Advanced Topics Data Science and AI

Automated Planning and Acting

Nondeterministic Models

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2. Planning and Acting with **Refinement** Methods
3. Planning and Acting with **Temporal** Models
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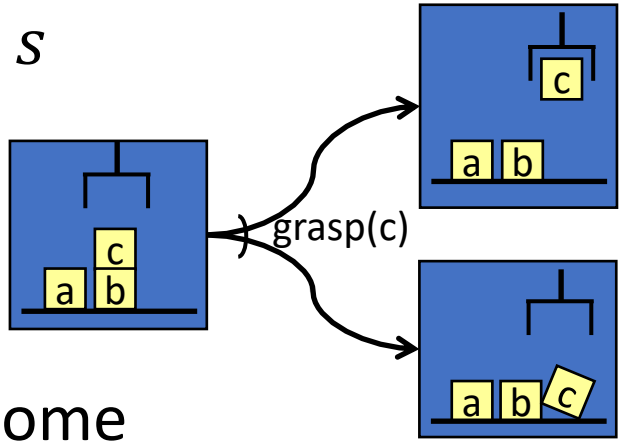
   b. And/Or Graph Search
   c. Determinisation
   d. Online Approaches
5. Making Simple Decisions
6. Making Complex Decisions
7. Planning and Acting with **Probabilistic** Models
8. Provably Beneficial AI

- Other: open world, perceiving, learning
  - If time permits

Motivation

- We have 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

Outline per the Book

5.2 Planning Problem

- Planning domains
- Plans as policies
- Planning problems and solutions

5.3 And/Or Graph Search

- Planning by forward search

5.5 Determinisation Techniques

- Guided planning for safe solutions
- Planning for safe solutions by determinisation

5.6 Online Approaches

- Lookahead
- Lookahead by Determinisation
- Lookahead with a bounded number of steps

Nondeterministic Planning Domains

- Planning domain: 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 $\gamma(s, a) \neq \emptyset$
- $Applicable(s) = \{\text{all actions applicable in } s\} = \{a \in A | \gamma(s, a) \neq \emptyset\}$
- One action representation:
  - n mutually exclusive "effects" lists
  - Problem: n may be combinatorially large
    - Suppose a can cause any possible combination of effects $e_1, e_2, \ldots, e_k$
    - Need eff_1, eff_2, …, eff_{2^k}
      - One for for each combination
    - Section 5.4: a way to alleviate this
  - For now, ignore most of that
    - states, actions ⇔ nodes, edges in a graph

$a(z_1, \ldots, z_k)$

pre: $p_1, \ldots, p_m$

eff_1: $e_{11}, e_{12}, \ldots$

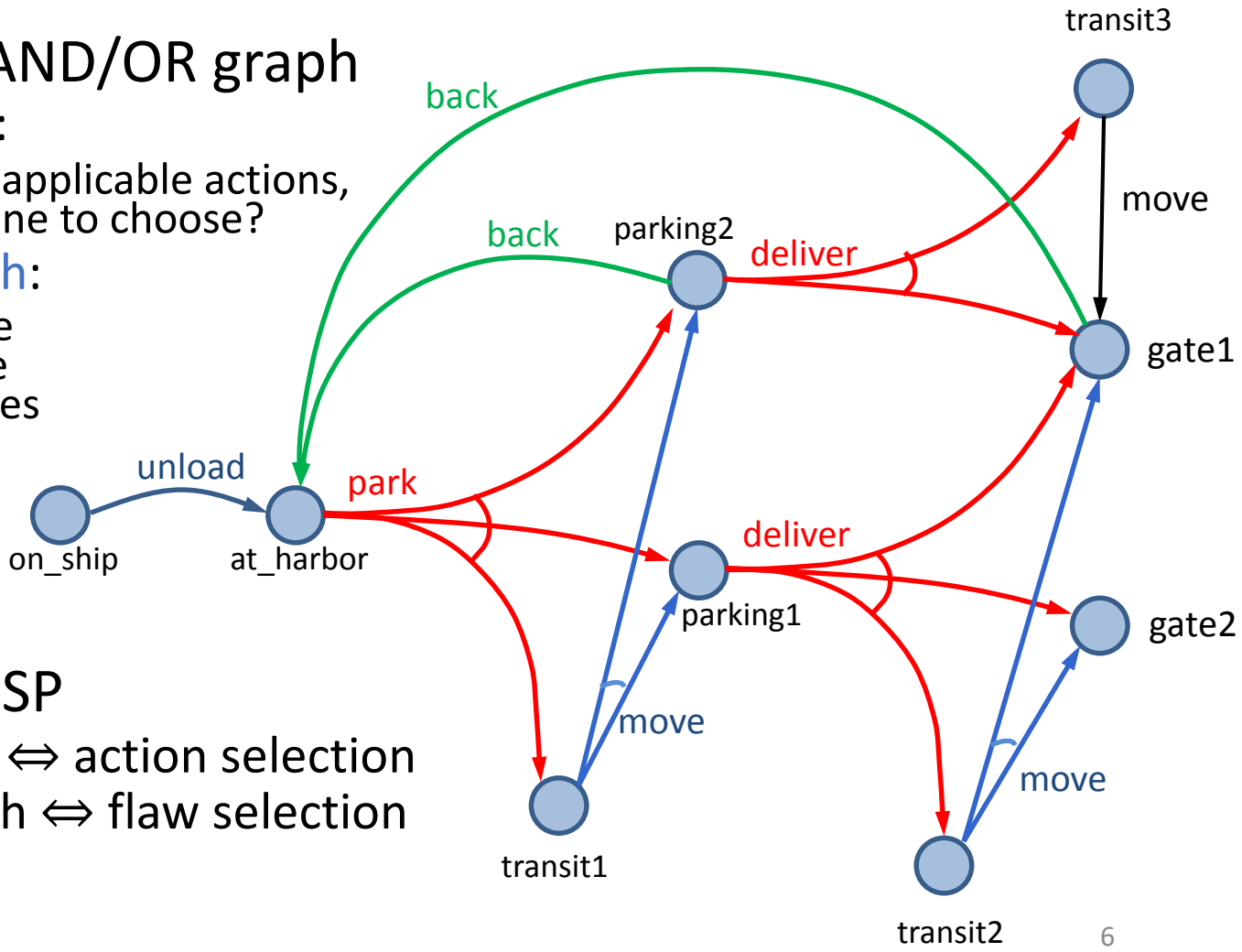
eff_2: $e_{21}, e_{22}, \ldots$

⋮

eff_n: $e_{n1}, e_{n2}, \ldots$

Nondeterministic Planning Domains

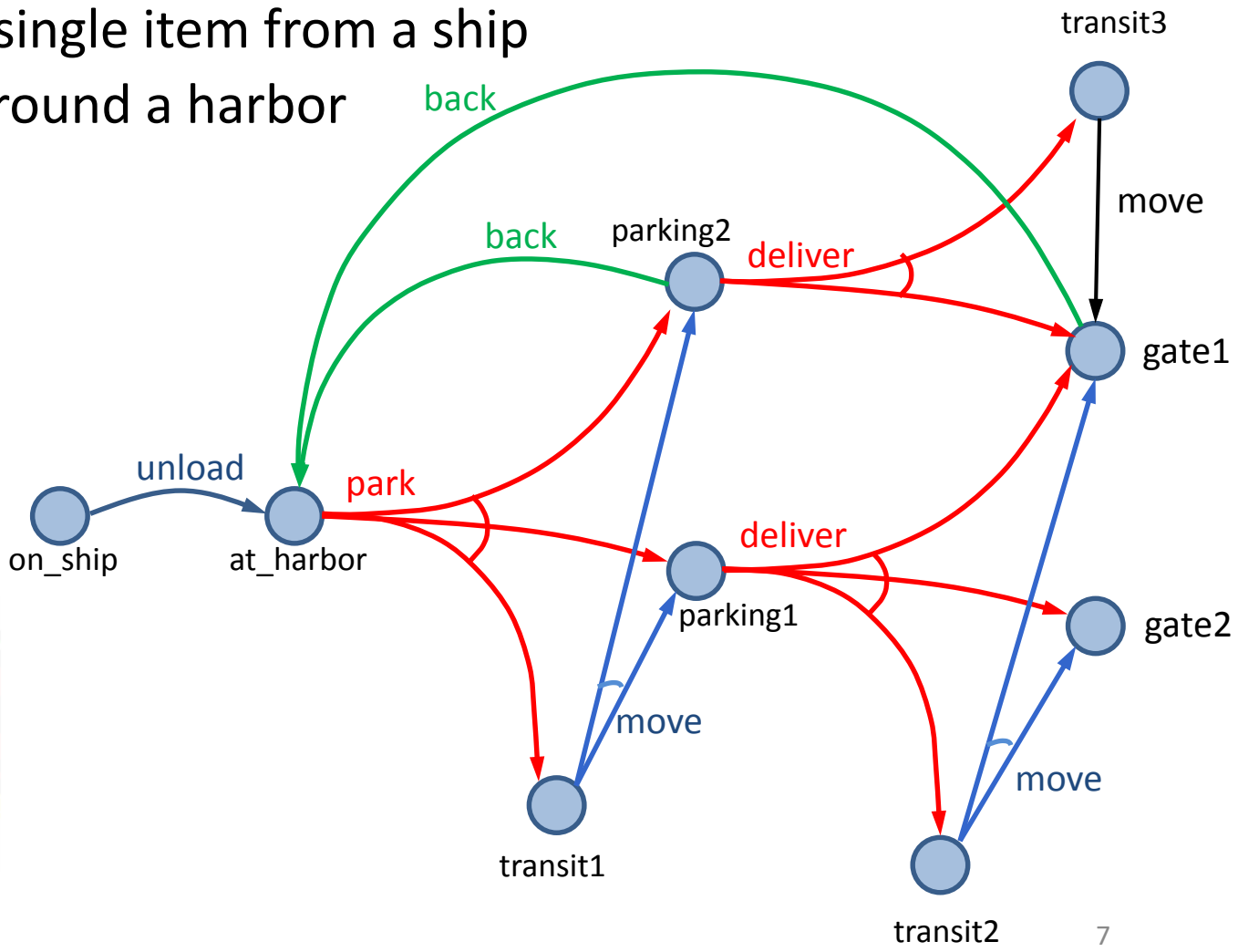
- For deterministic planning problems, search space was a graph
- Now it's an AND/OR graph
  - OR branch:
    - Several applicable actions, which one to choose?
  - AND branch:
    - Multiple possible outcomes
    - Must handle all of them



- Analogy to PSP
  - *OR* branch ⇔ action selection
  - *AND* branch ⇔ flaw selection

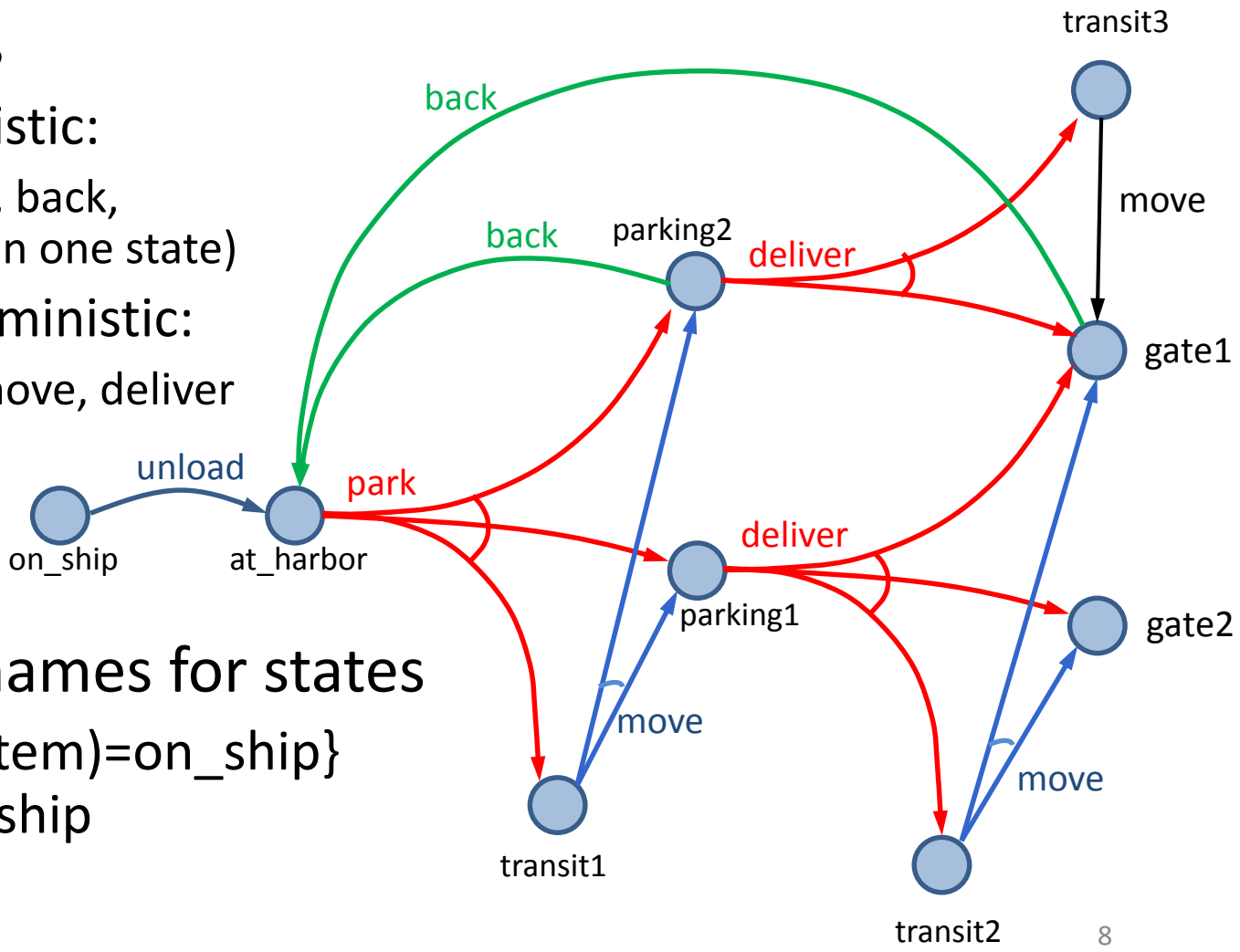
Example

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



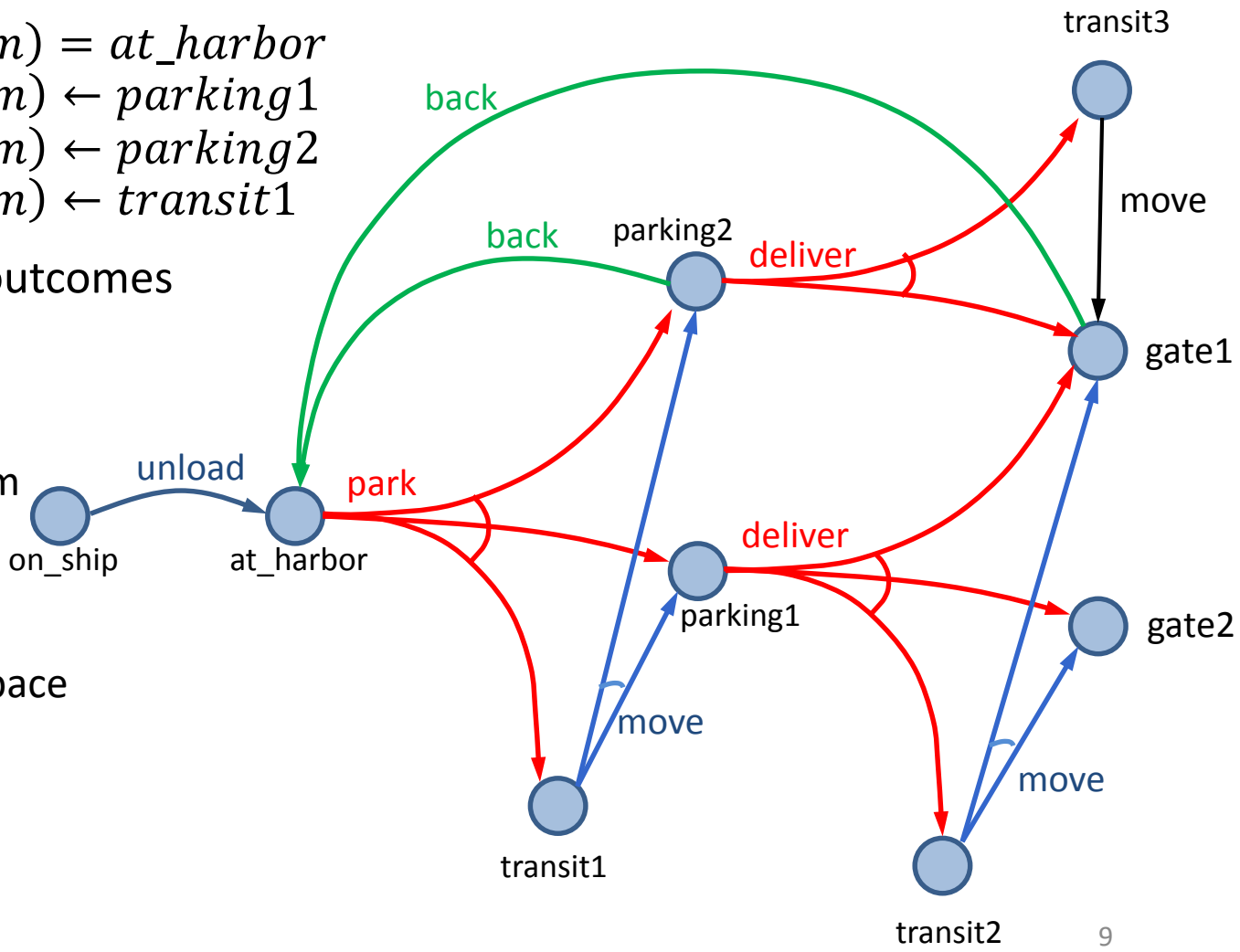
Example

- One state variable: pos(item)
- Five actions
  - Deterministic:
    - unload, back,
      (move in one state)
  - Nondeterministic:
    - park, move, deliver
- Simplified names for states
  - For {pos(item)=on_ship}
    write on_ship



