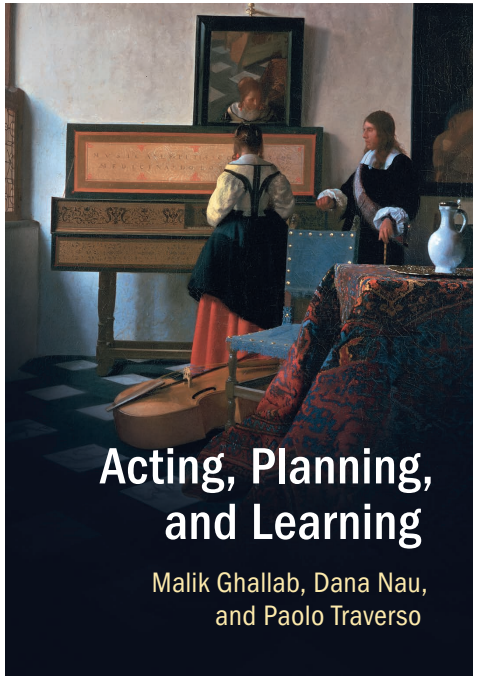
Last update: 11:09 PM, March 7, 2025



Chapter 12
Planning with Nondeterministic Models

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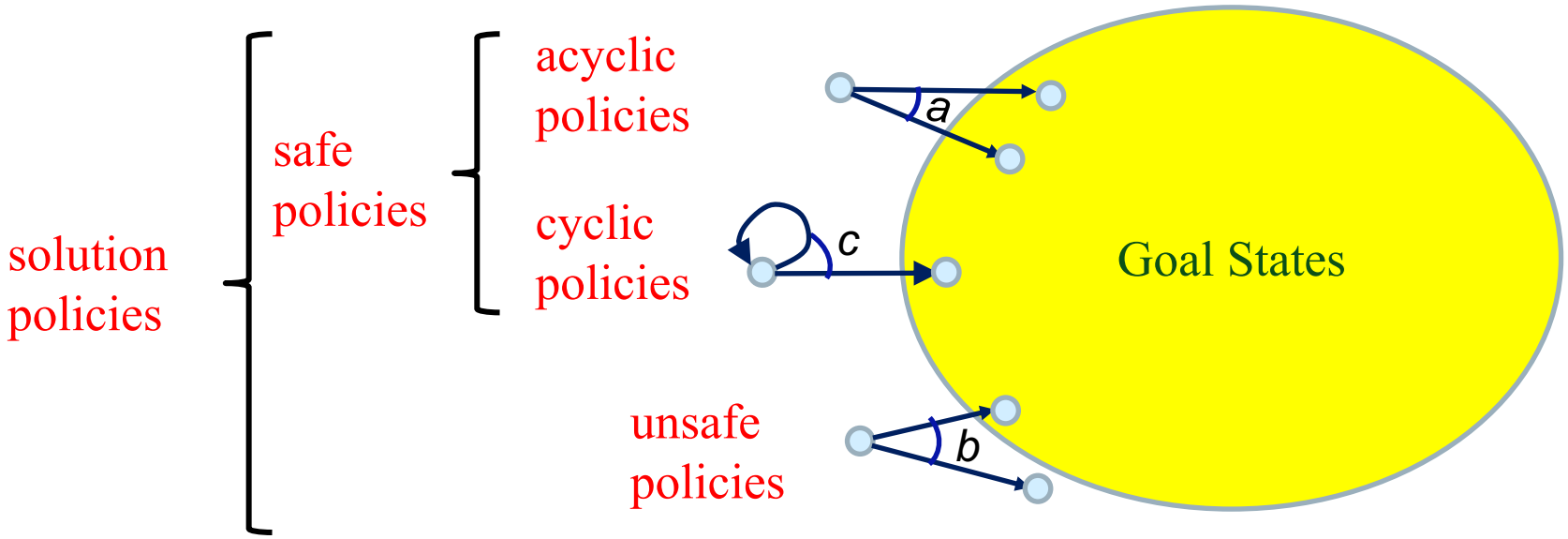
Kinds of Solution Policies



Finding (Unsafe) Solutions

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

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

Decide which state to plan for

Cycle-checking

For comparison:

Forward-search (Σ, s_0, g)

  $s \leftarrow s_0$; $\pi \leftarrow \langle\rangle$

  while $s \not\models g$ **do**

    if $Applicable(s) = \emptyset$ **then return** failure

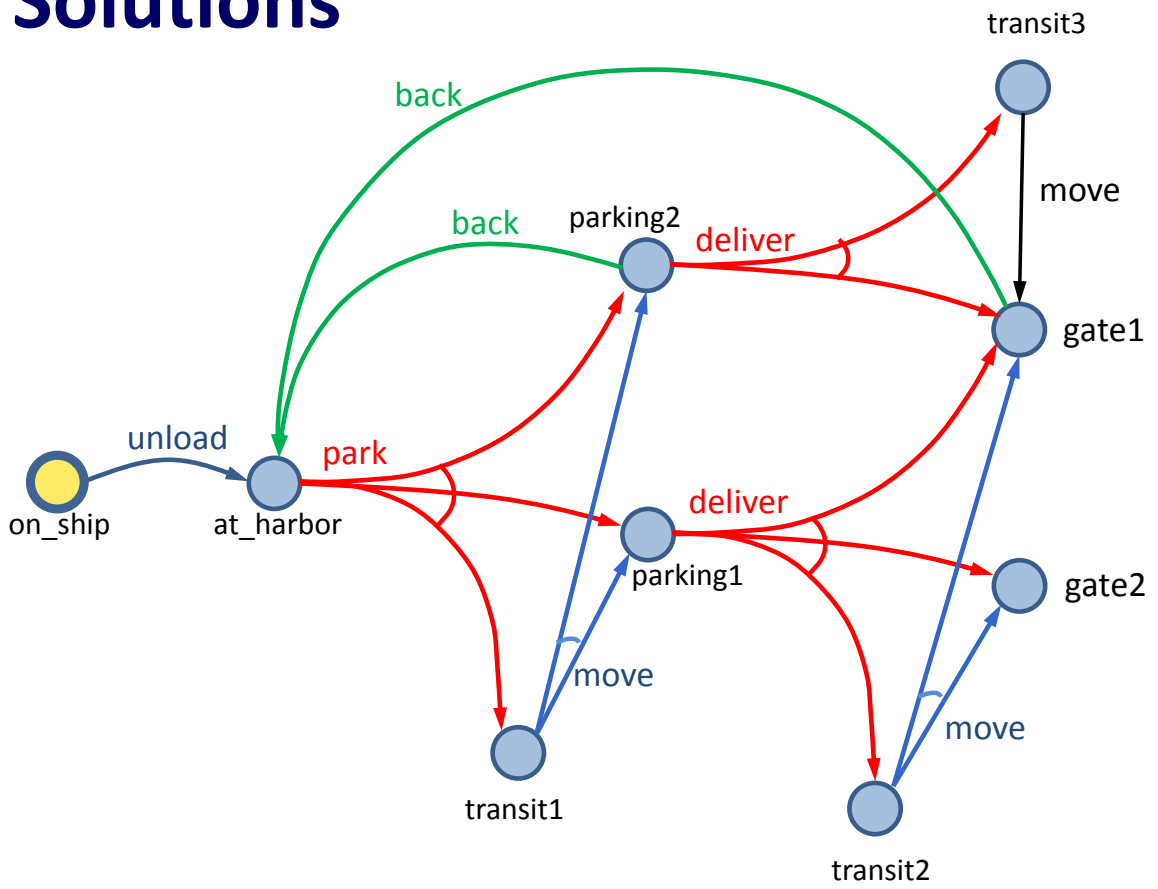
    nondeterministically choose $a \in Applicable(s)$

    $s \leftarrow \gamma(s,a)$; $\pi \leftarrow \pi \cdot a$

  return π

Finding (Unsafe) Solutions

Poll: which should (*) be?
A. nondeterministically choose
B. arbitrarily choose
C. don't know



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  if $A' = \varnothing$ then return failure
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(*) nondeterministically choose $s' \in \gamma(s, a)$
  if $s' \in \mathit{Visited}$ then return failure
  $\pi(s) \leftarrow a;\ \mathit{Visited} \leftarrow \mathit{Visited} \cup \{s'\};\ s \leftarrow s'$

Decide which state to plan for

Cycle-checking

Find-Solution (Σ, s_0, S_g)

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  nondeterministically choose $a \in A'$

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

  if $s' \in Visited$ then return failure

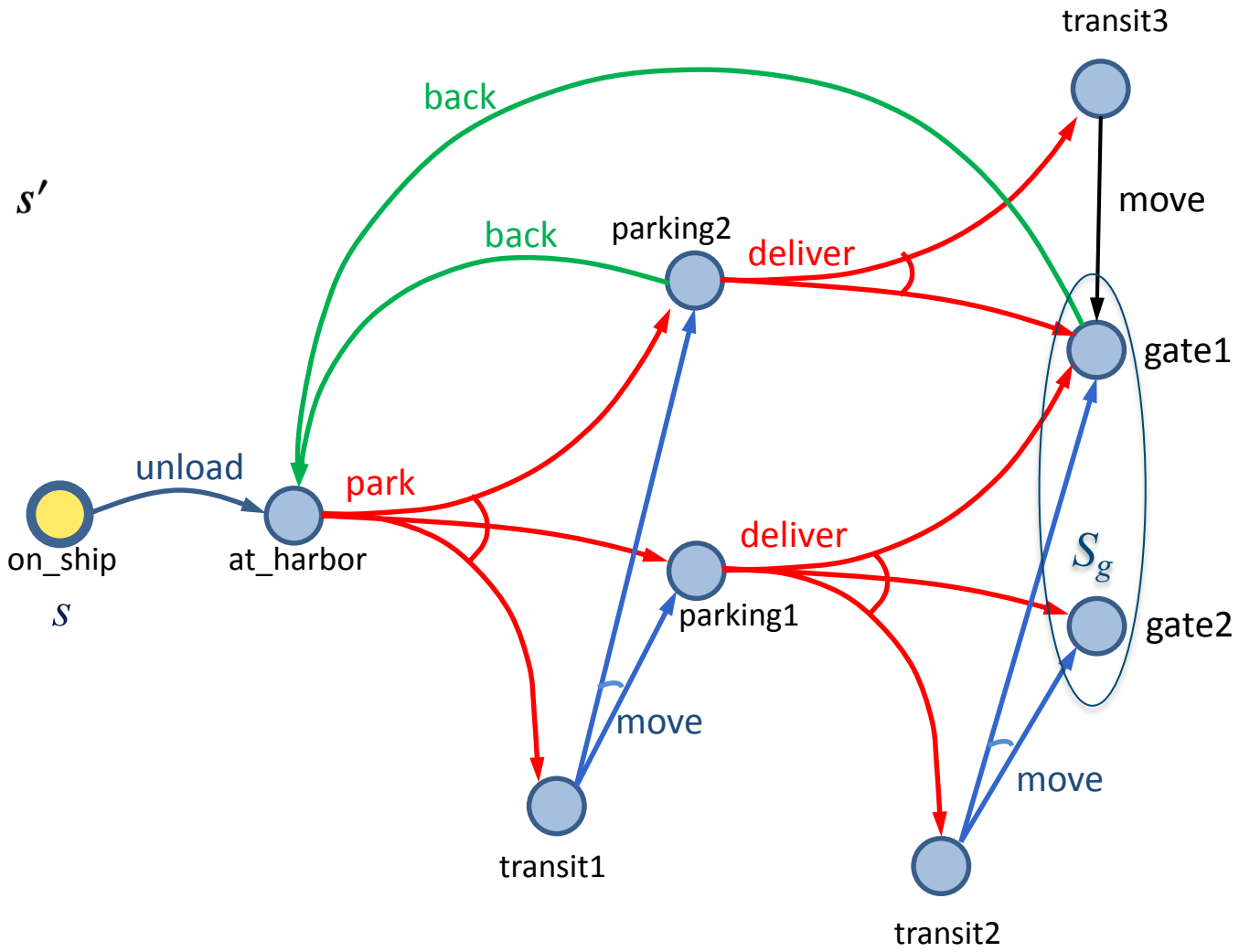
  $\pi(s) \leftarrow a;\ Visited \leftarrow Visited \cup \{s'\};\ s \leftarrow s'$

s = on_ship

$\pi = \{\}$

$Visited = \{on\_ship\}$

Example



Example

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

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

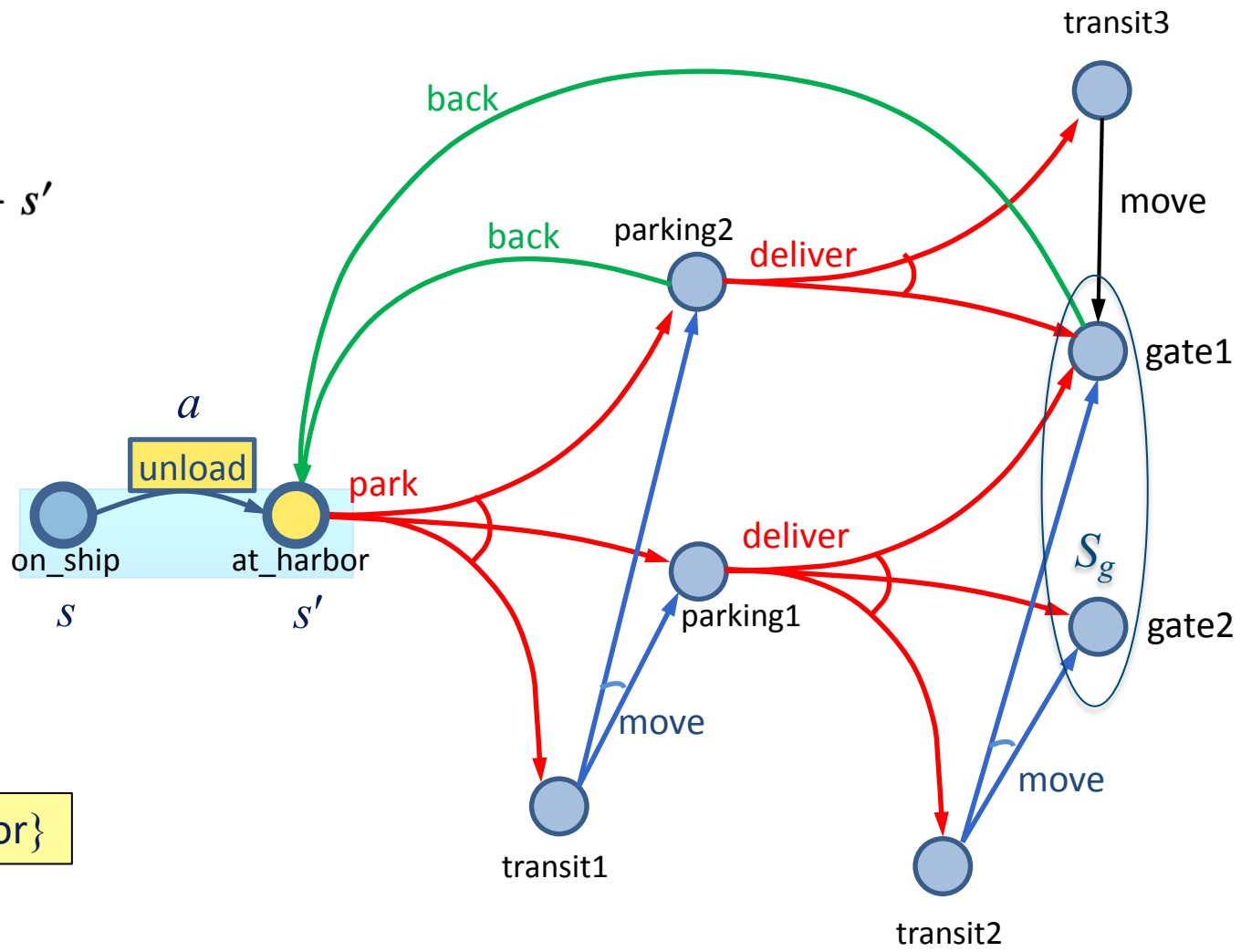
  if $s' \in Visited$ then return failure

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

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

π = {(on_ship, unload)}

Visited = {on_ship, at_harbor}



Example

Find-Solution (Σ, s_0, S_g)

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

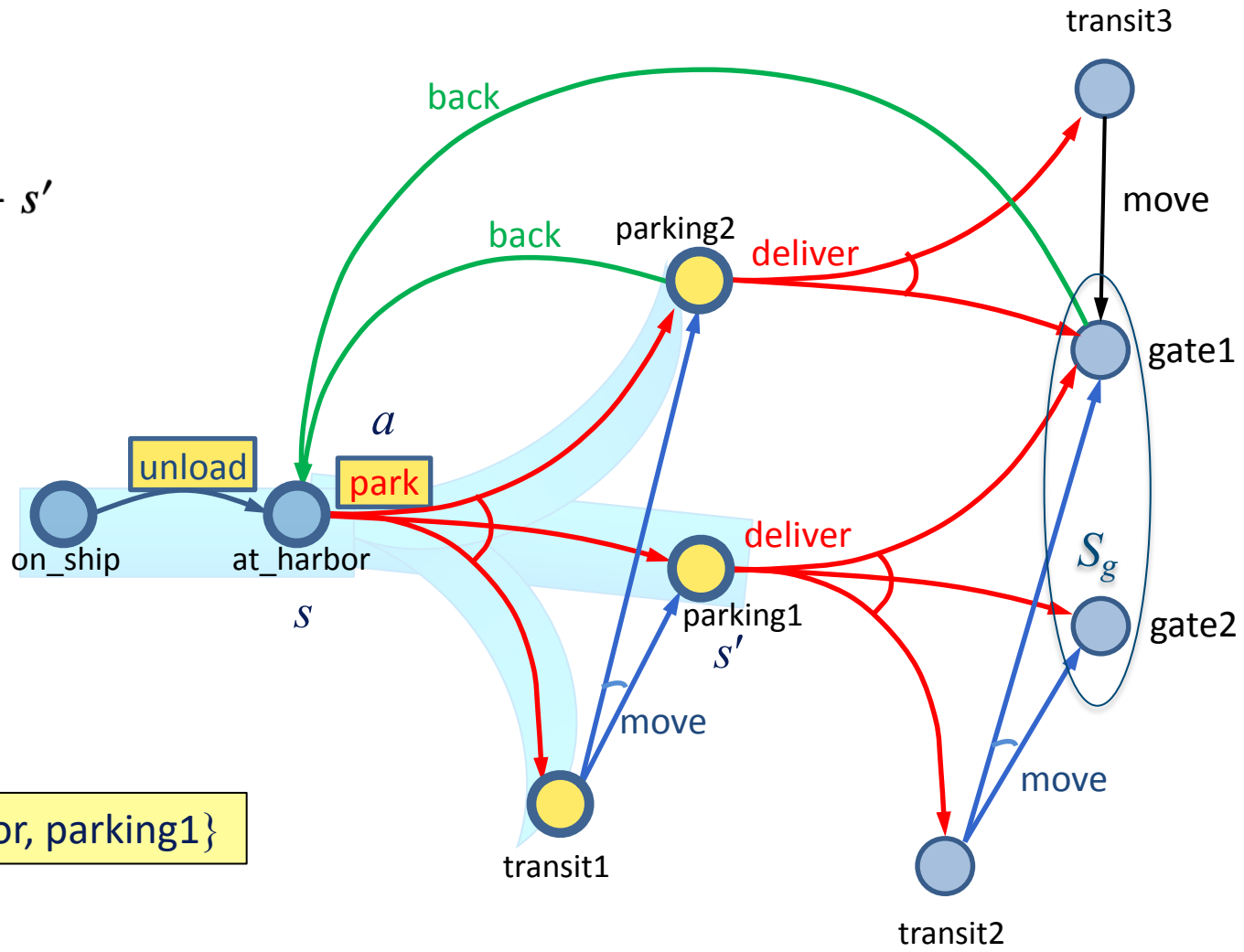
  if $s' \in Visited$ then return failure

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

s = at_harbor
a = park
$\gamma(s,a)$ = {parking1, parking2, transit1}
$s \leftarrow s'$ = parking1

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

$Visited$ = {on_ship, at_harbor, parking1}



Example

Find-Solution (Σ, s_0, S_g)

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loop

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  $A' \leftarrow Applicable(s)$

  if $A' = \varnothing$ then return failure

  nondeterministically choose $a \in A'$

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

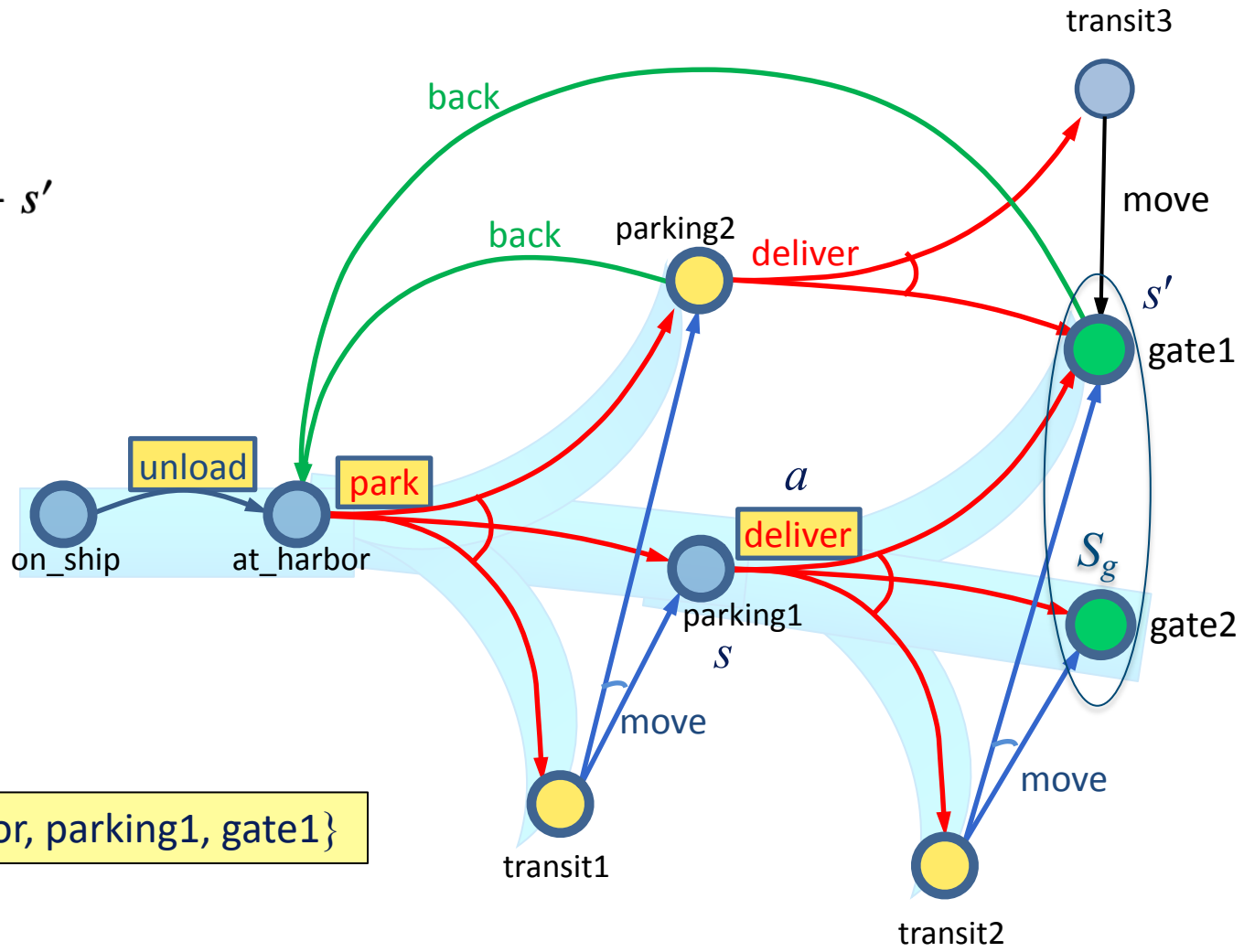
  if $s' \in Visited$ then return failure

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

s = parking1
a = deliver
$\gamma(s,a)$ = {gate1, gate2, transit2}
$s \leftarrow s'$ = gate1

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

$Visited$ = {on_ship, at_harbor, parking1, gate1}



Example

Find-Solution (Σ, s_0, S_g)

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

  if $A' = \varnothing$ then return failure

  nondeterministically choose $a \in A'$

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

  if $s' \in \mathit{Visited}$ then return failure

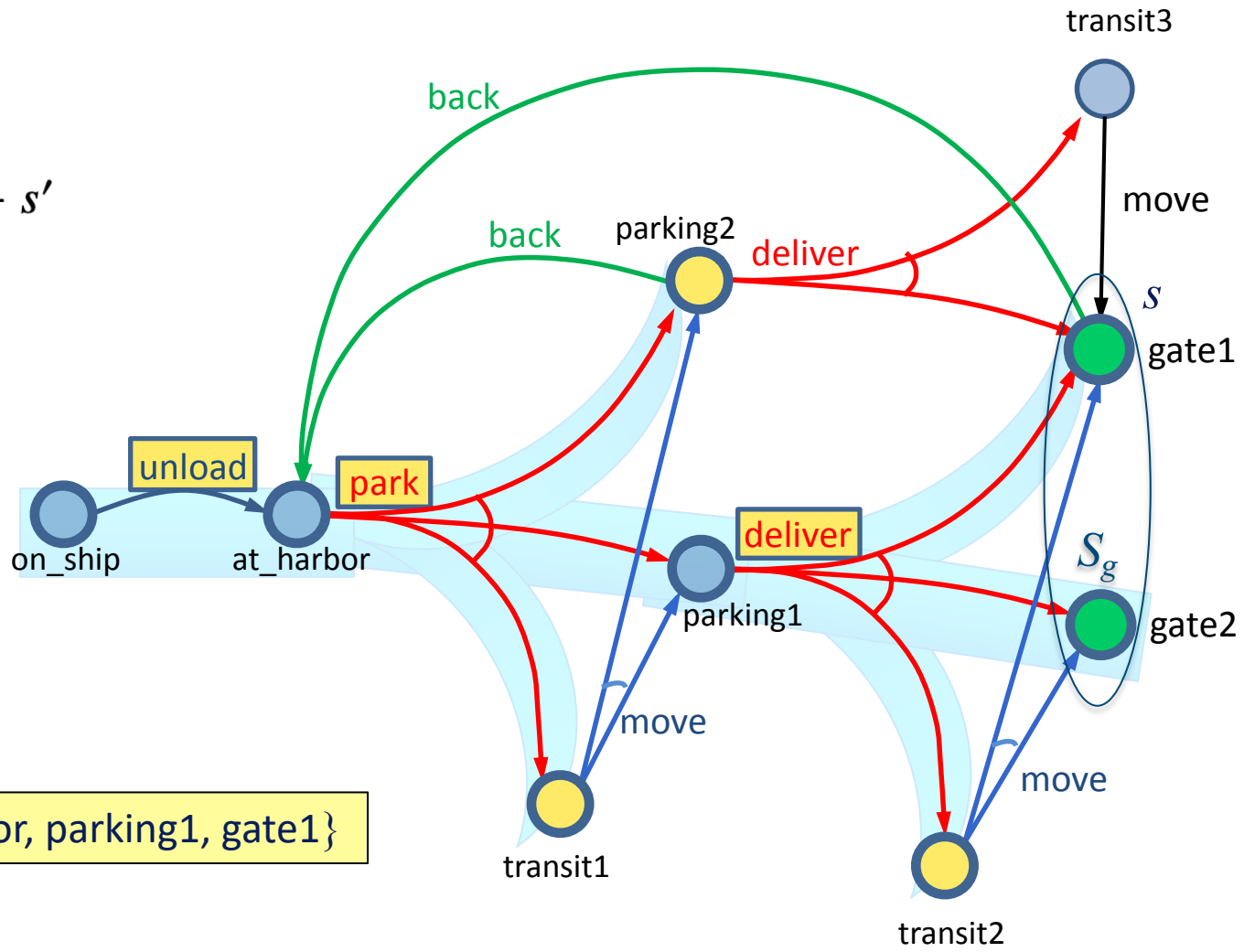
  $\pi(s) \leftarrow a;\ \mathit{Visited} \leftarrow \mathit{Visited} \cup \{s'\};\ s \leftarrow s'$

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}



Find-Acyclic-Solution

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 $a \in Applicable(s)$
    $\pi \leftarrow \pi \cup (s, a)$
    $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$
    if has-loops$(\pi, a, Frontier)$ then return failure
  return π

Keep track of unexpanded states, as in A*

Add all states s such that $\pi(s)$ isn't already defined

Check for cycles:

- Does $\gamma(s,a)$ include a state s' that is a π-ancestor of s?
  - for each $s' \in \gamma(s,a) \cap \text{Domain}(\pi)$, is $s \in \hat{\gamma}(s',\pi)$?

