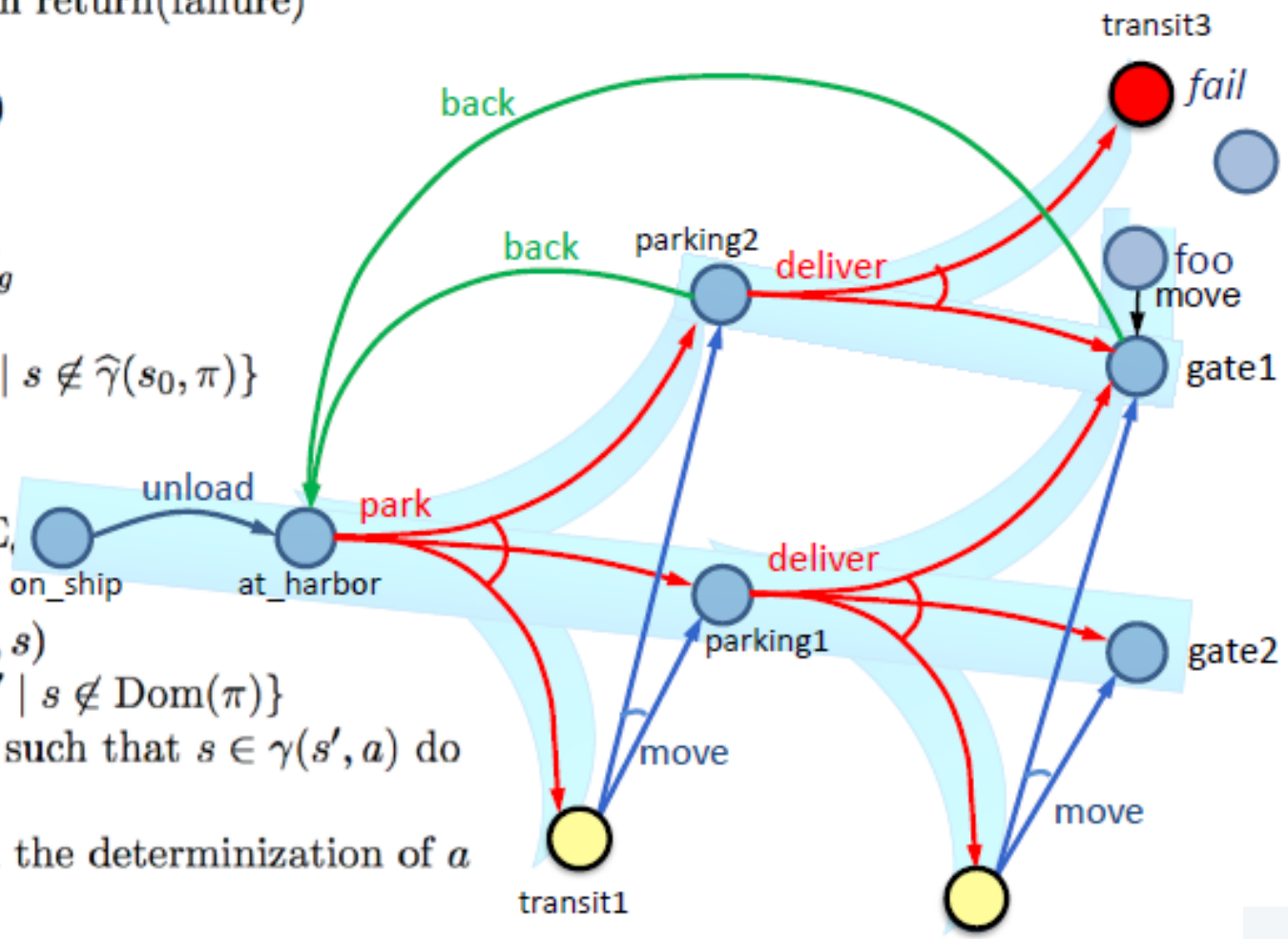

Stefan Edelkamp (cf. Book Automated Planning and Acting)