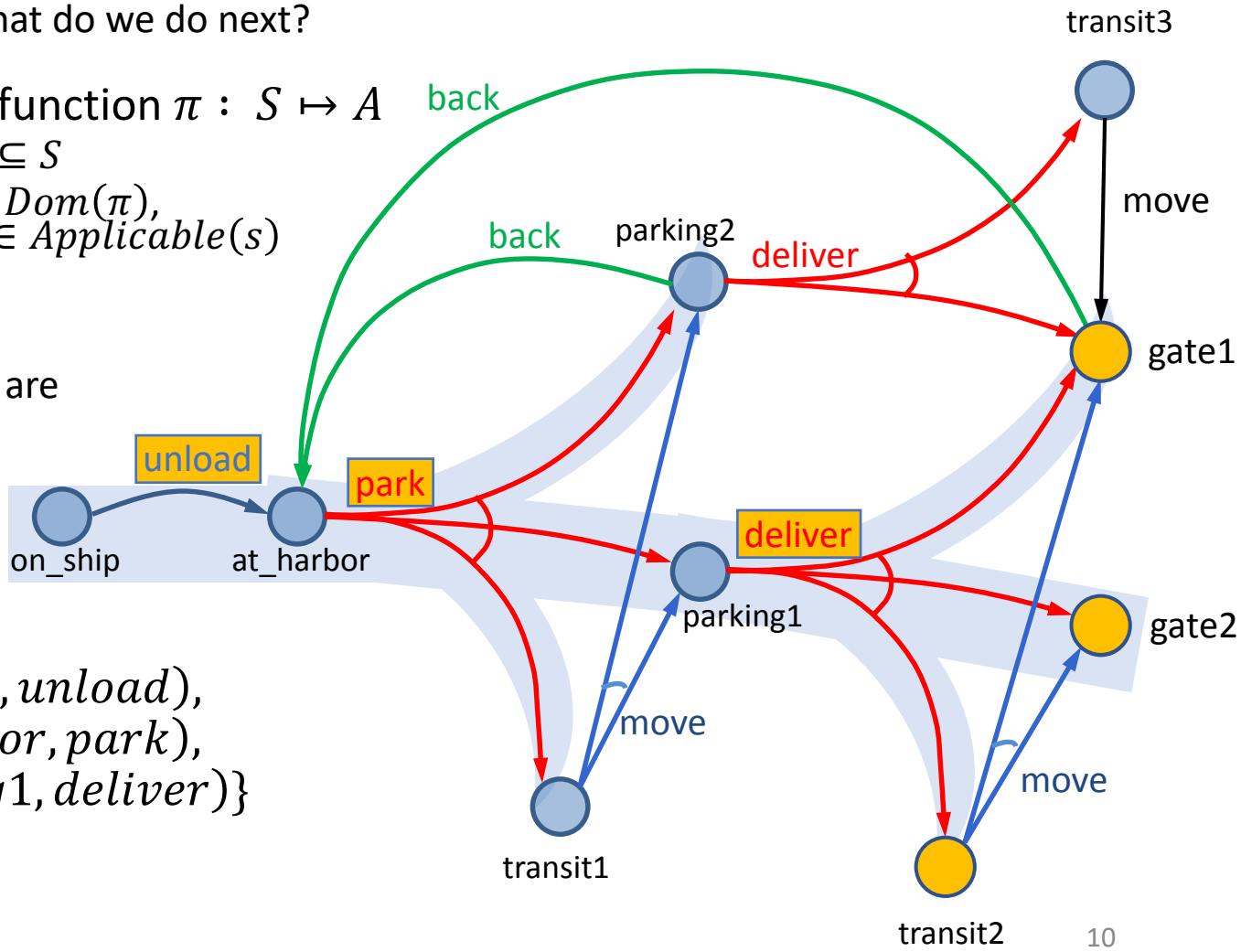
Actions

- Action:
  $park$
  pre: $pos(item) = at\_harbor$
  eff_1: $pos(item) \leftarrow parking1$
  eff_2: $pos(item) \leftarrow parking2$
  eff_3: $pos(item) \leftarrow transit1$
- Three possible outcomes
  - Put item in $parking1$ or $parking2$ if one of them has space or
  - in $transit1$ if there is no parking space



~~Plans~~ Policies

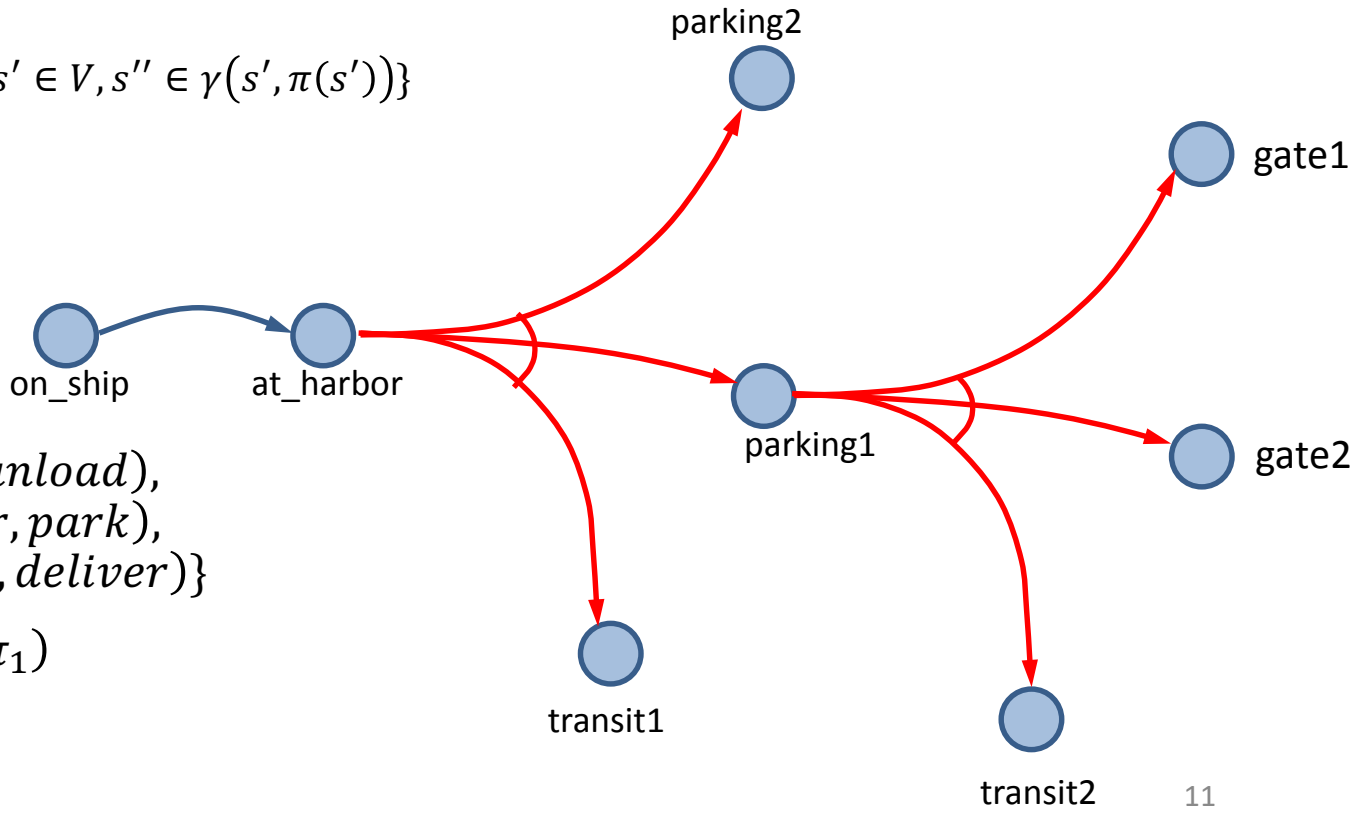
- Need something more general than a sequence of actions
  - After park, what do we do next?
- Policy: a *partial* function $\pi : S \mapsto A$
  - i.e., $Dom(\pi) \subseteq S$
  - For every $s \in Dom(\pi)$, require $\pi(s) \in Applicable(s)$
- Meaning:
  - Perform $\pi(s)$ whenever we are in state s



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

Definitions Over Policies

- Transitive closure:
  {all states reachable from s using π}
  - $\hat{\gamma}(s,\pi) = S_0 \cup S_1 \cup S_2 \cup \cdots$
    - $S_0 = \{s\}$
    - $S_{i+1} = \cup\{\gamma(s,\pi(s)) \mid s \in S_i\}, i \geq 0$
- Reachability graph $Graph(s,\pi) = (V,E)$
  - $V = \hat{\gamma}(s,\pi)$
  - $E = \{(s',s'') \mid s' \in V, s'' \in \gamma(s',\pi(s'))\}$



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

Definitions Over Policies

- Transitive closure:
  {all states reachable from s using π}
  - $\hat{\gamma}(s,\pi) = S_0 \cup S_1 \cup S_2 \cup \cdots$
    - $S_0 = \{s\}$
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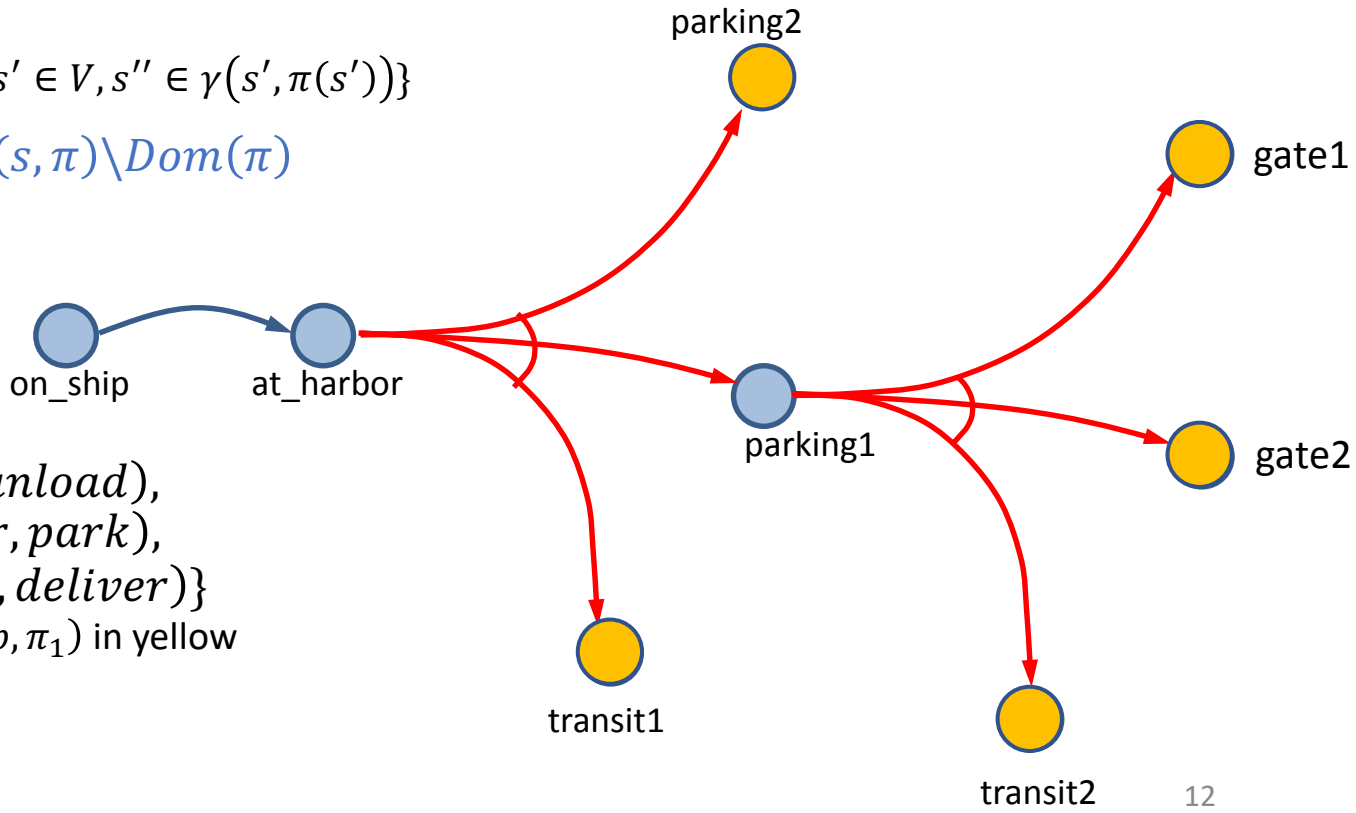
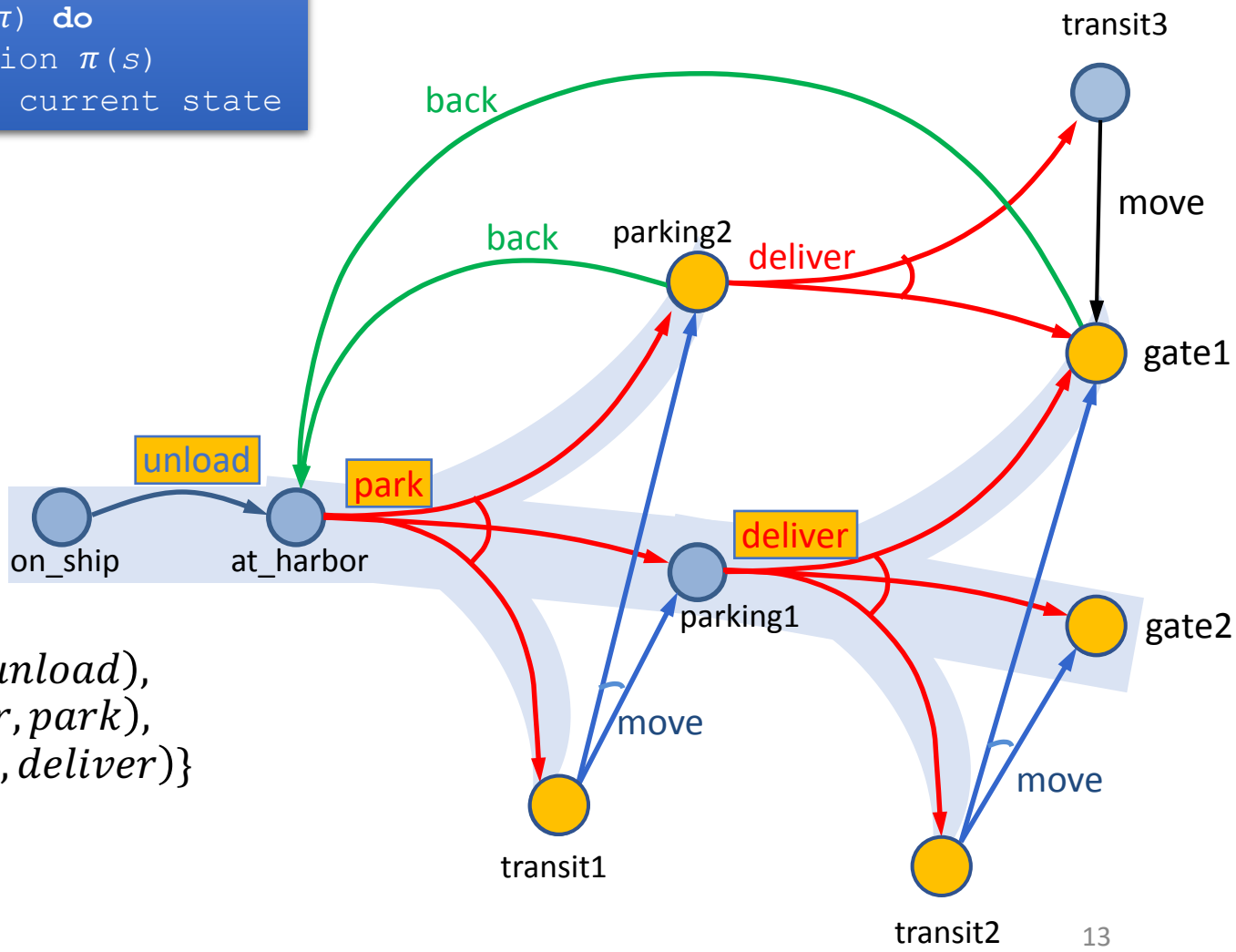
- Reachability graph $Graph(s,\pi) = (V,E)$
  - $V = \hat{\gamma}(s,\pi)$
  - $E = \{(s',s'') \mid s' \in V, s'' \in \gamma(s',\pi(s'))\}$
- $leaves(s,\pi) = \hat{\gamma}(s,\pi) \backslash Dom(\pi)$
  - May be empty



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

Performing a Policy

```
PerformPolicy(π)
    s ← observe current state
    while s ∈ Dom(π) do
        perform action π(s)
        s ← observe current state
```



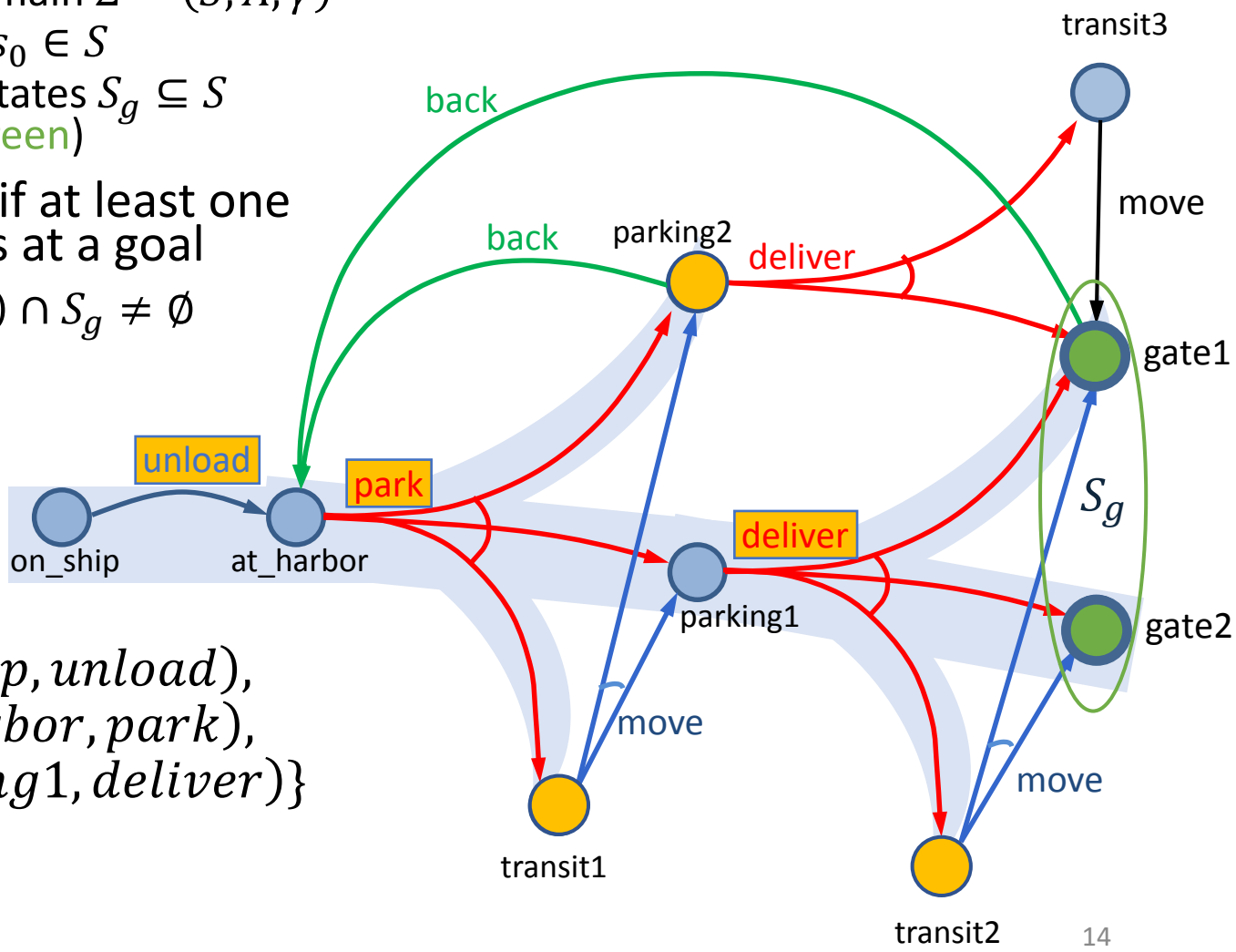
- $\pi_1 = \{(on\_ship, unload),$
  $(at\_harbor, park),$
  $(parking1, deliver)\}$

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
  - $leaves(s, \pi) \cap S_g \neq \emptyset$

Is π_1 a solution?