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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

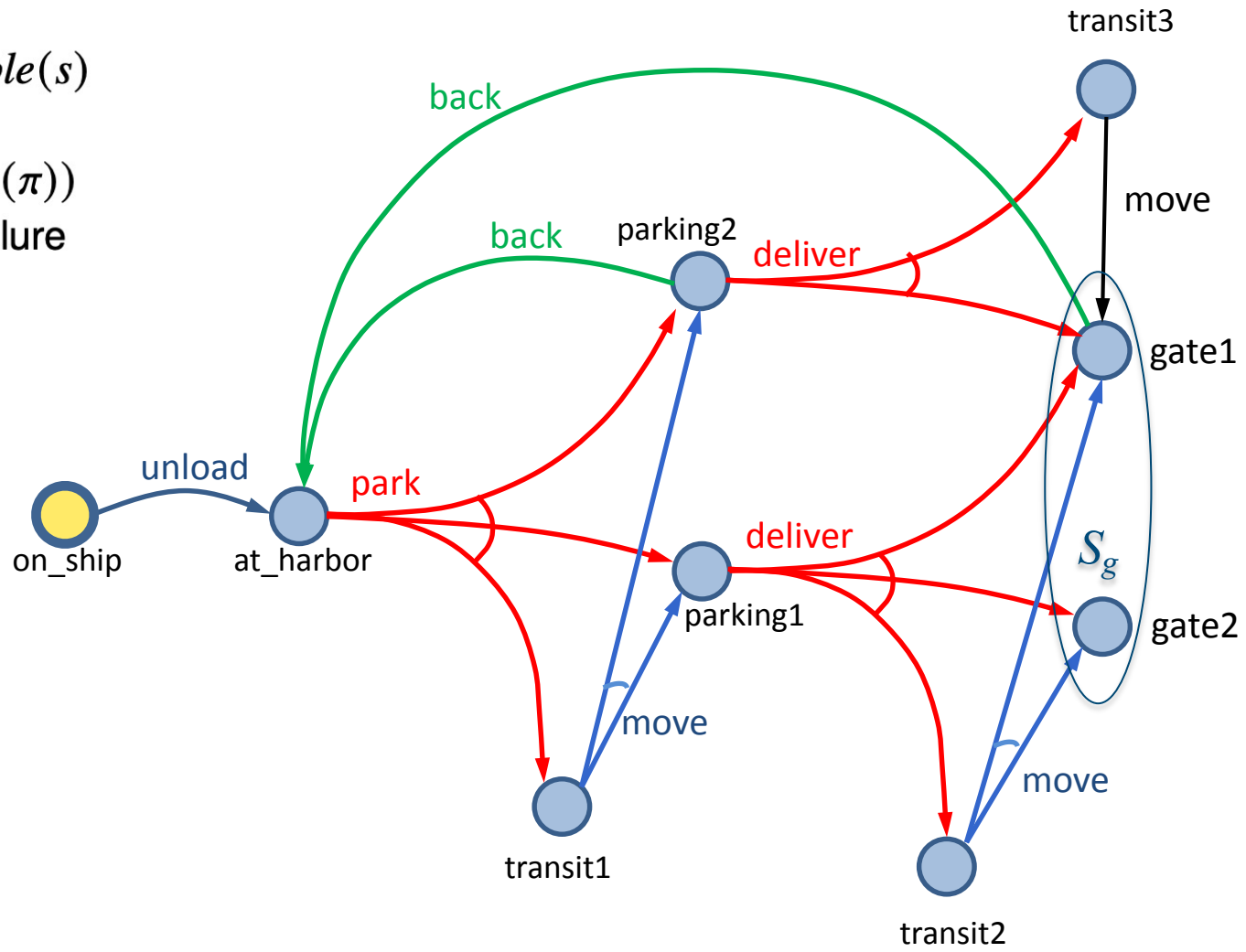
  if has-loops$(\pi, a, Frontier)$ then return failure

return π

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

$\pi = \{\}$

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

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

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

  nondeterministically choose $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

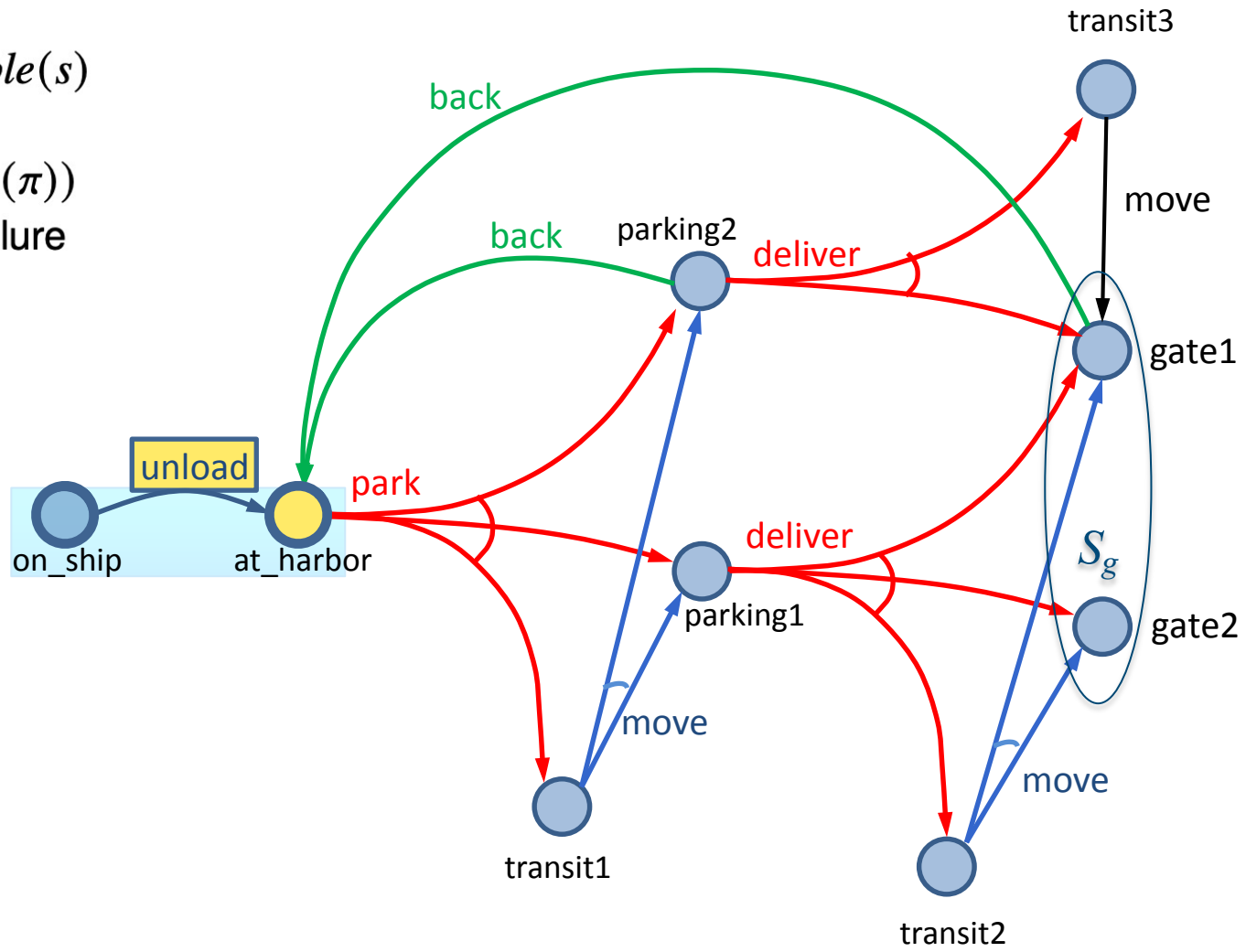
  if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{$at_harbor$\}$

$\pi = \{$(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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

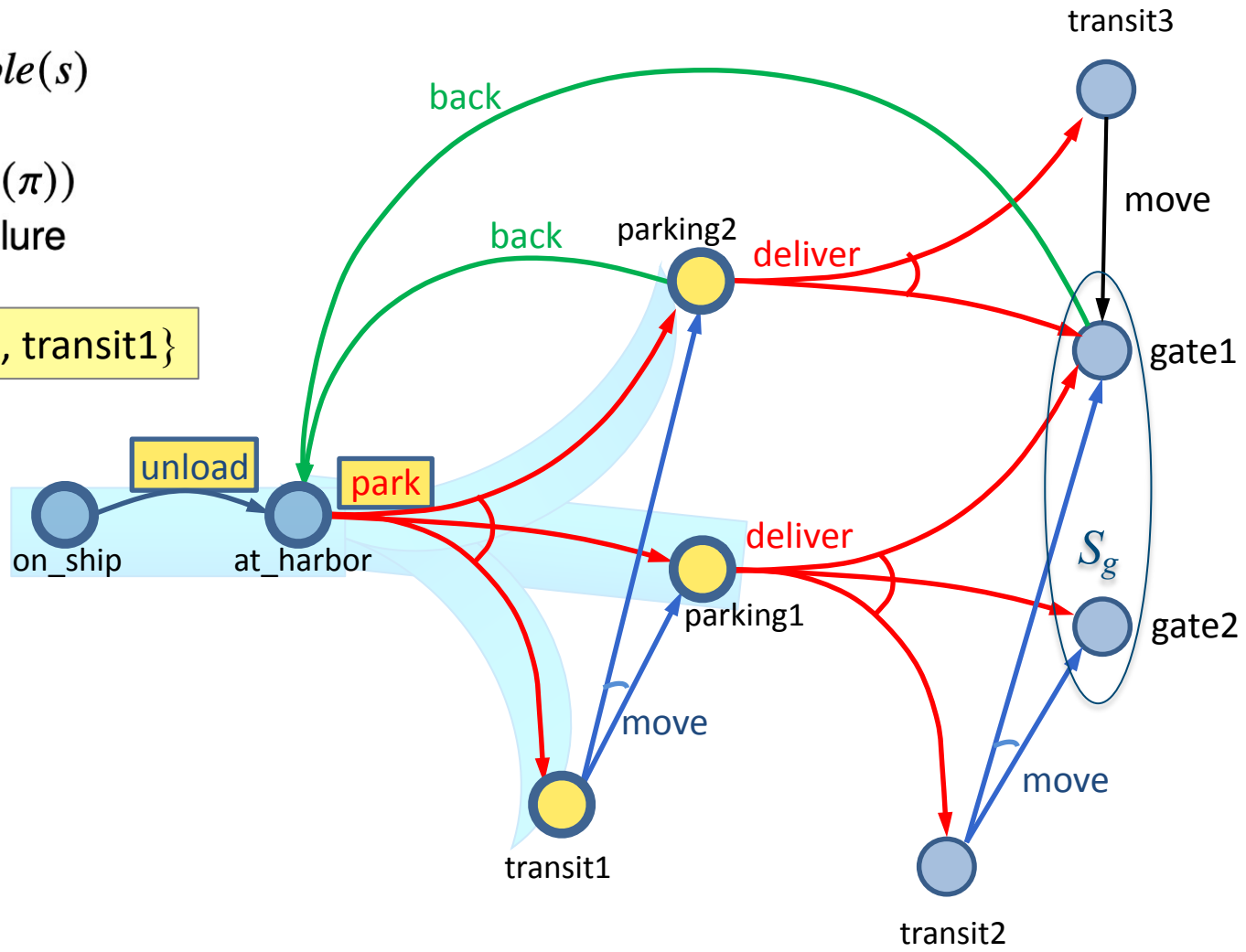
  if has-loops$(\pi, a, Frontier)$ then return failure

return π

Example

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

$\pi = \{$(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 $a \in Applicable(s)$

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

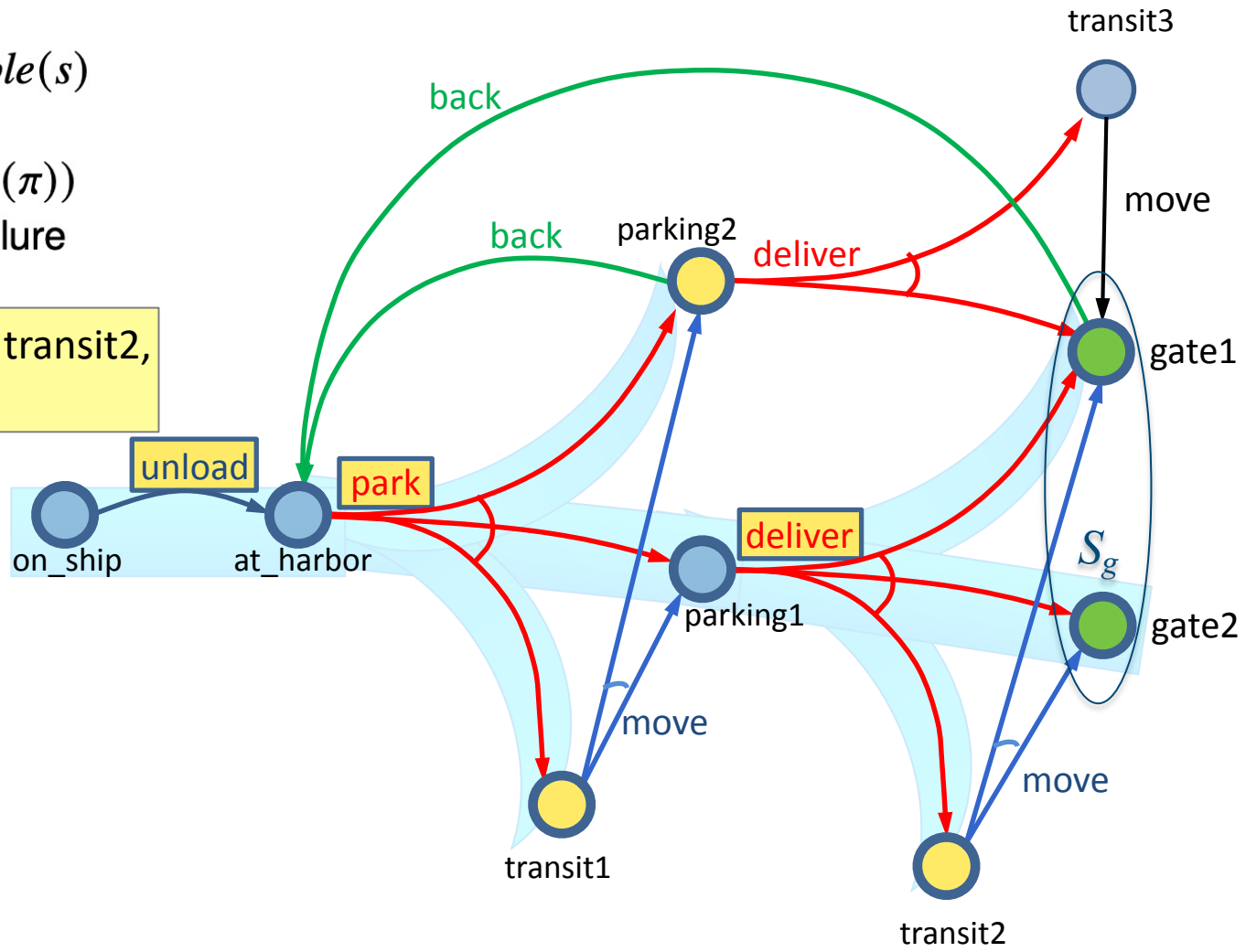
  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

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

return π

$Frontier = \{$parking2, transit1, transit2, gate1, gate2$\}$

$\pi = \{$(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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

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

return π

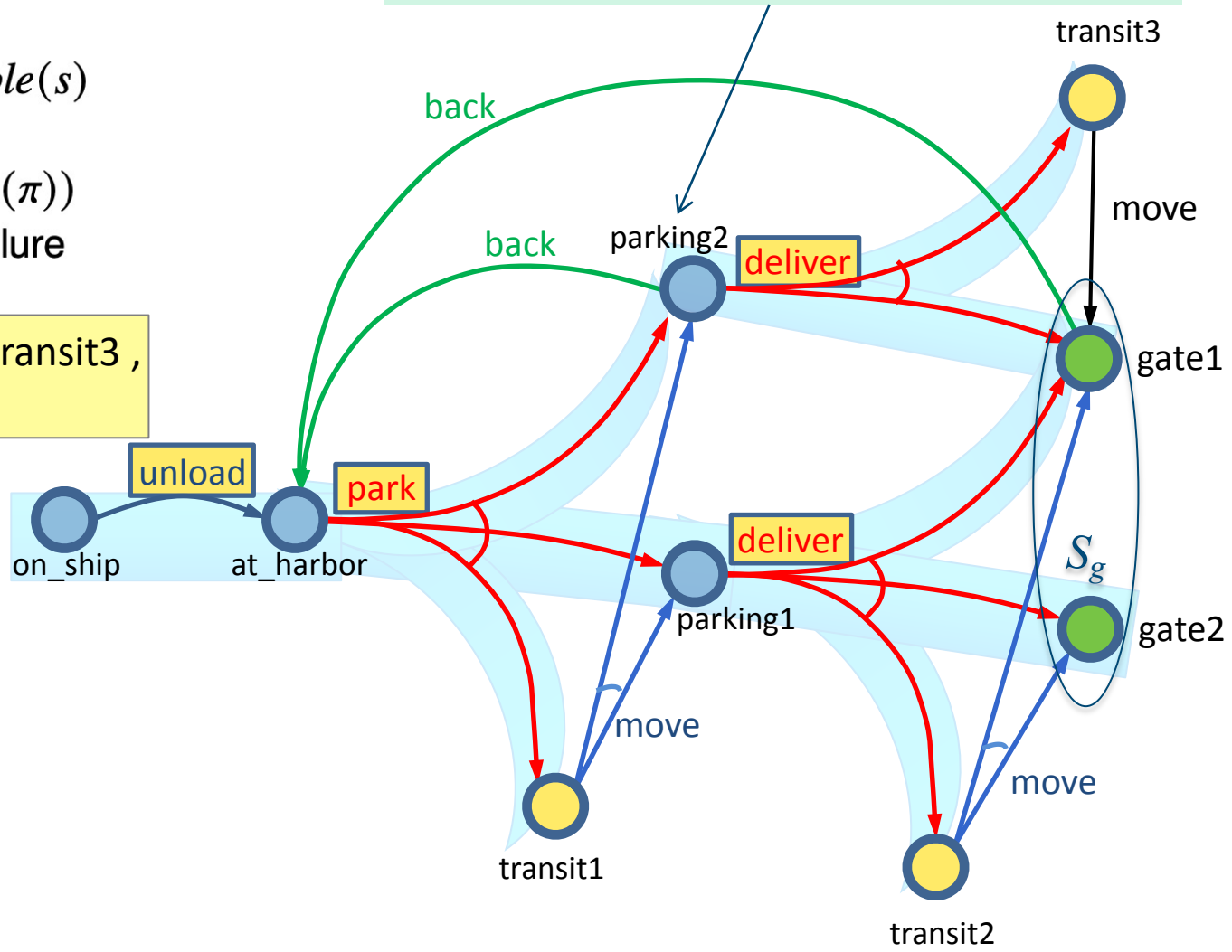
$Frontier = \{$transit1, transit2, transit3 , gate1, gate2$\}$

$\pi = \{$(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



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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

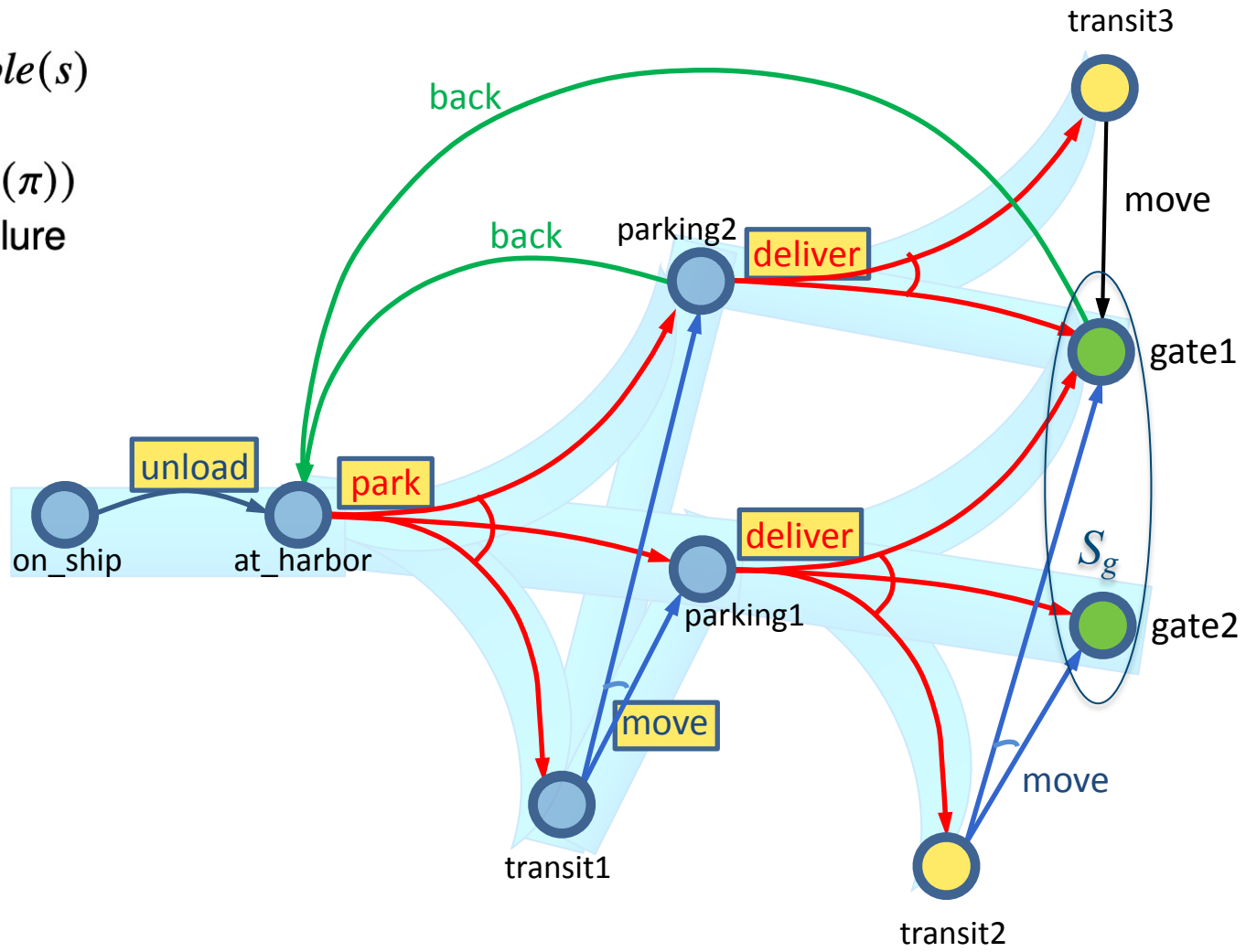
  if has-loops$(\pi, a, Frontier)$ then return failure

return π

Example

$Frontier = \{$transit2, transit3, gate1, gate2$\}$

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



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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

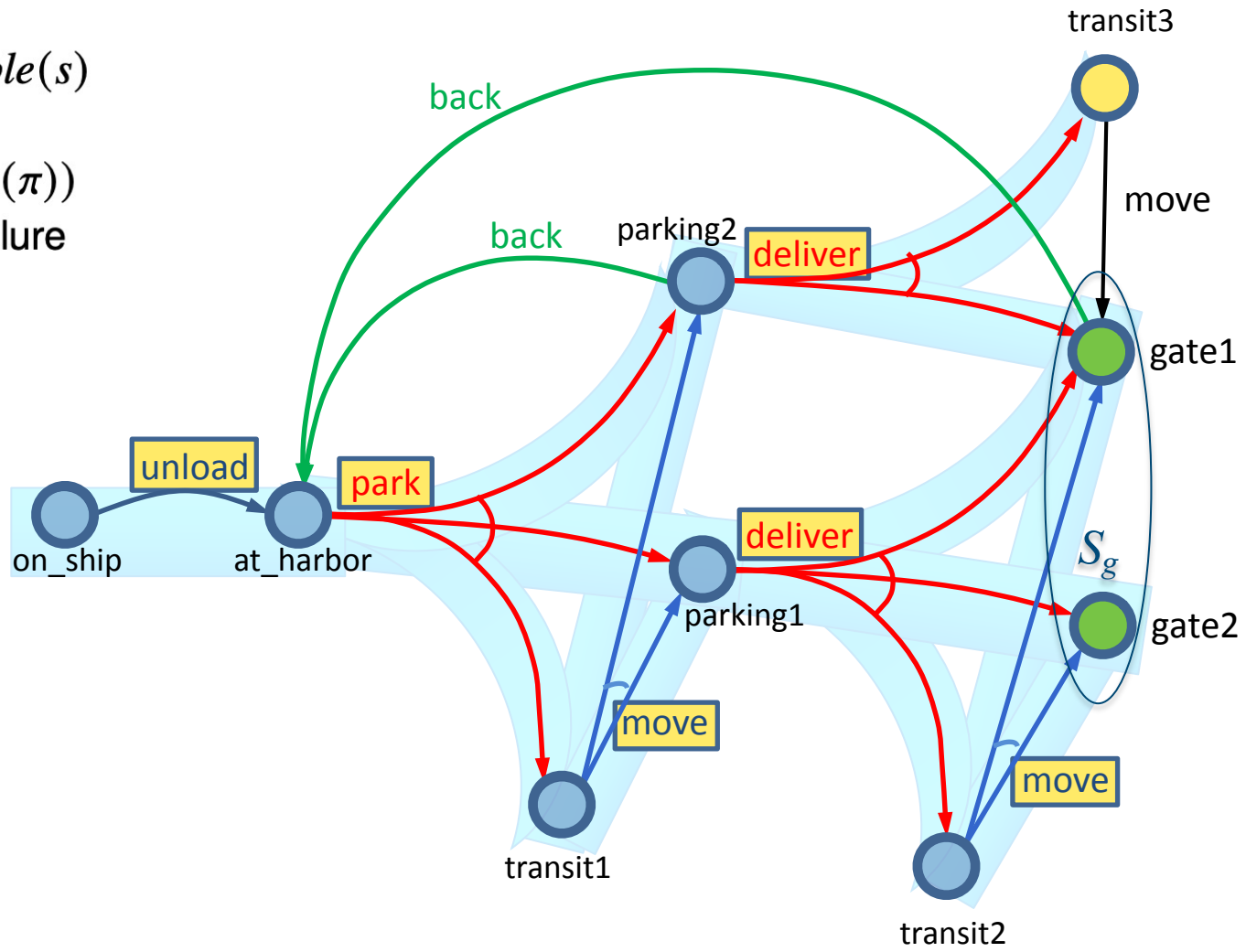
  if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{$transit3, gate1, gate2$\}$

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

Example



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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  nondeterministically choose $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

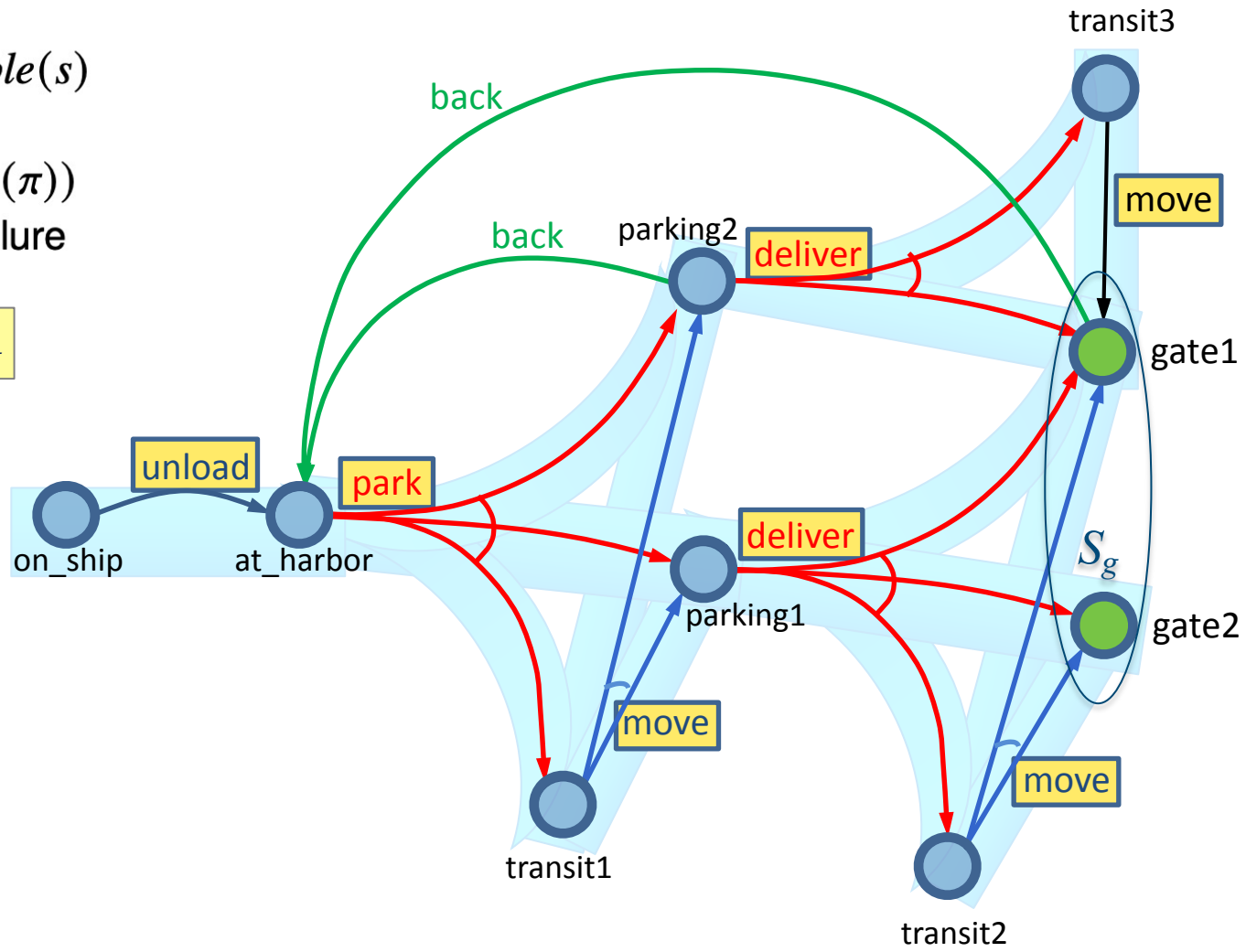
  if has-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{\text{gate1, gate2}\} \subseteq S_g$

Found a solution

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



Find-Safe-Solution

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

Like Find-Acyclic-Solution except here:

Check for *unsafe* cycles:

- Does $\gamma(s,a)$ include a state s' from which π can't take us to the frontier?
  - For each $s' \in \gamma(s,a) \cap \mathrm{Dom}(\pi)$, is $\hat{\gamma}(s',\pi) \cap Frontier = \emptyset$?
- If so, then π contains a cycle that can't be escaped

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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