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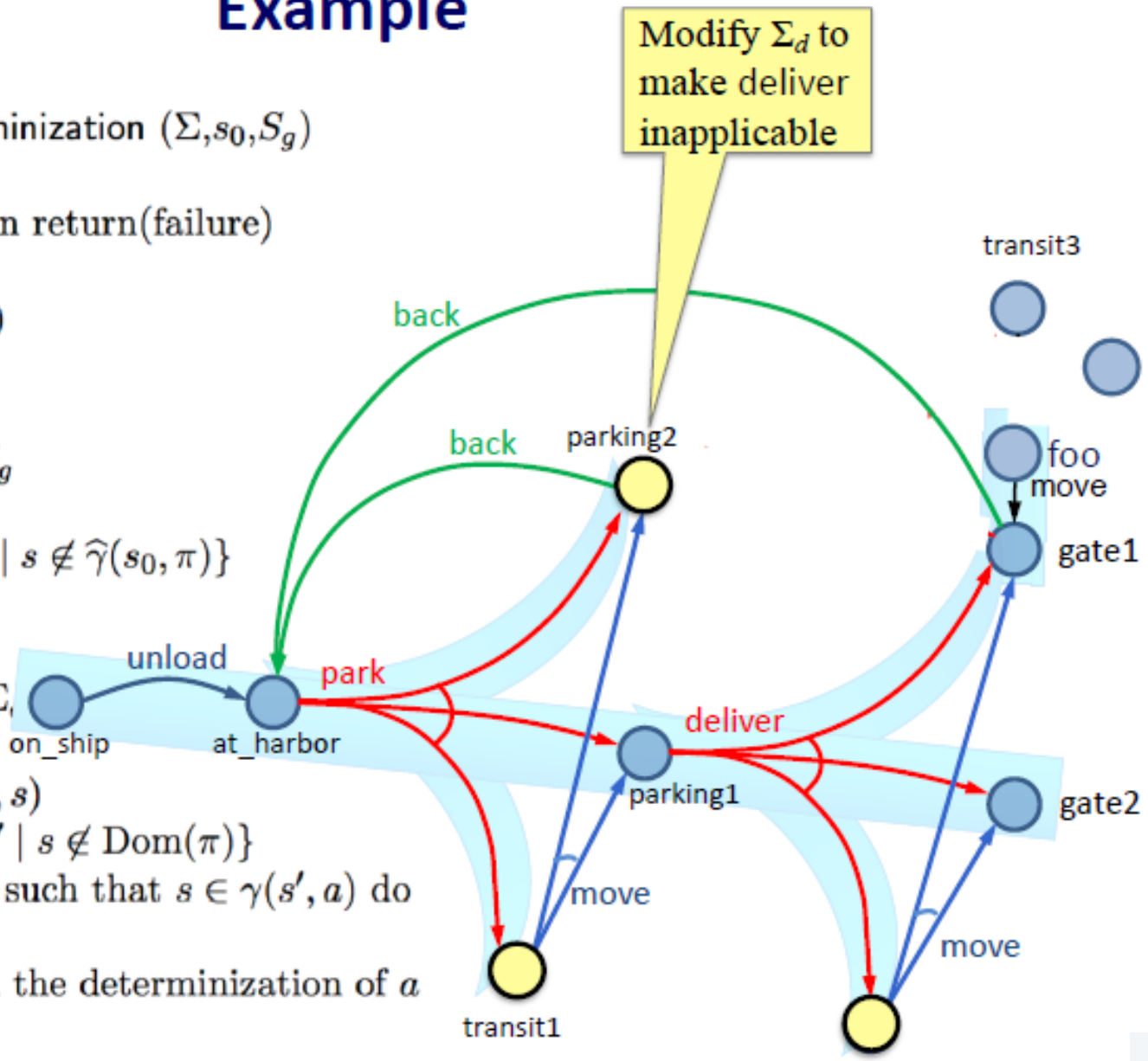

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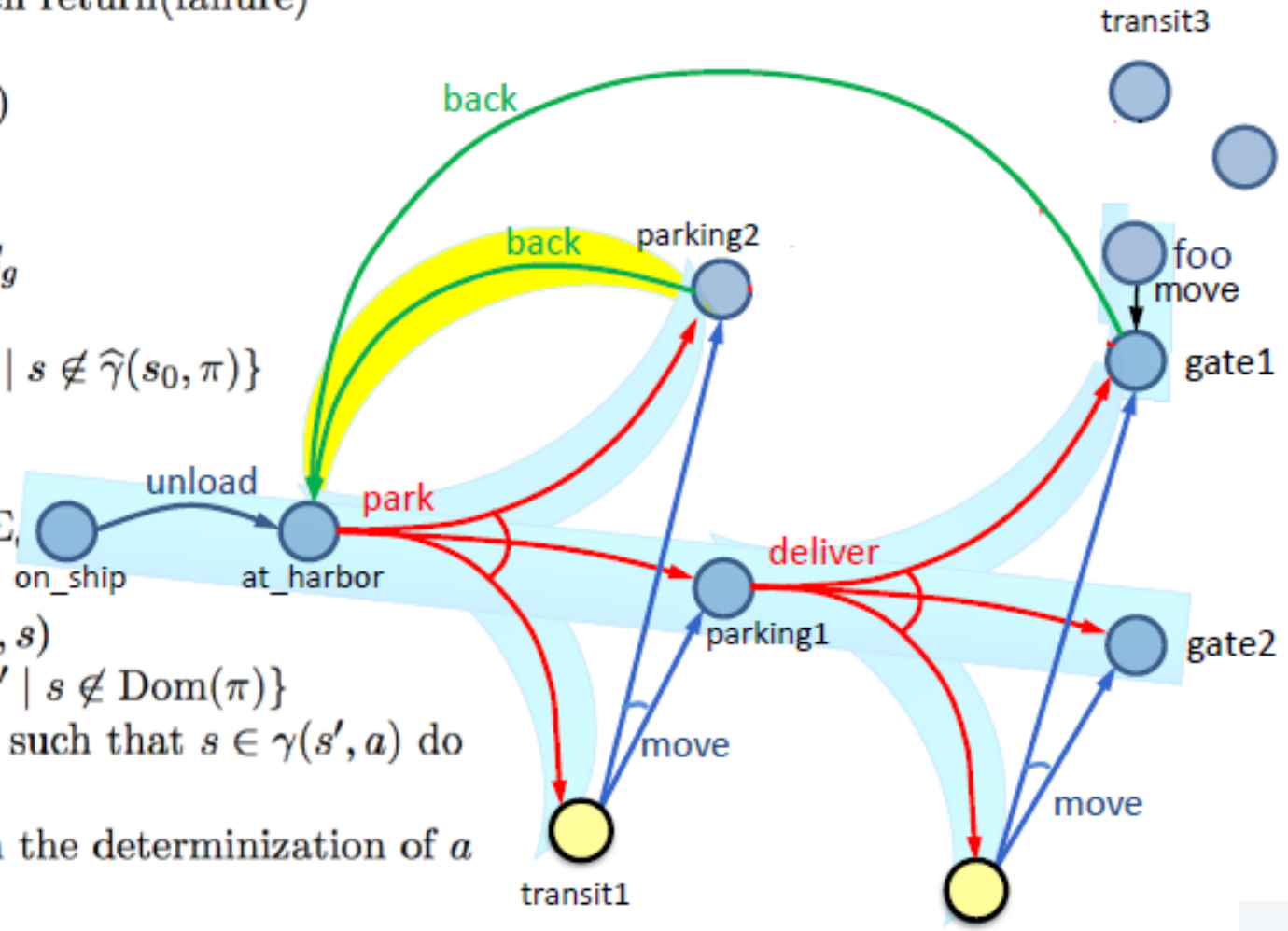