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

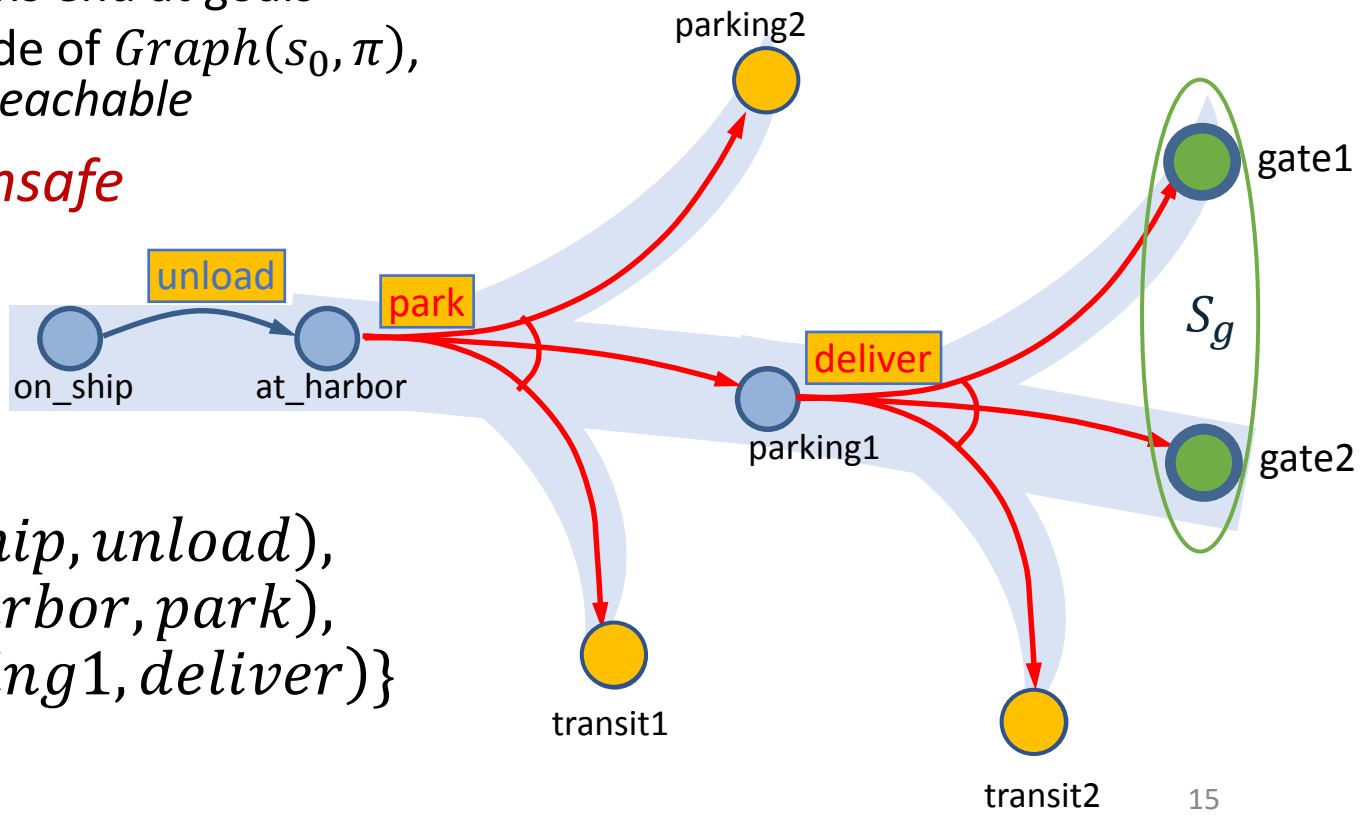


Safe Solutions

- 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 $Graph(s_0, \pi)$, the goal is *reachable*
- Otherwise, *unsafe*

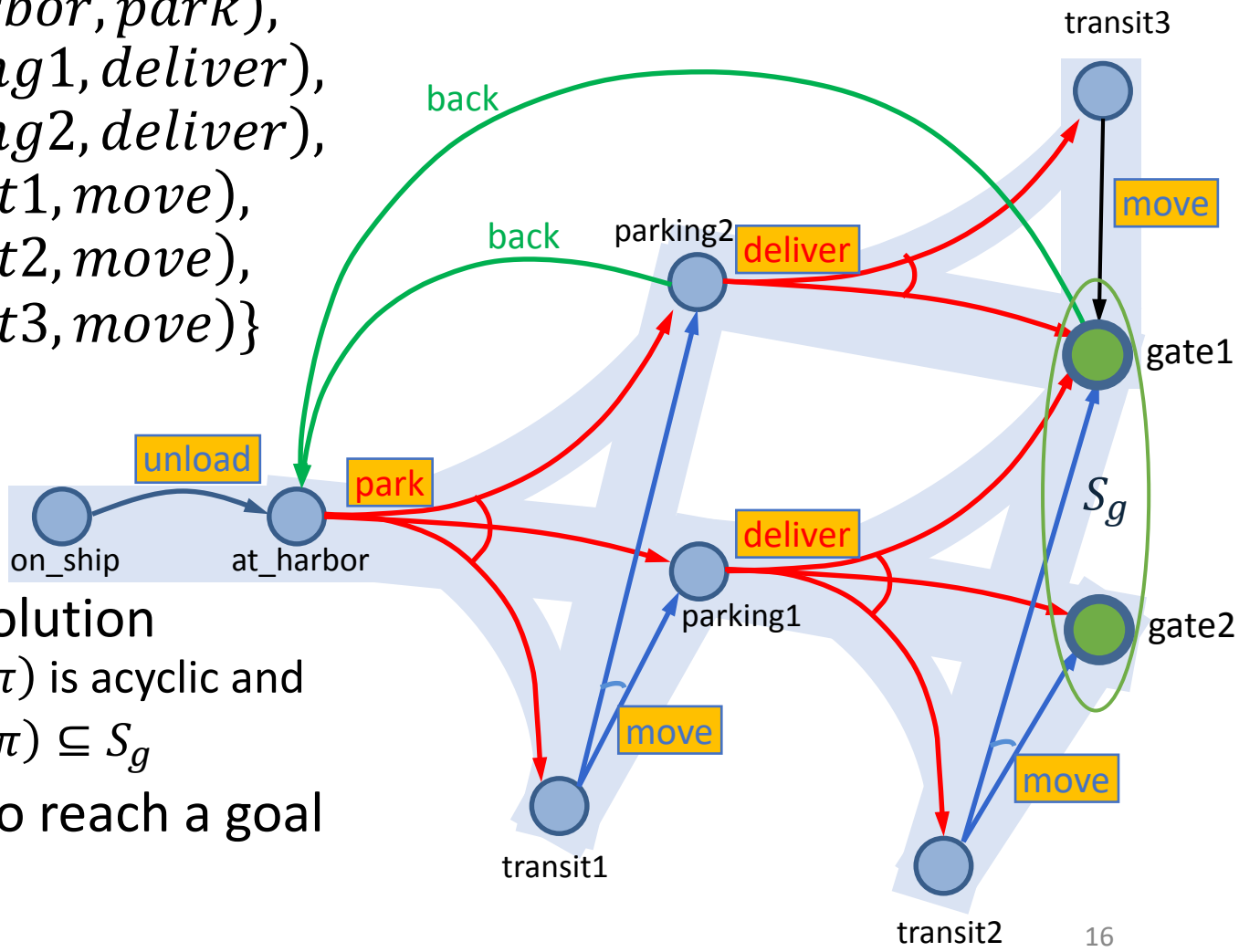


Is π_1 safe?

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

Safe Solutions

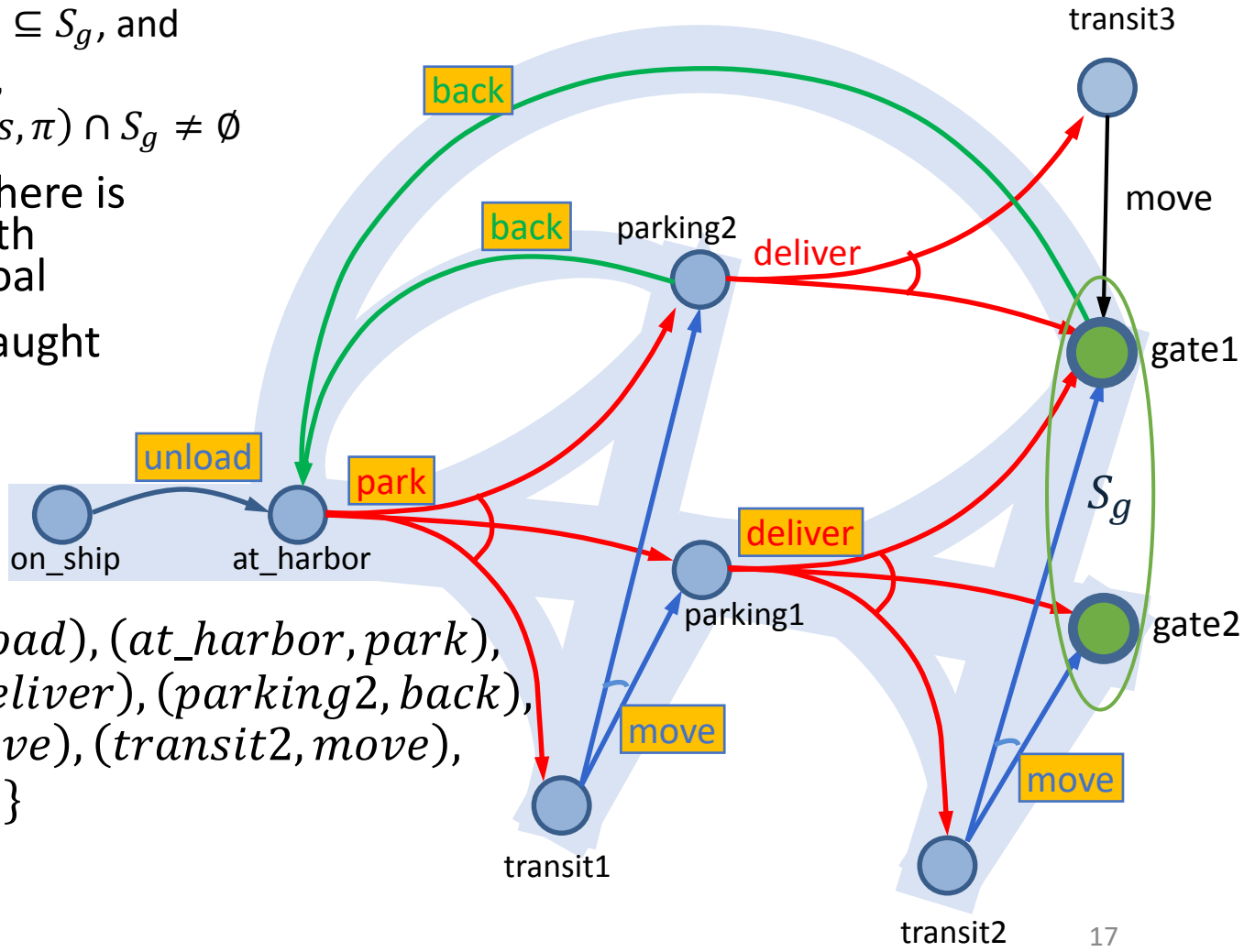
- $\pi_2 = \{(on\_ship, unload),$
  $(at\_harbor, park),$
  $(parking1, deliver),$
  $(parking2, deliver),$
  $(transit1, move),$
  $(transit2, move),$
  $(transit3, move)\}$



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

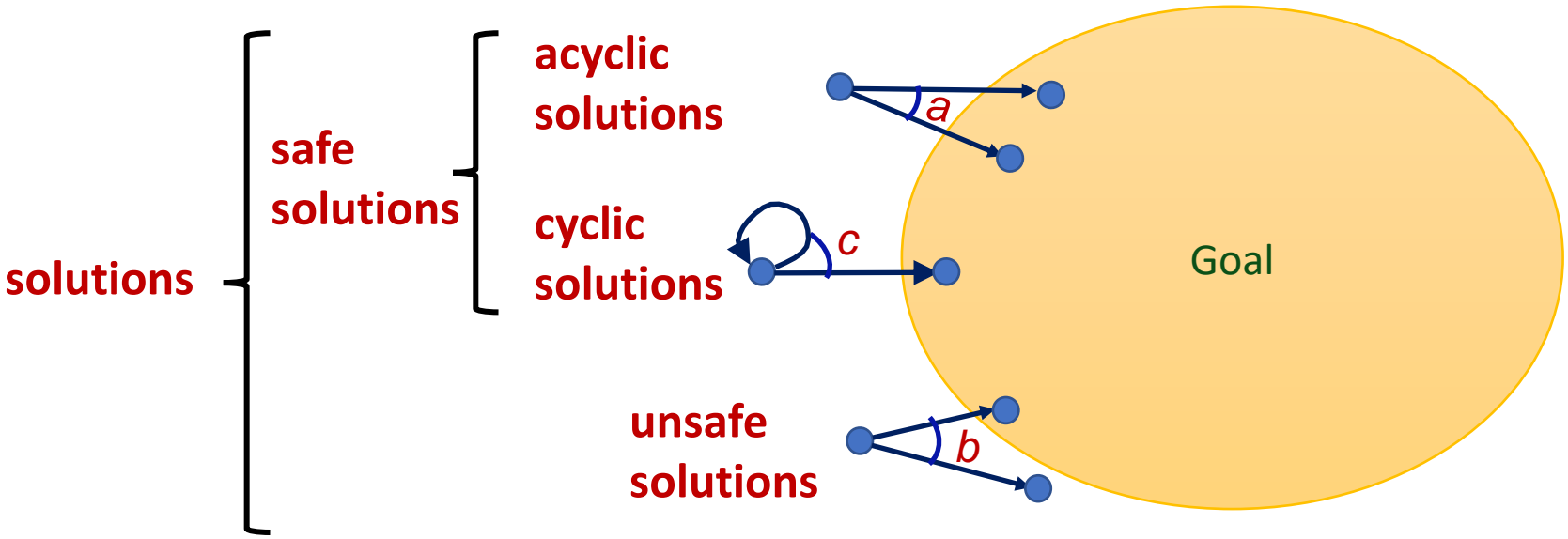
Safe Solutions

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



- $\pi_3 = \{(on\_ship, unload), (at\_harbor, park), (parking1, deliver), (parking2, back), (transit1, move), (transit2, move), (gate1, back)\}$

Kinds of Solutions



Intermediate Summary

- Planning Problems
  - Planning domains
  - Plans as policies
  - Planning problems and solutions
    - Types of solutions: safe, unsafe, acyclic, cyclic

Outline per the Book

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Finding (Unsafe) Solutions

For comparison: Forward-search with deterministic models

```
Forward-search(Σ, s_0, g)
    s ← s_0
    π ← ⟨⟩
    loop
        if s satisfies g then
            return π
        A' ←{a ∈ A | a is applicable in s}
        if A' = ∅ then
            return failure
        nondeterministically choose a ∈ A'
        s ← γ(s,a)
        π ← π.a
```

```
Find-Solution(Σ, s_0, S_g)
    s ← s_0
    π ← ∅
    Visited ← {s_0}
    loop
        if s ∈ S_g then
            return π
        A' ← Applicable(s)
        if A' = ∅ then
            return failure
        nondeterministically choose a ∈ A'
        nondeterministically choose s' ∈ γ(s,a)
        if s' ∈ Visited then
            return failure
        π(s) ← a
        Visited ← Visited ∪ {s'}
        s ← s'
```

Decide which state to plan for

Cycle-checking

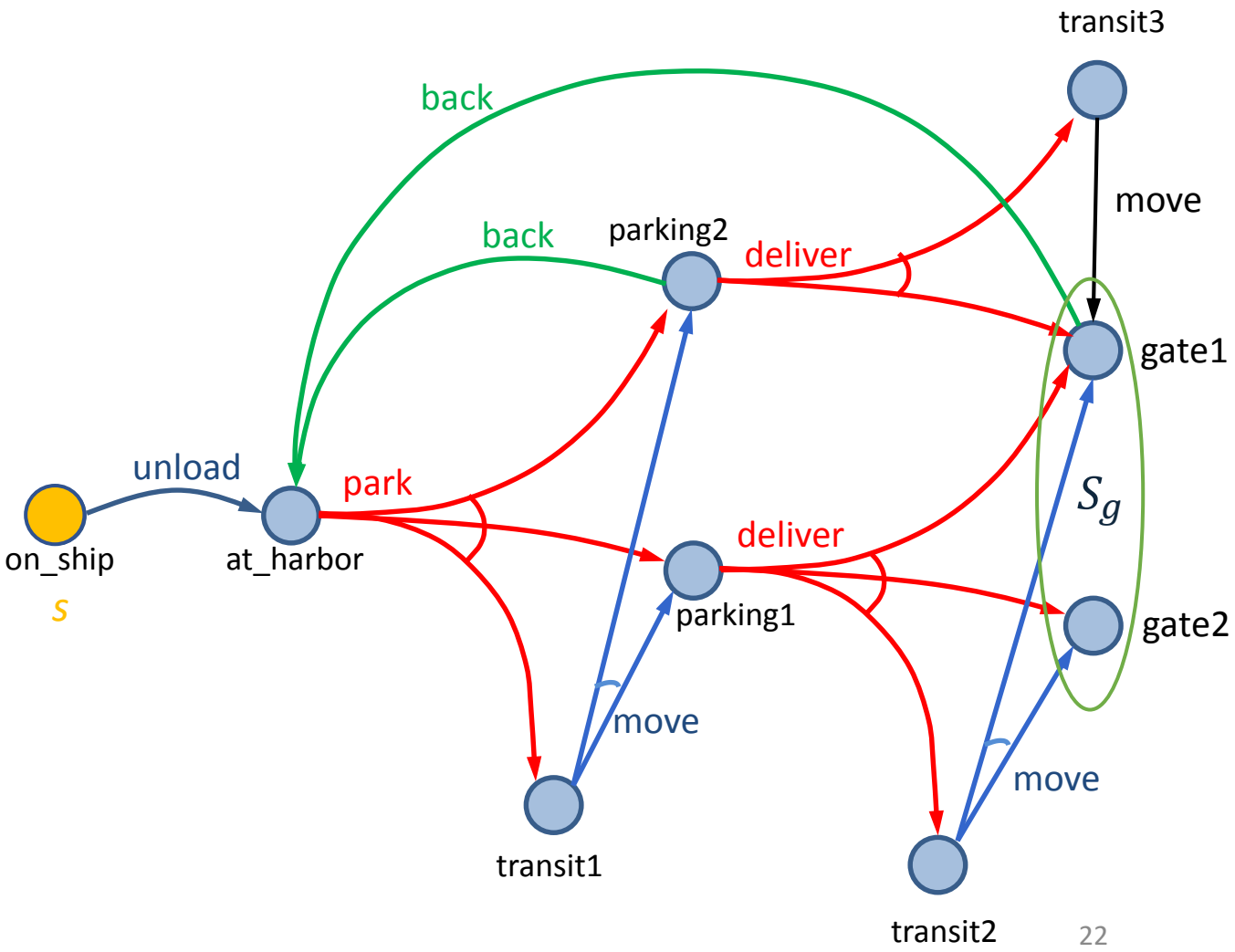
```
Find-Solution(Σ, s0, Sg)
    s ← s0
    π ← ∅
    Visited ← {s0}
    ...
```

Example

s = on_ship

π = {}

Visited = {on_ship}



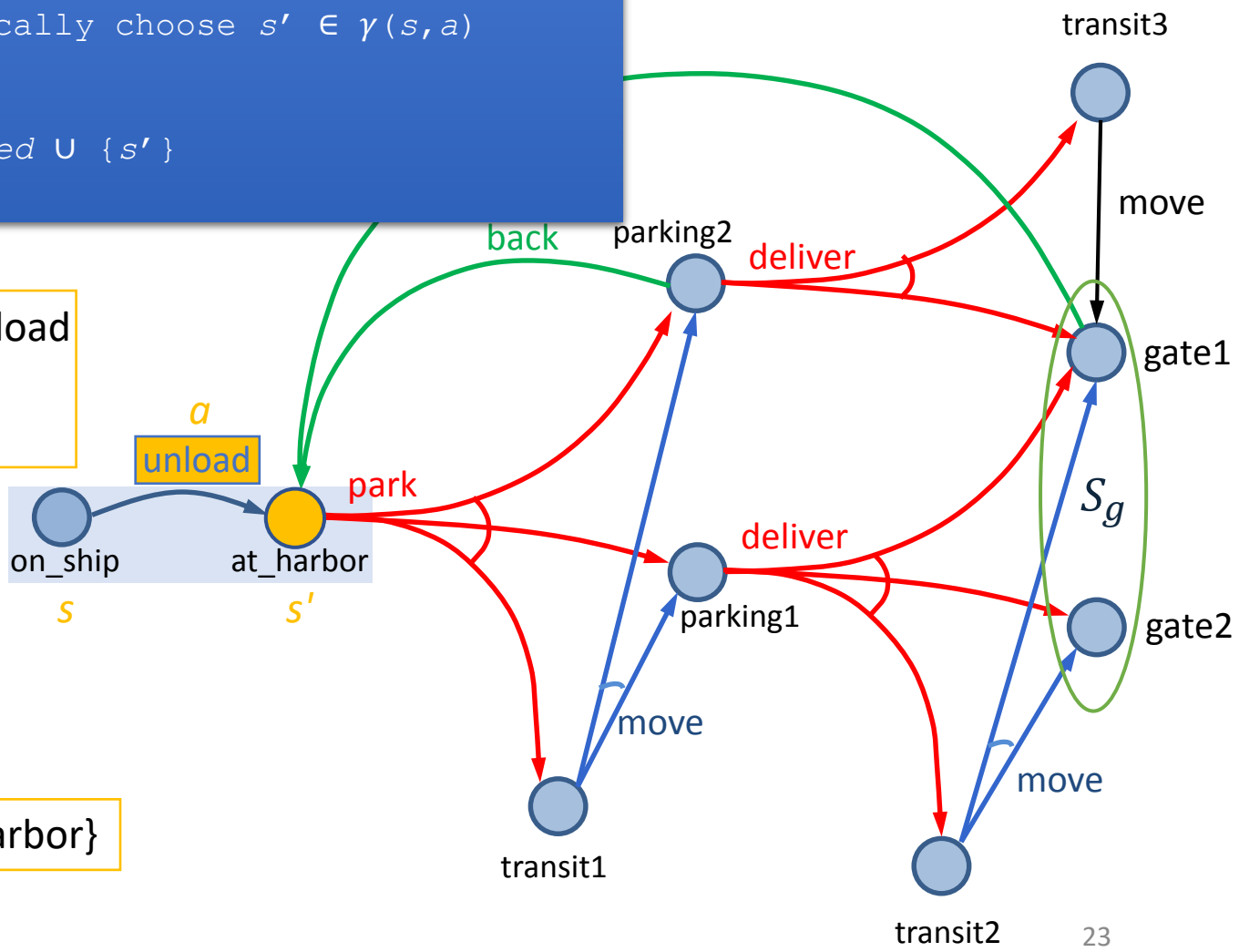
```
Find-Solution(Σ, s_0, S_g)
    ...
    loop
        if s ∈ S_g then
            return π
        ...
        nondeterministically choose a ∈ Applicable(s)
        nondeterministically choose s' ∈ γ(s,a)
        ...
        π(s) ← a
        Visited ← Visited ∪ {s'}
        s ← s'
```