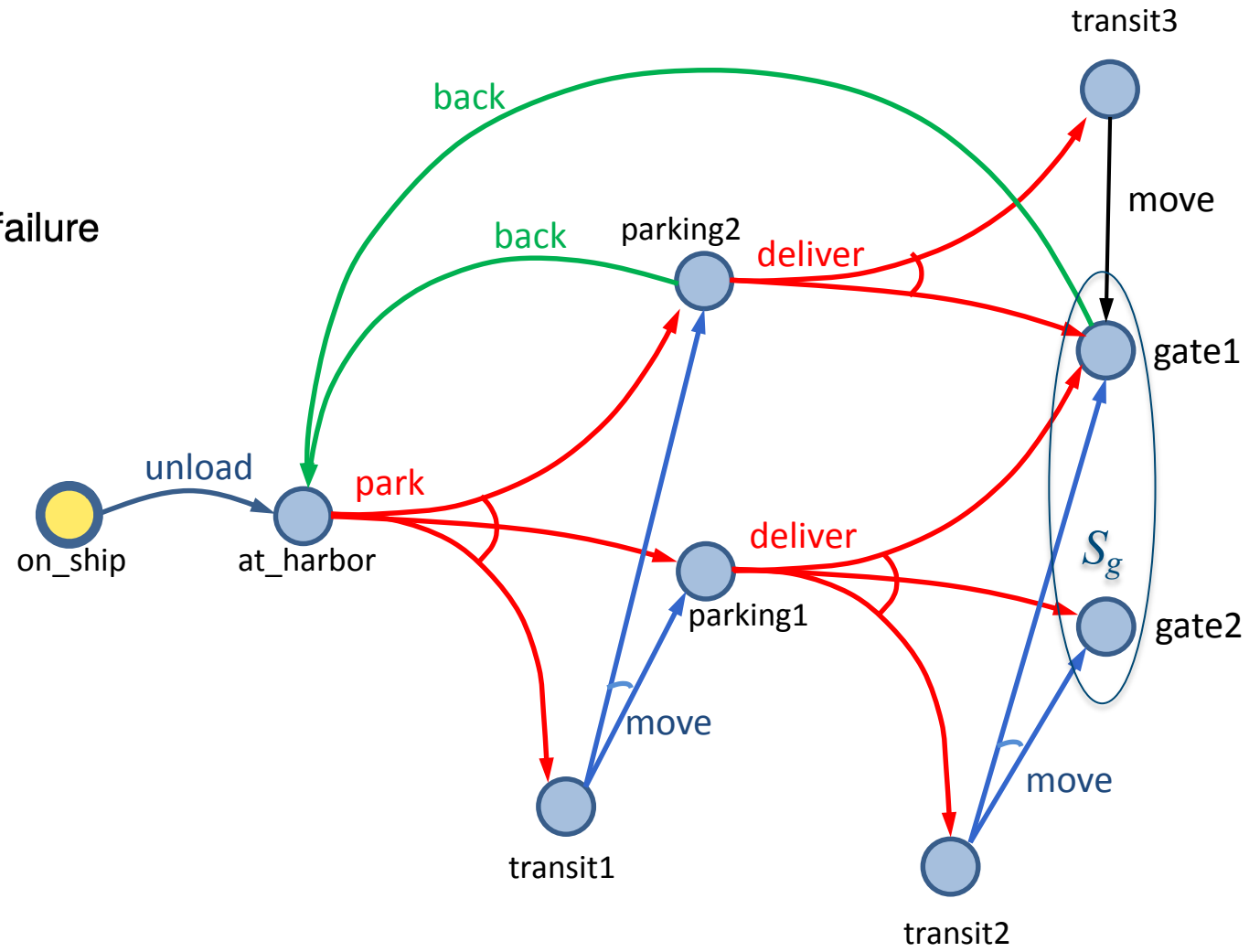
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

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

$\pi = \{\}$

Example



Find-Safe-Solution (Σ, s_0, S_g)

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

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  nondeterministically choose $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

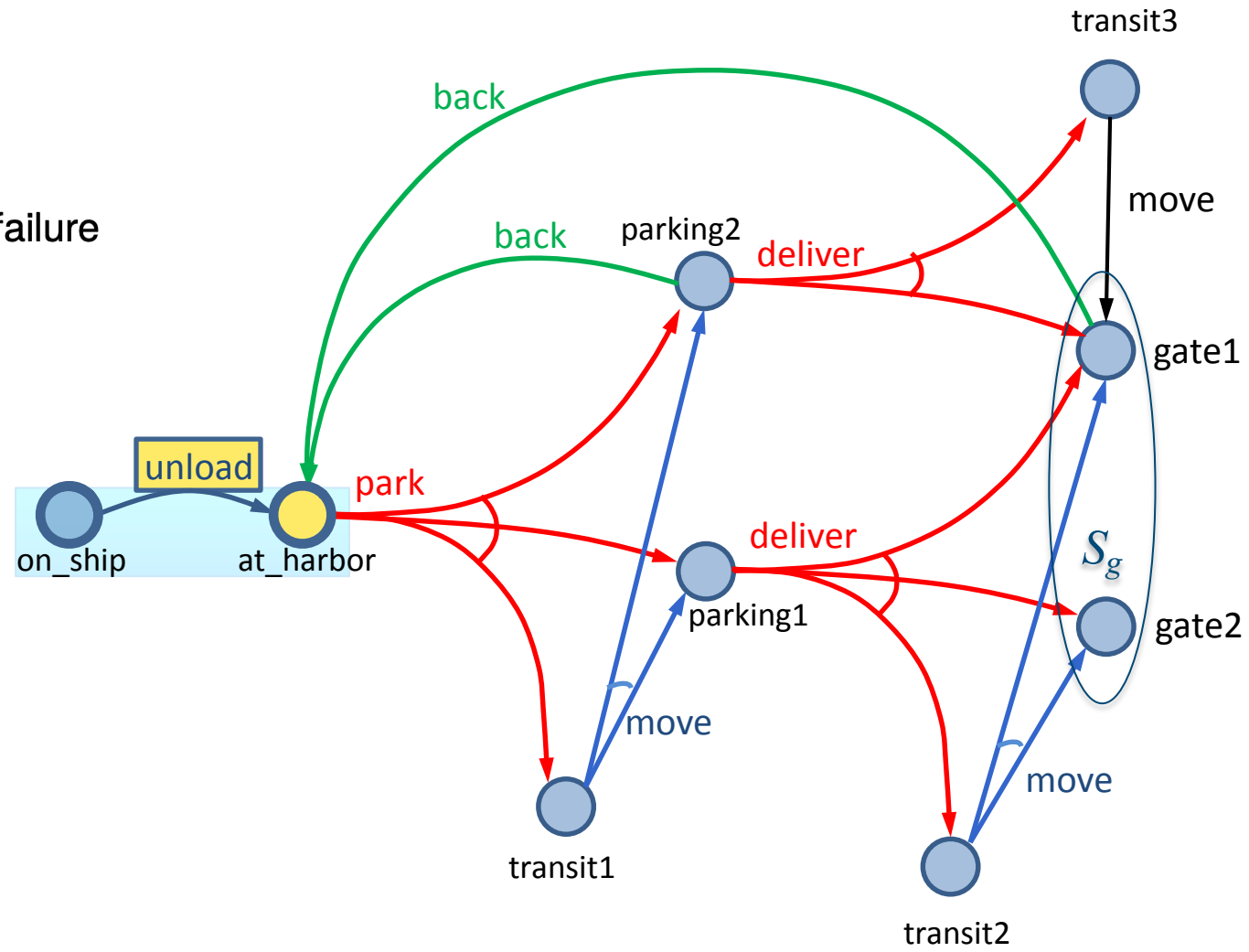
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{$at_harbor$\}$

$\pi = \{$(on_ship, unload)$\}$

Example



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

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  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

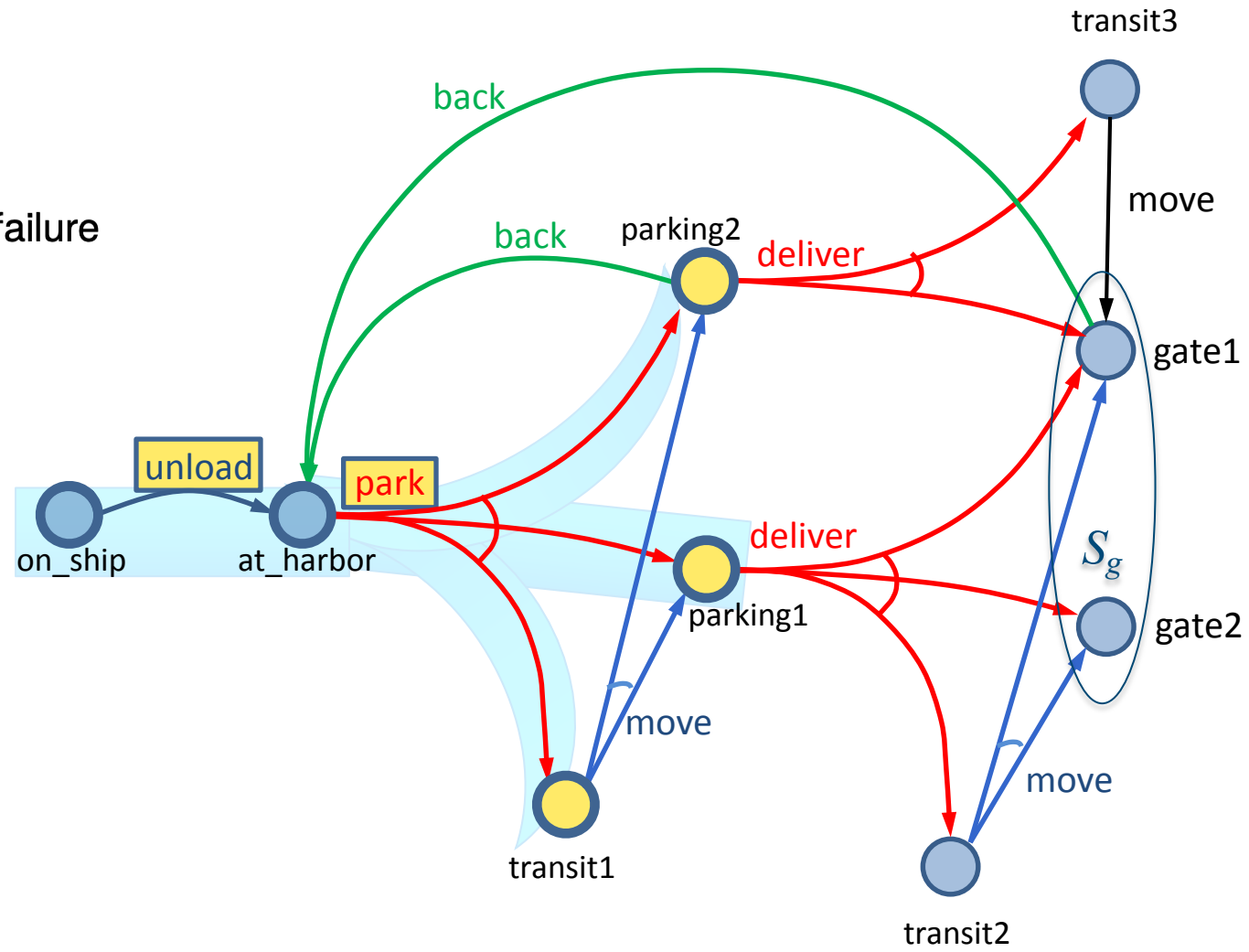
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

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

$\pi = \{$(on_ship, unload), (at_harbor, park)$\}$

Example



Find-Safe-Solution (Σ, s_0, S_g)

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

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

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

  nondeterministically choose $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

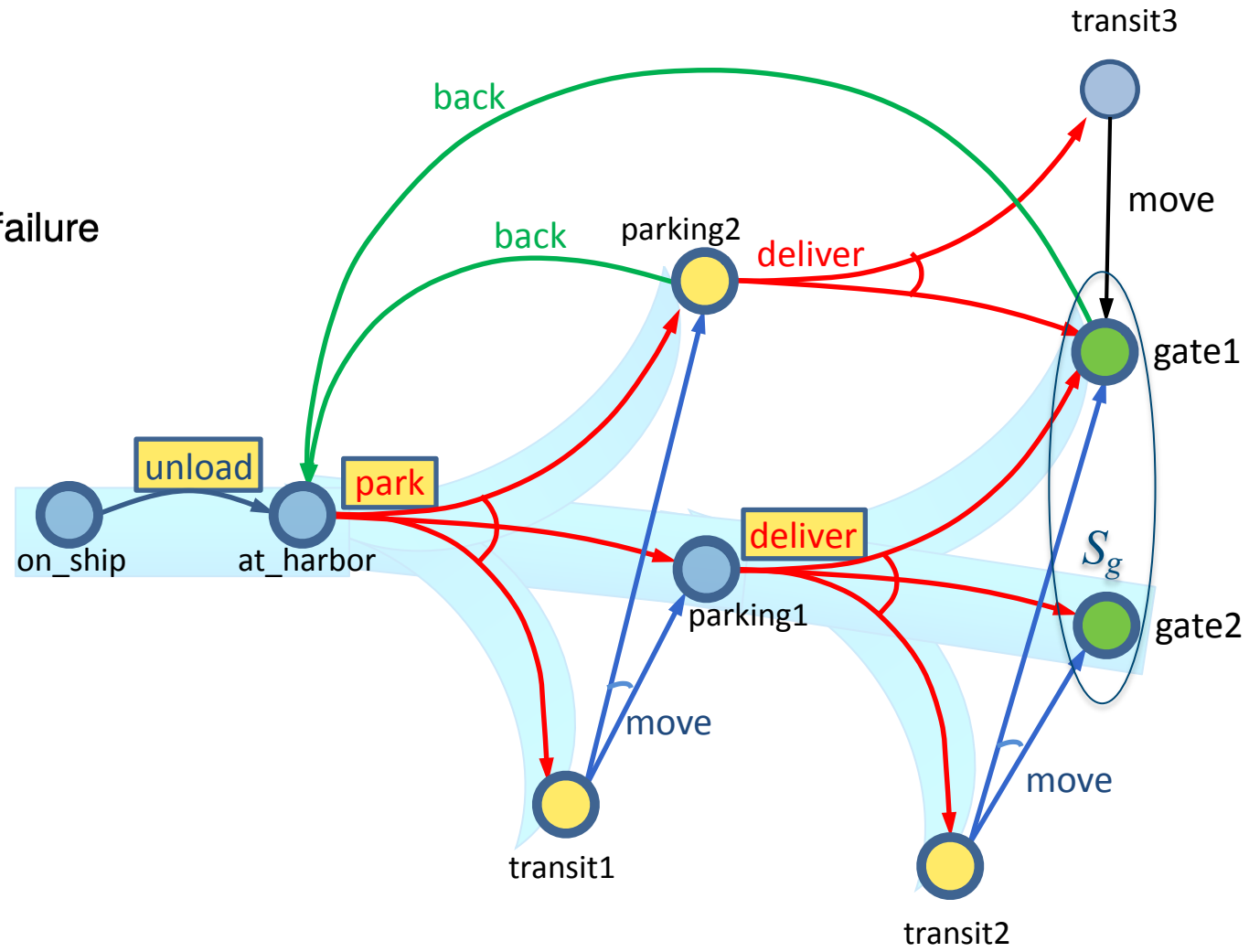
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{$parking2, transit1, transit2, gate1, gate2$\}$

$\pi = \{$(on_ship, unload), (at_harbor, park), (parking1, deliver)$\}$

Example



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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

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

return π

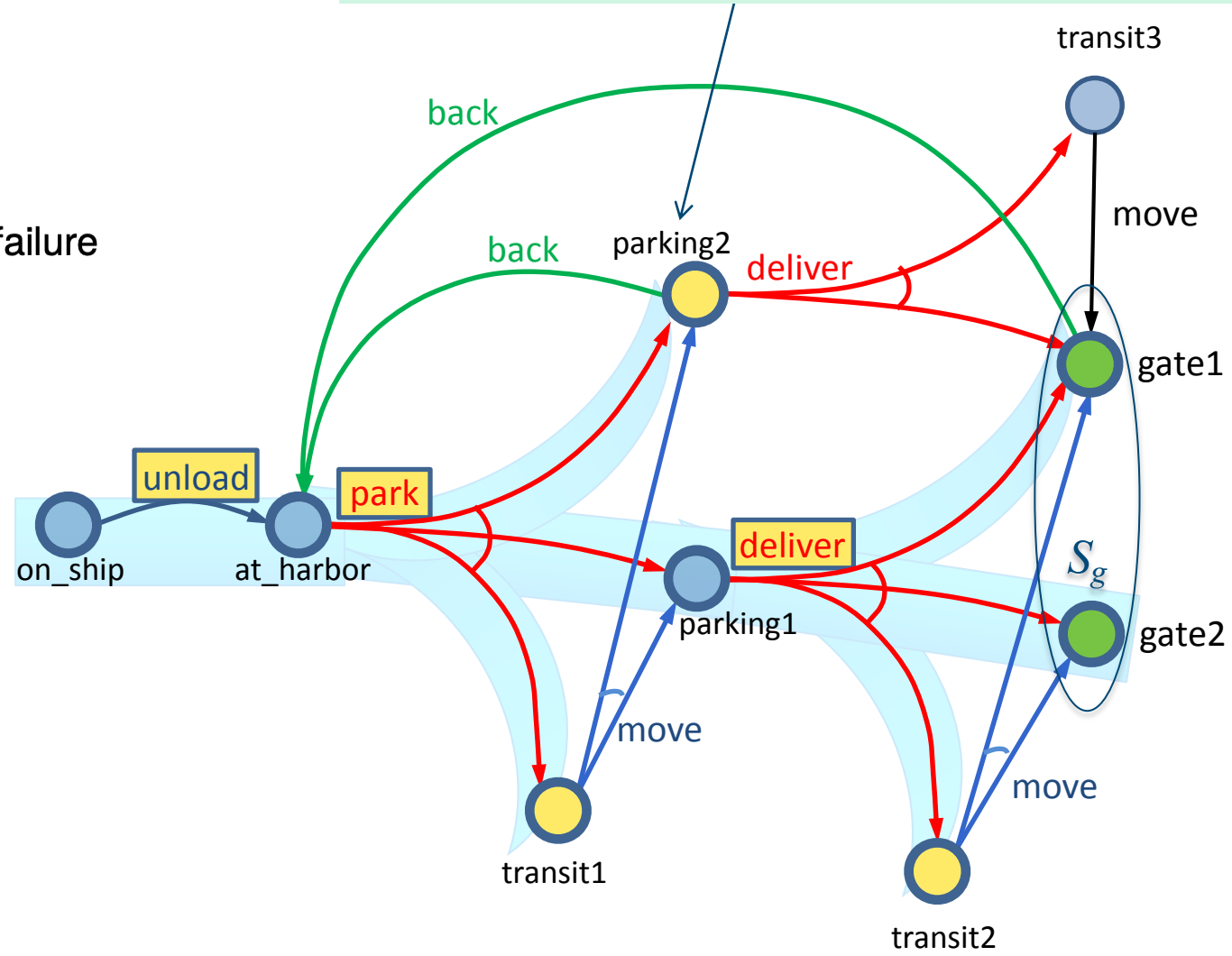
$Frontier = \{$parking2, transit1, transit2, gate1, gate2$\}$

$\pi = \{$(on_ship, unload), (at_harbor, park), (parking1, deliver)$\}$

Example

Nondeterministically choose either back or deliver

- back is OK because cycle is escapable



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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

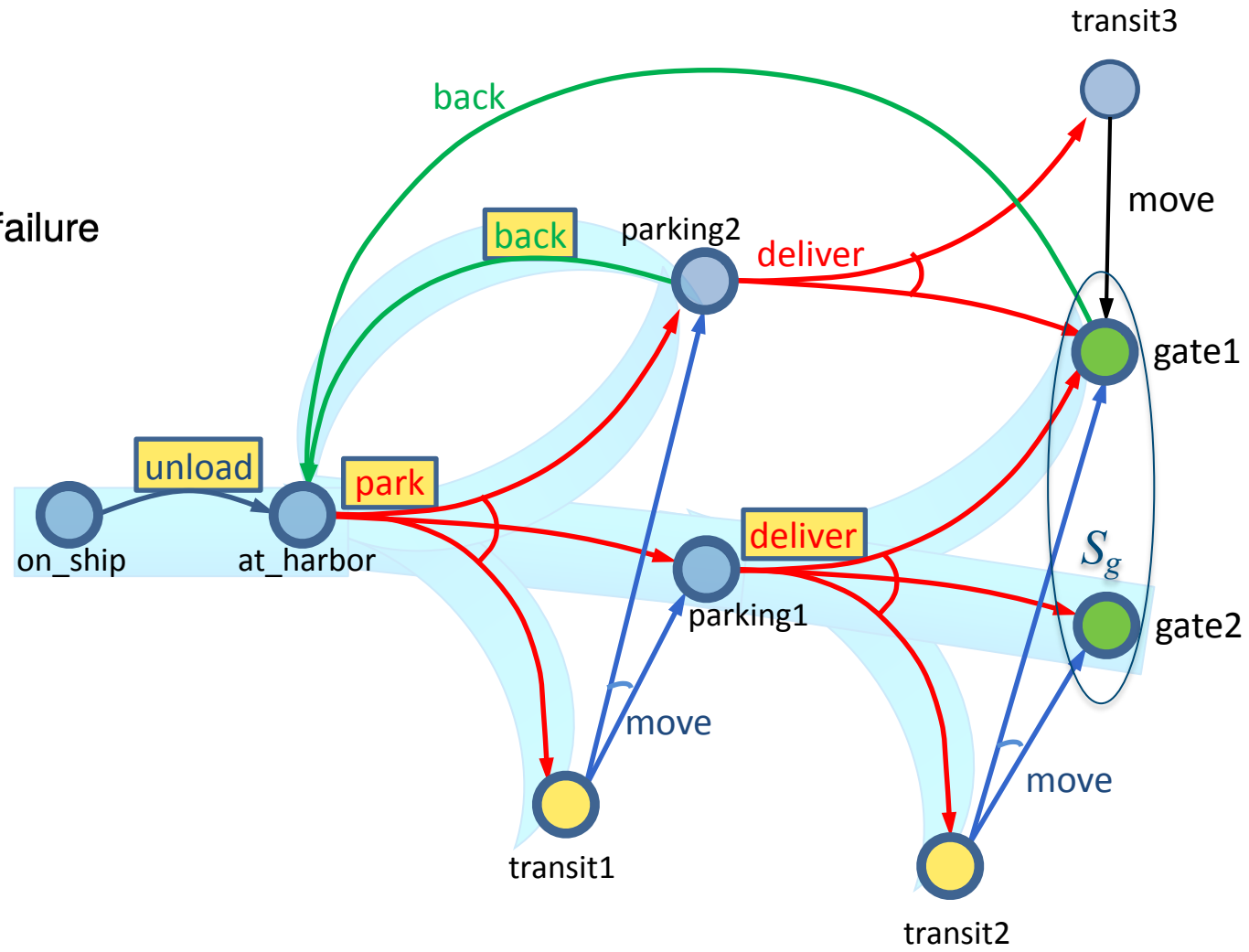
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{$transit1, transit2, gate1, gate2$\}$

$\pi = \{$(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

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

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

  nondeterministically choose $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

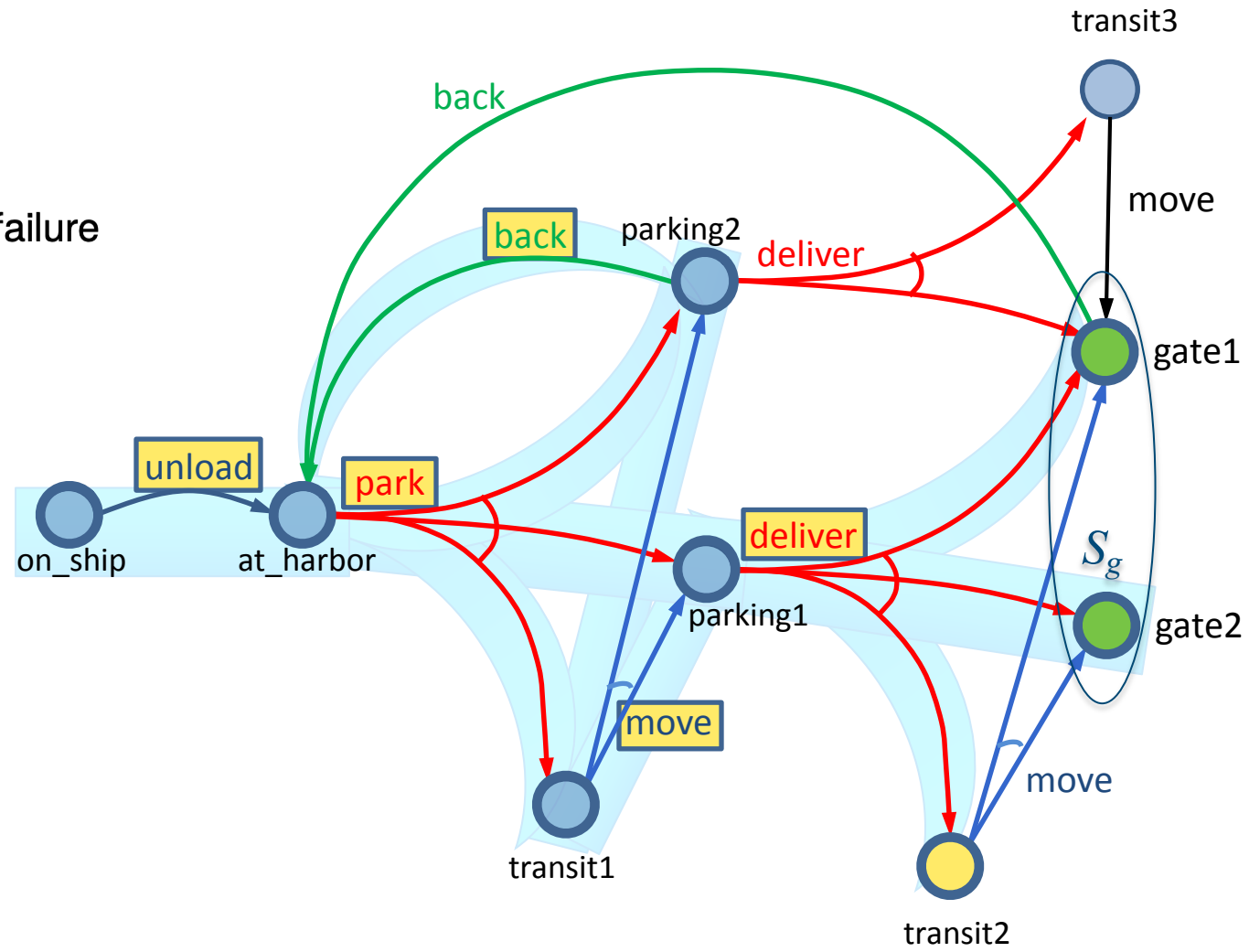
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{$transit2, gate1, gate2$\}$

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

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 $a \in Applicable(s)$

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

  $Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$

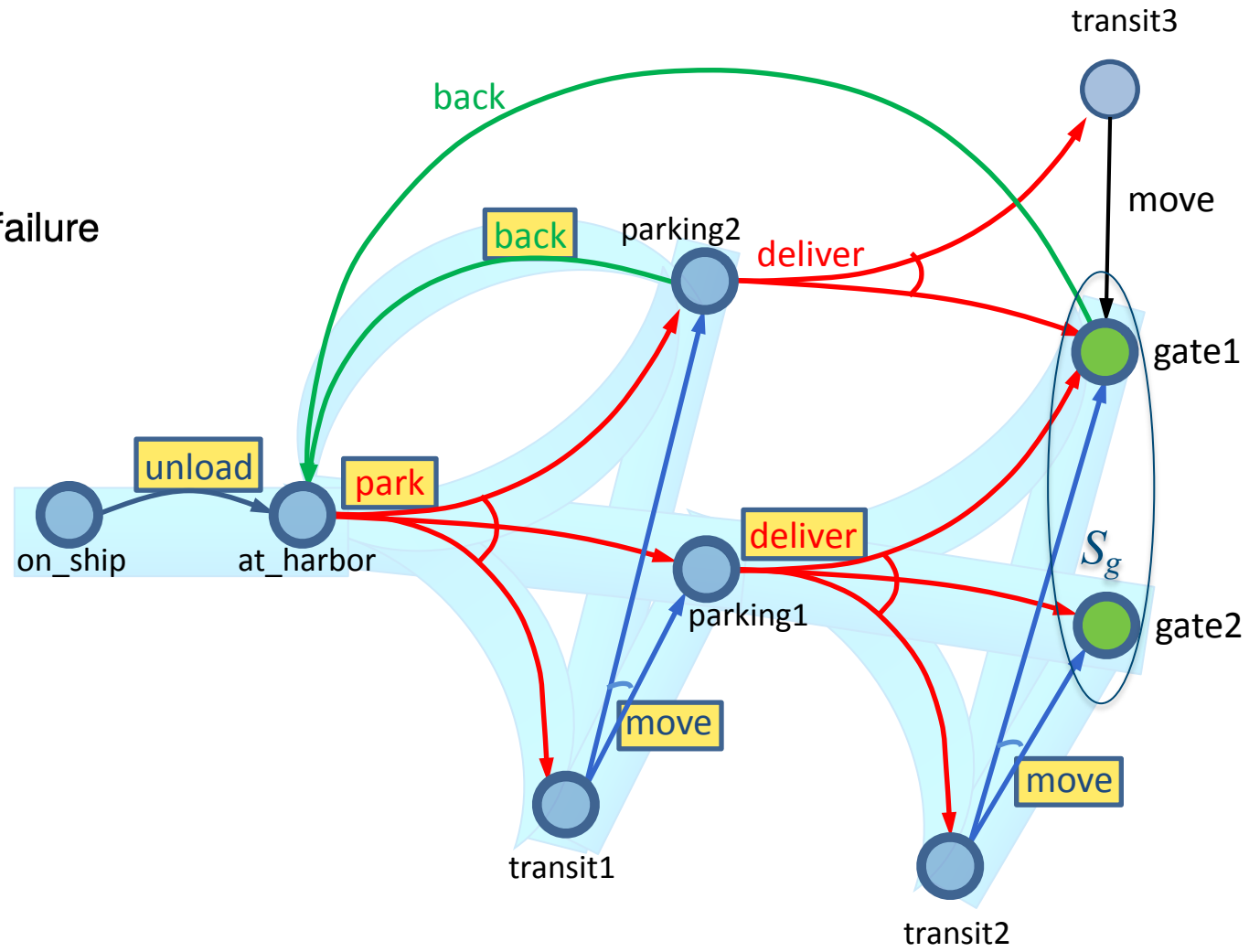
  if has-unsafe-loops$(\pi, a, Frontier)$ then return failure

return π

$Frontier = \{\text{gate1, gate2}\} \subseteq S_g$

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

Example



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 (possibly unsafe) solution π
    - For each each leaf node of π
      - If the leaf node isn't a goal,
        - find a (possibly unsafe) 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
      $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
    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 (possibly unsafe) solution π' for s.