Example

Find-Safe-Solution-by-Determinization (Σ, s_0, S_g)
  if $s_0 \in S_g$ then return$(\varnothing)$
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  $\pi \leftarrow \varnothing$
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  loop

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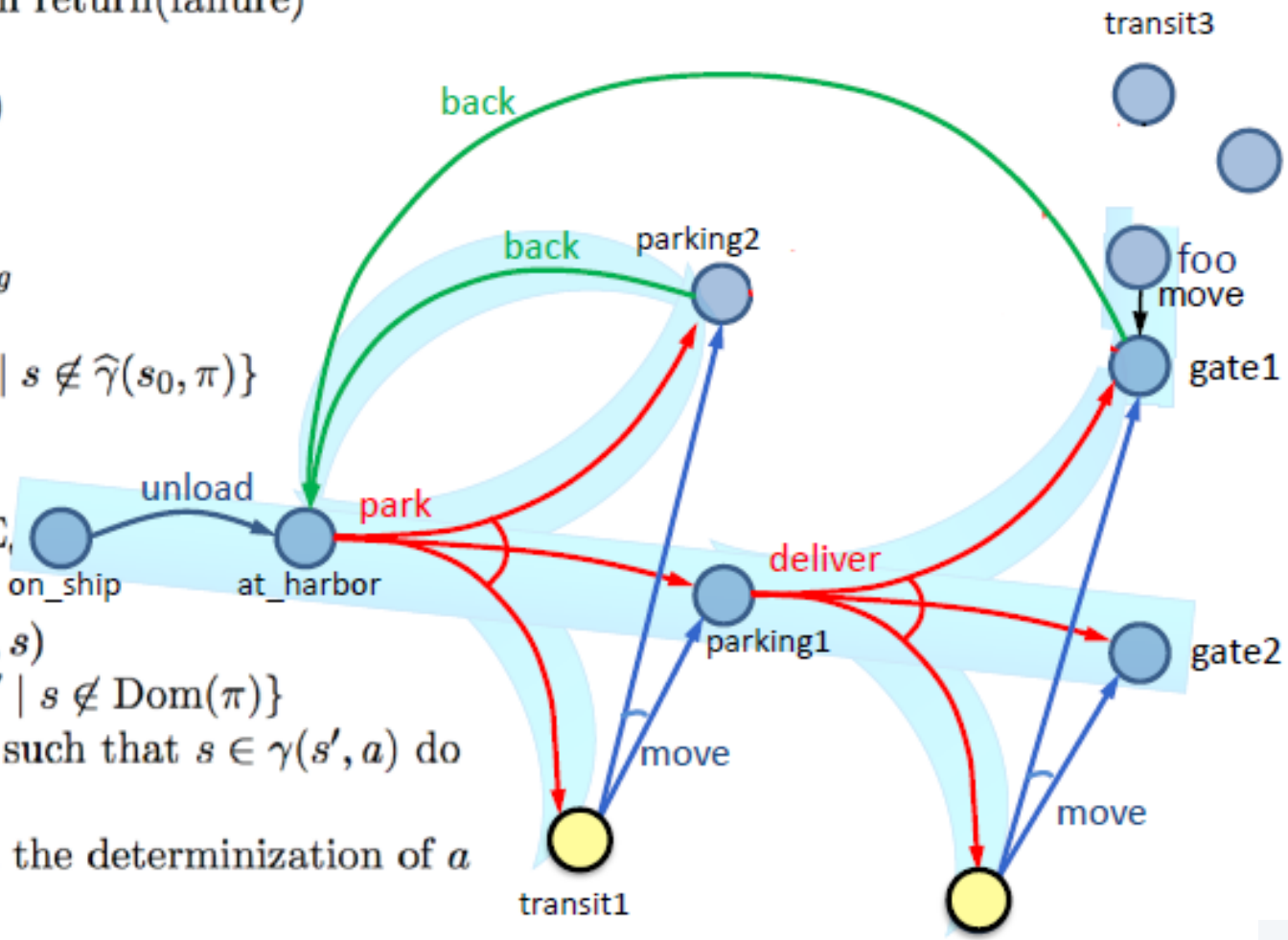