Example

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

π = {(on_ship, unload)}

Visited = {on_ship, at_harbor}



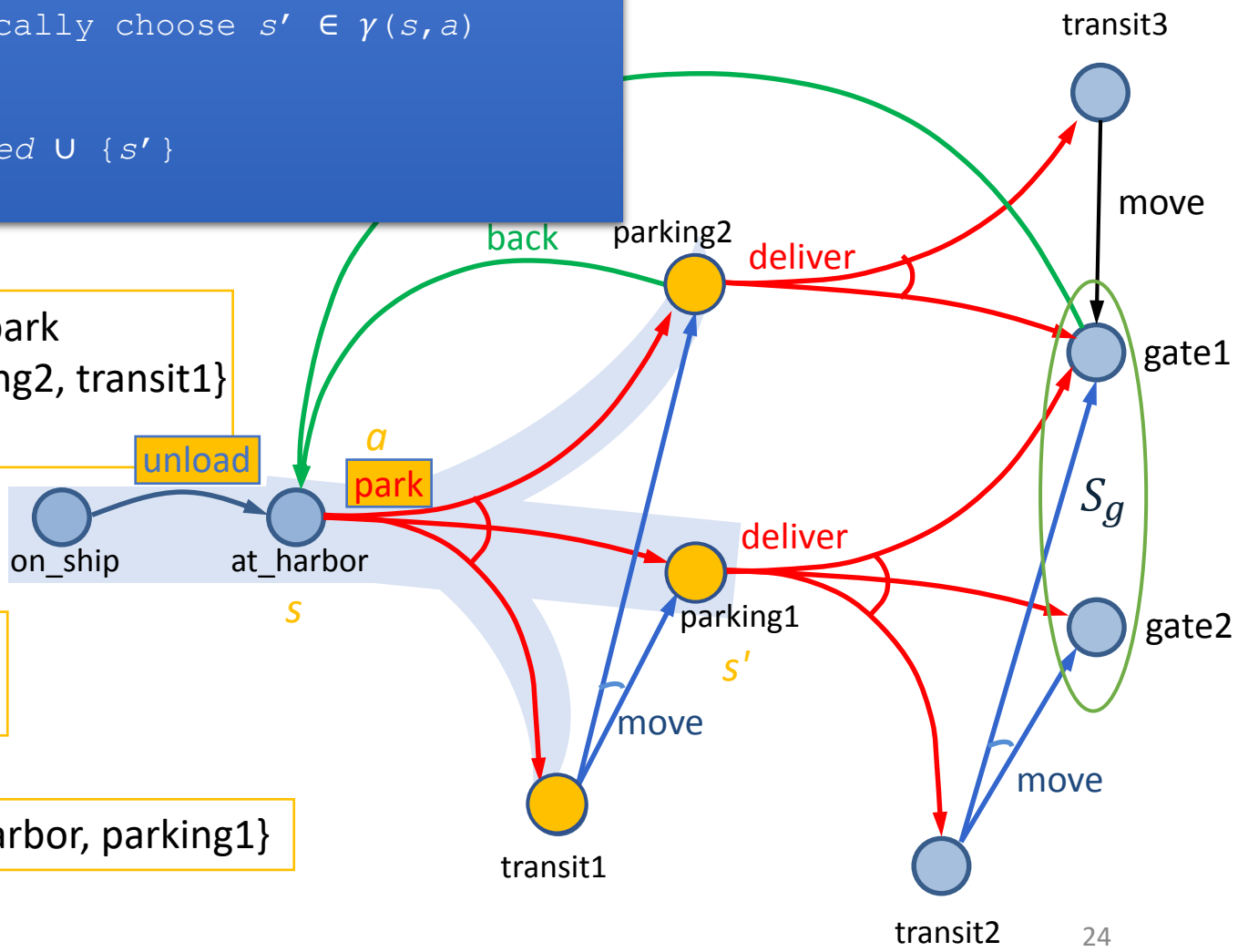
Example

```
Find-Solution(Σ, s0, Sg)
    ...
    loop
        if s ∈ Sg then
            return π
        ...
        nondeterministically choose a ∈ Applicable(s)
        nondeterministically choose s′ ∈ γ(s,a)
        ...
        π(s) ← a
        Visited ← Visited ∪ {s′}
        s ← 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}



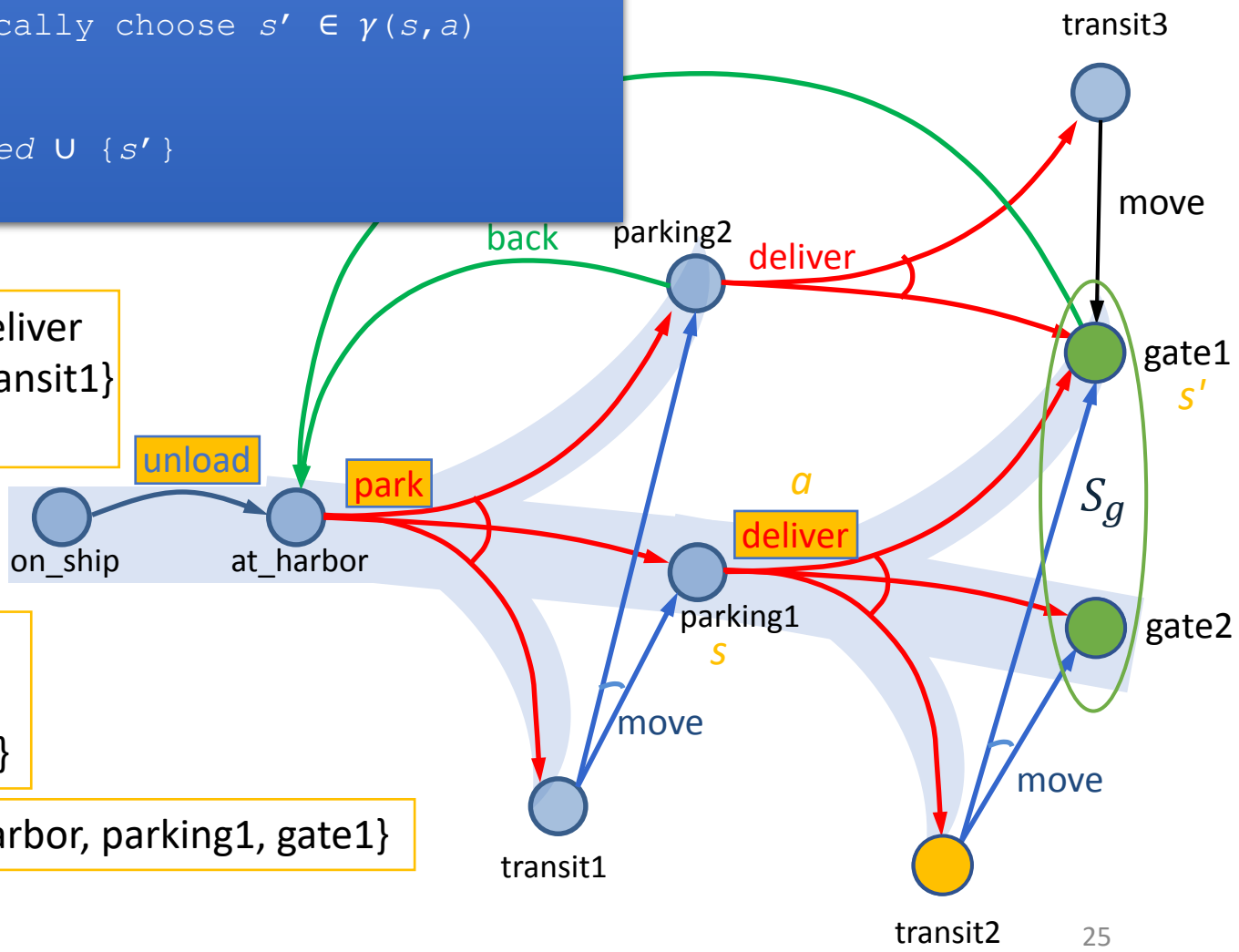
```
Find-Solution(Σ, s_0, S_g)
    ...
    loop
        if s ∈ S_g then
            return π
        ...
        nondeterministically choose a ∈ Applicable(s)
        nondeterministically choose s′ ∈ γ(s,a)
        ...
        π(s) ← a
        Visited ← Visited ∪ {s′}
        s ← s′
```

Example

s = parking1, a = deliver
$\gamma(s,a)$ = {gate1, gate2, transit1}
s' = gate1

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

Visited = {on_ship, at_harbor, parking1, gate1}



Example

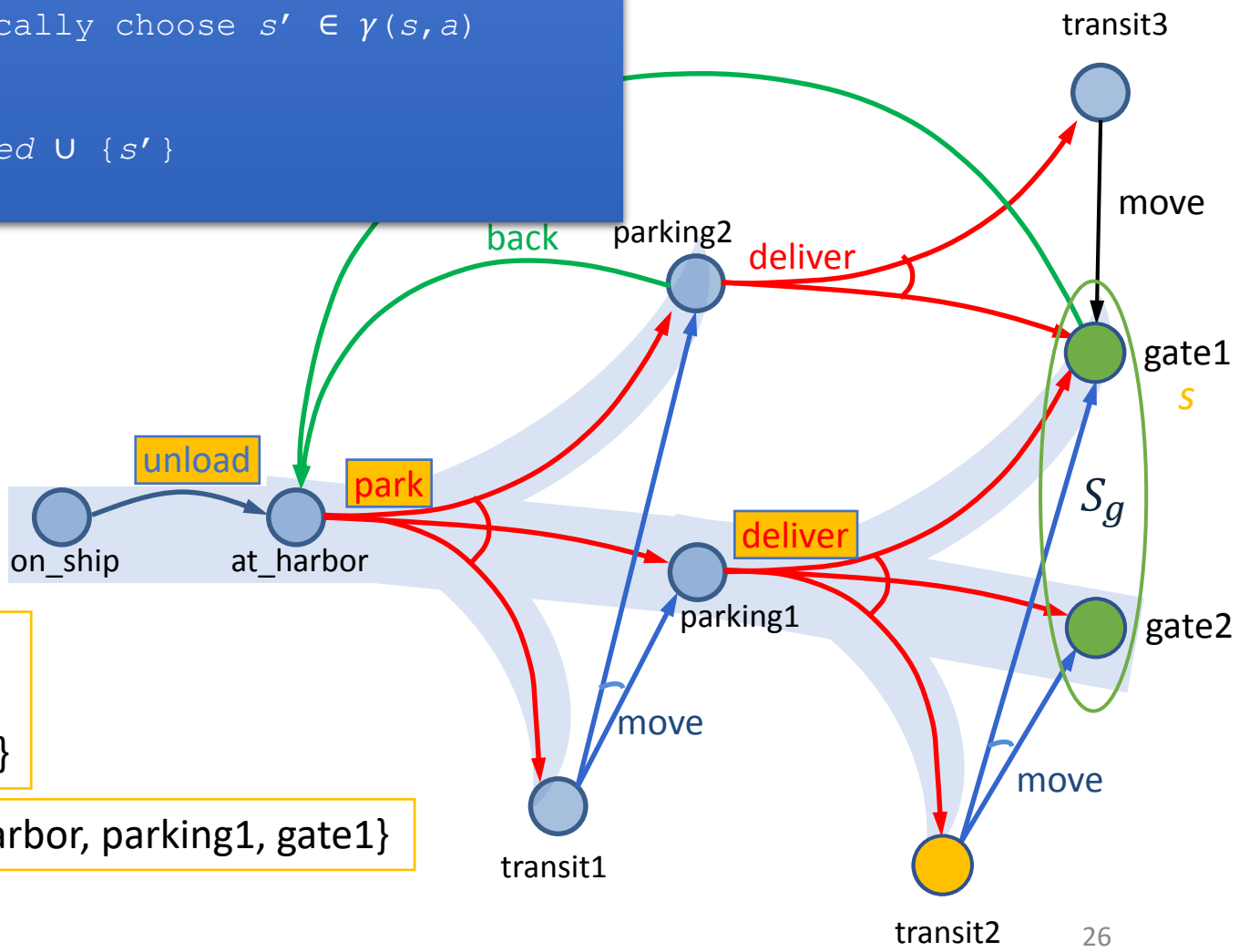
```
Find-Solution(Σ, s_0, S_g)
    ...
    loop
        if s ∈ S_g then
            return π
        ...
        nondeterministically choose a ∈ Applicable(s)
        nondeterministically choose s' ∈ γ(s,a)
        ...
        π(s) ← a
        Visited ← Visited ∪ {s'}
        s ← s'
```

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}



Finding Acyclic Safe Solutions

```
Find-Acyclic-Solution(Σ, s_0, S_g)
    π ← ∅
    Frontier ← {s_0}
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        if Applicable(s) = ∅ then
            return failure
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

Keep track of unexpanded states, like A*

Add all outcomes that π does not already handle

Cycle-checking

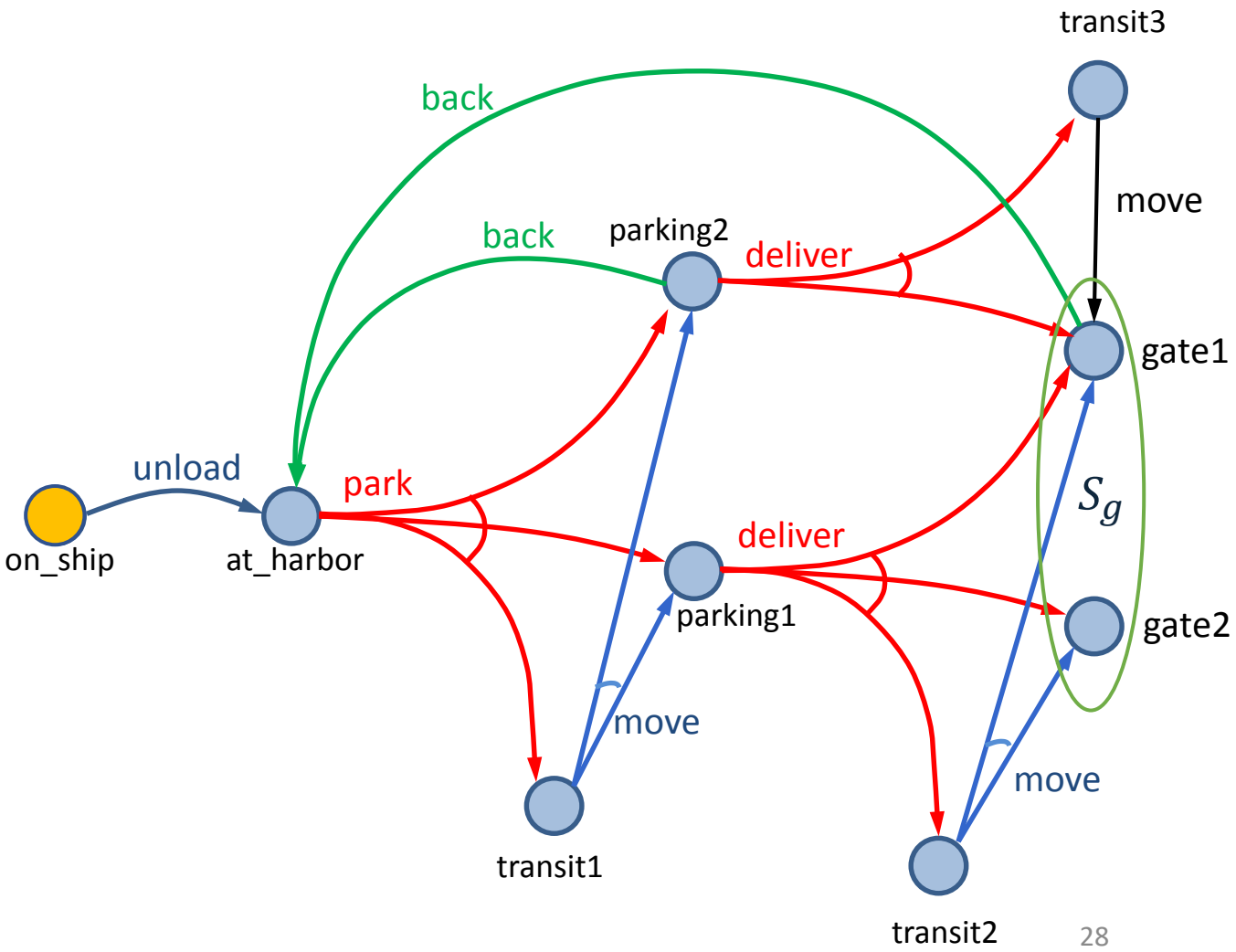
- Check for cycles
  - For each $s' \in \left(\gamma(s,a) \cap Dom(\pi)\right)$
    - Is $s' \in \hat{\gamma}(s', \pi)$?
  - Formally, $has{-}loops(\pi, s, Frontier)$ iff
    $$\exists s' \in \left(\gamma(s,a) \cap Dom(\pi)\right) : \; s' \in \hat{\gamma}(s', \pi)$$
  - I.e., a state s' is reachable from itself

```
Find-Acyclic-Solution(Σ, s_0, S_g)
    π ← ∅
    Frontier ← {s_0}
    ...
```