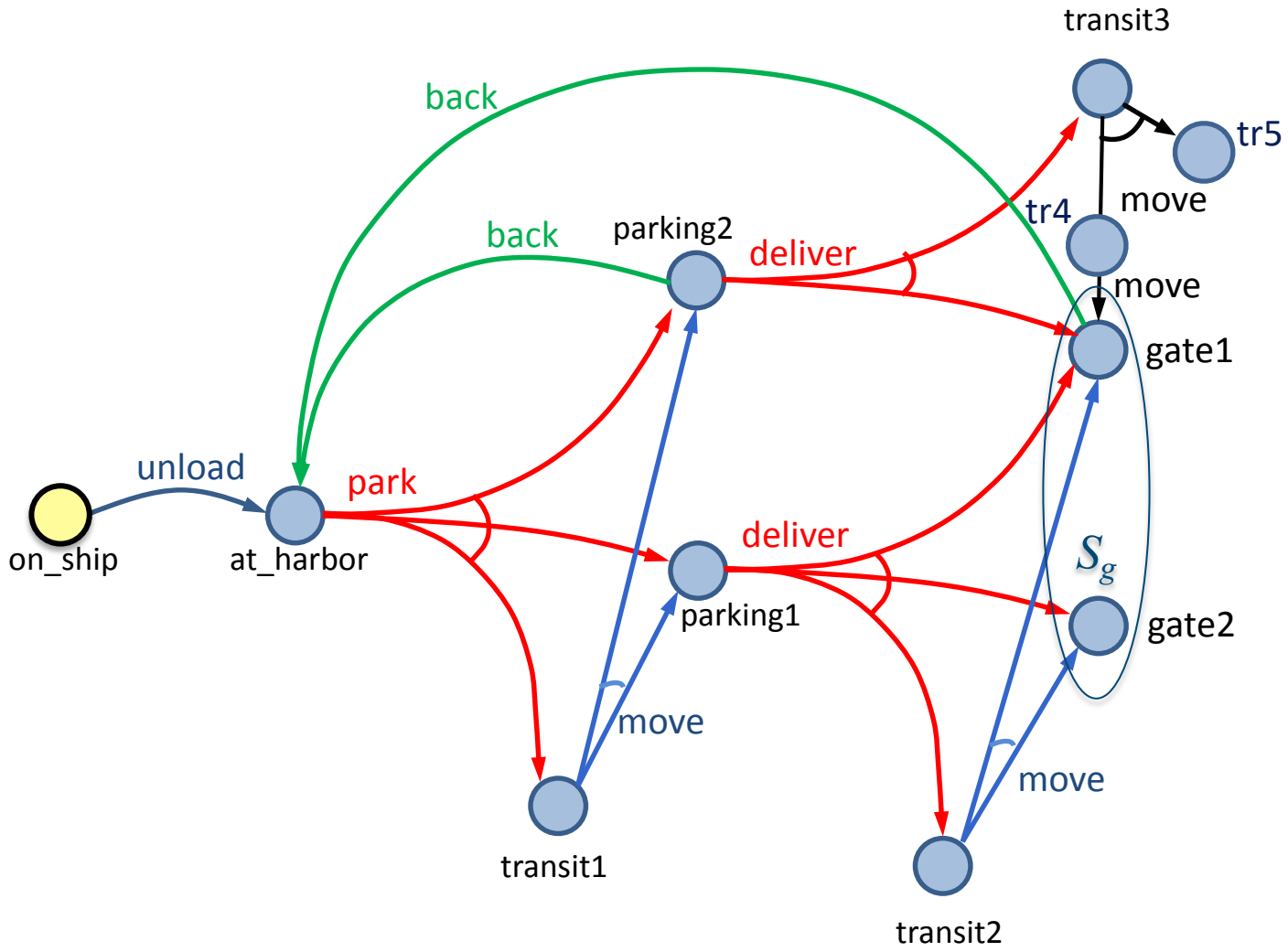
For each (s,a) in π', add to π unless π already has an action at s

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

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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

Example



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
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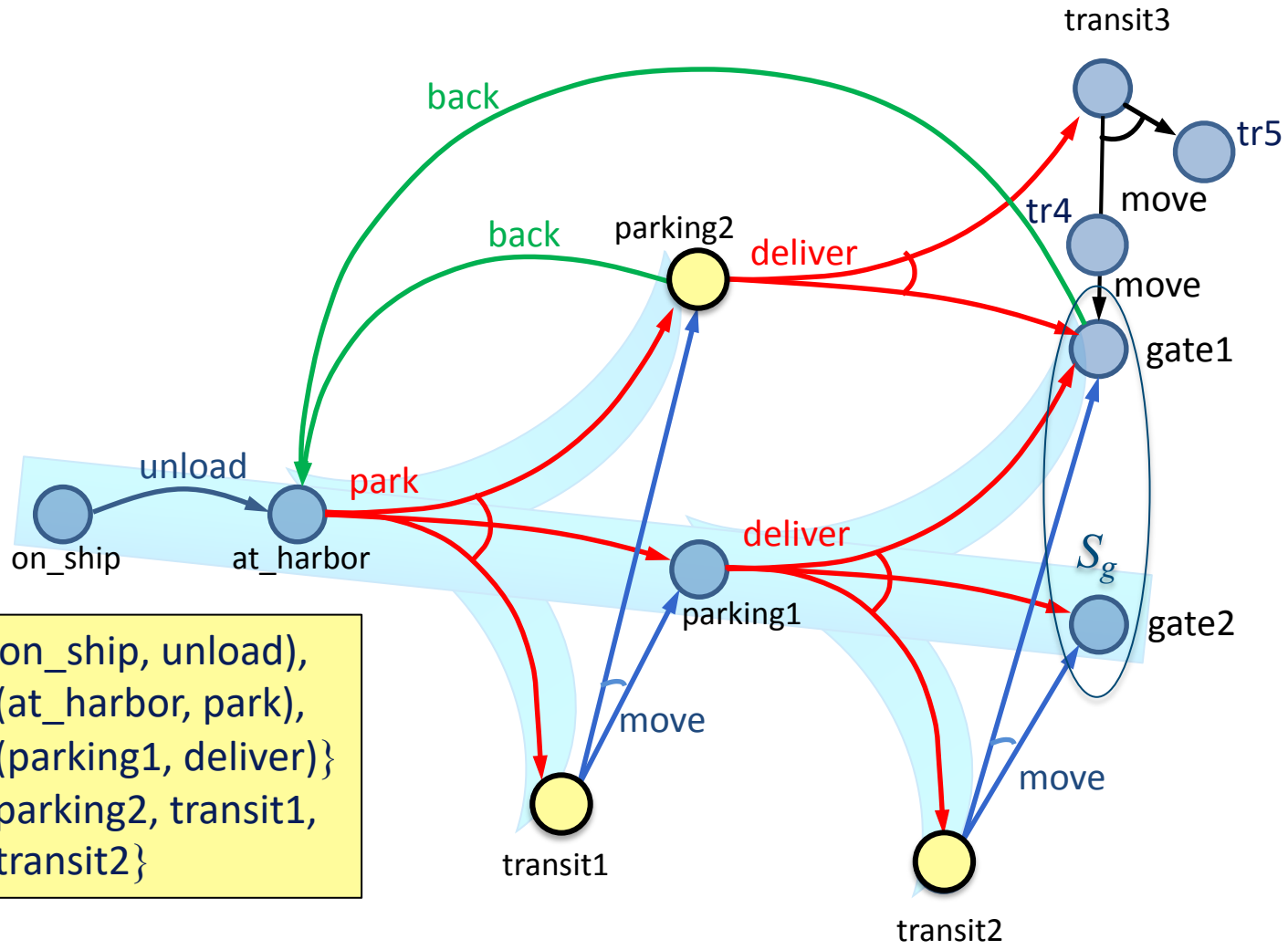
  $\pi' \leftarrow$ Find-Solution(Σ, s, S_g)
  if $\pi' \neq$ failure then do
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$
    make a not applicable in s'

Example



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

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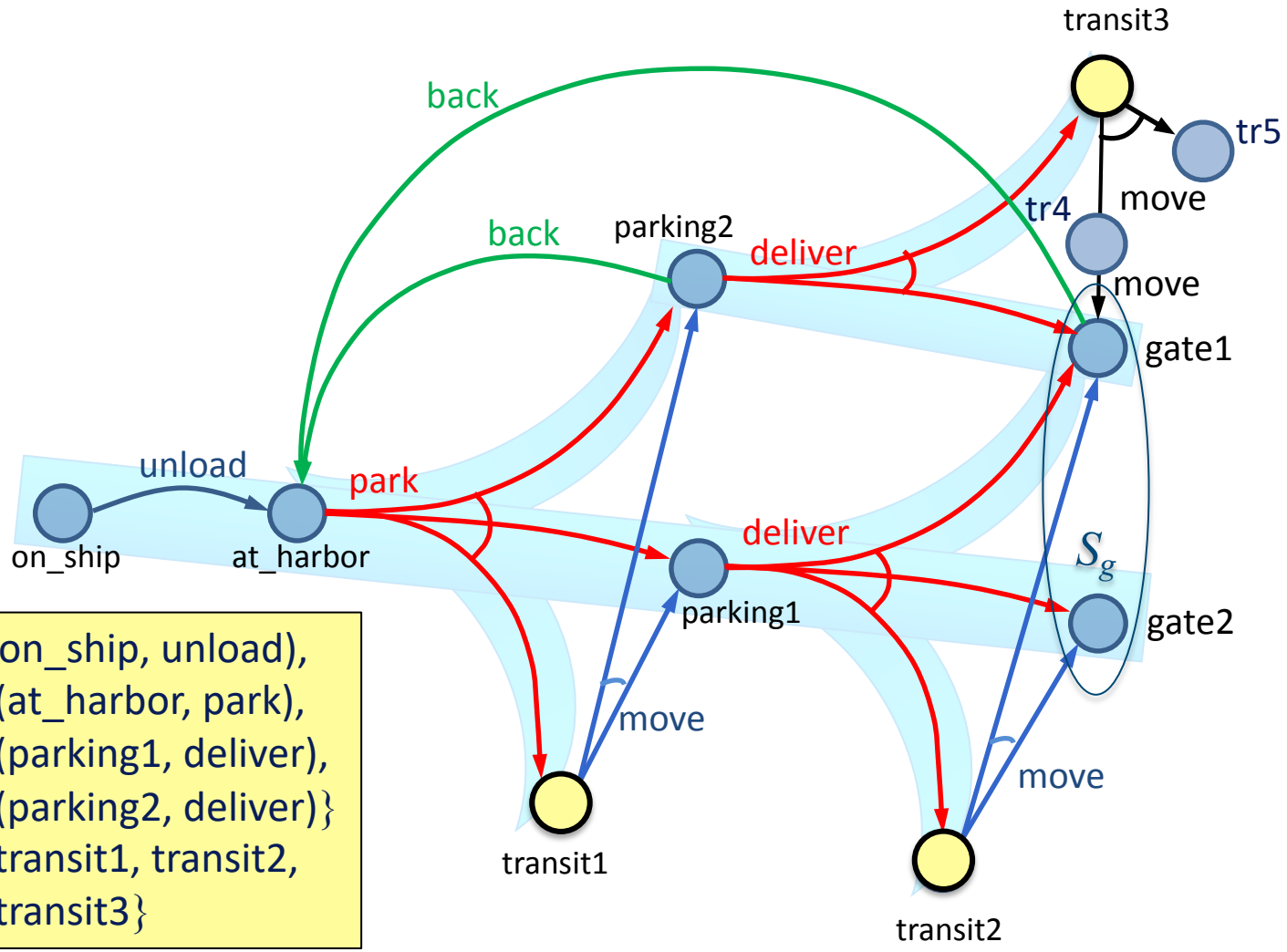
    return(π)
  select arbitrarily $s \in Q$
  $\pi' \leftarrow$ Find-Solution(Σ, s, S_g)
  if $\pi' \neq$ failure then do
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$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

Example

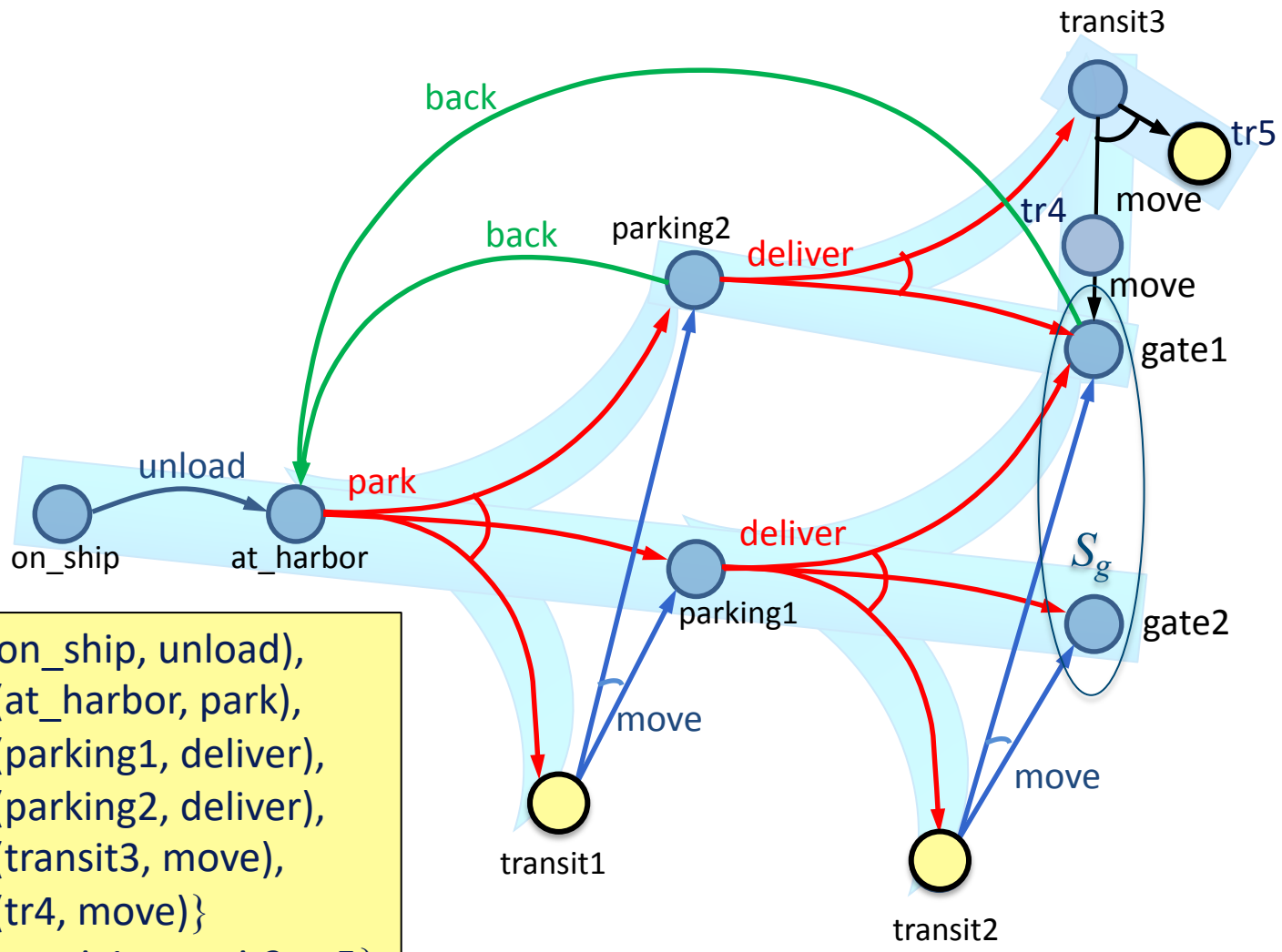


$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver)$\}$
$Q = \{$transit1, transit2,
transit3$\}$

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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

Example

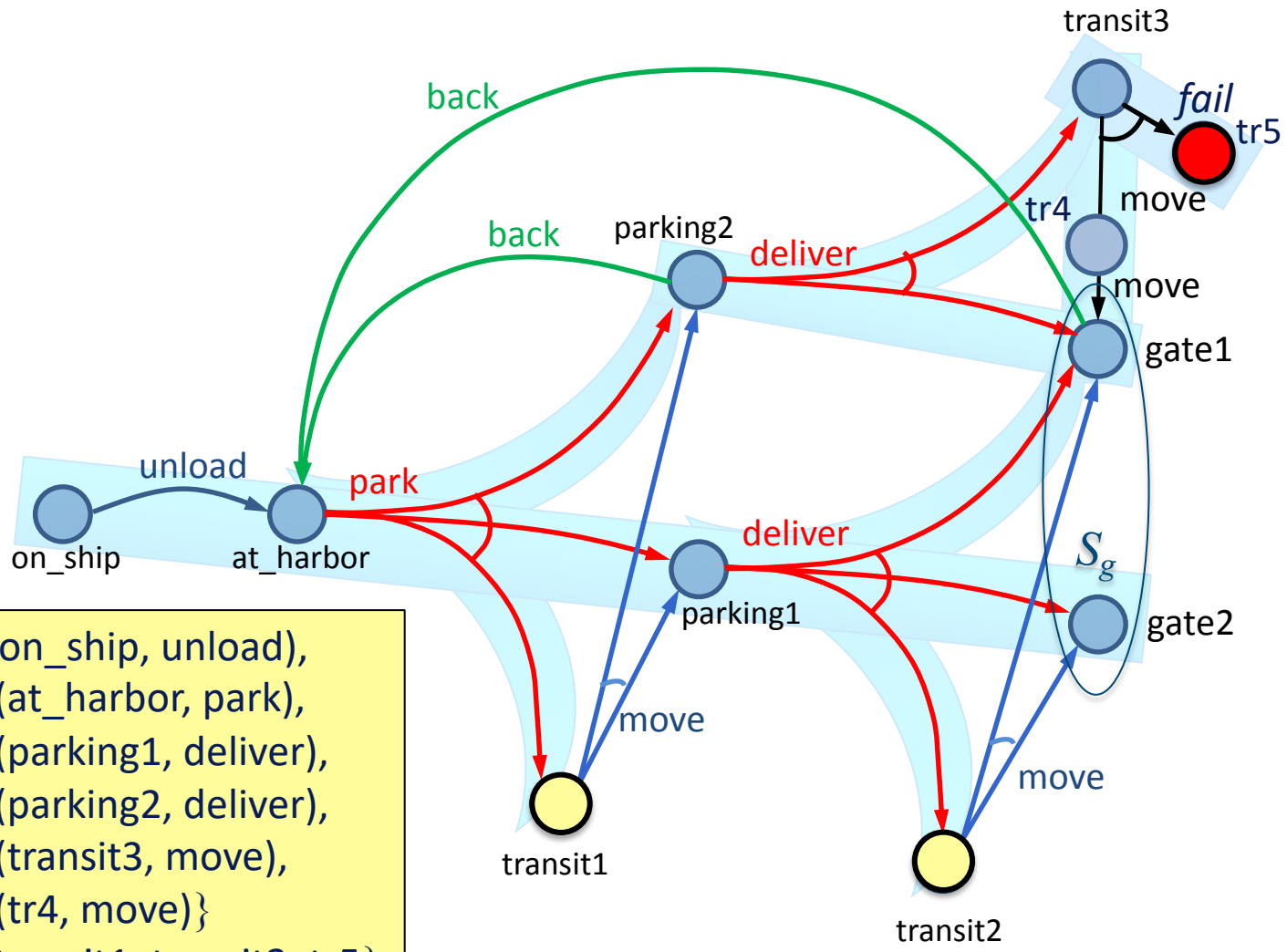


$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit3, move),
(tr4, move)$\}$
$Q = \{$transit1, transit2, tr5$\}$

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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

Example



$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit3, move),
(tr4, move)$\}$
$Q = \{$transit1, transit2, tr5$\}$

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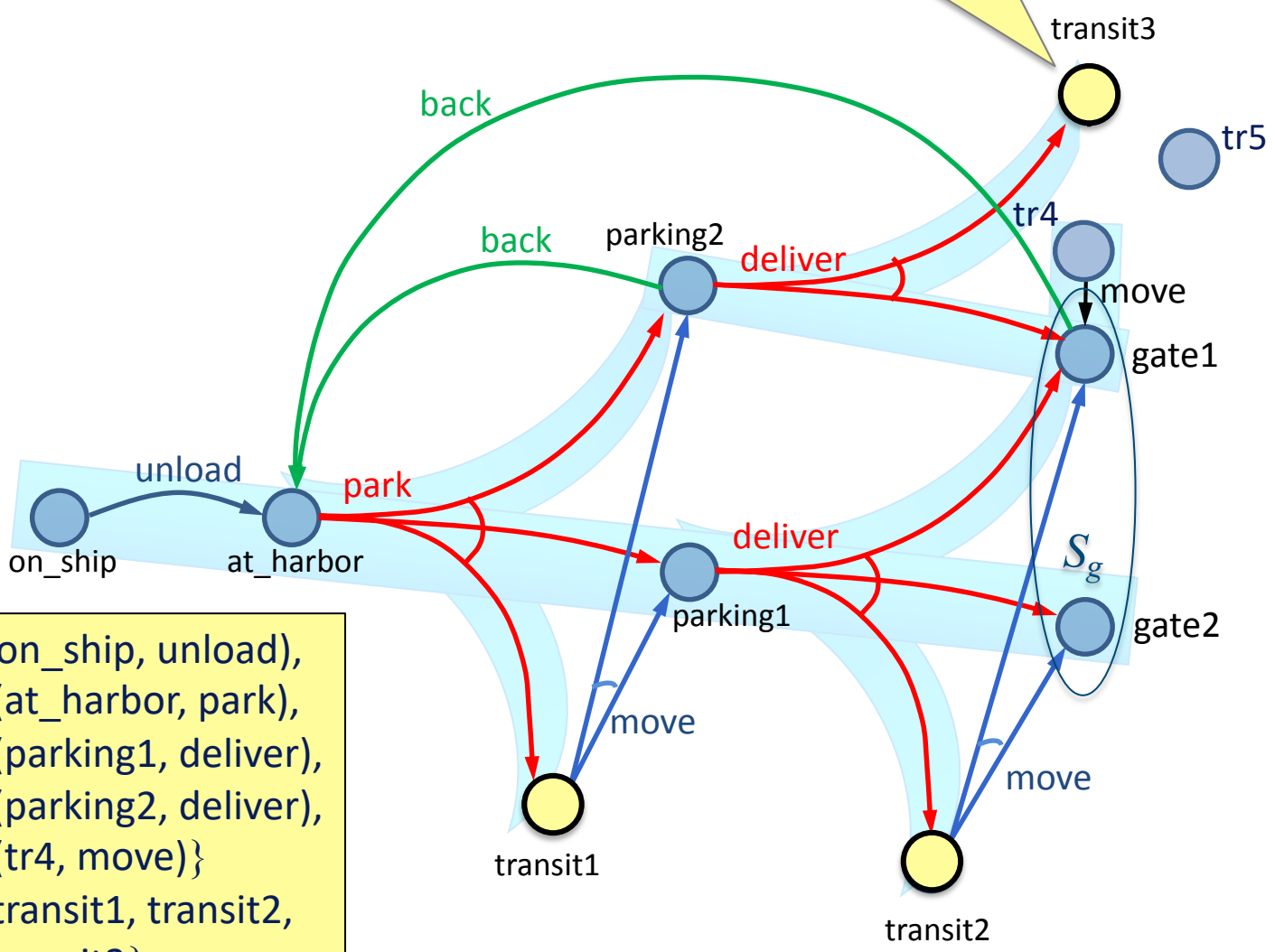
    return(π)
  select arbitrarily $s \in Q$
  $\pi' \leftarrow$ Find-Solution(Σ, s, S_g)
  if $\pi' \neq$ failure then do
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$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

Example

Modify Σ to make move inapplicable at transit3

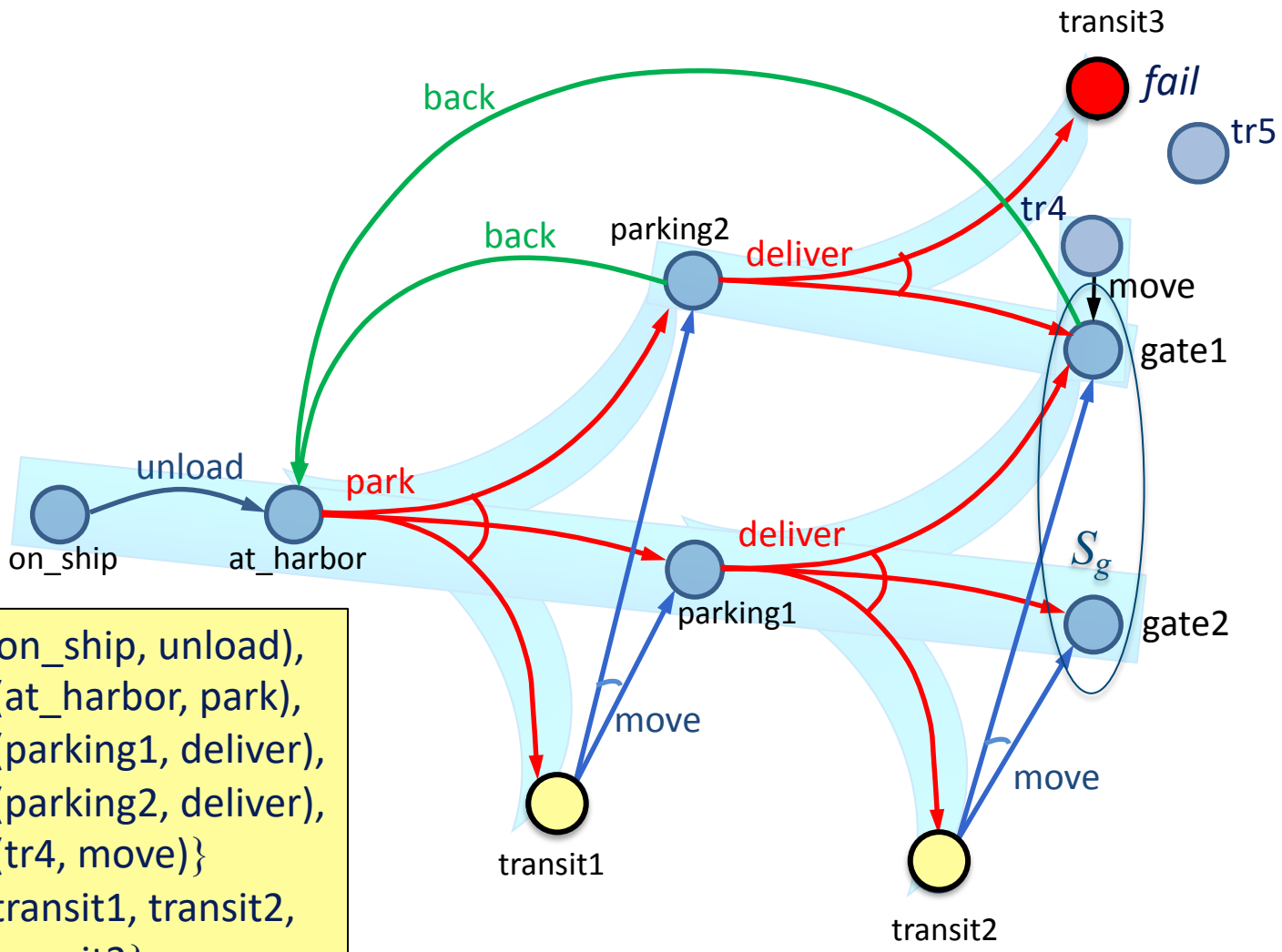


$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(tr4, move)$\}$
$Q = \{$transit1, transit2,
transit3$\}$

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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

Example

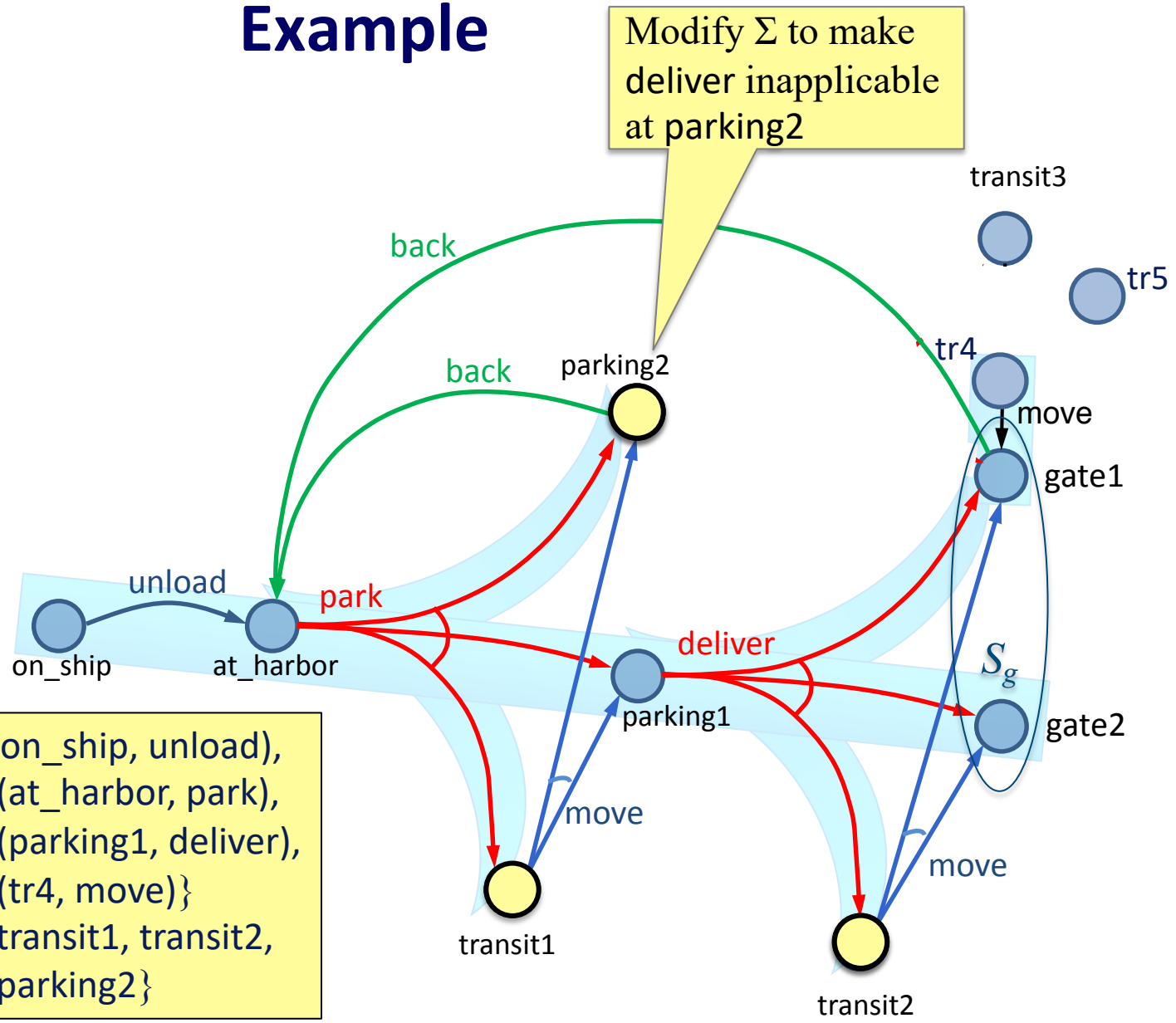


$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(tr4, move)$\}$
$Q = \{$transit1, transit2,
transit3$\}$

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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

Example



$\pi = \{$(on_ship, unload), (at_harbor, park), (parking1, deliver), (tr4, move)$\}$
$Q = \{$transit1, transit2, parking2$\}$