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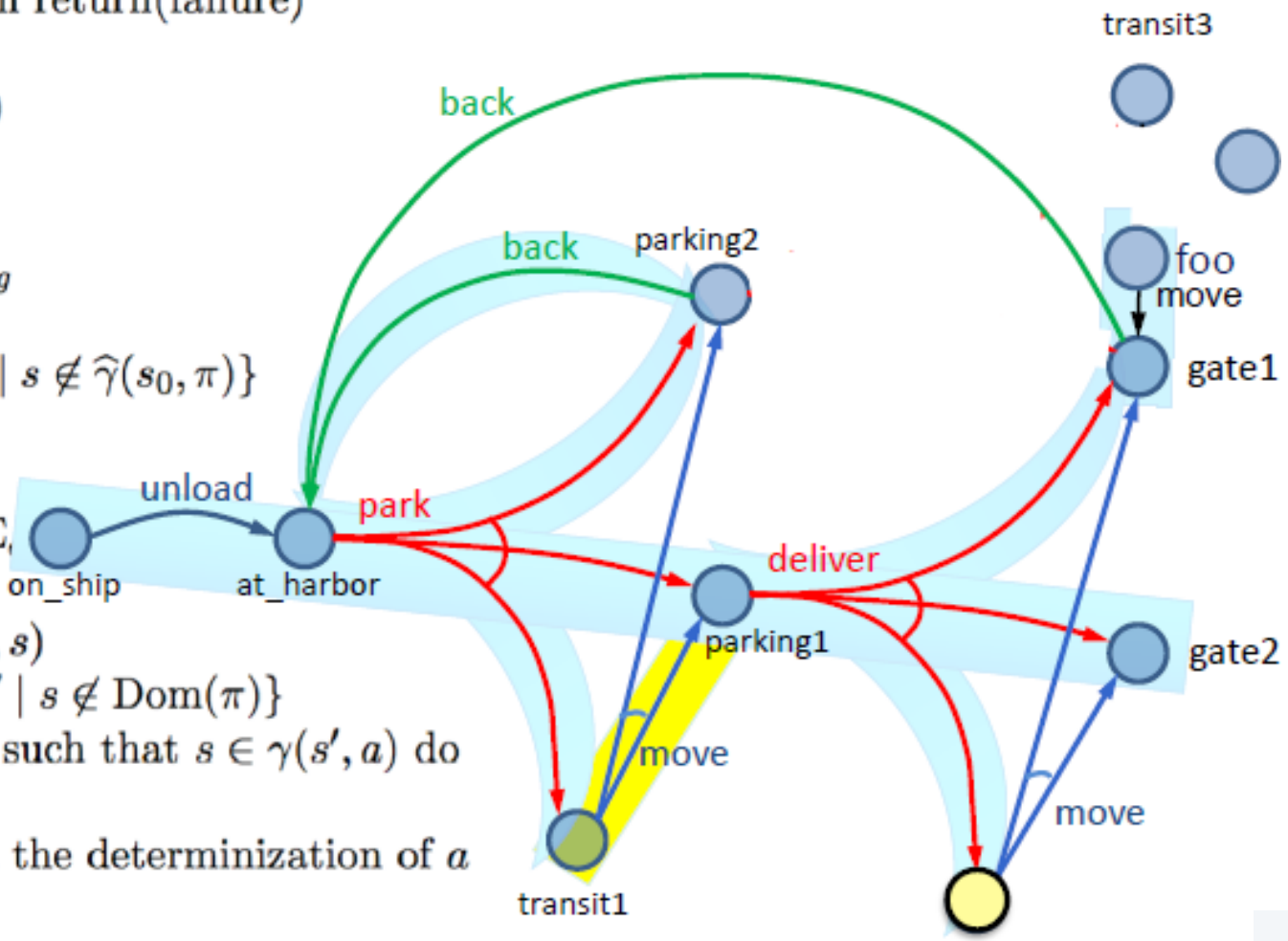