Example

Frontier \ S_g = {on_ship}

π = {}



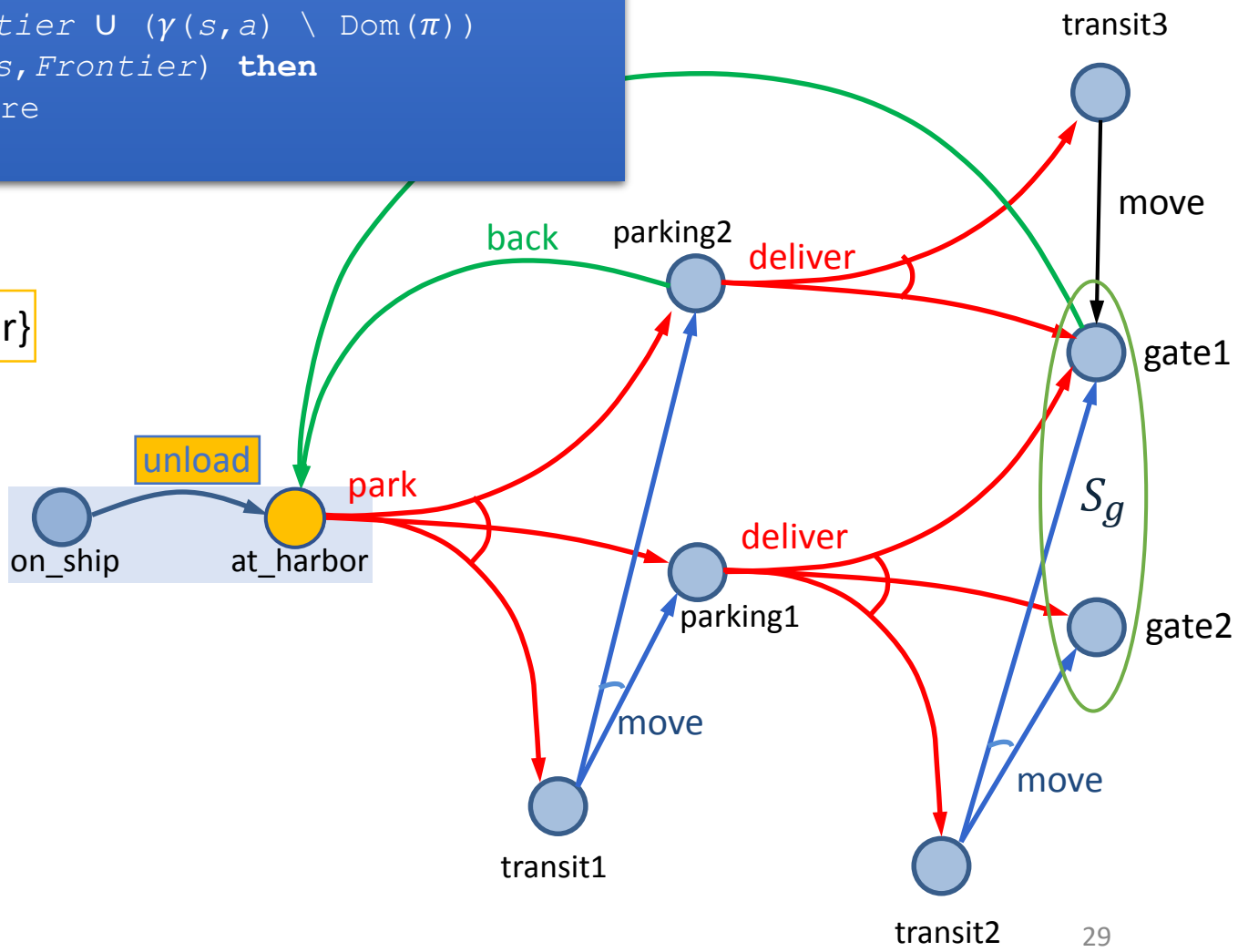
```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

Example

s = on_ship

$Frontier \setminus S_g$ = {at_harbor}

π = {(on_ship, unload)}



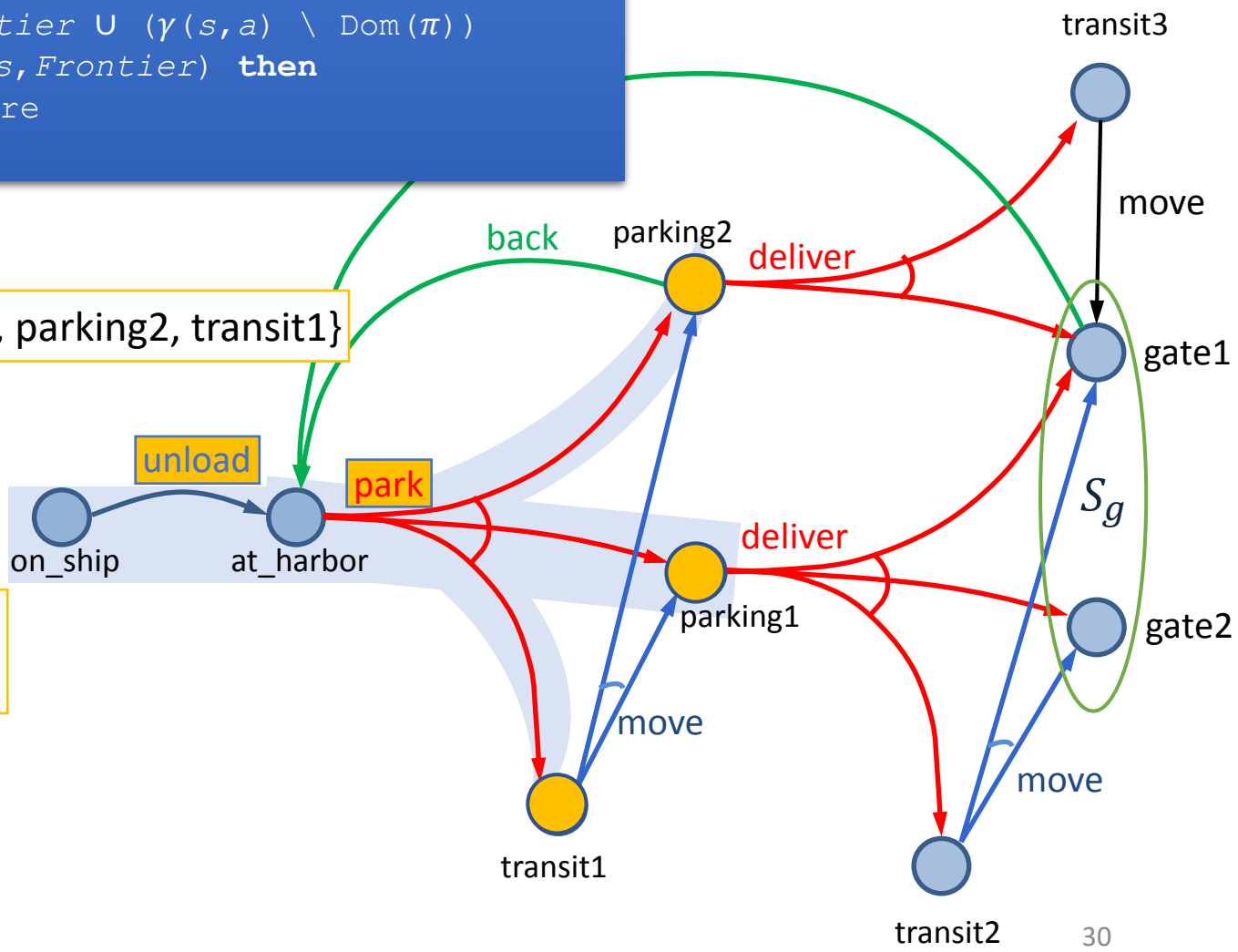
```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

Example

s = at_harbor

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

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



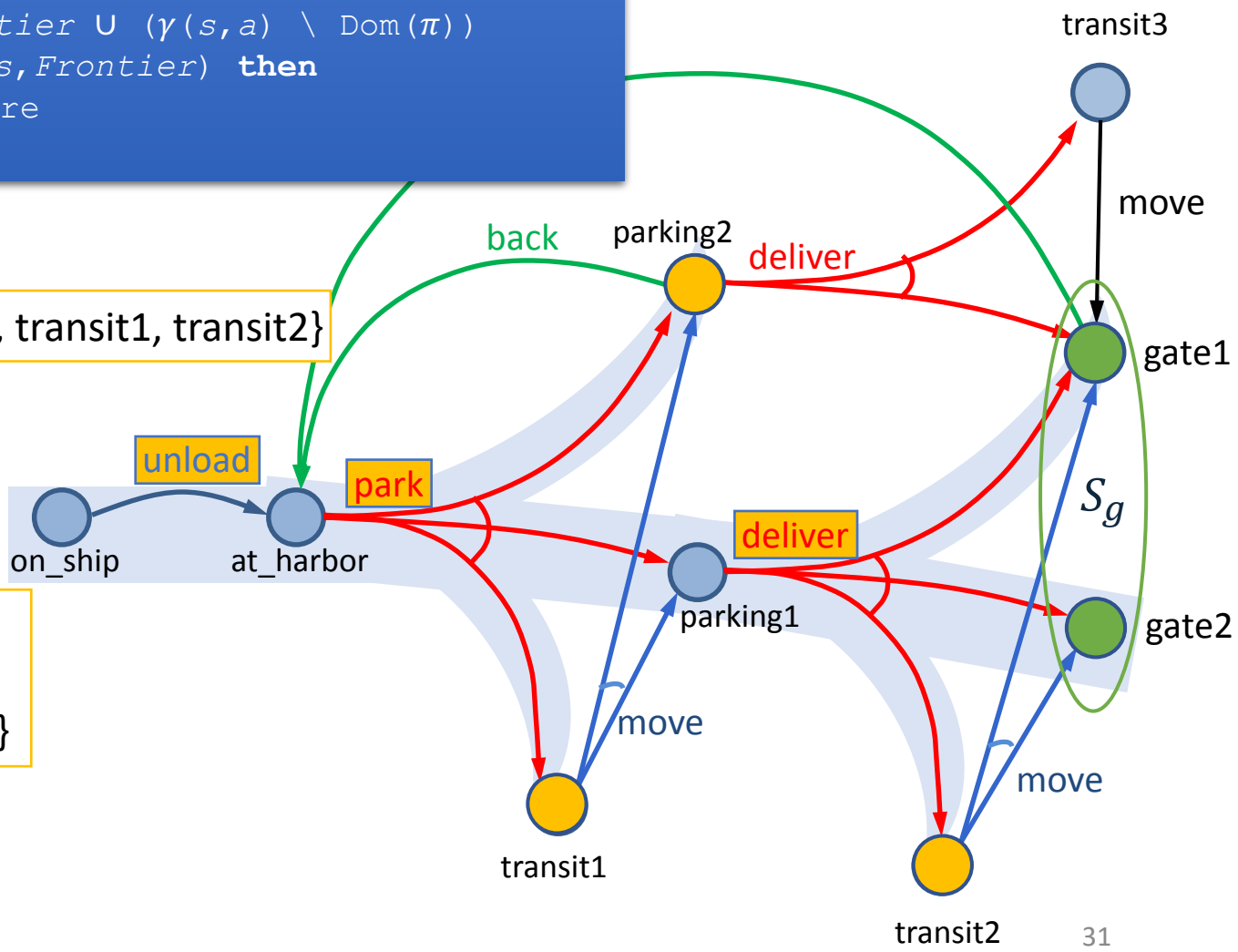
Example

```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

s = parking1

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

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



Example

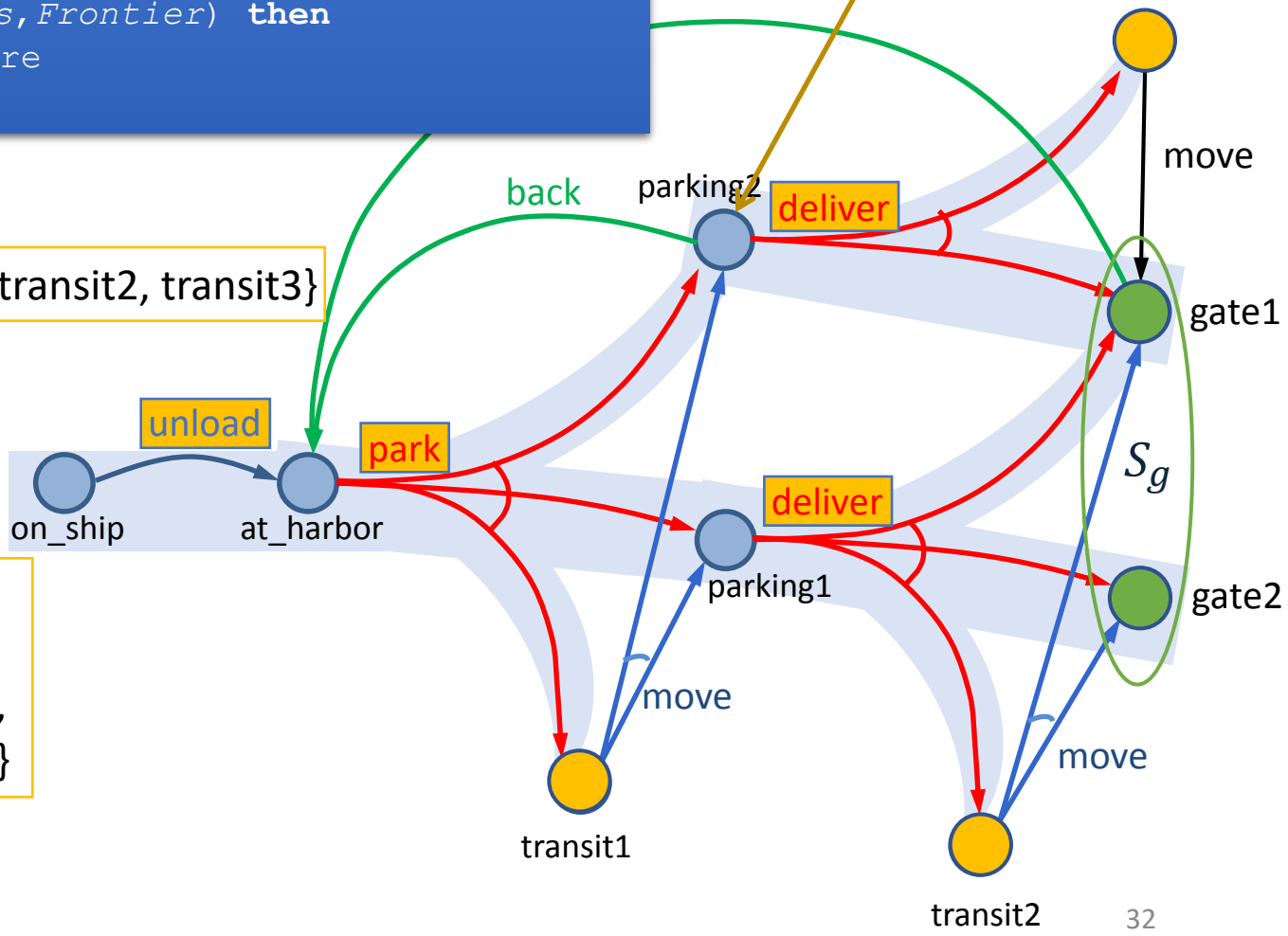
```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Appl
        π ← π ∪ (s,a)
        Frontier ← Frontier ∪ (γ(s,a) \ Dom(
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

nondeterministically choose back or deliver
- back ⇒ cycle, so return failure
- deliver ⇒ no cycle, so continue

s = parking2

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

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



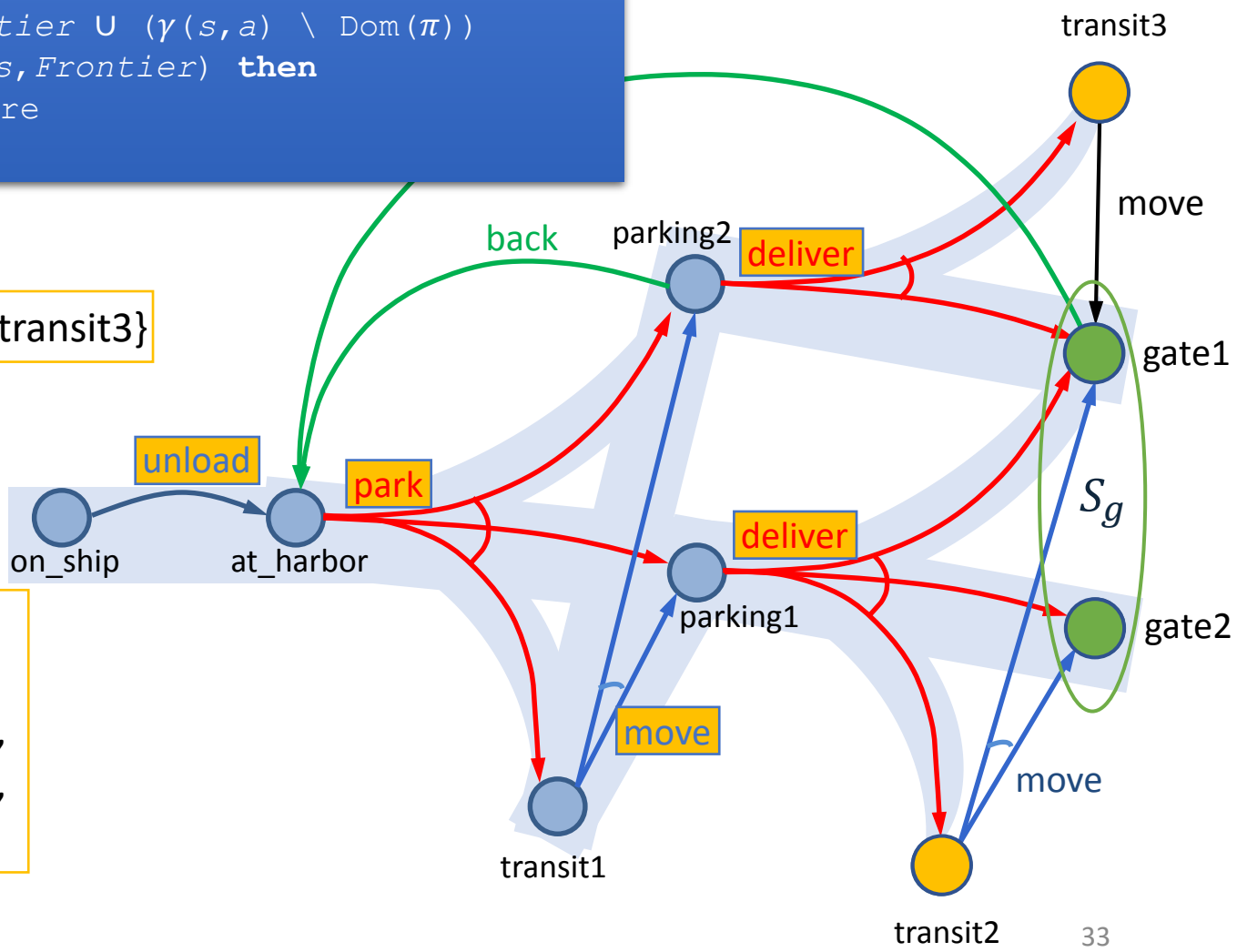
```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

Example

s = transit1

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

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



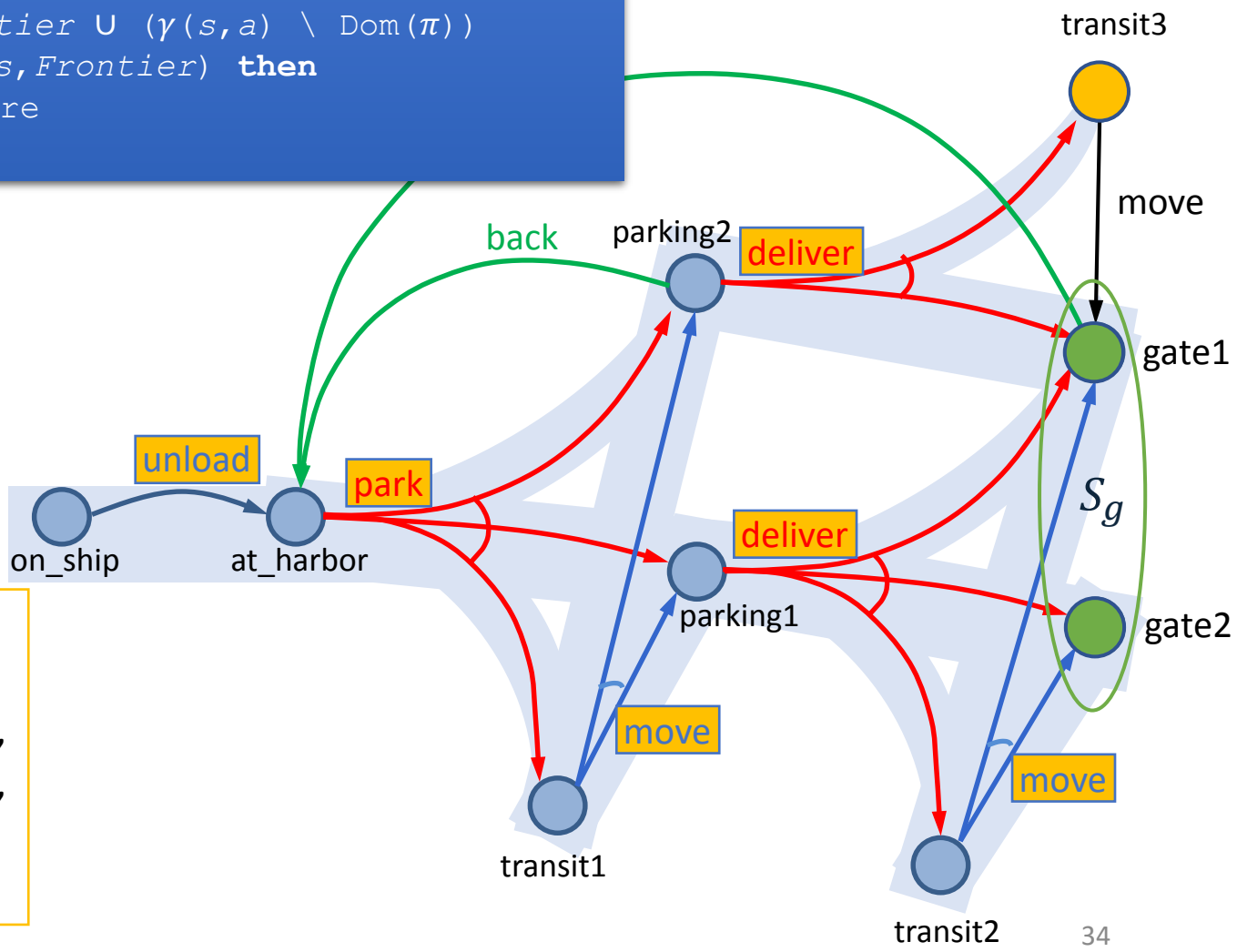
```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