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)
$\pi \leftarrow \varnothing$
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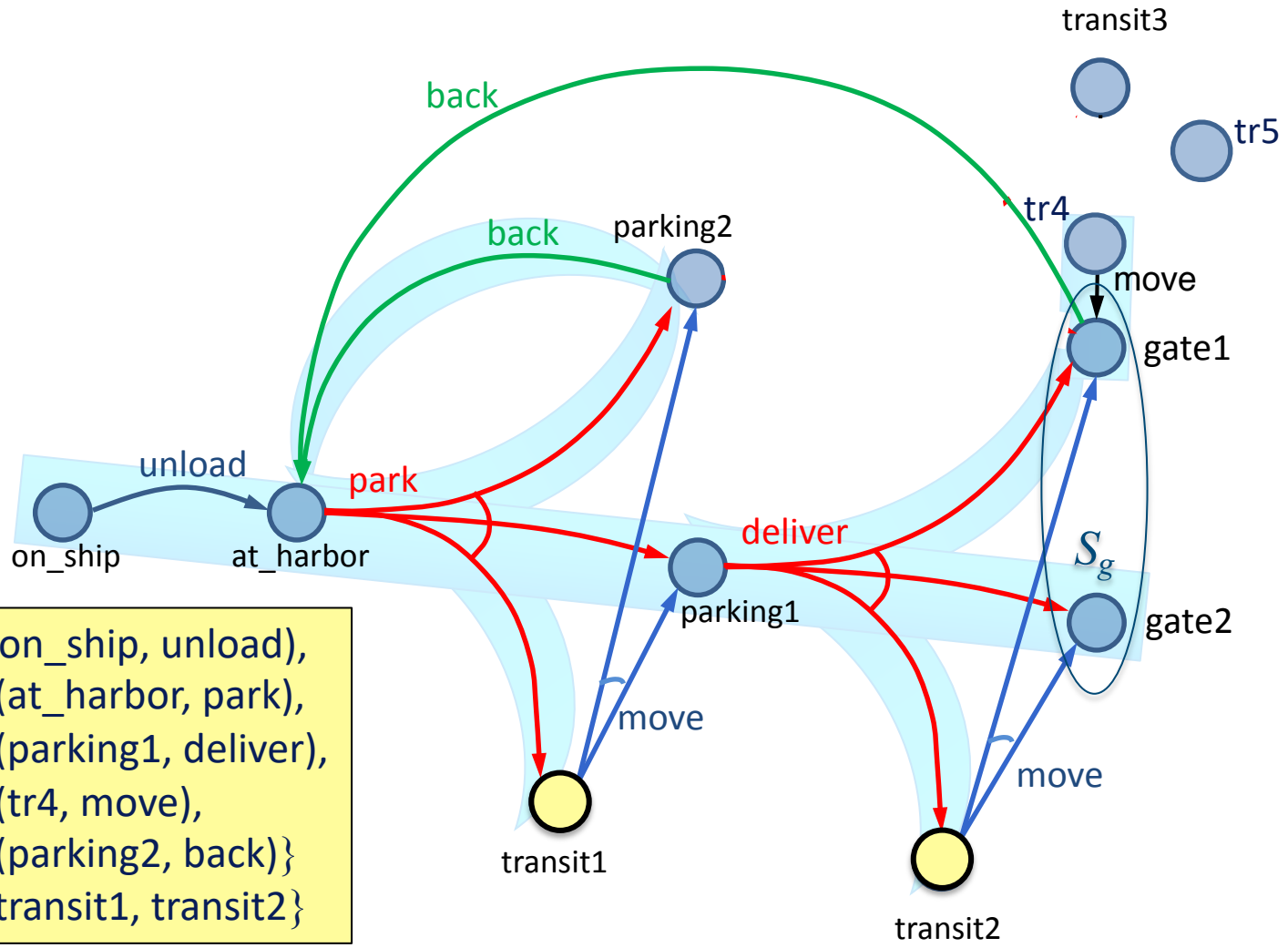
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$
    make a not applicable in s'

Example



$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(tr4, move),
(parking2, back)$\}$
$Q = \{$transit1, transit2$\}$

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)
$\pi \leftarrow \varnothing$
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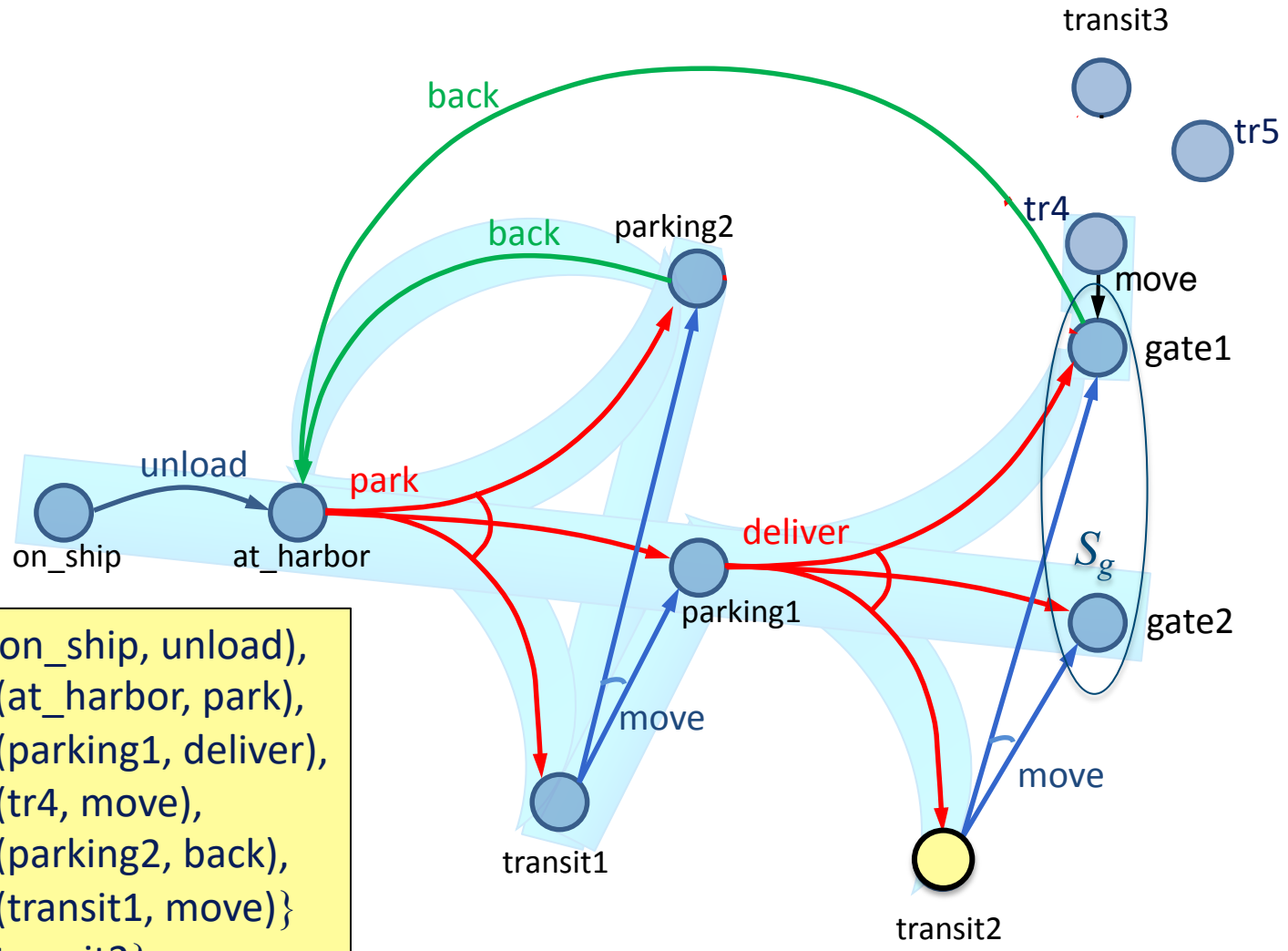
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$
    make a not applicable in s'

Example



$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(tr4, move),
(parking2, back),
(transit1, move)$\}$
$Q = \{$transit2$\}$

Guided-Find-Safe-Solution (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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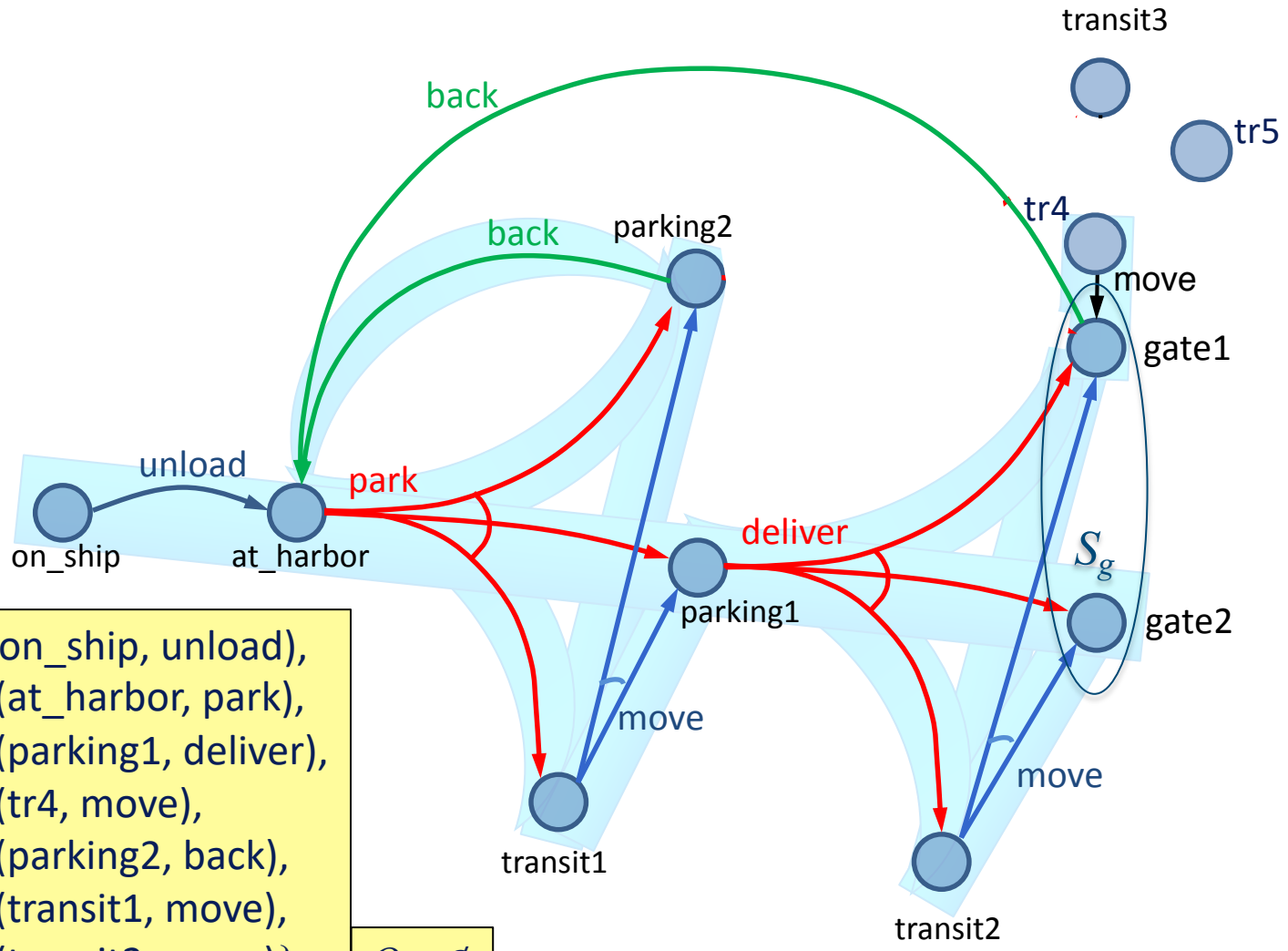
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$
    make a not applicable in s'

Example



$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(tr4, move),
(parking2, back),
(transit1, move),
(transit2, move)$\}$

$Q = \emptyset$

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)
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  if $\pi' \neq$ failure then do
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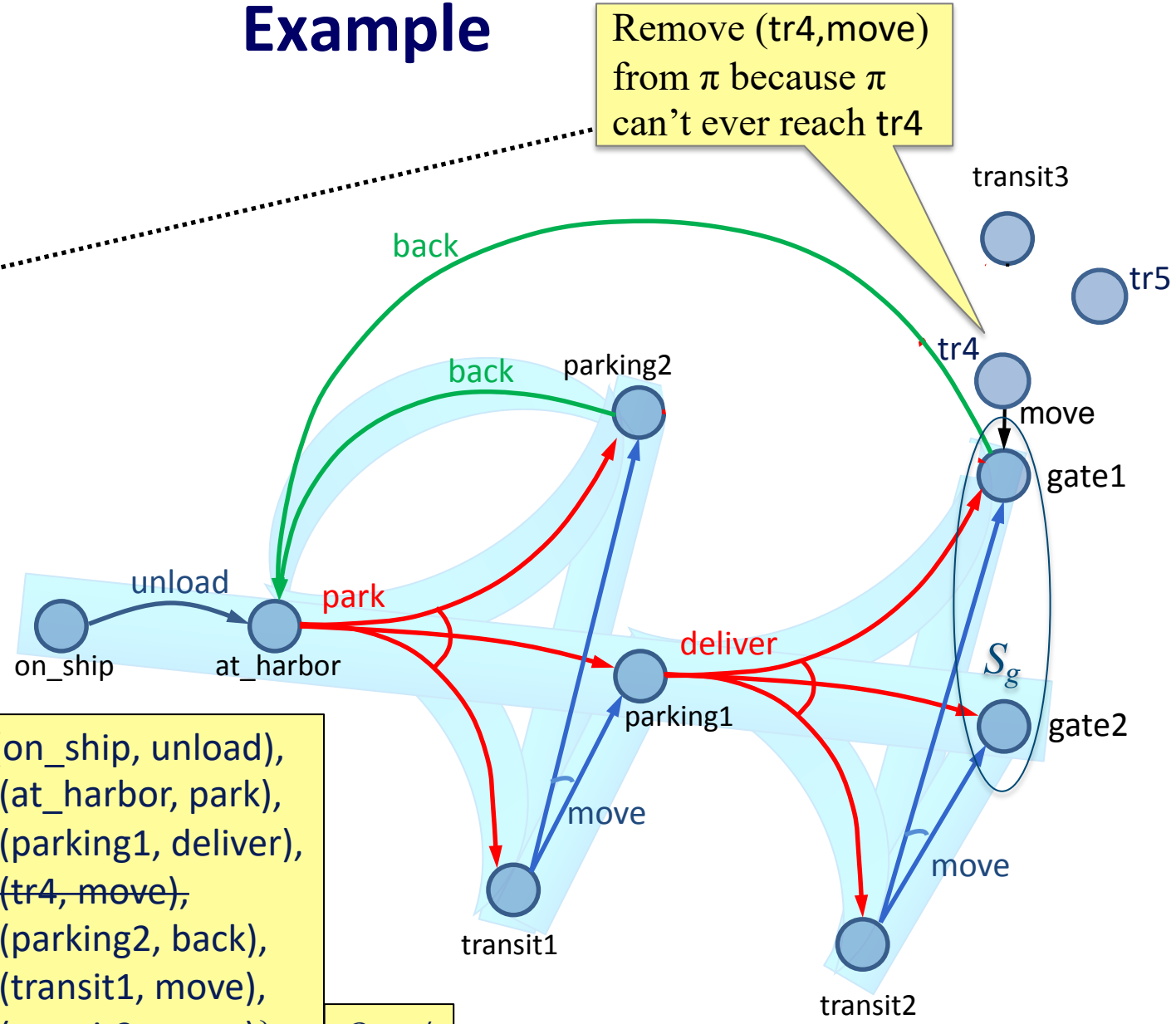
  else for every s' and a such that $s \in \gamma(s', a)$ do
    $\pi \leftarrow \pi \setminus \{(s', a)\}$
    make a not applicable in s'

Example



$\pi = \{$(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
~~(tr4, move),~~
(parking2, back),
(transit1, move),
(transit2, move)$\}$

$Q = \emptyset$

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)
$\pi \leftarrow \varnothing$
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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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

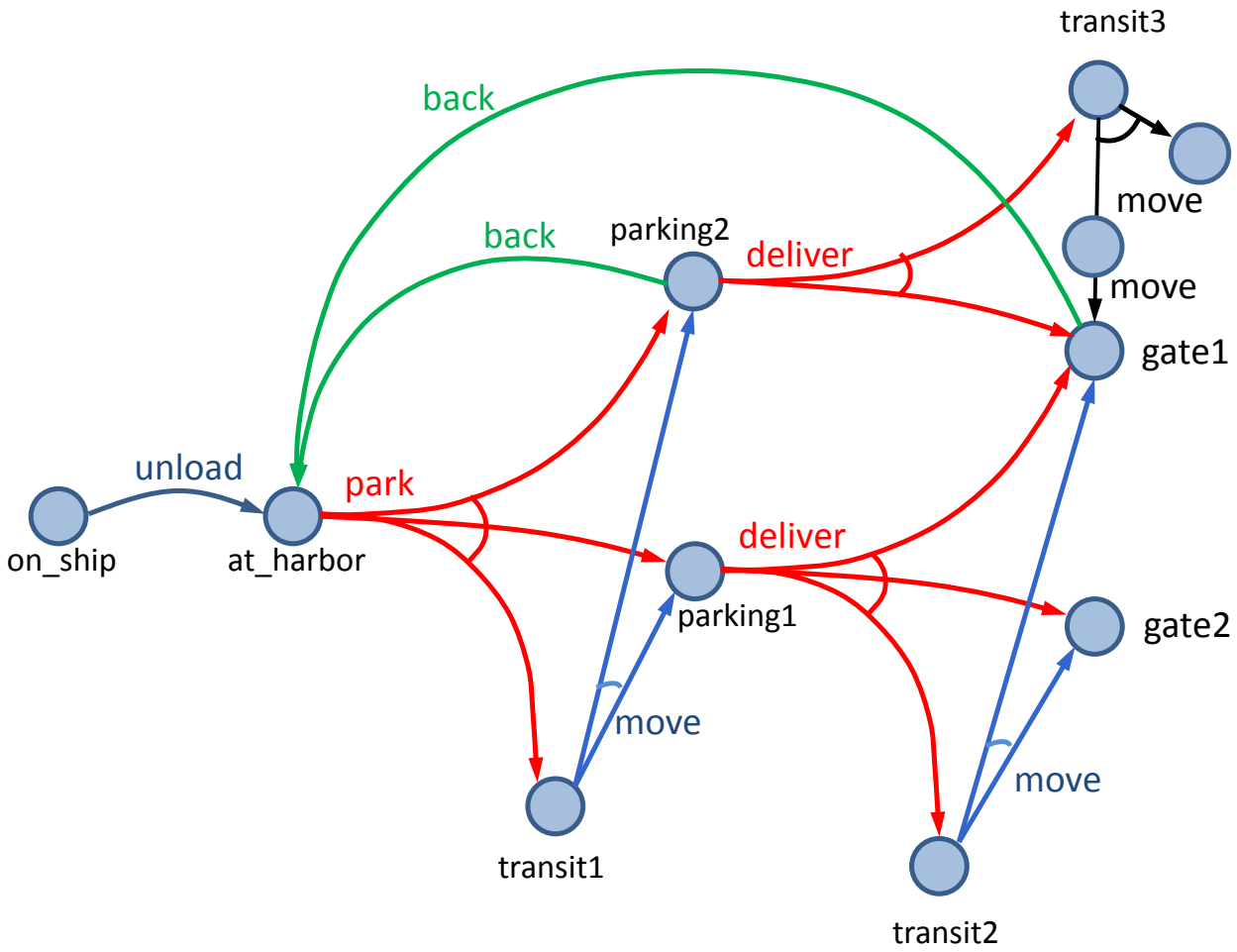
Discussion

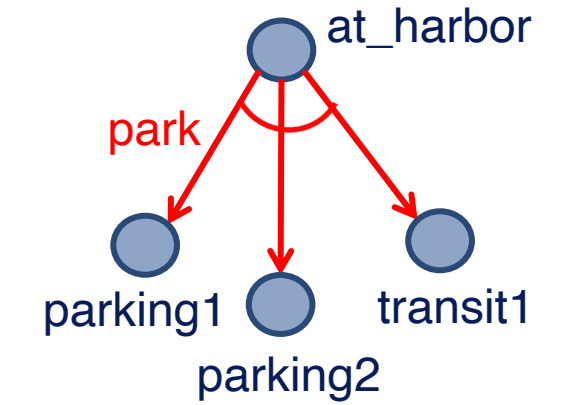
- How to implement it?
  - Need implementation of Find-Solution
  - Need it to be very efficient
    - We'll call it many times
- Idea: instead of Find-Solution, use a classical planner
  - Any of the algorithms from Chapter 2
  - Efficient algorithms, search heuristics
- Need to convert the actions into something the classical planner can use …

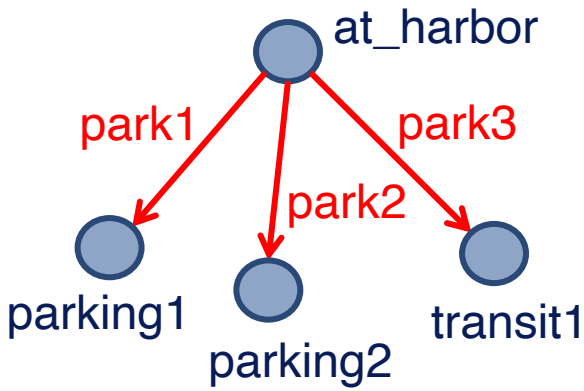
Determinization

- Let a_i be a nondeterministic action with n possible outcomes
- *Determinization* of a_i =

  {n deterministic actions, one for each outcome of a_i }



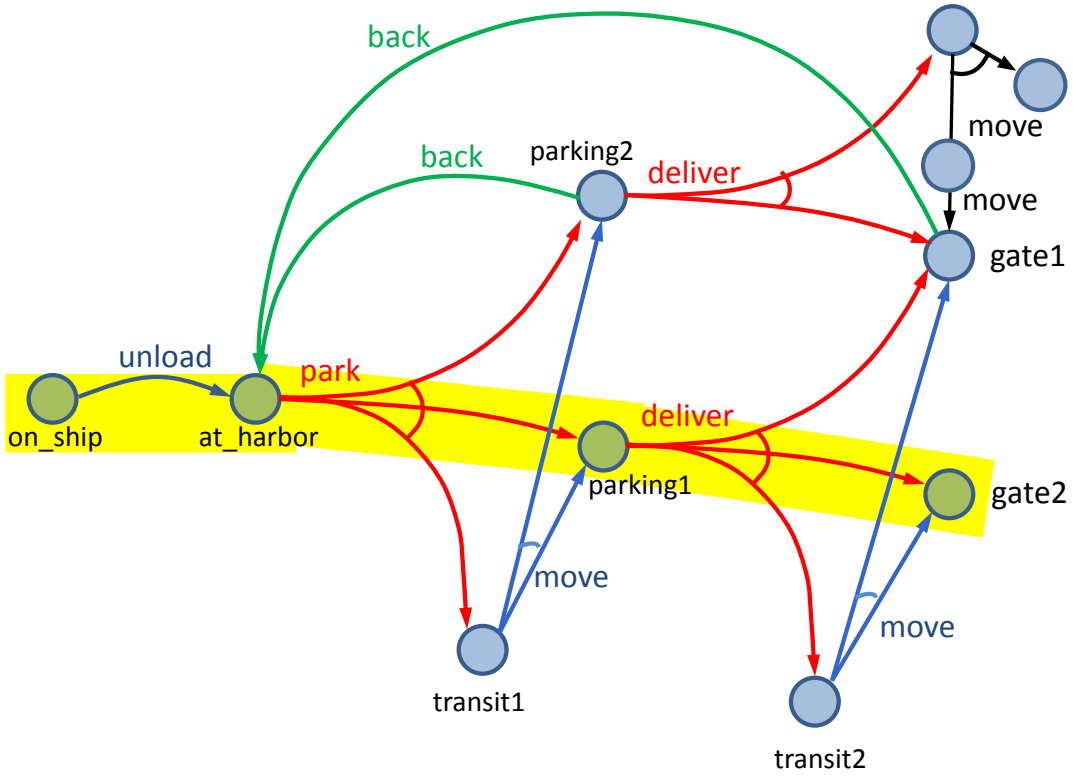


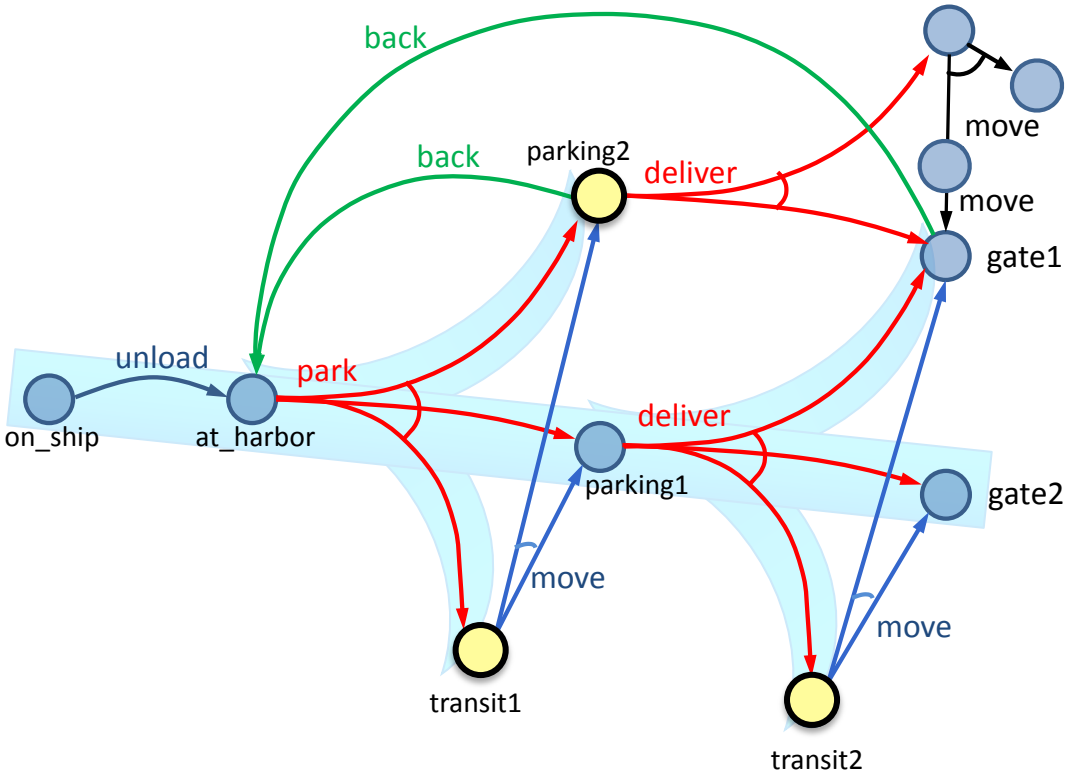


Determinization

- Suppose a classical planner returns an acyclic plan $p = \langle a_1, a_2, \ldots, a_n \rangle$
- Actions and states: $\langle s_0, a_1, s_1, a_2, s_2, a_3, \ldots, a_n, s_n \rangle$
- Convert p to a policy $\langle (s_0, \boldsymbol{a}_1), (s_1, \boldsymbol{a}_2), \ldots, (s_{n-1}, \boldsymbol{a}_n) \rangle$
  - $\boldsymbol{a}_1$ = the nondeterministic action whose determinization includes 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





Find-Safe-Solution-by-Determinization

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
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

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 $p' \neq$ failure then do
    $\pi' \leftarrow$ Plan2policy(p', s)
    $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  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'

Any classical planner that doesn't return cyclic plans

Example

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

if $s_0 \in S_g$ then return$(\varnothing)$
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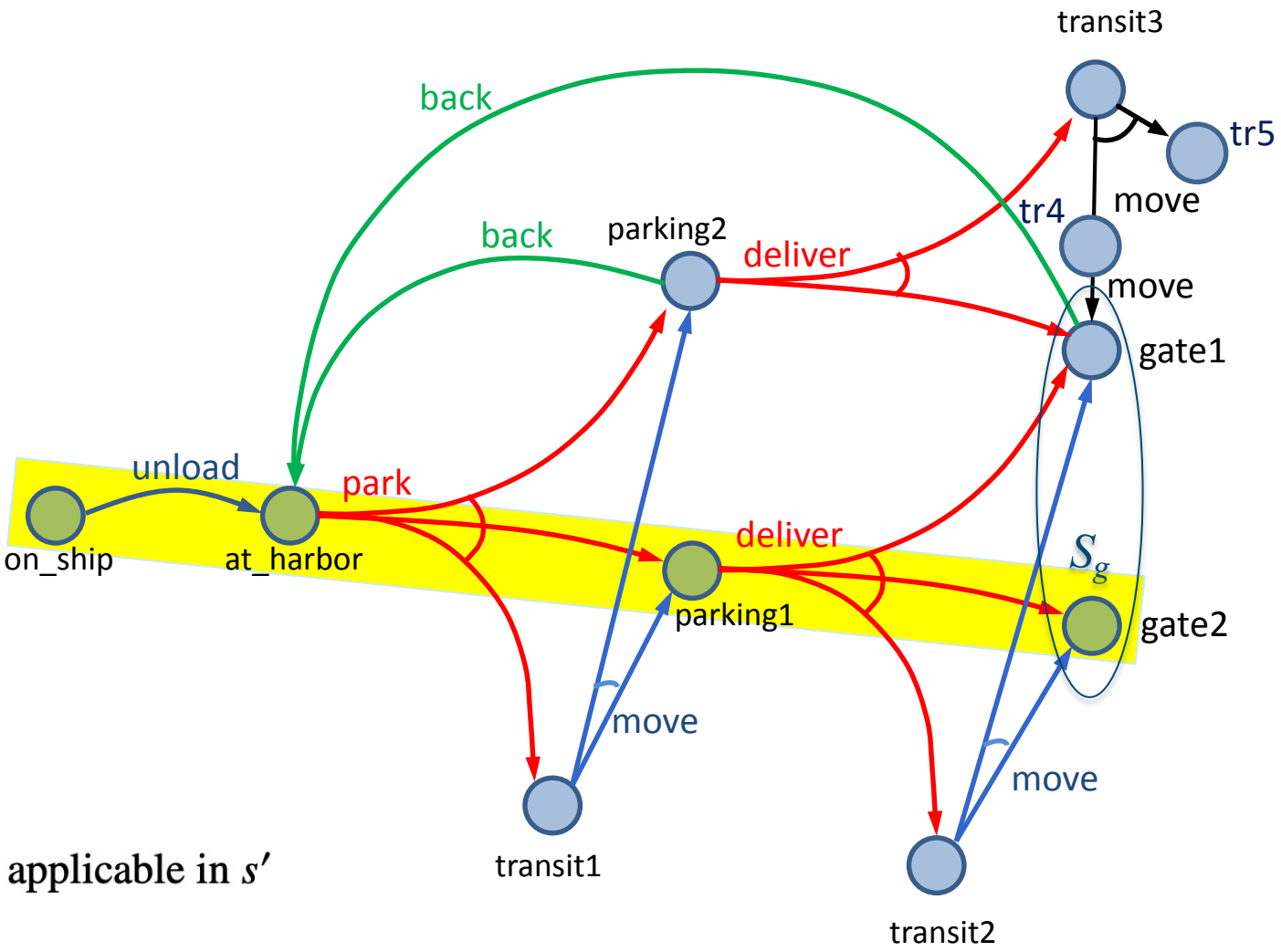