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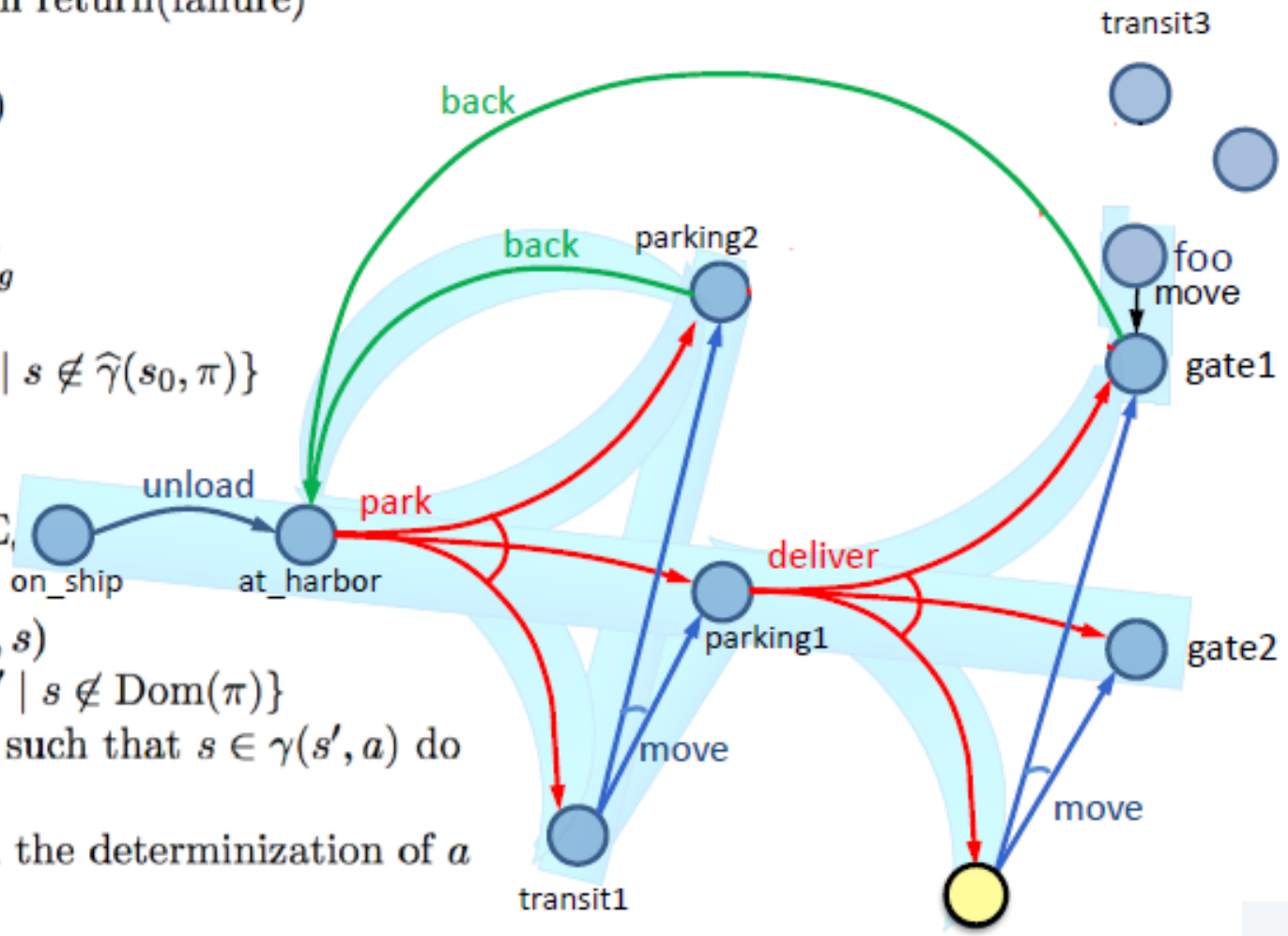

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Example

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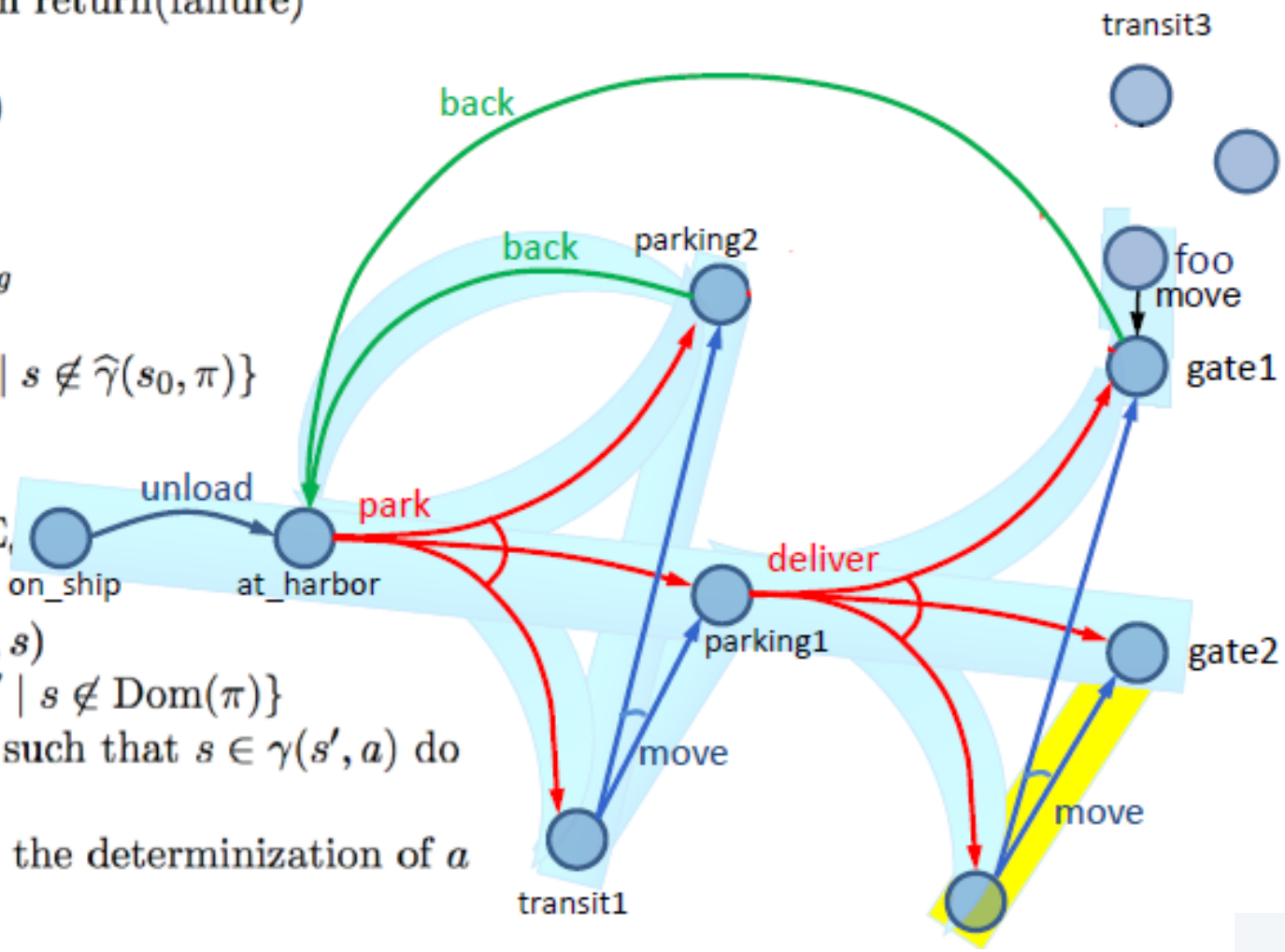