Example

s = transit2

$Frontier \setminus S_g$ = {transit3}

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



```
Find-Acyclic-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-loops(π, s, Frontier) then
            return failure
    return π
```

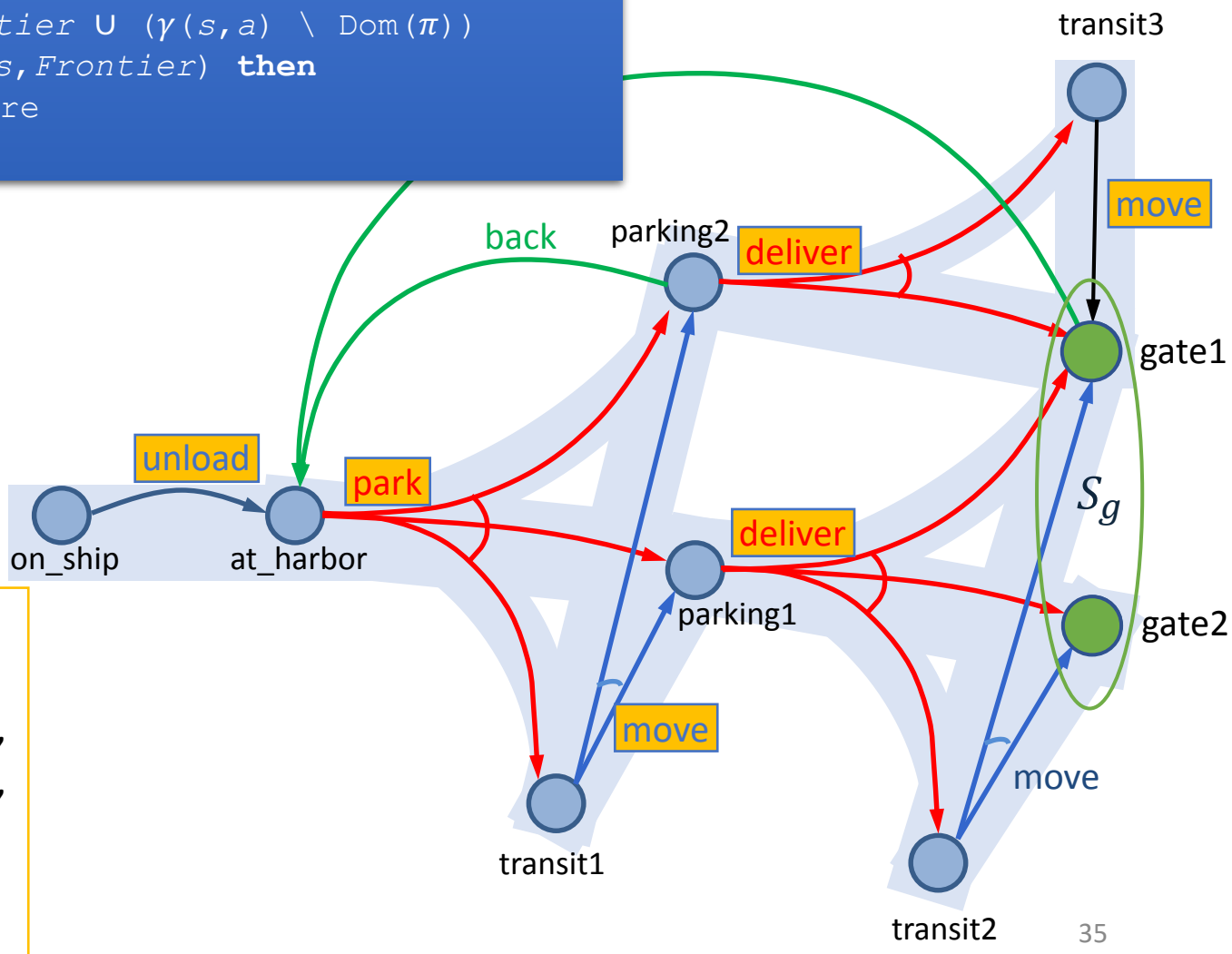
Example

s = transit3

$Frontier \setminus S_g = \emptyset$

Found a solution, so return π

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



Finding Safe Solutions

```
Find-Safe-Solution(Σ, s_0, S_g)
    π ← ∅
    Frontier ← {s_0}
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        if Applicable(s) = ∅ then
            return failure
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

Different cycle-checking

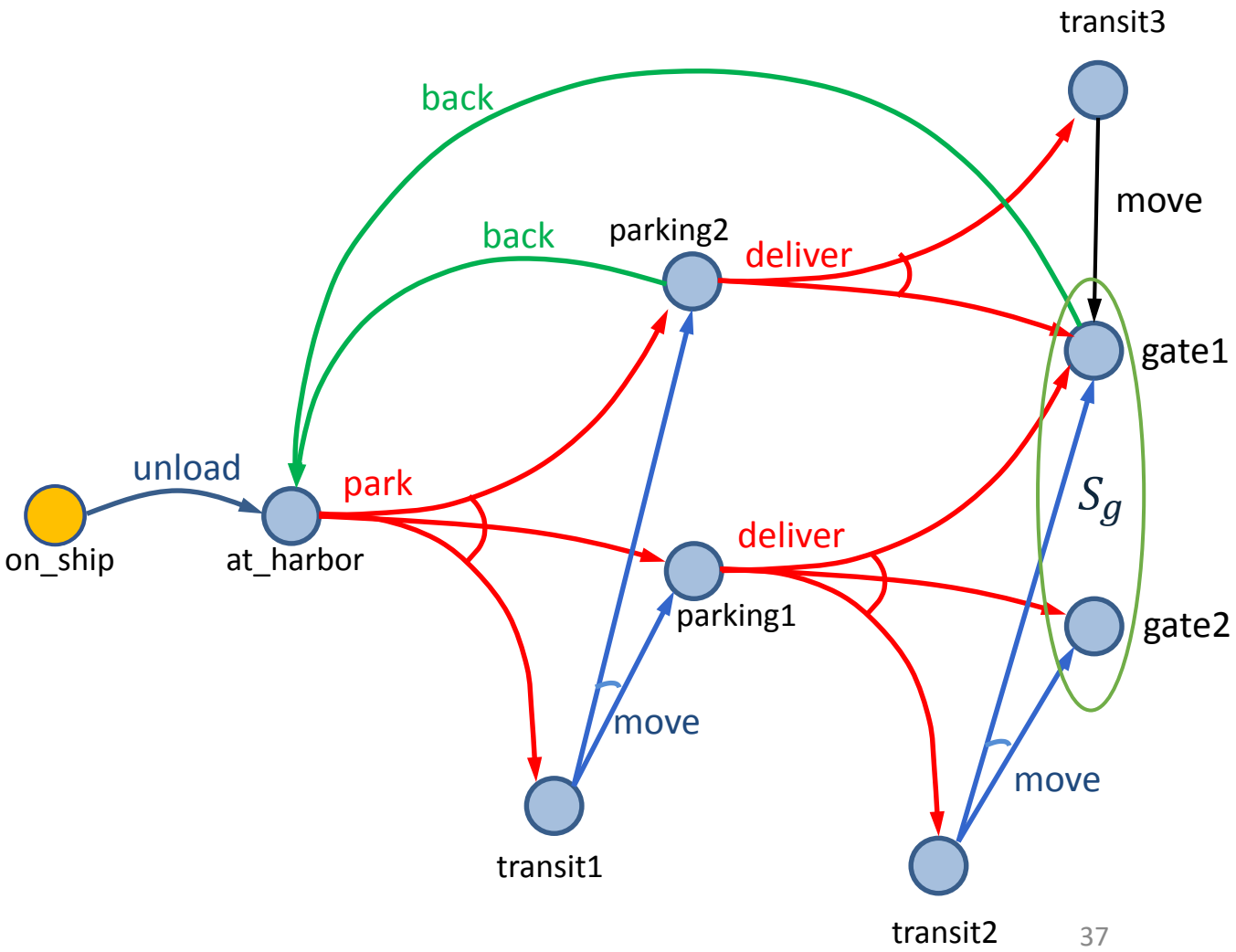
- Same as `Find-Acyclic-Solution` except for cycle-checking
- `has-unsafe-loops` instead of `has-loops`
- Check if π contains any cycles that cannot be escaped:
  - For each $s' \in \left(\gamma(s,a) \cap Dom(\pi)\right)$
    - Is $\hat{\gamma}(s',\pi) \cap Frontier = \emptyset$?
  - Formally, $has{-}unsafe{-}loops(\pi, s, Frontier)$ iff
    $\exists s' \in \left(\gamma(s,a) \cap Dom(\pi)\right) : \hat{\gamma}(s',\pi) \cap Frontier = \emptyset$

```
Find-Safe-Solution(Σ, s_0, S_g)
    π ← ∅
    Frontier ← {s_0}
    ...
```

Example

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

$\pi = \{\}$



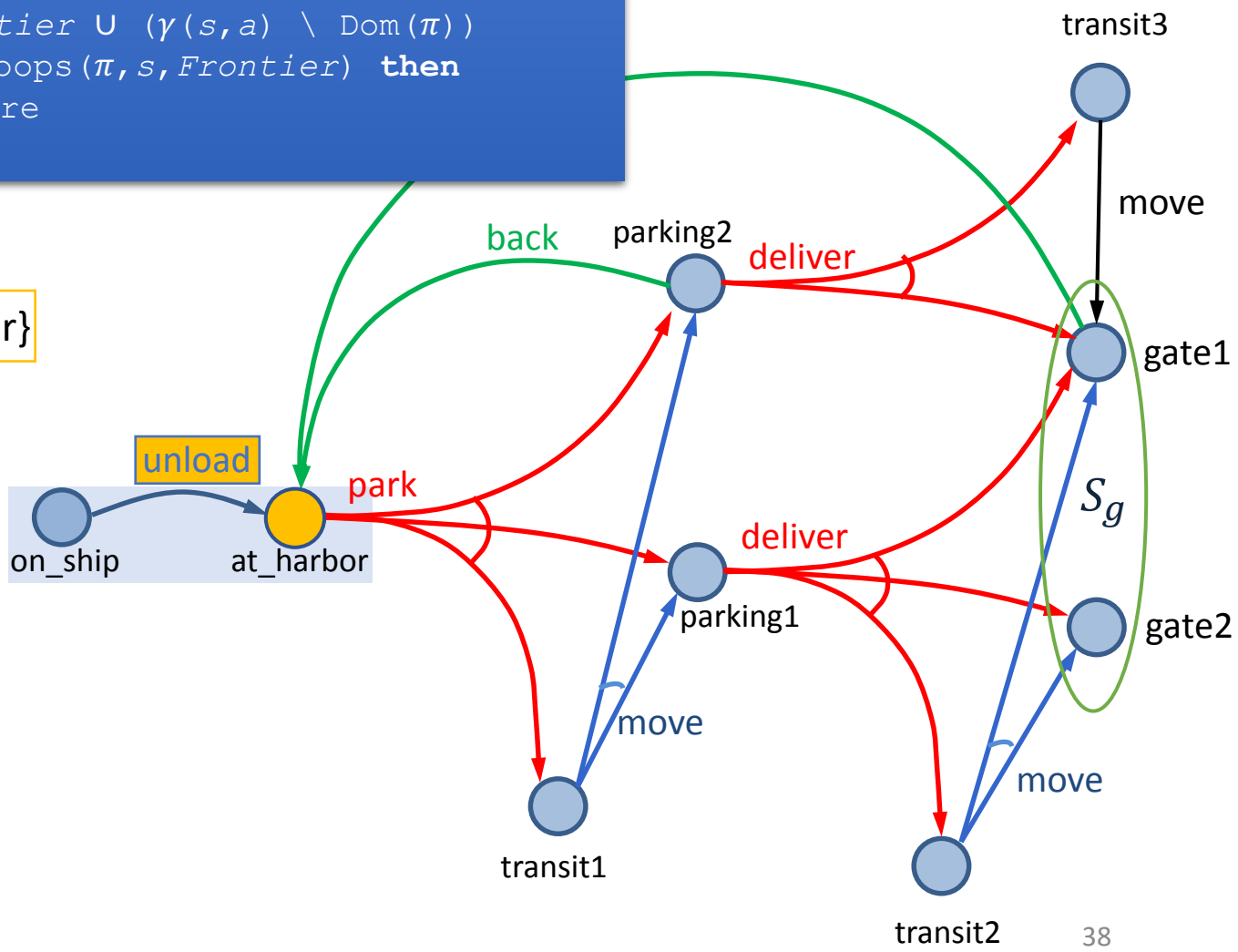
Example

```
Find-Safe-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

s = on_ship

$Frontier \setminus S_g$ = {at_harbor}

π = {(on_ship, unload)}



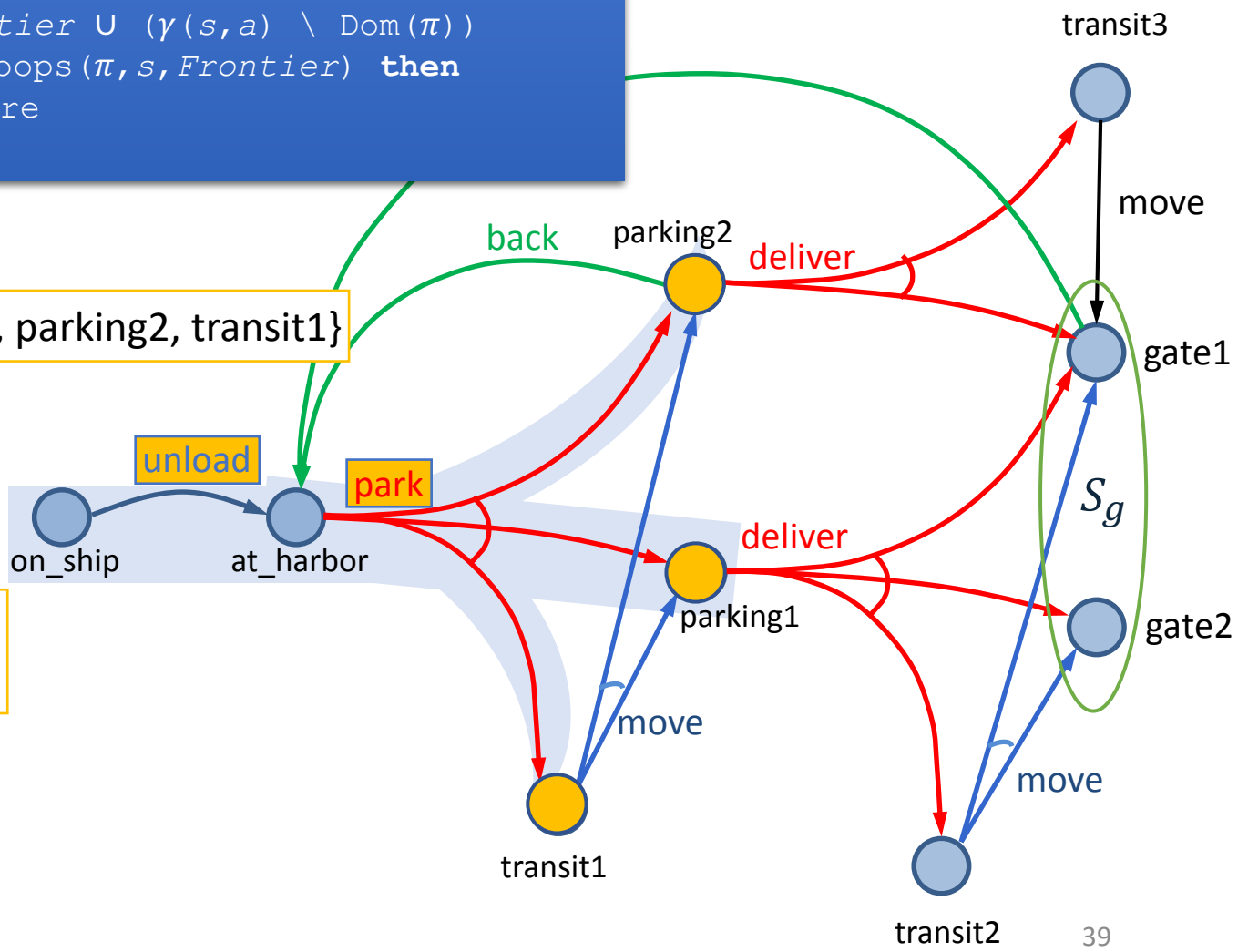
Example

```
Find-Safe-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

s = at_harbor

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

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



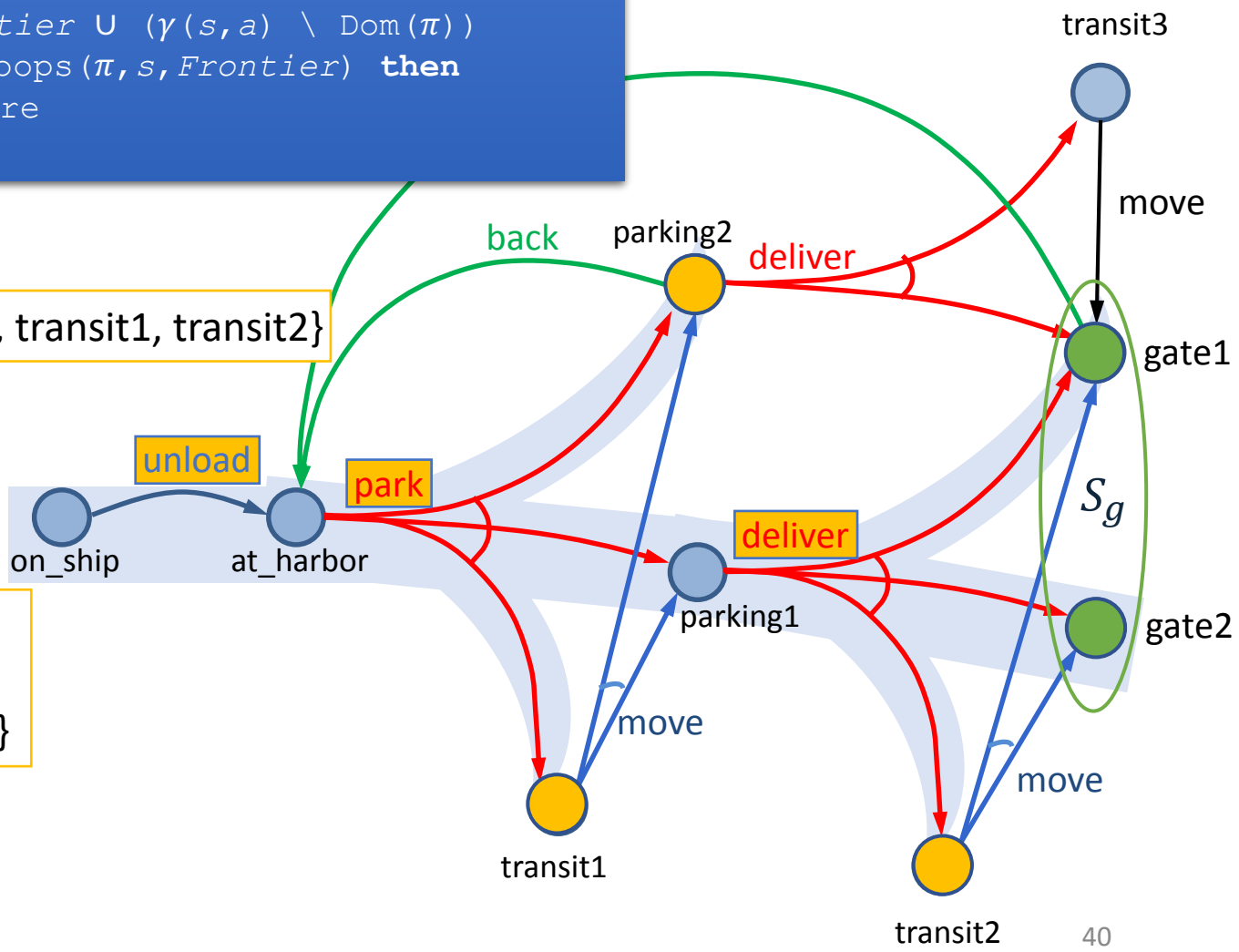
Example