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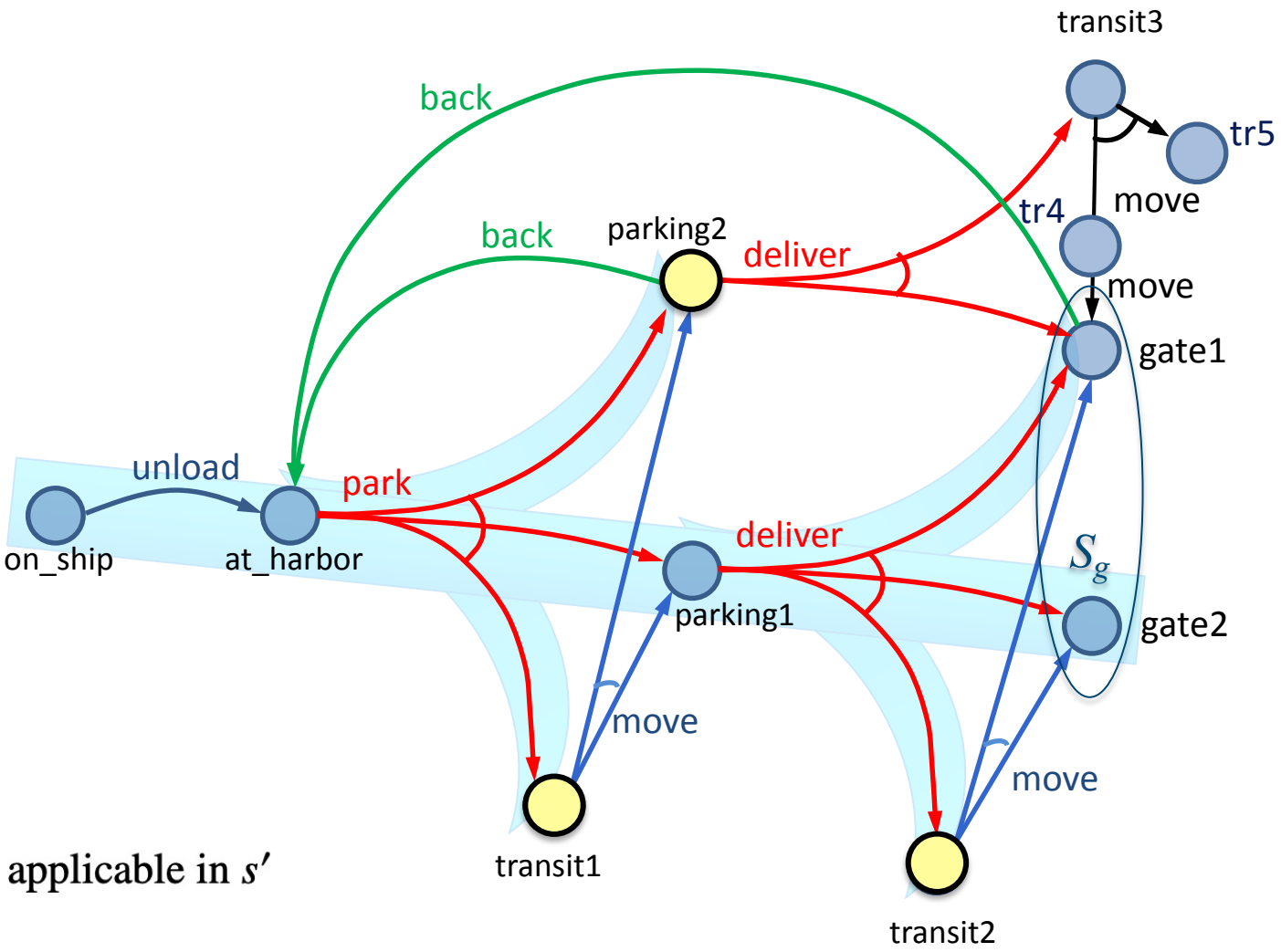

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return(π)

select $s \in Q$

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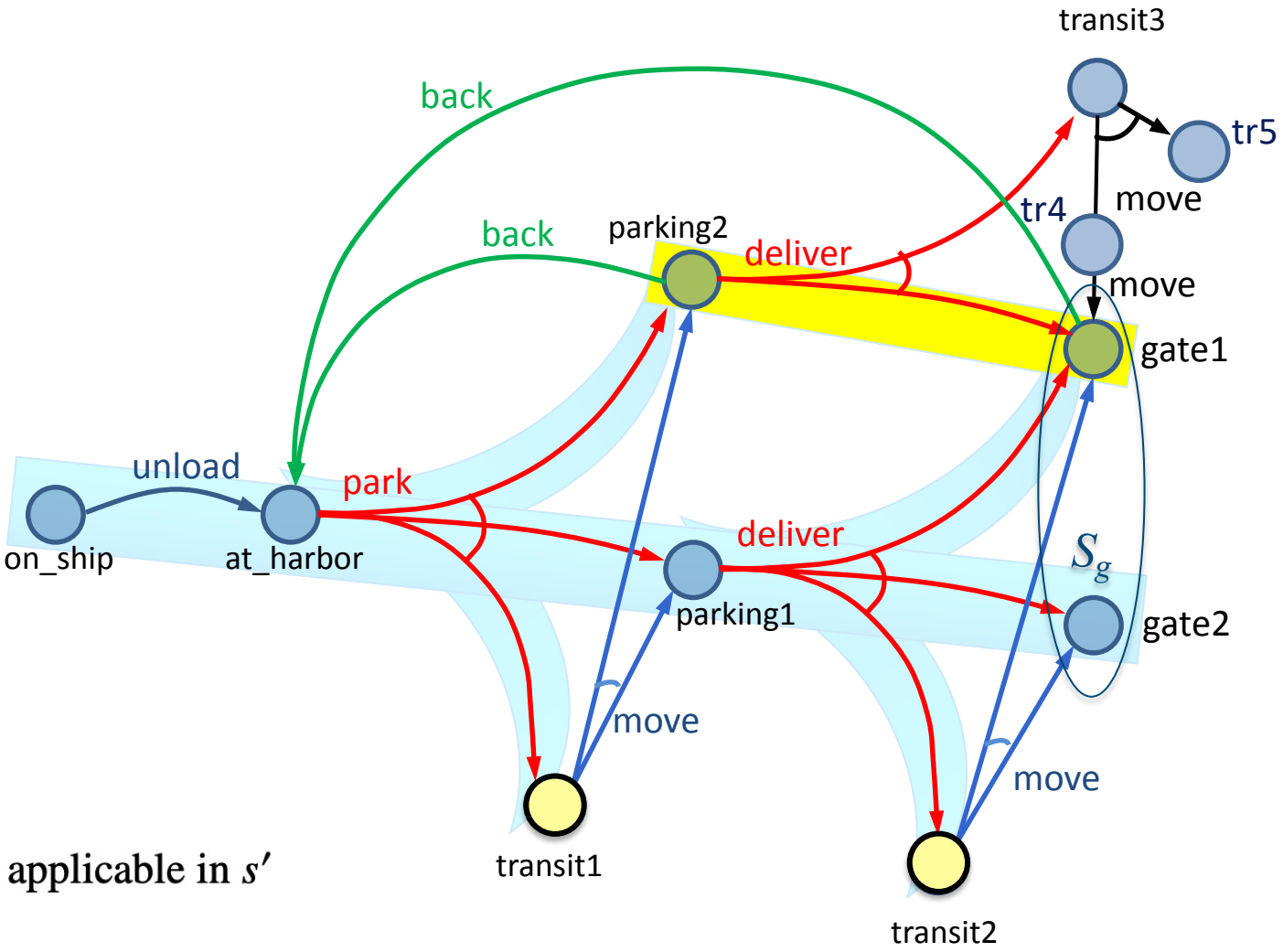

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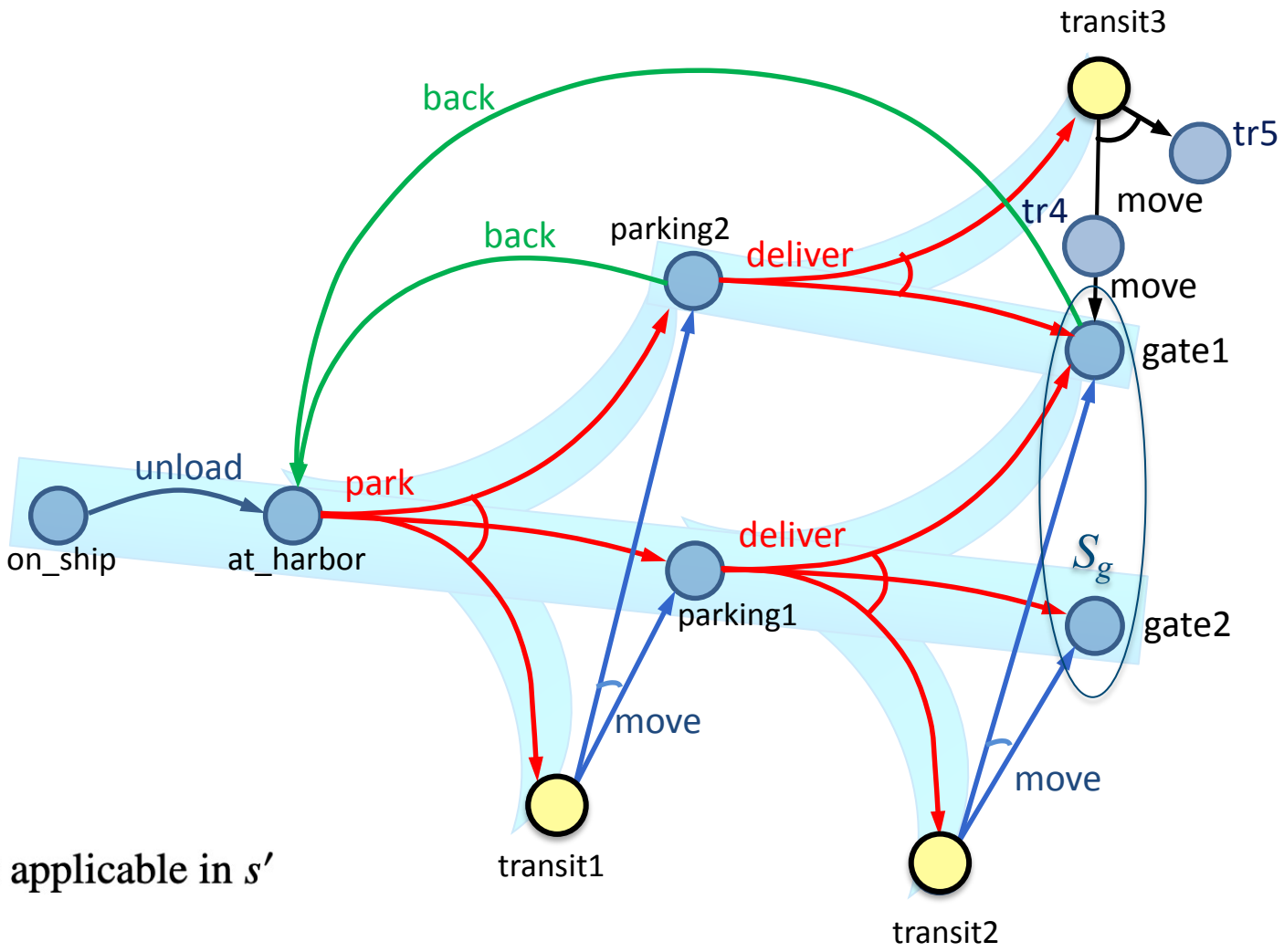

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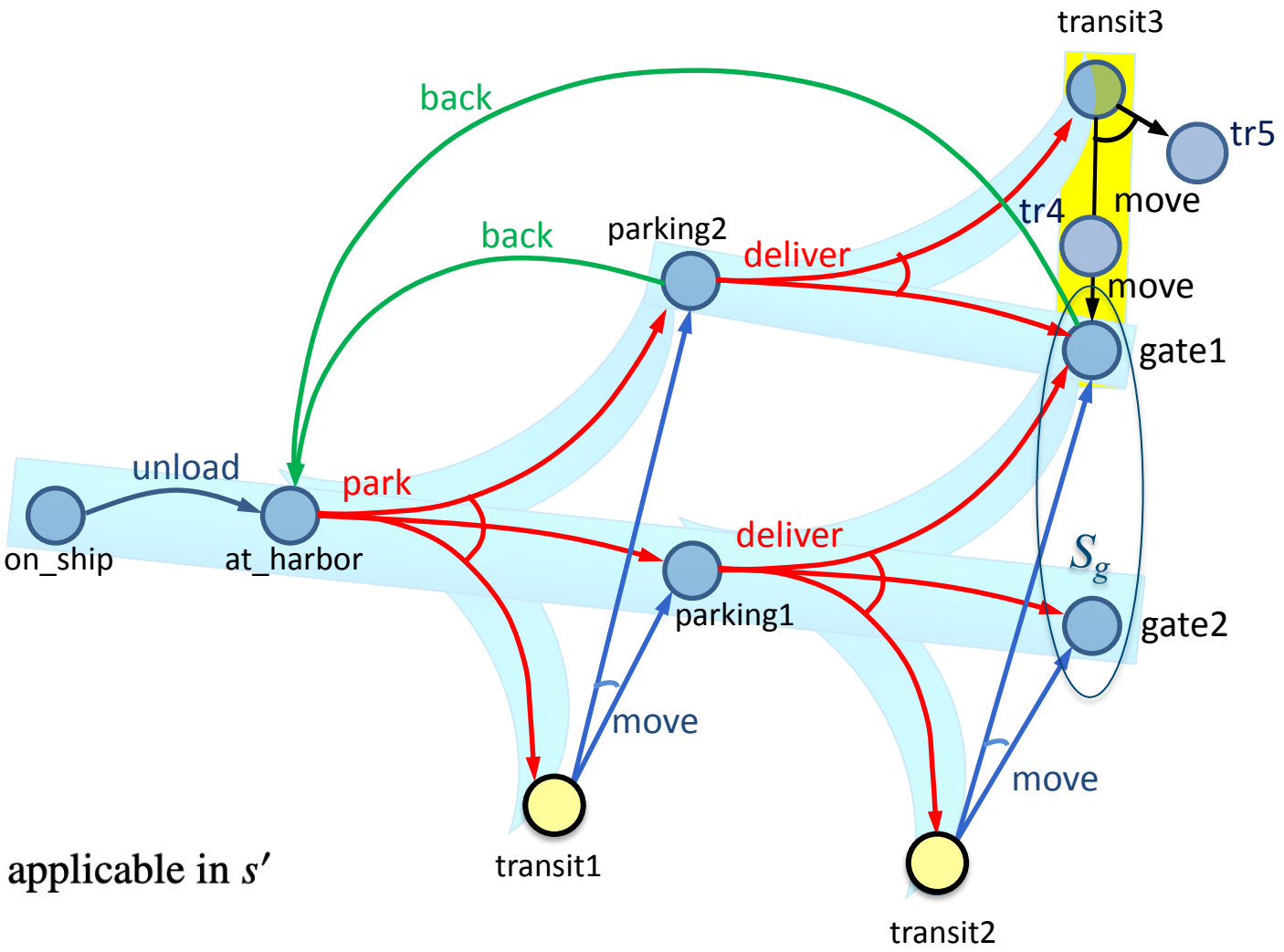

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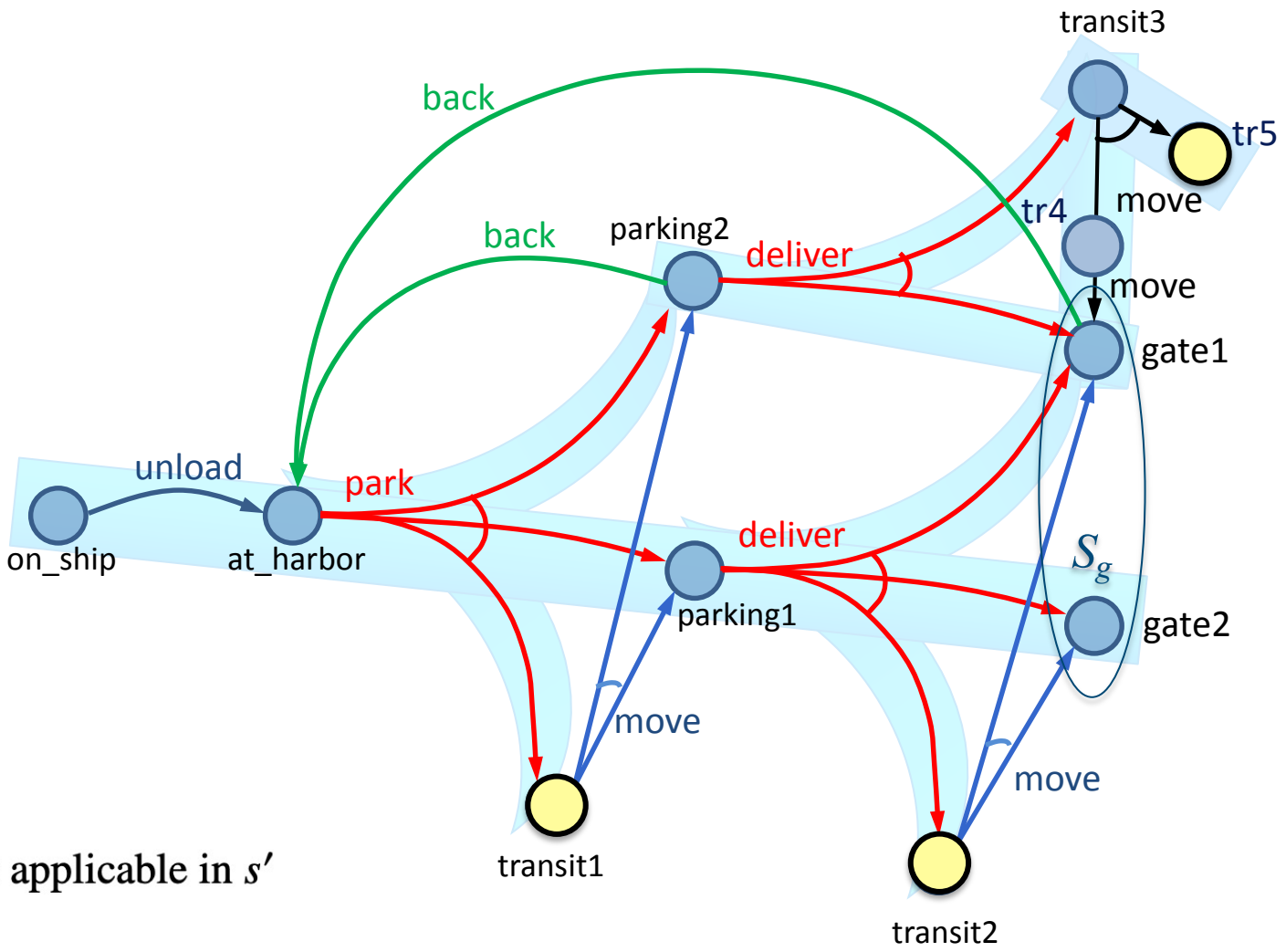

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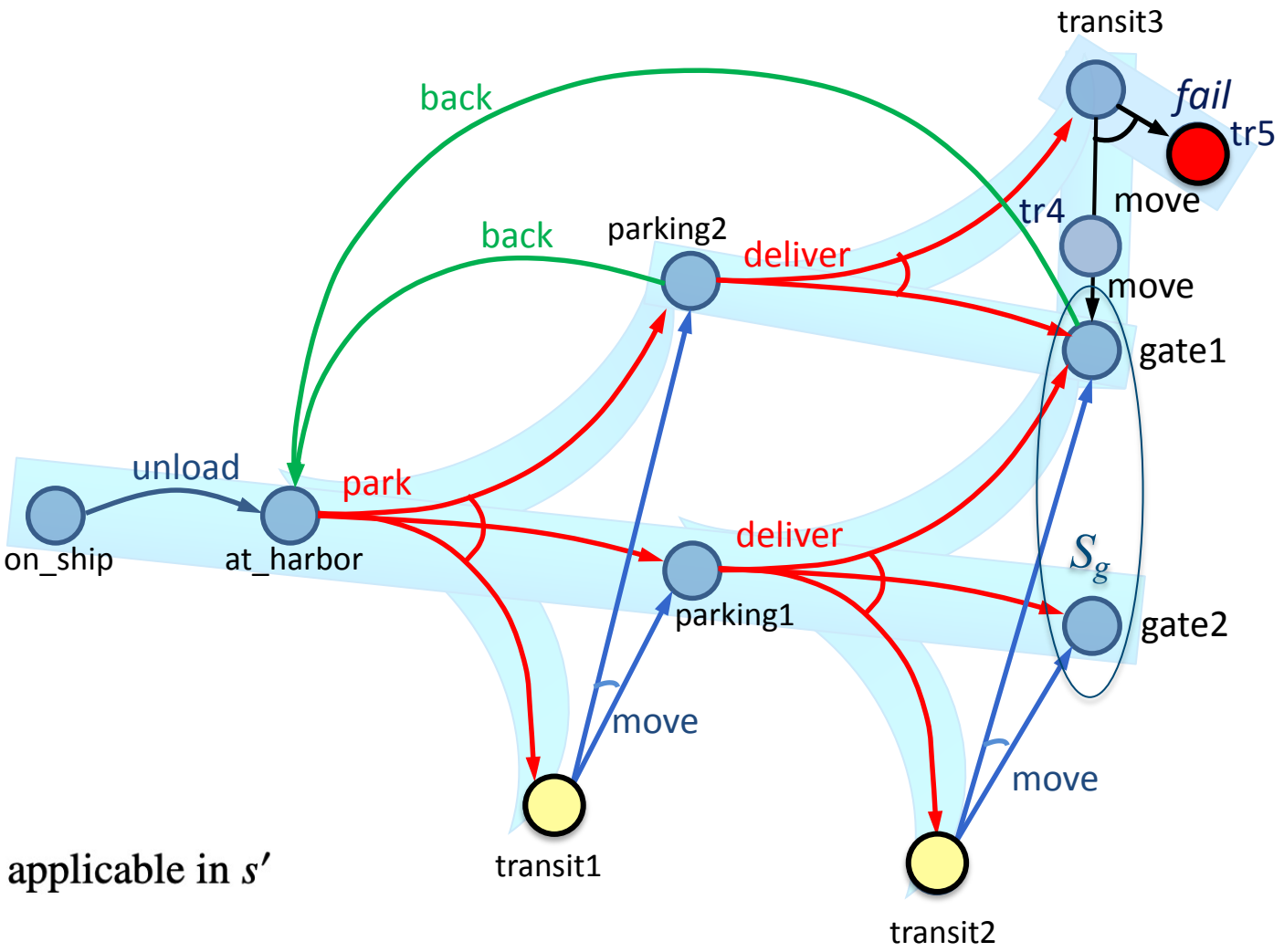

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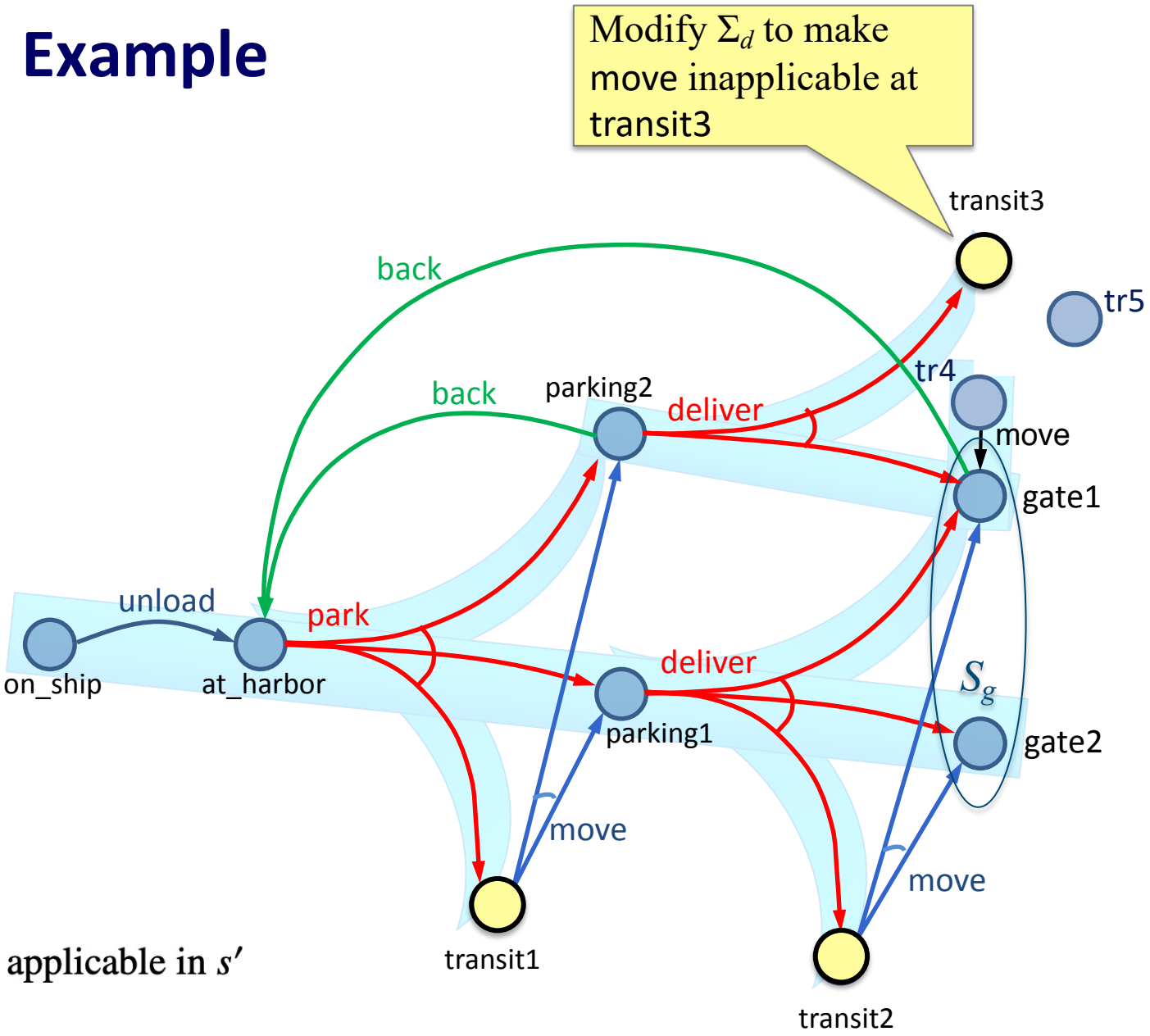

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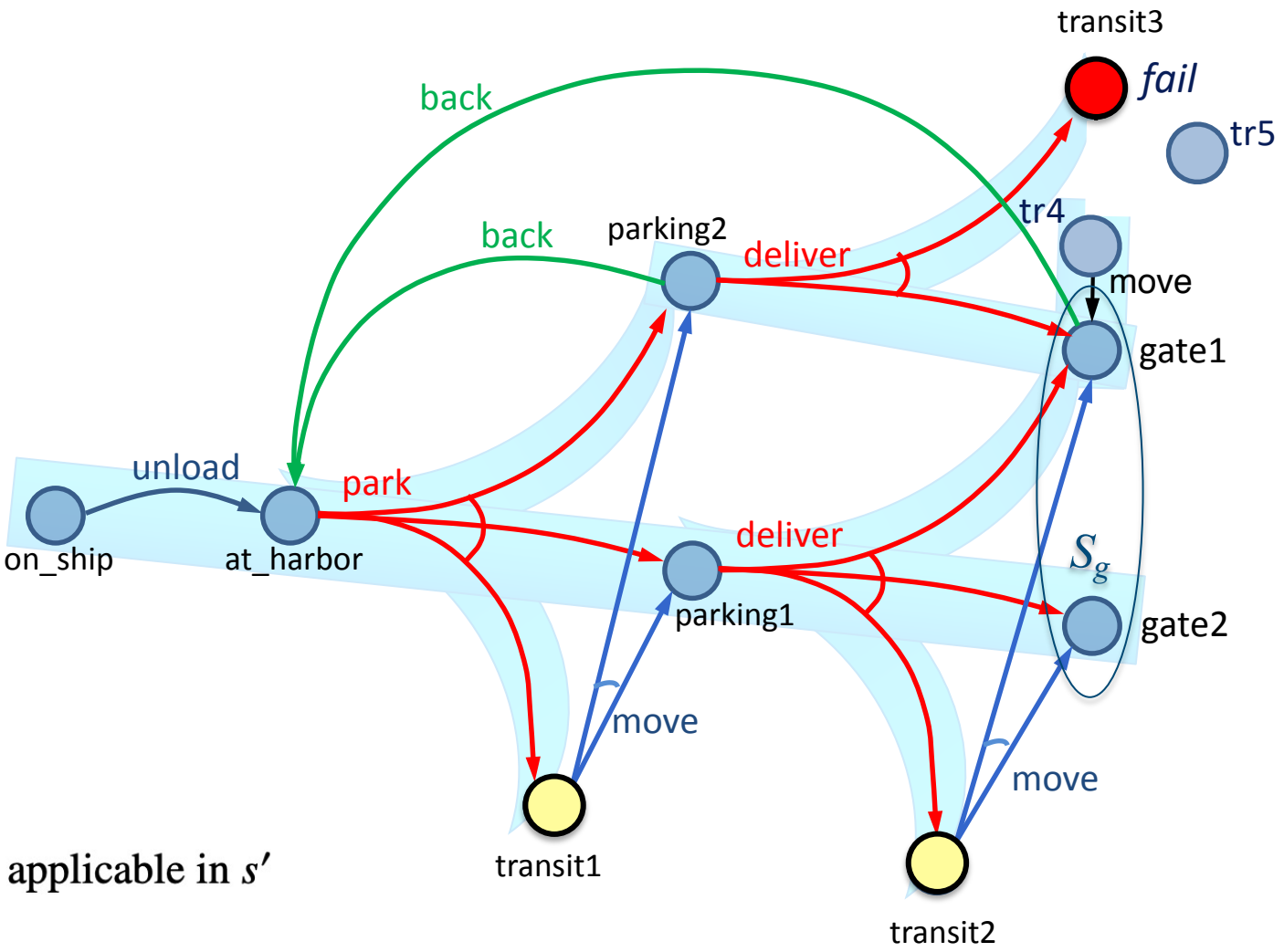