Stefan Edelkamp (cf. Book Automated Planning and Acting)

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Example

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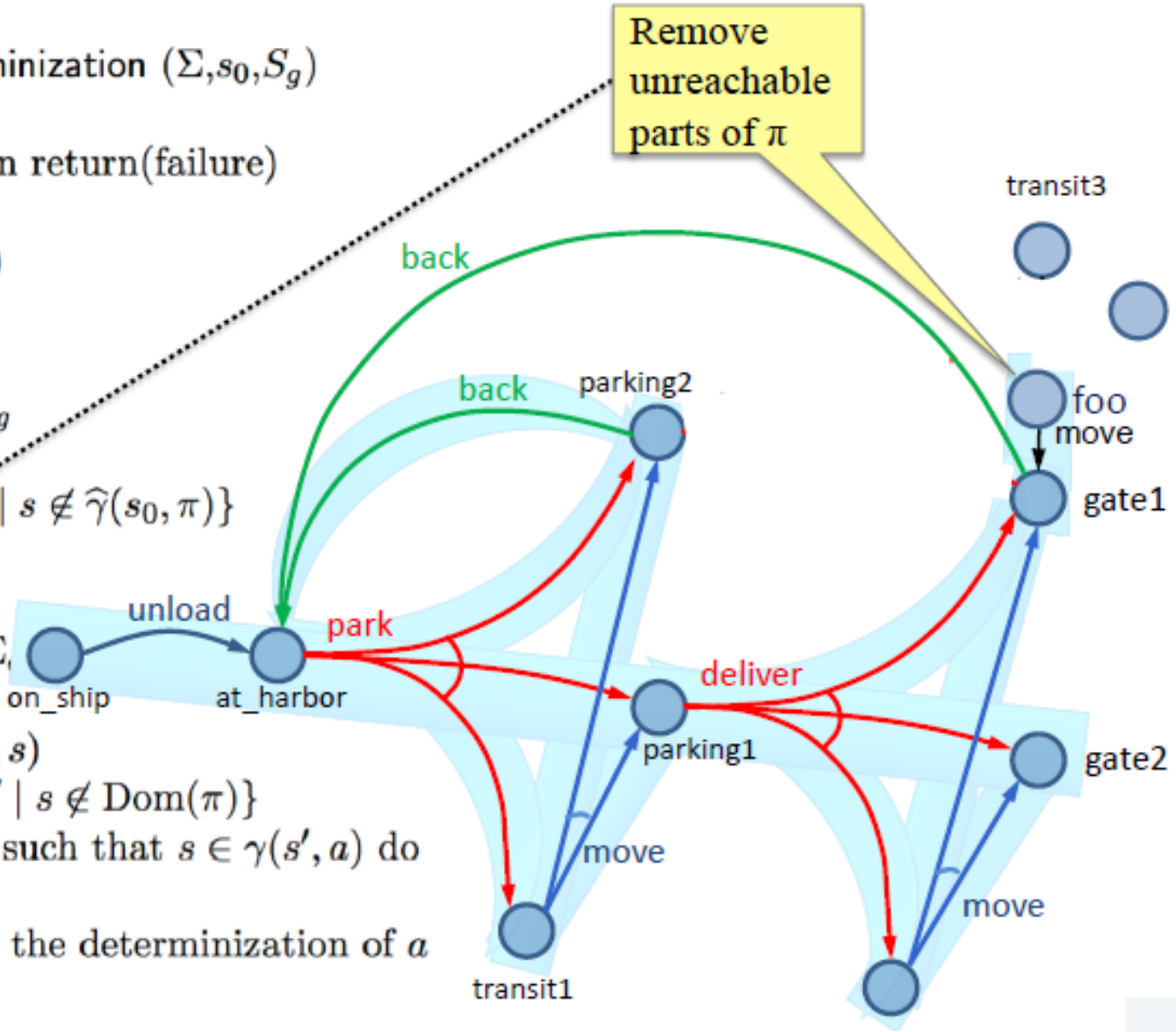