```
Find-Safe-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

s = parking1

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

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



Example

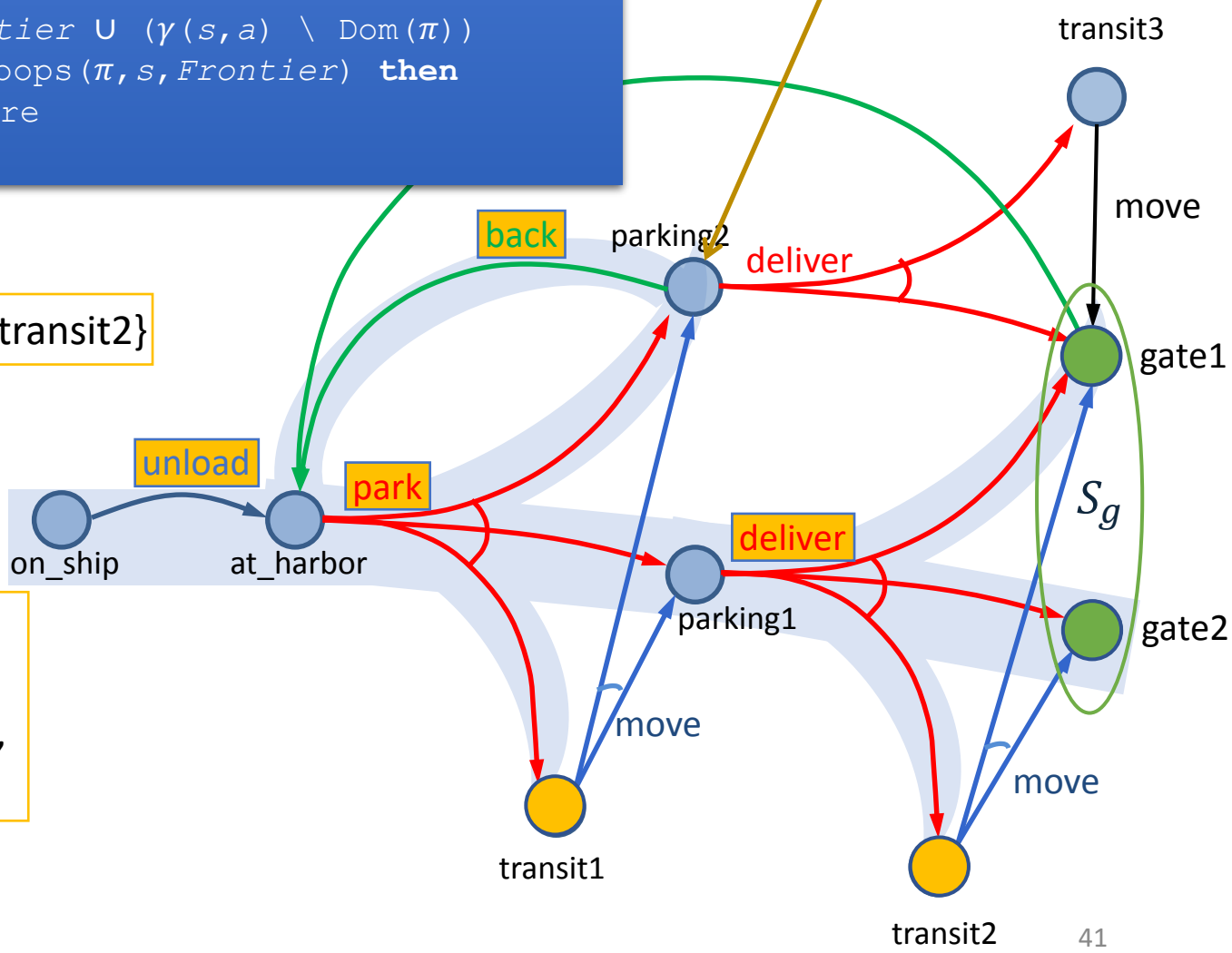
```
Find-Safe-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Appl
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

nondeterministically choose back or deliver
- back is okay: escapable cycle

s = parking2

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

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



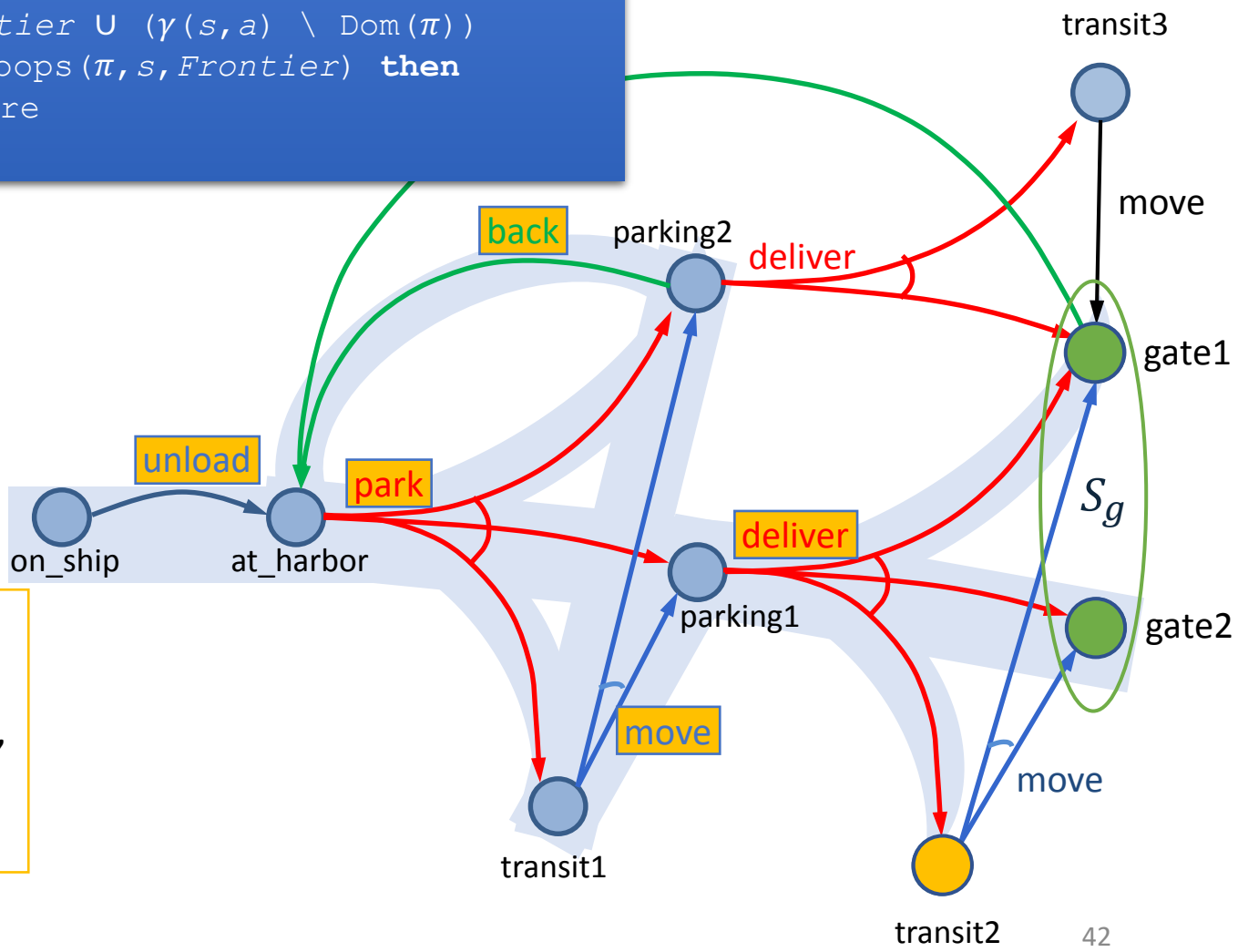
Example

```
Find-Safe-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

s = transit1

$Frontier \setminus S_g$ = {transit2}

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



```
Find-Safe-Solution(Σ, s_0, S_g)
    ...
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s, a)
        Frontier ← Frontier ∪ (γ(s, a) \ Dom(π))
        if has-unsafe-loops(π, s, Frontier) then
            return failure
    return π
```

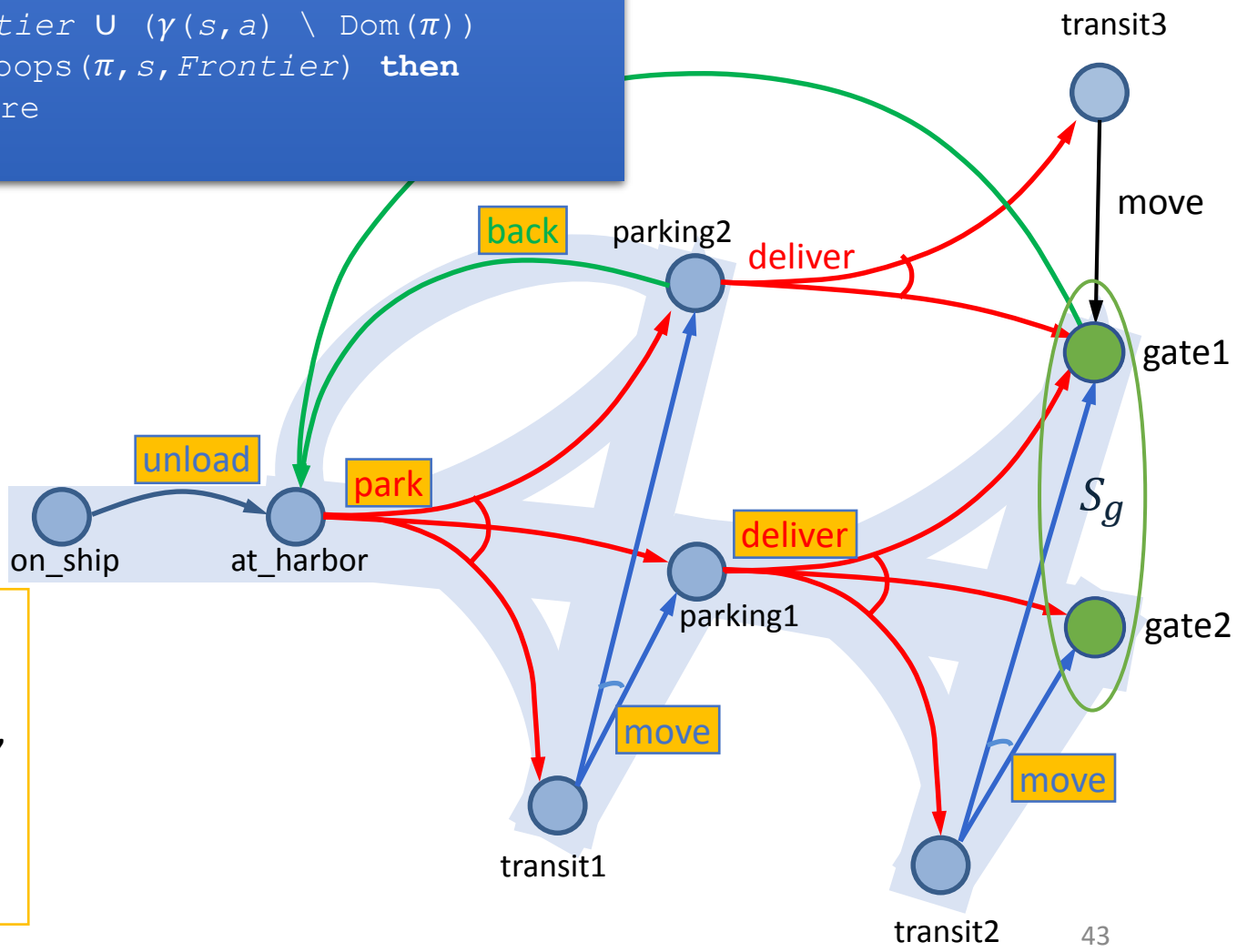
Example

s = transit2

$Frontier \setminus S_g = \emptyset$

Found a solution, so return π

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



Intermediate Summary

- And/Or Graph Search
  - Algorithms for each type of solution
    - unsafe, cyclic safe, acyclic safe

Outline per the Book

5.2 Planning Problem

- Planning domains
- Plans as policies
- Planning problems and solutions

5.3 And/Or Graph Search

- Planning by forward search

5.5 Determinisation Techniques

- Guided planning for safe solutions
- Planning for safe solutions by determinisation

5.6 Online Approaches

- Lookahead
- Lookahead by Determinisation
- Lookahead with a bounded number of steps

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 is not 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 ∈ S_g then
        return ∅
    if Applicable(s_0) = ∅ then
        return failure
    π ← ∅
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        arbitrarily select s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

⇐ not in the book

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

Choose any leaf s that is not 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.

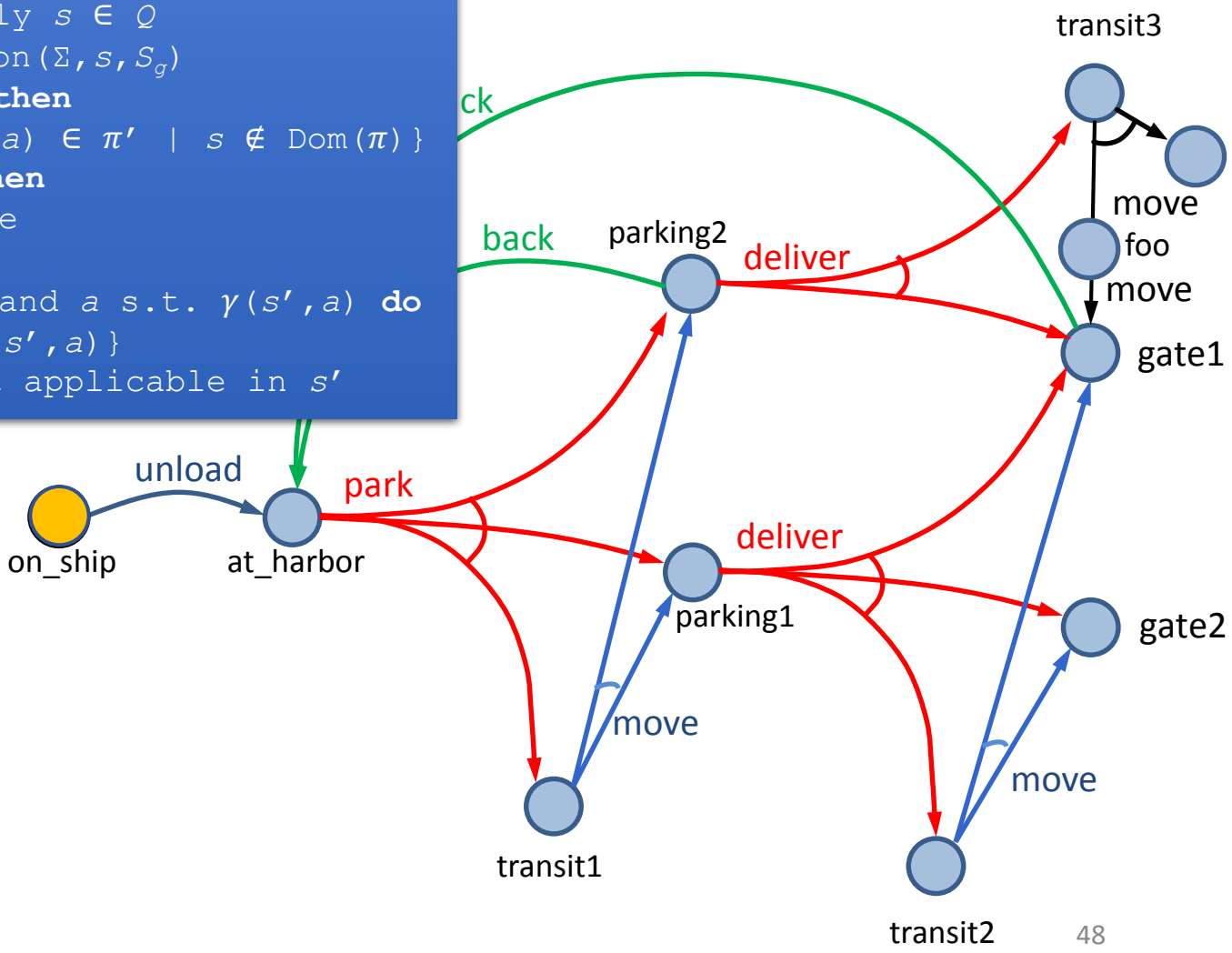
s is unsolvable. For each (s', a) that can produce s, modify π and Σ so we will never use a at s'