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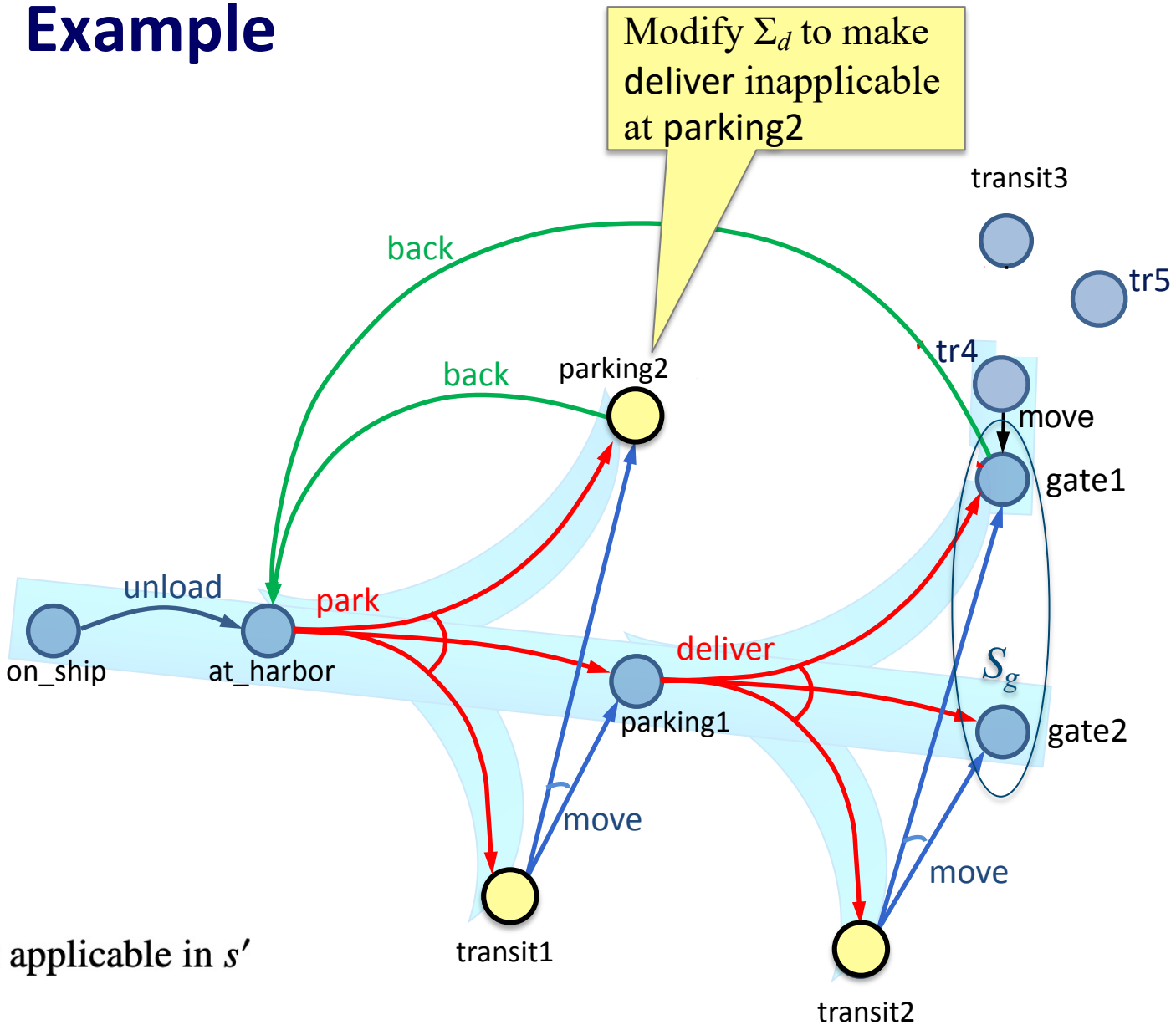

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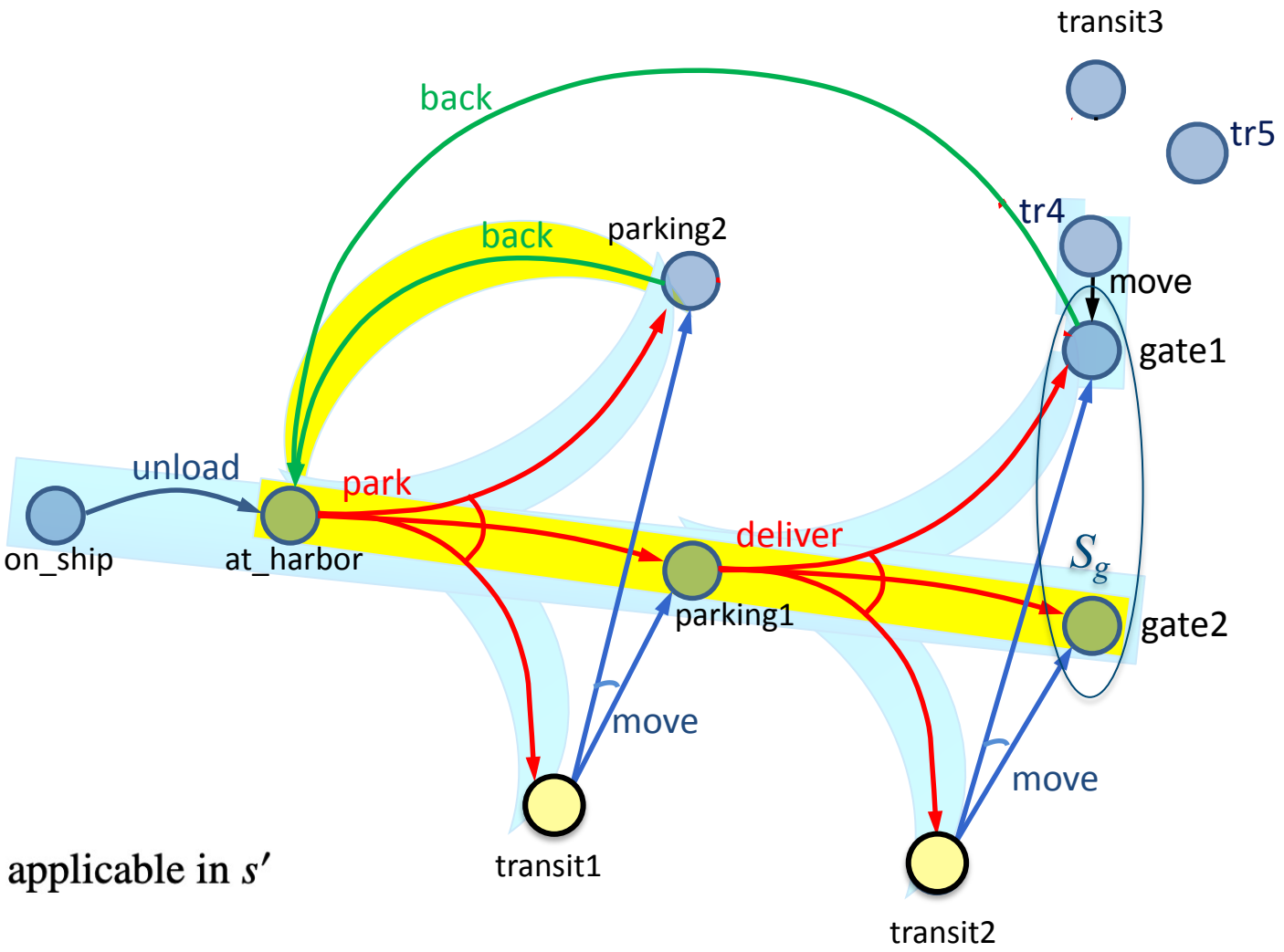

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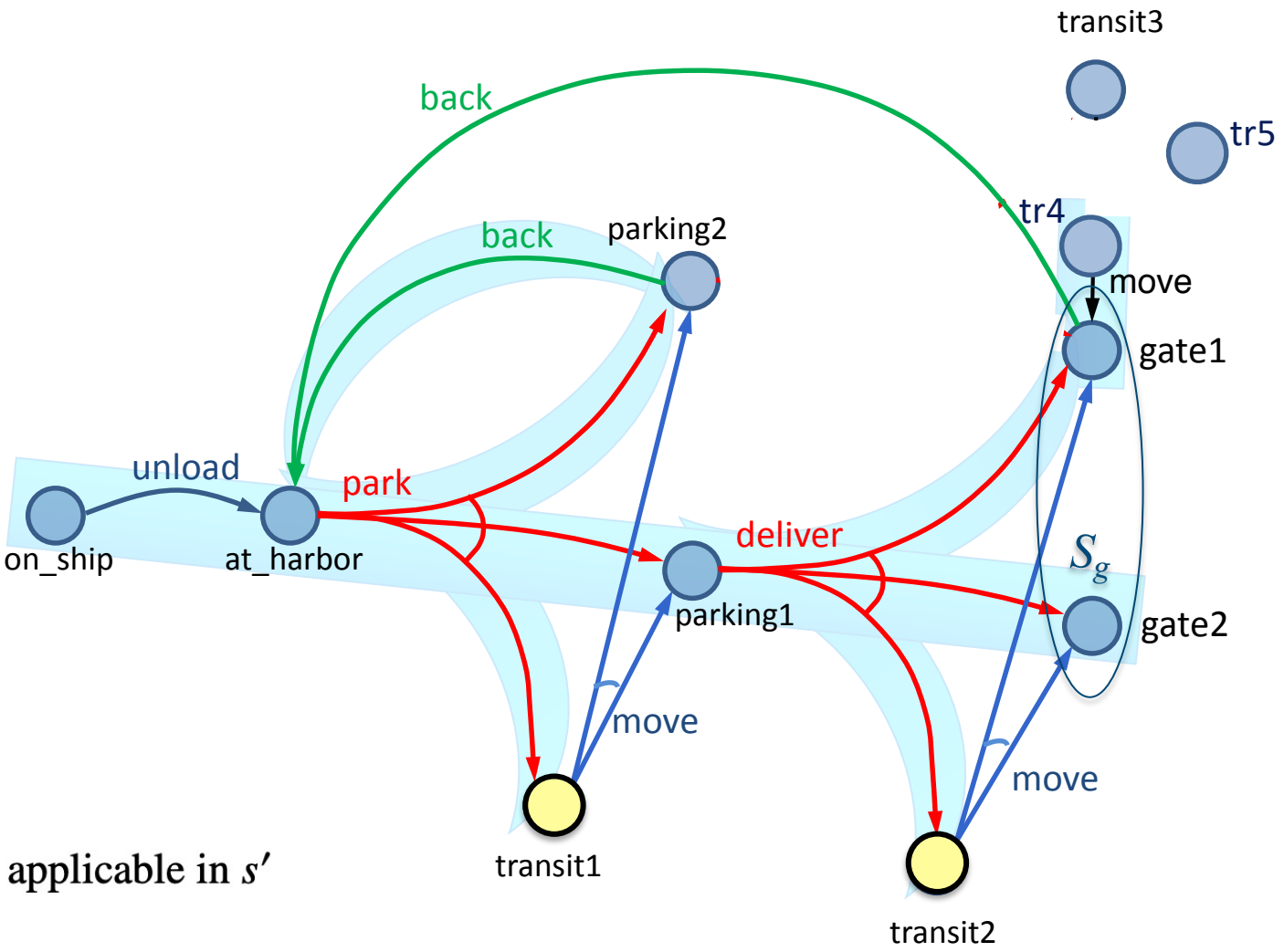

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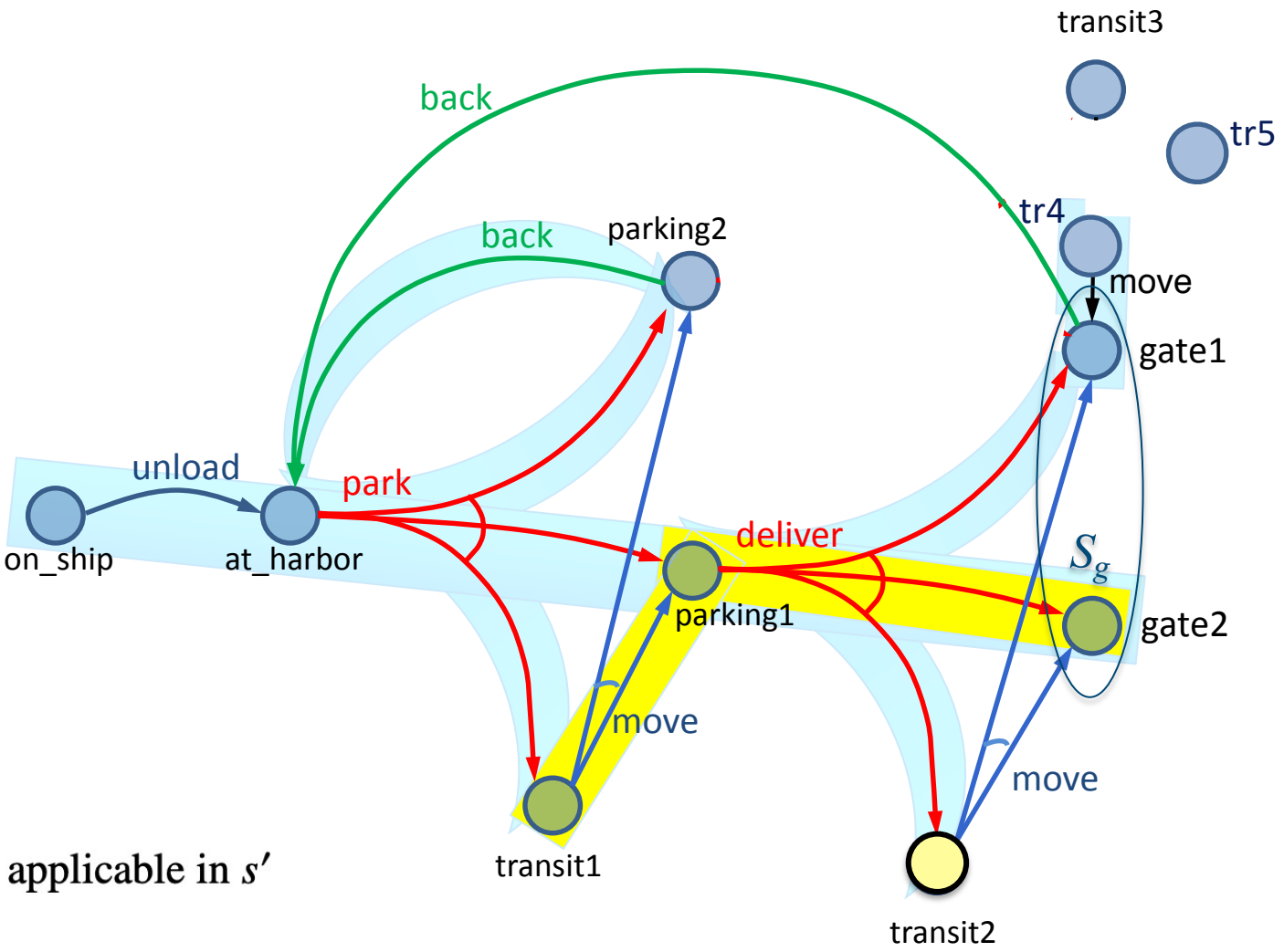

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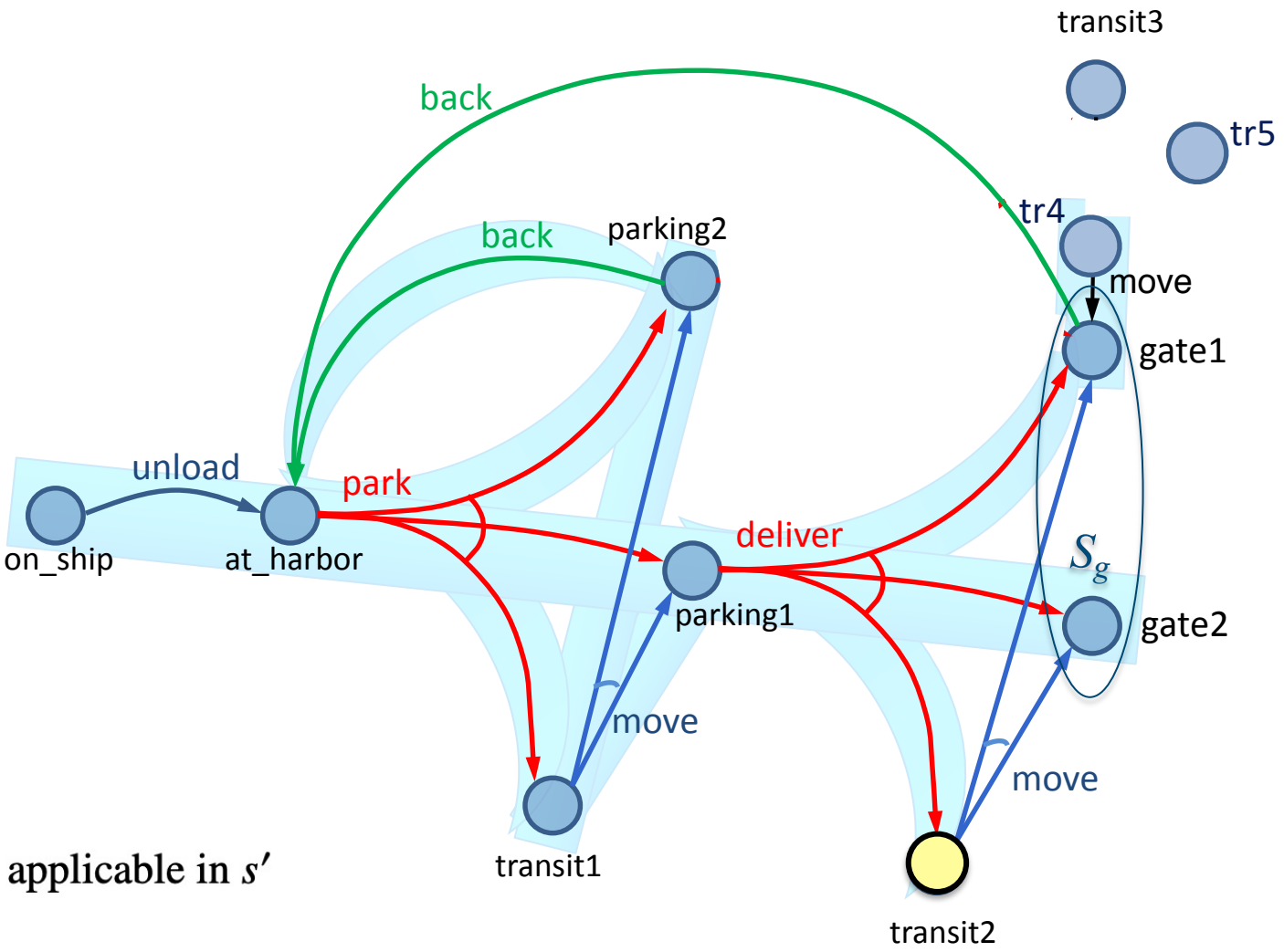

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loop

$Q \leftarrow leaves(s_0, \pi) \setminus S_g$

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 $p' \neq$ failure then do

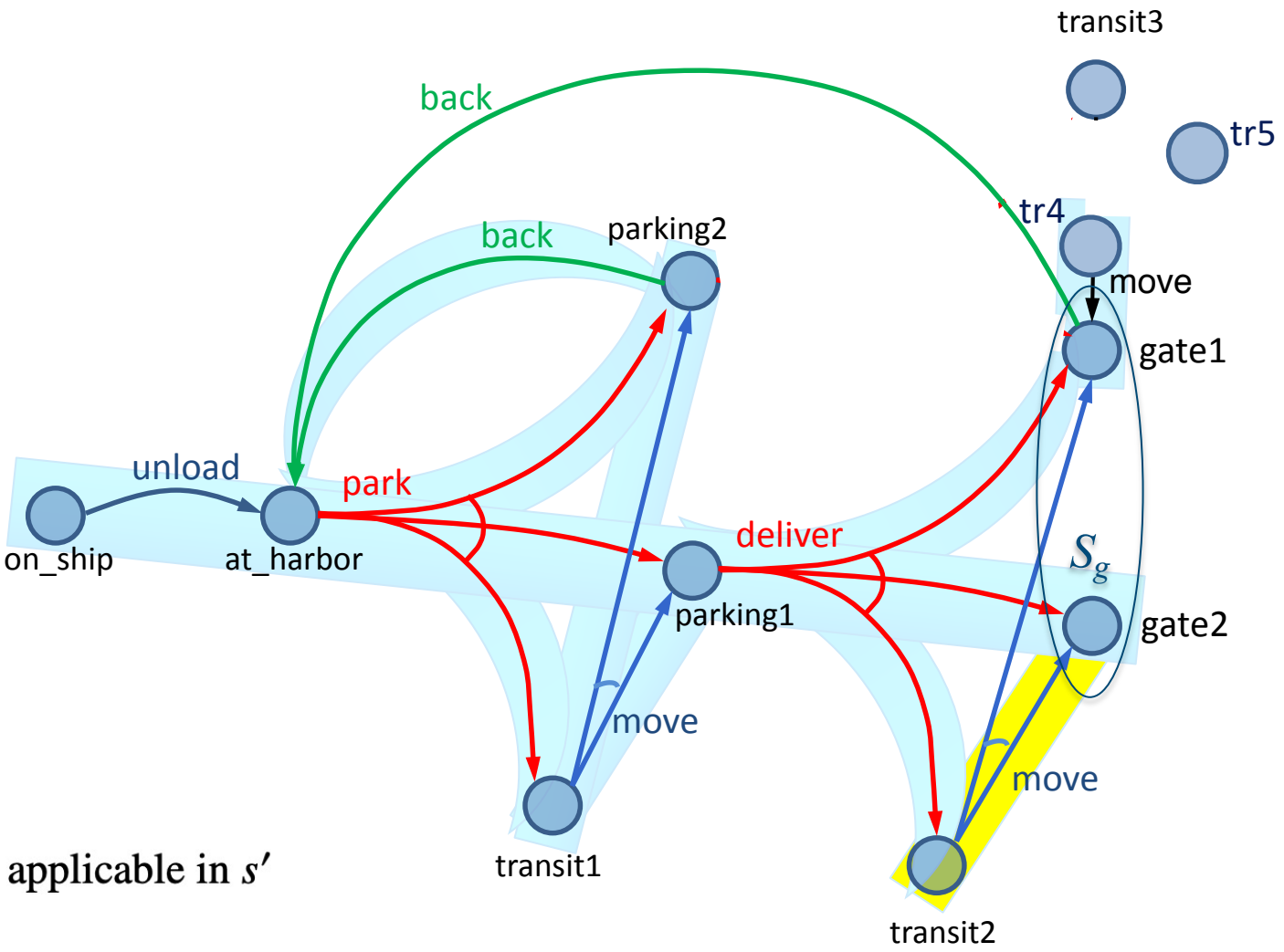
$\pi' \leftarrow$ Plan2policy(p', s)

$\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$

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'



Example

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 $p' \neq$ failure then do

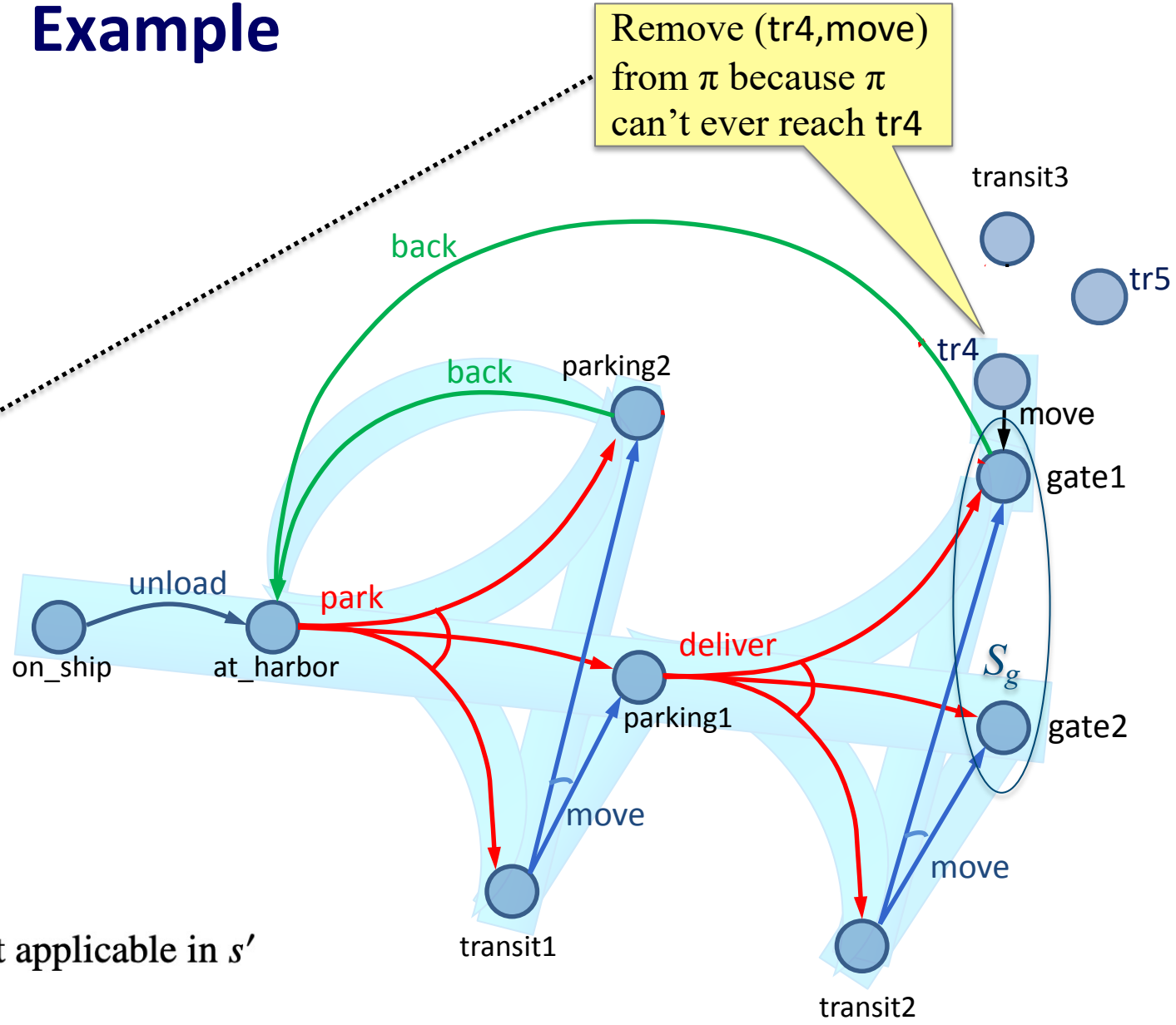
$\pi' \leftarrow$ Plan2policy(p', s)

$\pi \leftarrow \pi \cup \{(s,a) \in \pi' \mid s \notin Domain(\pi)\}$

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'



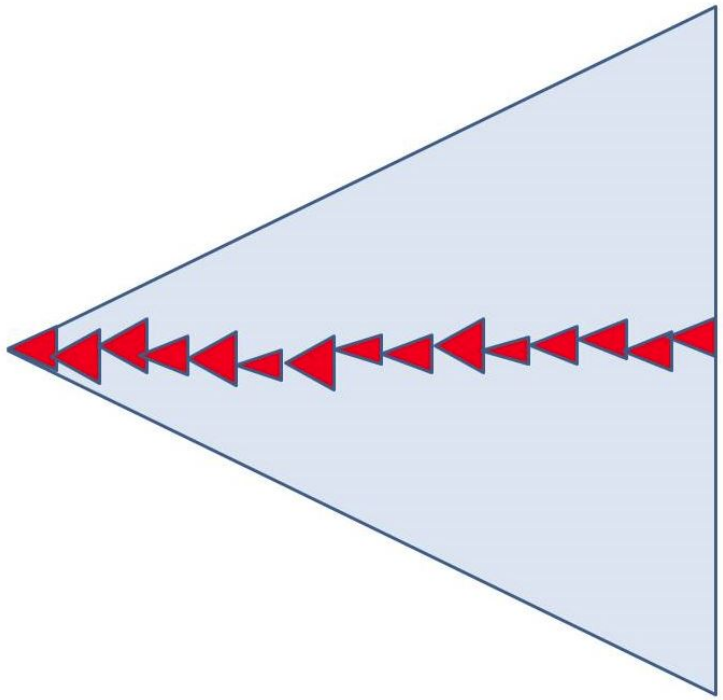
Making Actions Inapplicable

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 $p' \neq$ failure then do
    - $\pi' \leftarrow$ Plan2policy(p', s)
    - $\pi \leftarrow \pi \cup \{(s, a) \in \pi' \mid s \notin Domain(\pi)\}$
  - 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 a inapplicable at s
  - worst-case exponential time
- Better: hash 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 $Applicable(s) \setminus Bad[s]$

12.1.3 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

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 always reachable
- In domains with 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's battery goes dead
    - Applicable actions, but caught in a loop
      - robot goes into a collection of rooms from which there's no exit
  - But partial planning can still make success more likely

Lookahead-Partial-Plan

- Adaptation of Run-Lazy-Lookahead (Chapter 2)
- Lookahead is any planning algorithm that returns a policy π
  - π may be partial or unsafe solution
- Execute π as far as it will go, then call Lookahead again

Lookahead-Partial-Policy(Σ, s_0, S_g)