Making Actions Inapplicable

Find-Safe-Solution-by-Determinization (Σ, s_0, S_g)

if $s_0 \in S_g$ then return$(\varnothing)$
if $Applicable(s_0) = \varnothing$ then return(failure)
$\pi \leftarrow \varnothing$
$\Sigma_d \leftarrow$ mk-deterministic(Σ)
loop

$Q \leftarrow leaves(s_0, \pi) \setminus S_g$
if $Q = \varnothing$ then do
  $\pi \leftarrow \pi \setminus \{(s,a) \in \pi \mid s \notin \widehat{\gamma}(s_0, \pi)\}$
  return(π)
select $s \in Q$
$p' \leftarrow$ Forward-search (Σ_d, s, S_g)
if $p' \neq fail$ then do
  $\pi' \leftarrow$ Plan2policy(p', s)
  $\pi \leftarrow \pi \cup \{(s,a) \in \pi' \mid s \notin \text{Dom}(\pi)\}$
else for every s' and a such that $s \in \gamma(s', a)$ do
  $\pi \leftarrow \pi \setminus \{(s', a)\}$
  make the actions in the determinization of a not applicable in s'

- Modify Σ_d to make actions inapplicable
  - worst-case exponential time
- Better: table of bad state-action pairs
  - For every (s',a) such that $s \in \gamma(s',a)$, $Bad[s'] \leftarrow Bad[s'] \cup$ determinization(a)
  - Modify classical planner to take the table as an argument
    - if s is current state, only choose actions in $Applicable(s) \setminus Bad(s)$

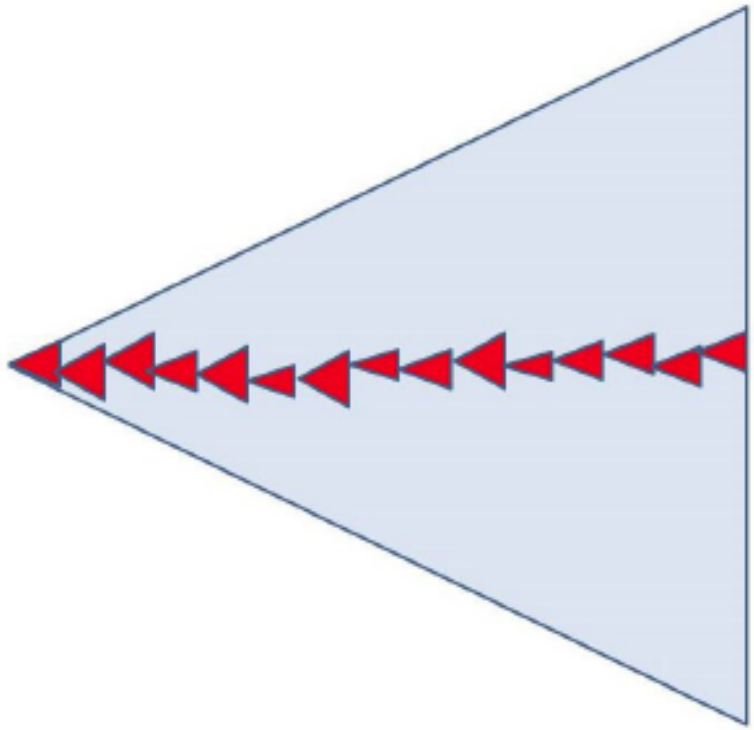
Stefan Edelkamp (cf. Book Automated Planning and Acting)

Skip Ahead

- Several topics I'll skip for now
  - will come back later if there's time
  - Other kinds of search algorithms
    - min-max search
  - Symbolic model checking techniques
    - Backward search
    - BDD representation
      - Reduce search-space size by planning over sets of states

5.6 Online Approaches

- Motivation
  - Planning models are approximate – execution seldom works out as planned
  - Large problems may require too much planning time
- 2nd motivation even more stronger in nondeterministic domains
  - Nondeterminism makes planning exponentially harder
    - Exponentially more time, exponentially larger policies



Offline vs Runtime Search Spaces

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Online Approaches

- Need to identify *good* actions without exploring entire search space
  - Can be done using heuristic estimates
- Some domains are *safely explorable*
  - Safe to create partial plans, because goal states are reachable from all situations
- Other domains contain dead-ends, partial planning won't guarantee success
  - Can get trapped in dead ends that we would have detected if we had planned fully
    - No applicable actions
      - robot goes down a steep incline and can't come back up
    - Applicable actions, but caught in a loop
      - robot goes into a collection of rooms from which there's no exit
  - However, partial planning can still make success more likely

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Lookahead-Partial-Plan

- Adaptation of
  Run-Lazy-Lookahead (Chapter 2)

- Lookahead is any planning algorithm that returns a policy π

  - π may be partial solution, or unsafe solution
  - Lookahead-Partial-Plan executes π as far as it will go, then calls Lookahead again

```
Lookahead-Partial-Plan(Σ, s_0, S_g)
    s ← s_0
    while s ∉ S_g and Applicable(s) ≠ ∅ do
        π ← Lookahead(s, θ)
        if π = ∅ then return failure
        else do
            perform partial plan π
            s ← observe current state
```