$s \leftarrow s_0$

while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do

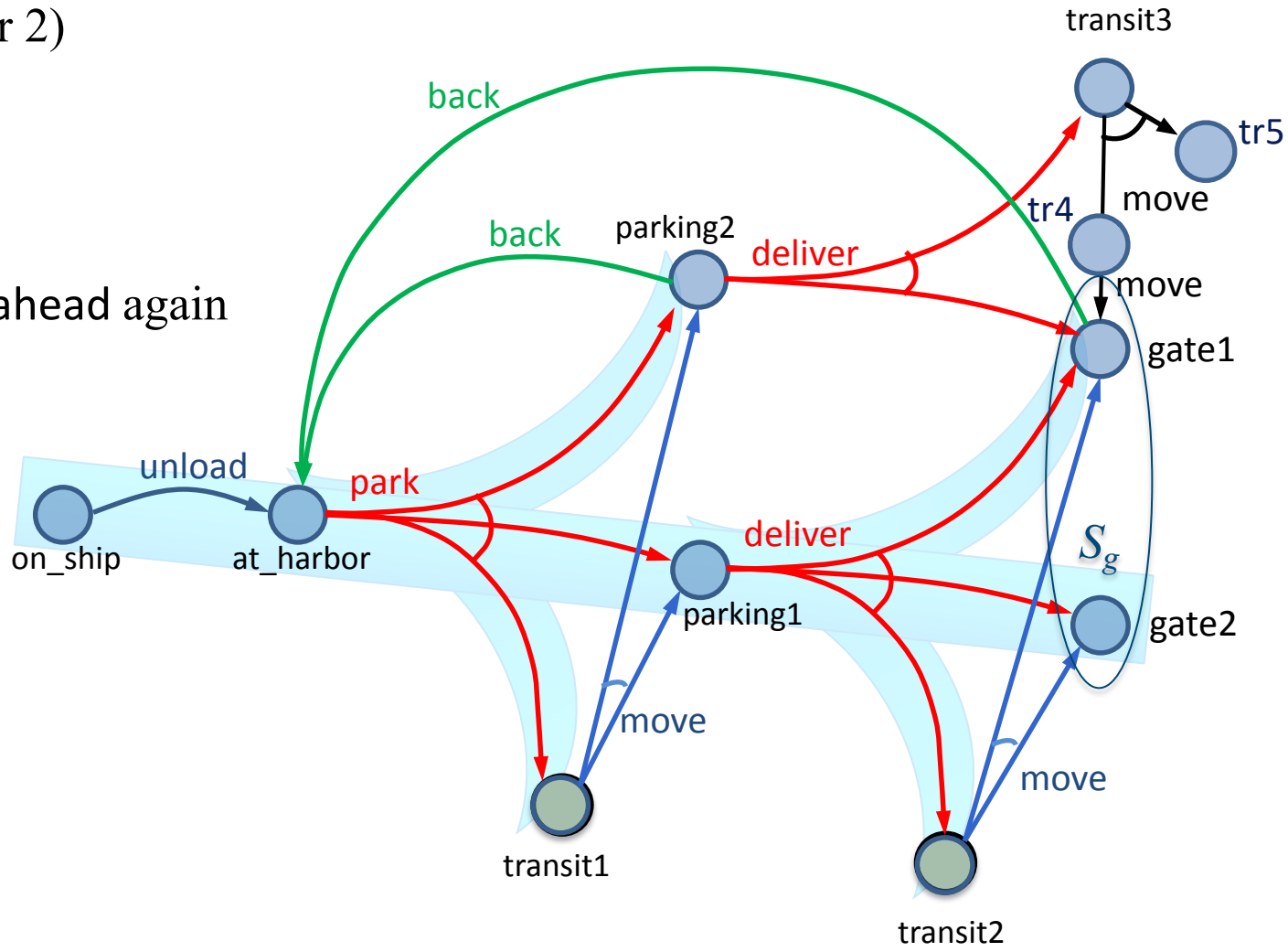
$\pi \leftarrow$ **Lookahead**(s, θ)

if $\pi = \varnothing$ then return failure

else do

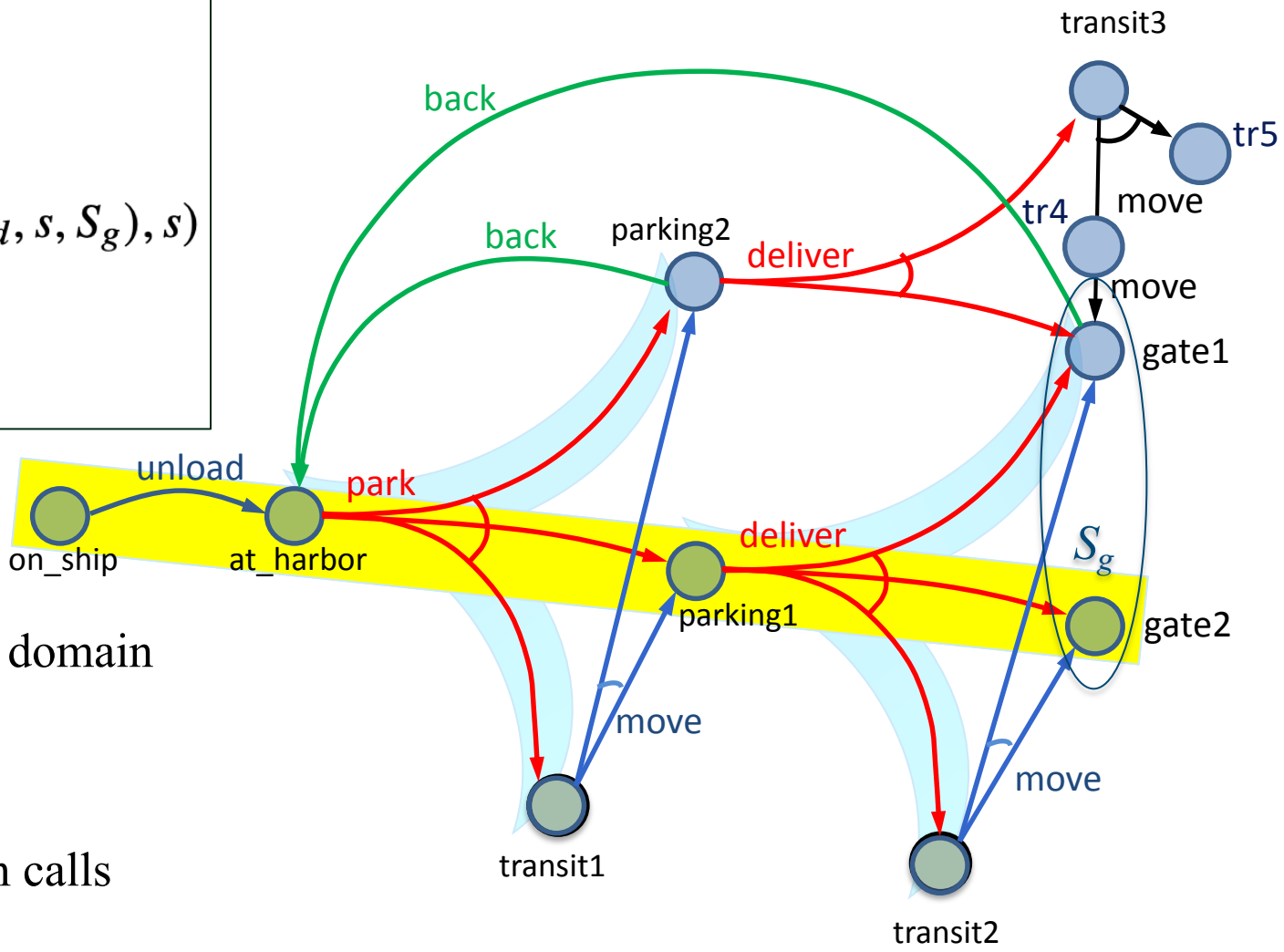
act according to the partial policy π

$s \leftarrow$ observe current state



FS-Replan

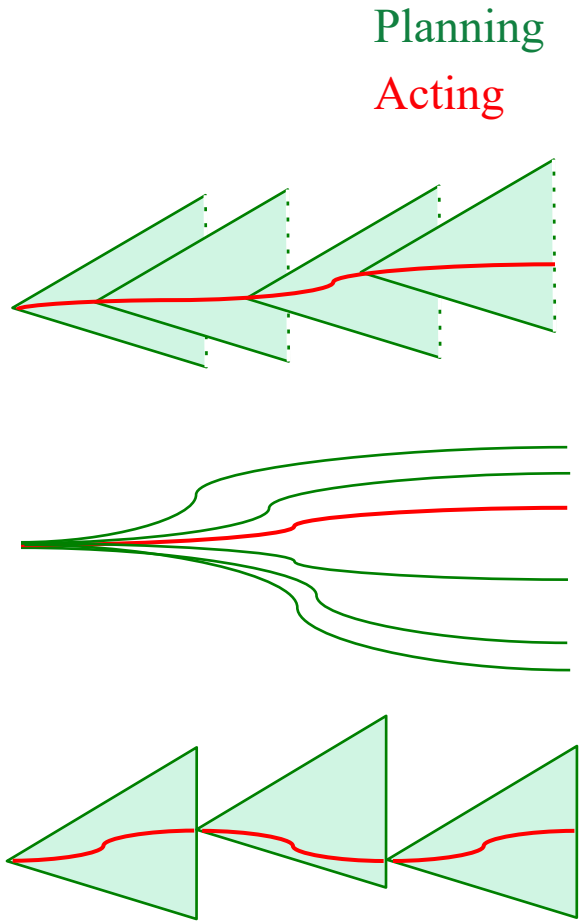
FS-Replan (Σ, s, S_g)
  $\pi_d \leftarrow \varnothing$
  while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do
    if π_d undefined for s then do
      $\pi_d \leftarrow$ Plan2policy(Forward-Search$(\Sigma_d, s, S_g), s)$
      if π_d = failure then return failure
    perform action $\pi_d(s)$
    $s \leftarrow$ observe resulting state



- Adaptation of Lookahead-Partial-Plan
  - Calls classical planner on determinized domain
  - Gets plan, converts converts to policy
    - Unsafe solution
  - Executes policy as far as it will go, then calls classical planner again

More Possibilities for Lookahead

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



More 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 each 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

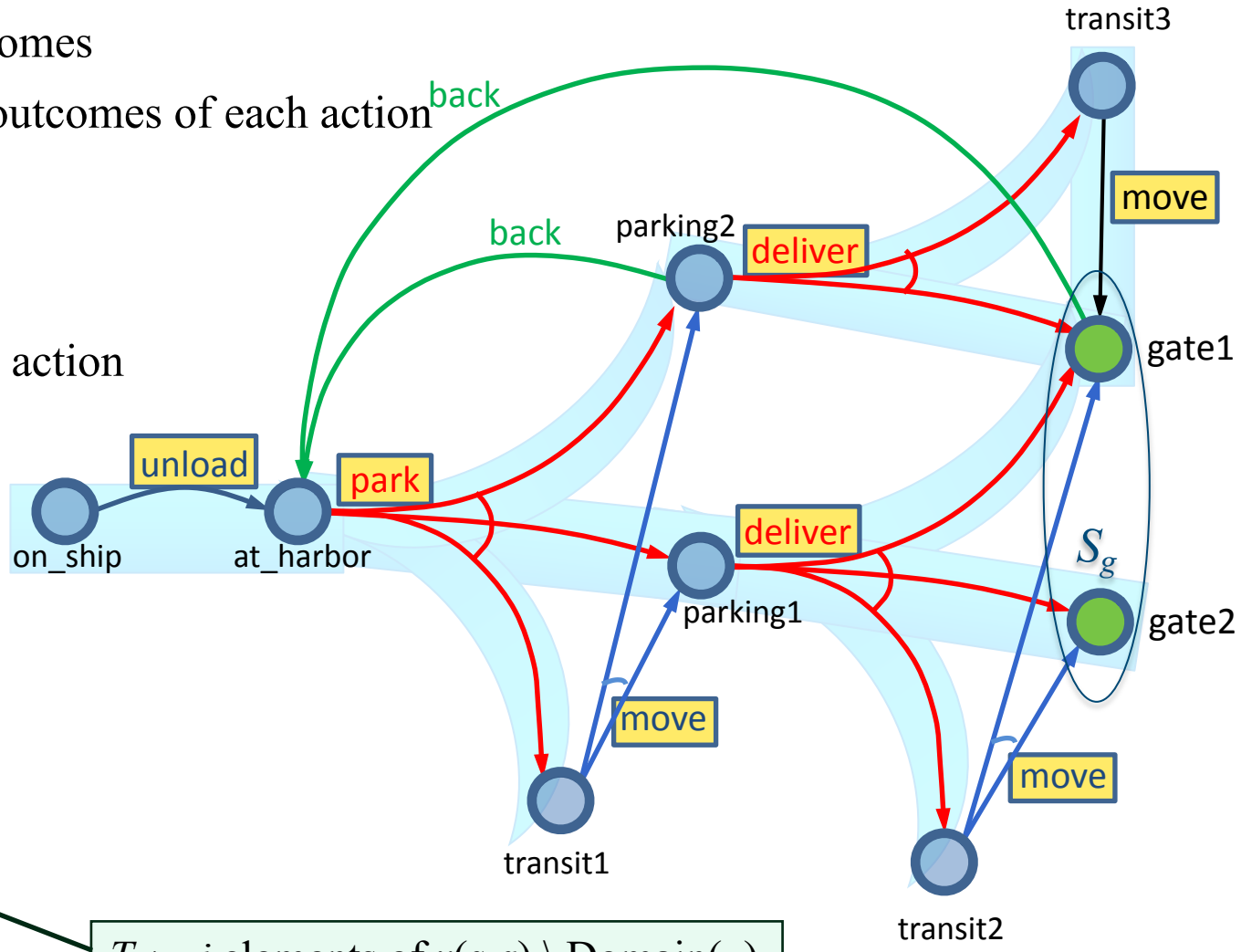
nondeterministically choose $a \in Applicable(s)$

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

~~$Frontier \leftarrow Frontier \cup (\gamma(s, a) \setminus Domain(\pi))$~~

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

return π



$T \leftarrow i$ elements of $\gamma(s,a) \setminus \text{Domain}(\pi)$

$Frontier \leftarrow Frontier \cup T$

Safely Explorable Domains

- *Safely explorable* domain
  - for every state s, at least one goal state is reachable from s

- For Lookahead, suppose we use Lookahead-Partial-Plan or FS-Replan
  - Then Lookahead never returns failure
- Every "fair" execution will eventually reach a goal

Poll: Suppose we just choose a random action each time. Is every "fair" execution guaranteed to reach a goal?

Min-Max LRTA*

MinMax LRTA* (Σ, s_0, S_g)

$s \leftarrow s_0$

while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do

$a \leftarrow \text{argmin}_{a \in Applicable(s)} \max_{s' \in \gamma(s,a)} h(s')$

$h(s) \leftarrow \max\{h(s), \text{cost}(s,a) + \max_{s' \in \gamma(s,a)} h(s')\}$

perform action a

$s \leftarrow$ the current state

- loop
  - choose an action a that (according to h) has optimal worst-case cost
    - Update $h(s)$ to use a's worst-case cost
    - Perform a

- In safely explorable domains with no "unfair" executions, guaranteed to reach a goal

Example

MinMax LRTA* (Σ, s_0, S_g)

$s \leftarrow s_0$

while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do

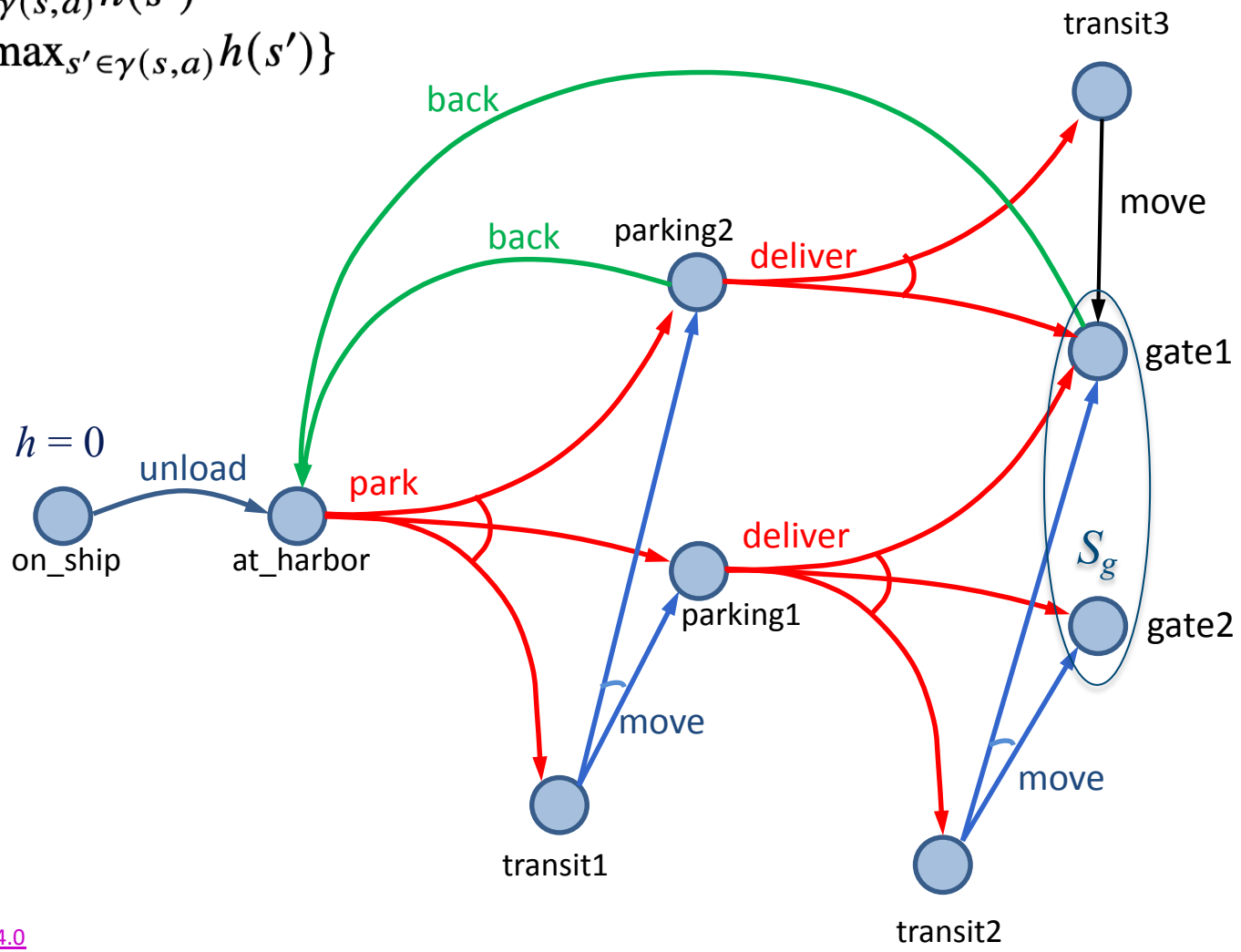
$a \leftarrow \text{argmin}_{a \in Applicable(s)} \max_{s' \in \gamma(s,a)} h(s')$

$h(s) \leftarrow \max\{h(s), \text{cost}(s,a) + \max_{s' \in \gamma(s,a)} h(s')\}$

perform action a

$s \leftarrow$ the current state

- Suppose that initially, $h(s) = 0$ for every s



Example

MinMax LRTA* (Σ, s_0, S_g)

$s \leftarrow s_0$

while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do

$a \leftarrow \text{argmin}_{a \in Applicable(s)} \max_{s' \in \gamma(s,a)} h(s')$

$h(s) \leftarrow \max\{h(s), \text{cost}(s,a) + \max_{s' \in \gamma(s,a)} h(s')\}$

perform action a

$s \leftarrow$ the current state

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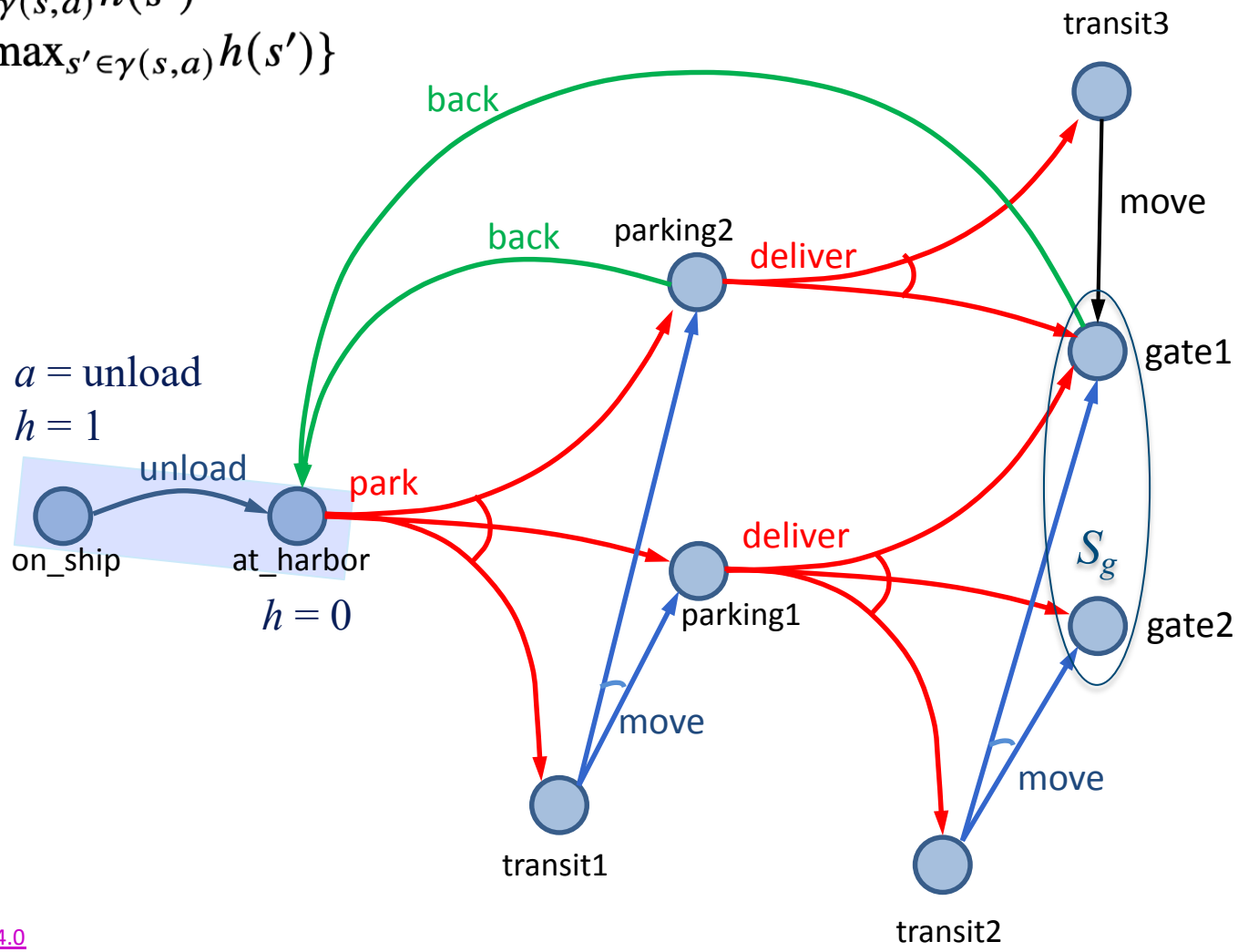


Example

MinMax LRTA* (Σ, s_0, S_g)

$s \leftarrow s_0$

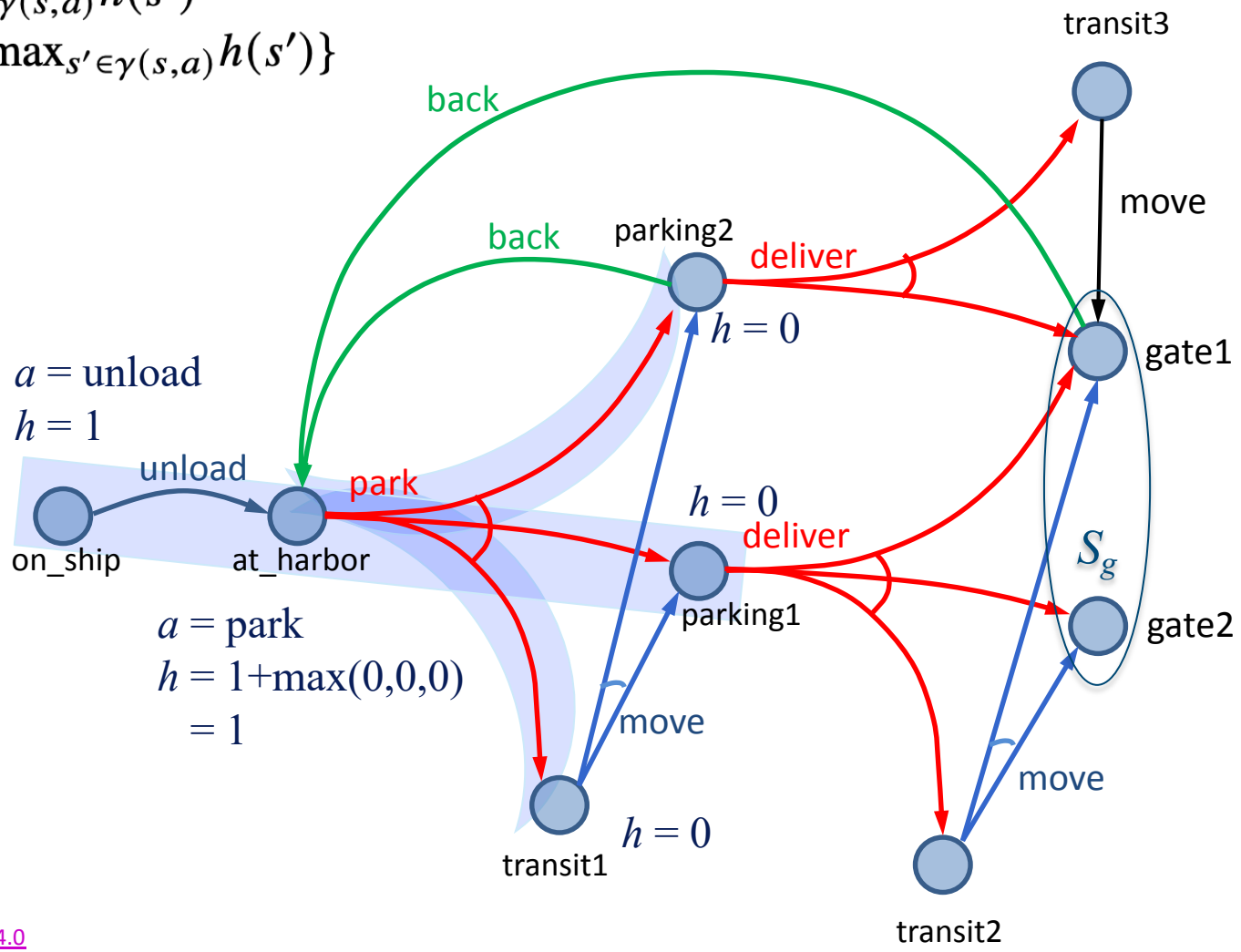
while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do

$a \leftarrow \text{argmin}_{a \in Applicable(s)} \max_{s' \in \gamma(s,a)} h(s')$

$h(s) \leftarrow \max\{h(s), \text{cost}(s,a) + \max_{s' \in \gamma(s,a)} h(s')\}$

perform action a

$s \leftarrow$ the current state



Example

MinMax LRTA* (Σ, s_0, S_g)

$s \leftarrow s_0$

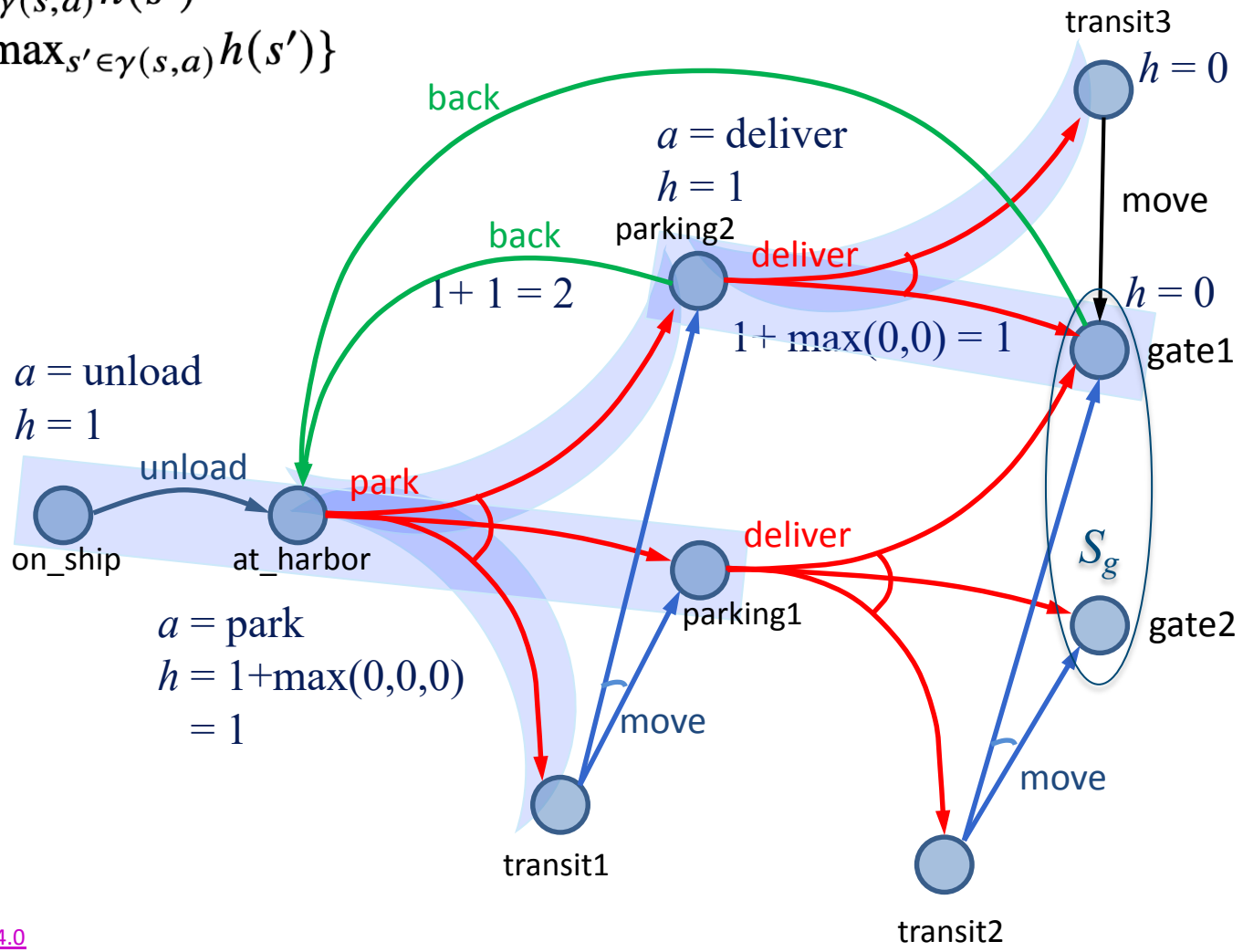
while $s \notin S_g$ and $Applicable(s) \neq \varnothing$ do

$a \leftarrow \text{argmin}_{a \in Applicable(s)} \max_{s' \in \gamma(s,a)} h(s')$

$h(s) \leftarrow \max\{h(s), \text{cost}(s,a) + \max_{s' \in \gamma(s,a)} h(s')\}$

perform action a

$s \leftarrow$ the current state



Summary

- Types of solutions: unsafe, safe (acyclic, cyclic)
- Find-Solution,
- Find-Acyclic-Solution
- Find-Safe-Solution
- Guided-Find-Safe-Solution
  - call Find-Solution to get an unsafe solution
  - call Find-Solution again on the leaves
  - if dead-ends are encountered, modify actions that lead to them
- Find-Safe-Solution-by-Determinization
  - Like Guided-Find-Safe-Solution, but call classical planner on determinized domain, convert plan into policy
- 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*