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FS-Replan

- Adaptation of Run-Lookahead
- Calls Forward-Search on determinized domain, converts to a policy
  - Unsafe solution

```
FS-Replan (Σ, s, S_g)
  π_d ← ∅
  while s ∉ S_g and Applicable(s) ≠ ∅ do
    if π_d undefined for s then do
      π_d ← Plan2policy(Forward-search(Σ_d, s, S_g), s)
      if π_d = failure then return failure
    perform action π_d(s)
    s ← observe resulting state
```

- Generalization:
  - Lookahead can be any planning algorithm that returns a policy π

```
FS-Replan (Σ, s, S_g)   (generalize)
  π_d ← ∅
  while s ∉ S_g and Applicable(s) ≠ ∅ do
    if π_d undefined for s then do
      π_d ← Lookahead(s,θ)
      if π_d = failure then return failure
    perform action π_d(s)
    s ← observe resulting state
```

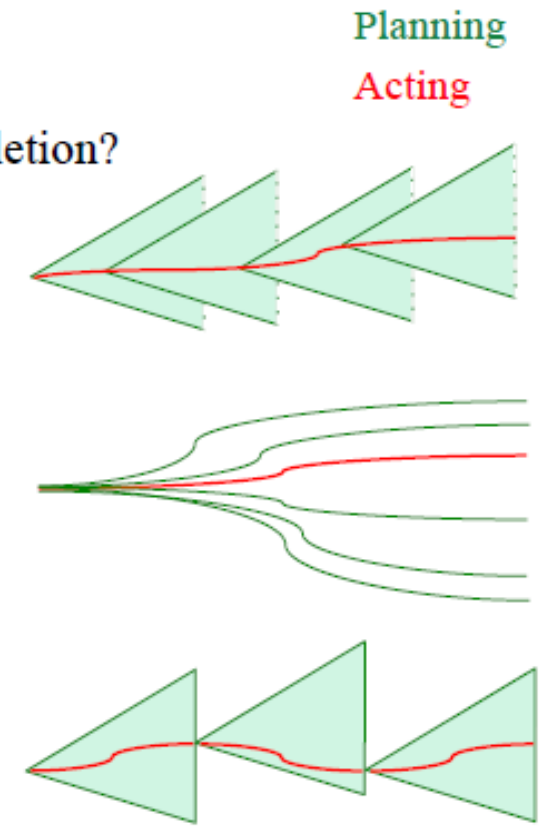
Stefan Edelkamp (cf. Book Automated Planning and Acting)

Possibilities for Lookahead

- Lookahead could be one of the algorithms we discussed earlier

  Find-Safe-Solution
  Find-Acyclic-Solution
  Guided-Find-Safe-Solution
  Find-Safe-Solution-by-Determinization

- What if it doesn't have time to run to completion?
  - Can use the same techniques we discussed in Chapter 3
    - Receding horizon
    - Sampling
    - Subgoaling
    - Iterative deepening



Stefan Edelkamp (cf. Book Automated Planning and Acting)

Possibilities for Lookahead

- *Full horizon, limited breadth:*
  - look for solution that works for *some* of the outcomes
  - E.g., modify Find-Acyclic-Solution to examine i outcomes of every action
- *Iterative broadening*:

  for $i = 1$ by 1 until time runs out

  look for a solution that handles i outcomes per action

Find-Acyclic-Solution (Σ, s_0, S_g)
  $\pi \leftarrow \varnothing$
  $Frontier \leftarrow \{s_0\}$
  for every $s \in Frontier \setminus S_g$ do
    $Frontier \leftarrow Frontier \setminus \{s\}$
    if Applicable$(s) = \varnothing$ then return failure
    nondeterministically choose $a \in$ Applicable(s)
    $\pi \leftarrow \pi \cup (s, a)$
    $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus \mathrm{Dom}(\pi))$
    if has-loops$(\pi, a, Frontier)$ then return failure
  return π

$T \leftarrow i$ elements of $\gamma(s,a) \setminus \mathrm{Dom}(\pi)$
$Frontier \leftarrow Frontier \cup T$

Safely Explorable Domains

- *Safely explorable* domain
  - for every state s, at least one goal state is reachable from s
- Suppose
  - We use Lookahead-Partial-Plan or FS-Replan in a safely explorable domain
  - Lookahead never returns failure
  - No "unfair" executions
- Then we will eventually reach a goal
- What would happen if we just chose a random action each time?

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Summary

- Actions, plans, policies, planning problems
- types of solutions: unsafe, cyclic safe, acyclic safe
  - algorithms for each
- Guided-find-safe-solution
  - call find-solution to get an unsafe solution
  - call find-solution additional times on the leaves
- find-safe-solution-by-determinization
  - use determinized actions
  - call classical planner rather than find-solution
  - if dead-ends are encountered, modify actions that lead to them

- continued on next page

Summary

- Online approaches
  - Lookahead-partial-plan
    - adaptation of Run-Lazy-Lookahead
  - FS-replan
    - adaptation of Run-Lookahead
- ways to do the lookahead
  - full breadth with limited depth,
    - iterative deepening
  - full depth with limited breadth
    - iterative broadening
  - convergence in safely explorable domains
- min-max-LRTA*

Can also adapt Run-Concurrent-Lookahead

Can put bounds on both depth and breadth

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