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

Example

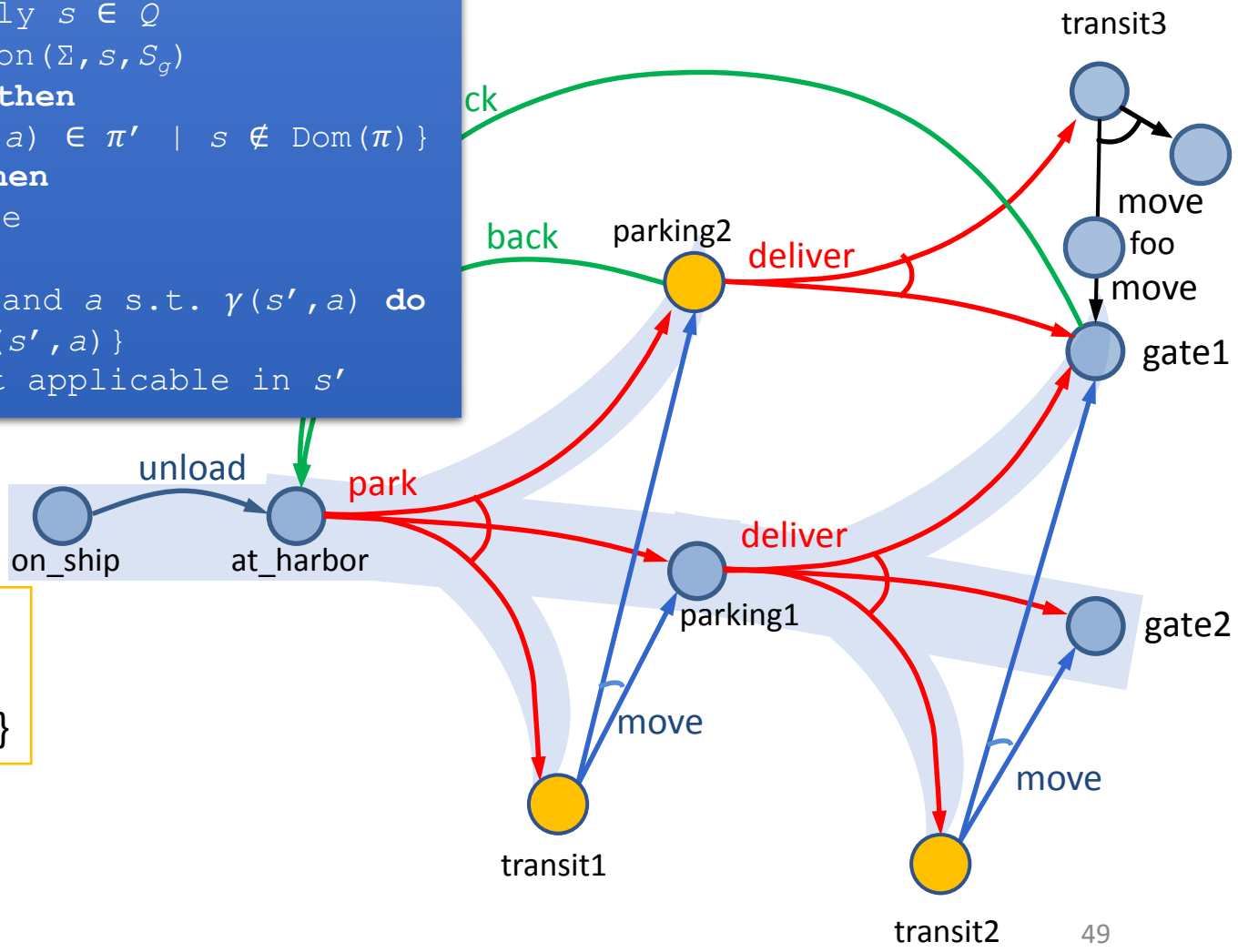
s_0 = on_ship

π = {}



Example

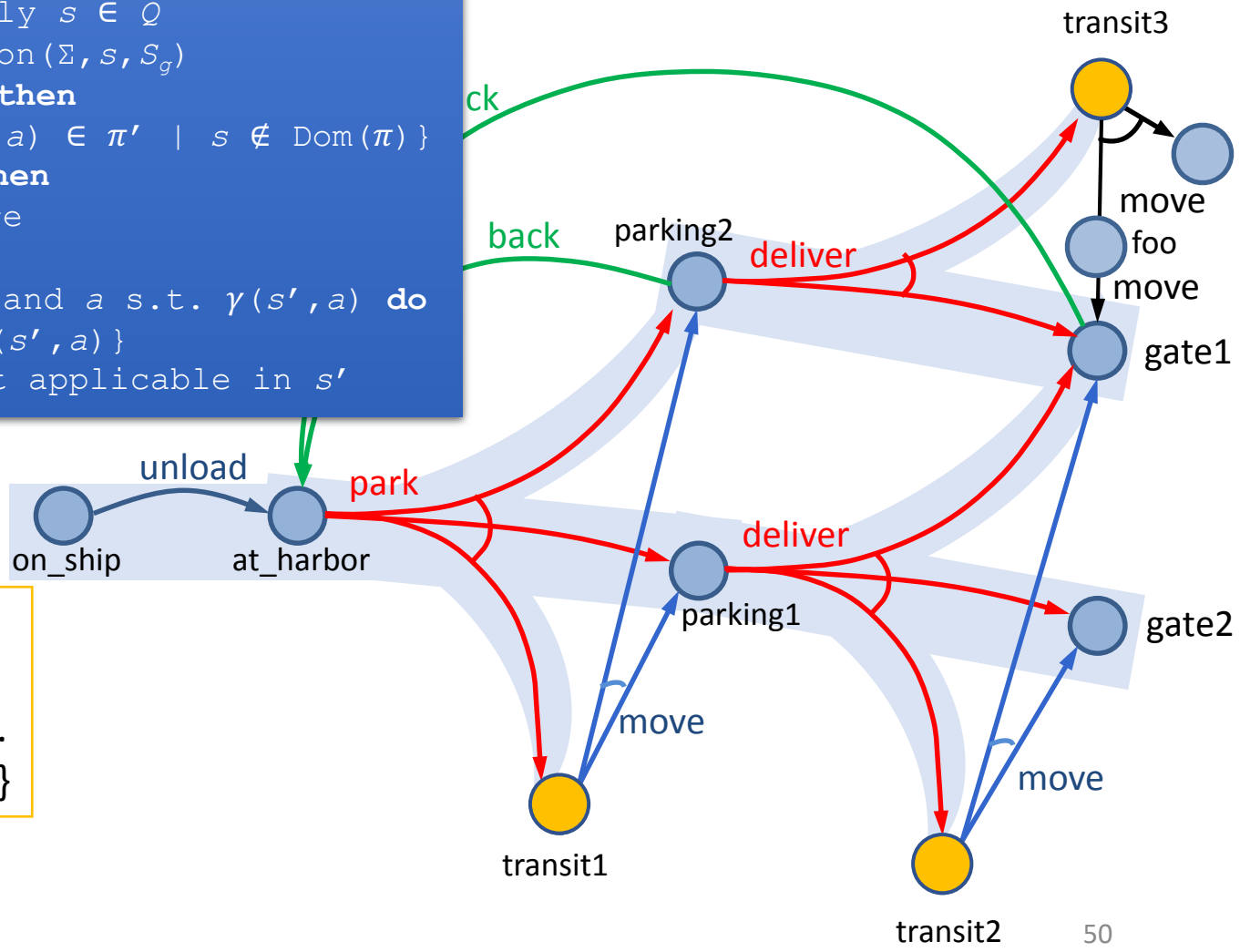
```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```



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

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

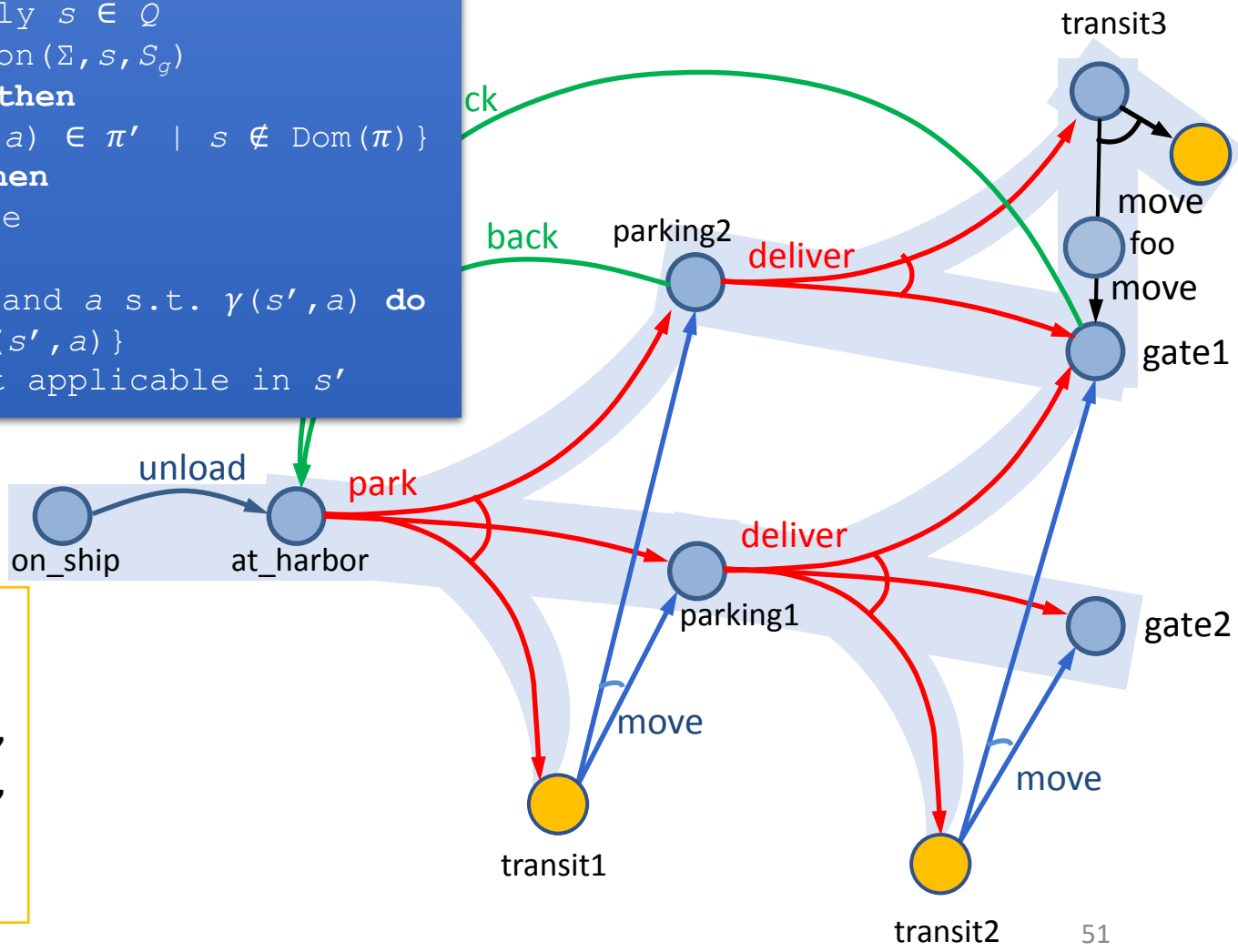
Example



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

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

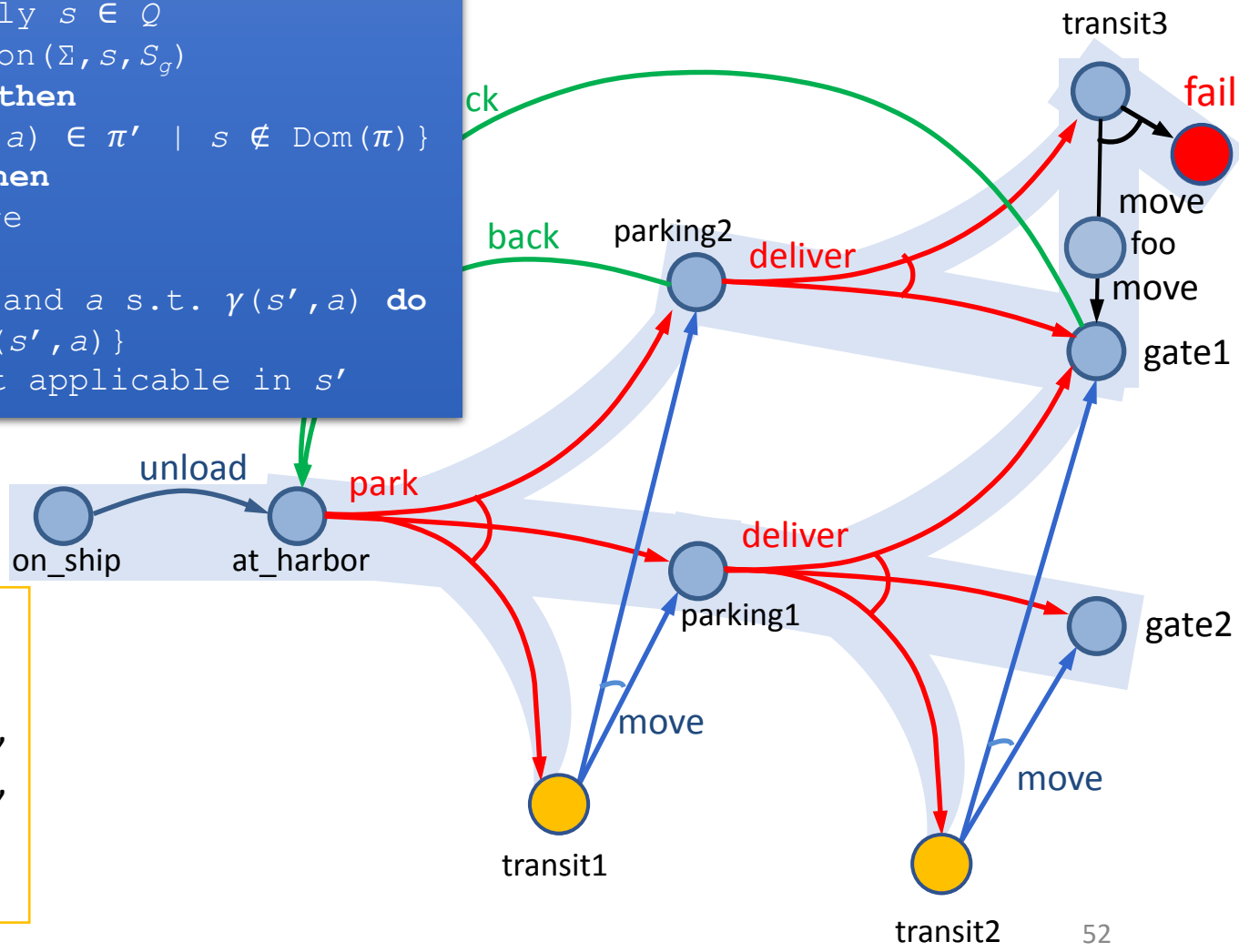
Example



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

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

Example



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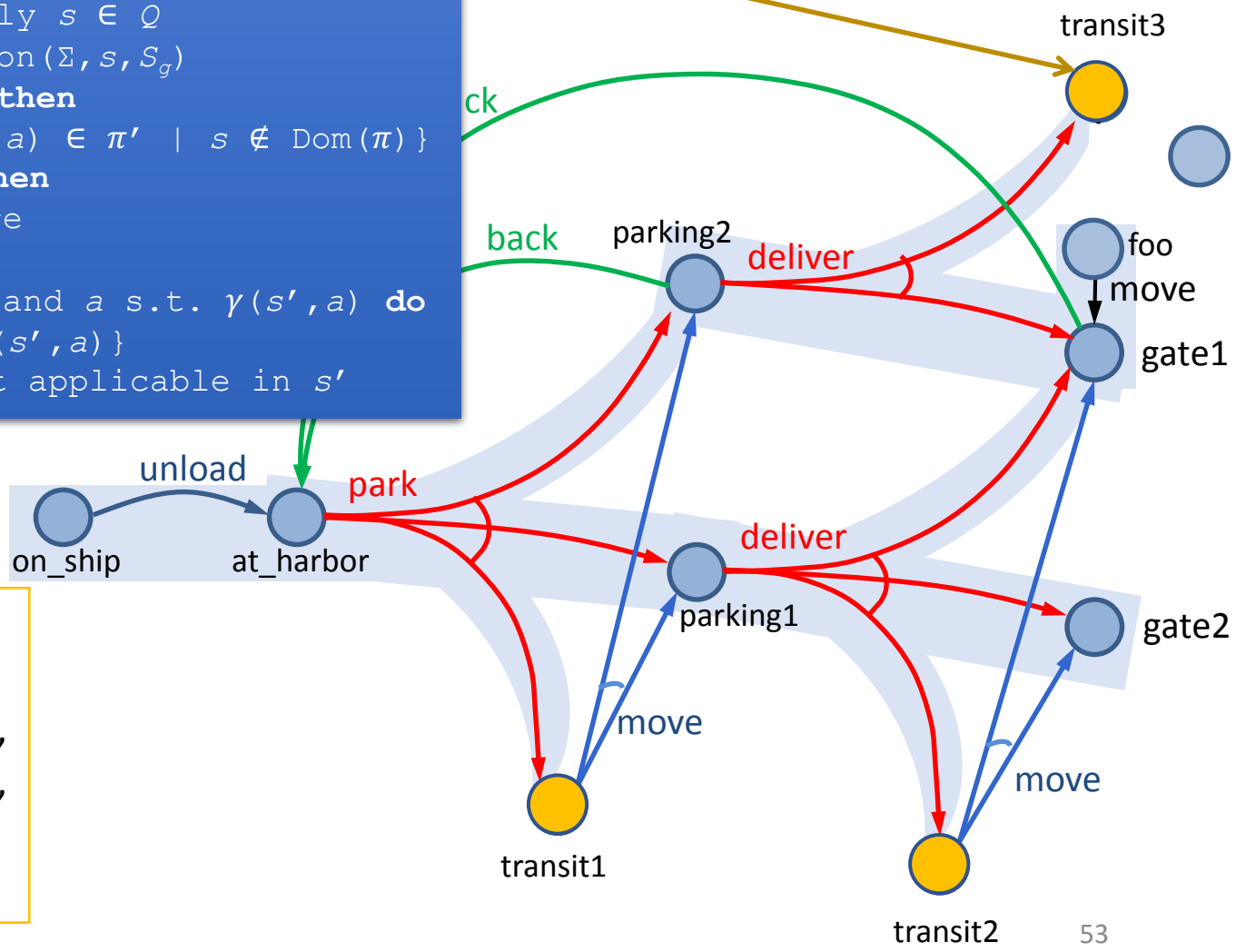
(parking1, deliver),
(parking2, deliver),
(transit3, move),
(foo, move)}

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

Example

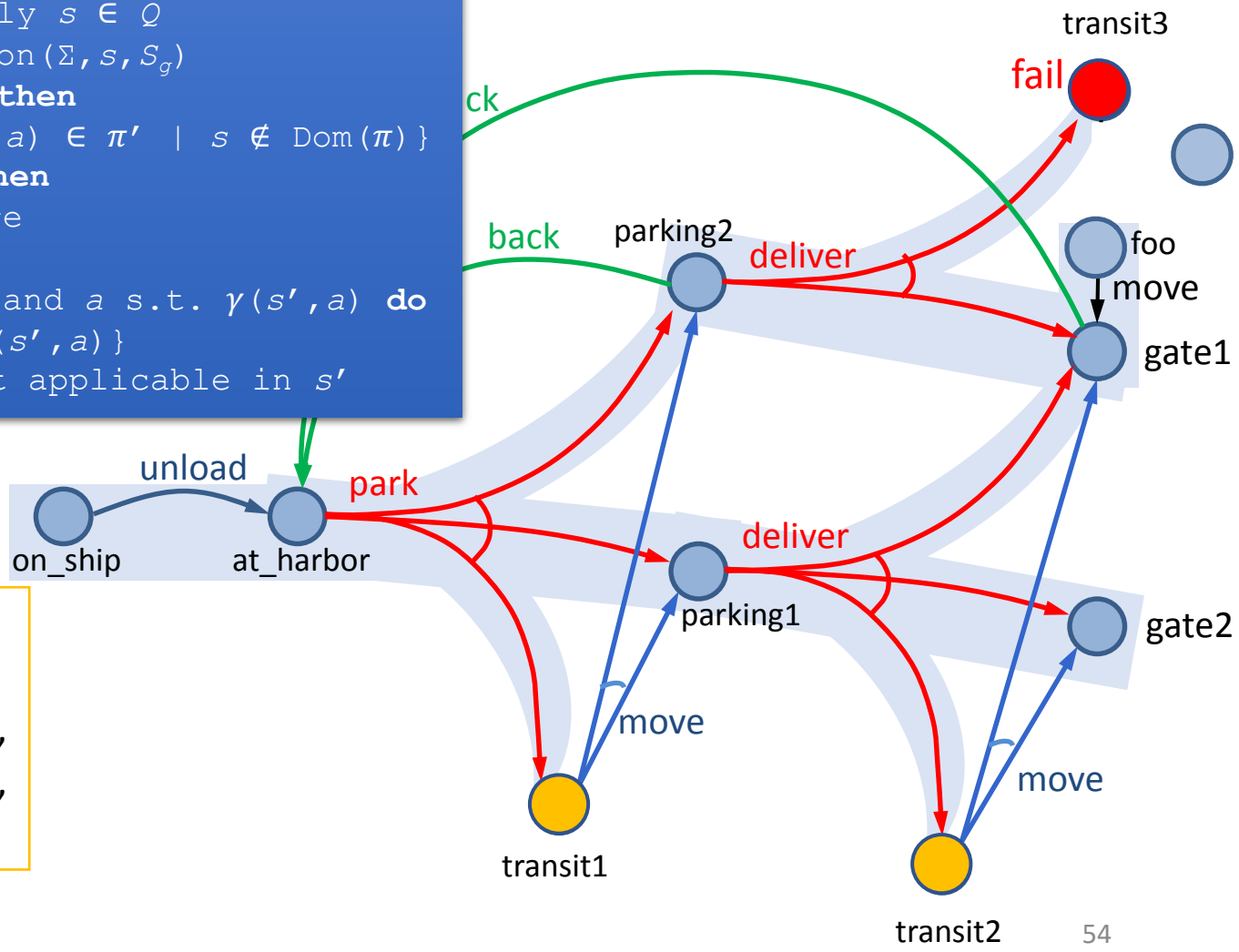
Modify Σ_d to make move inapplicable



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

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

Example

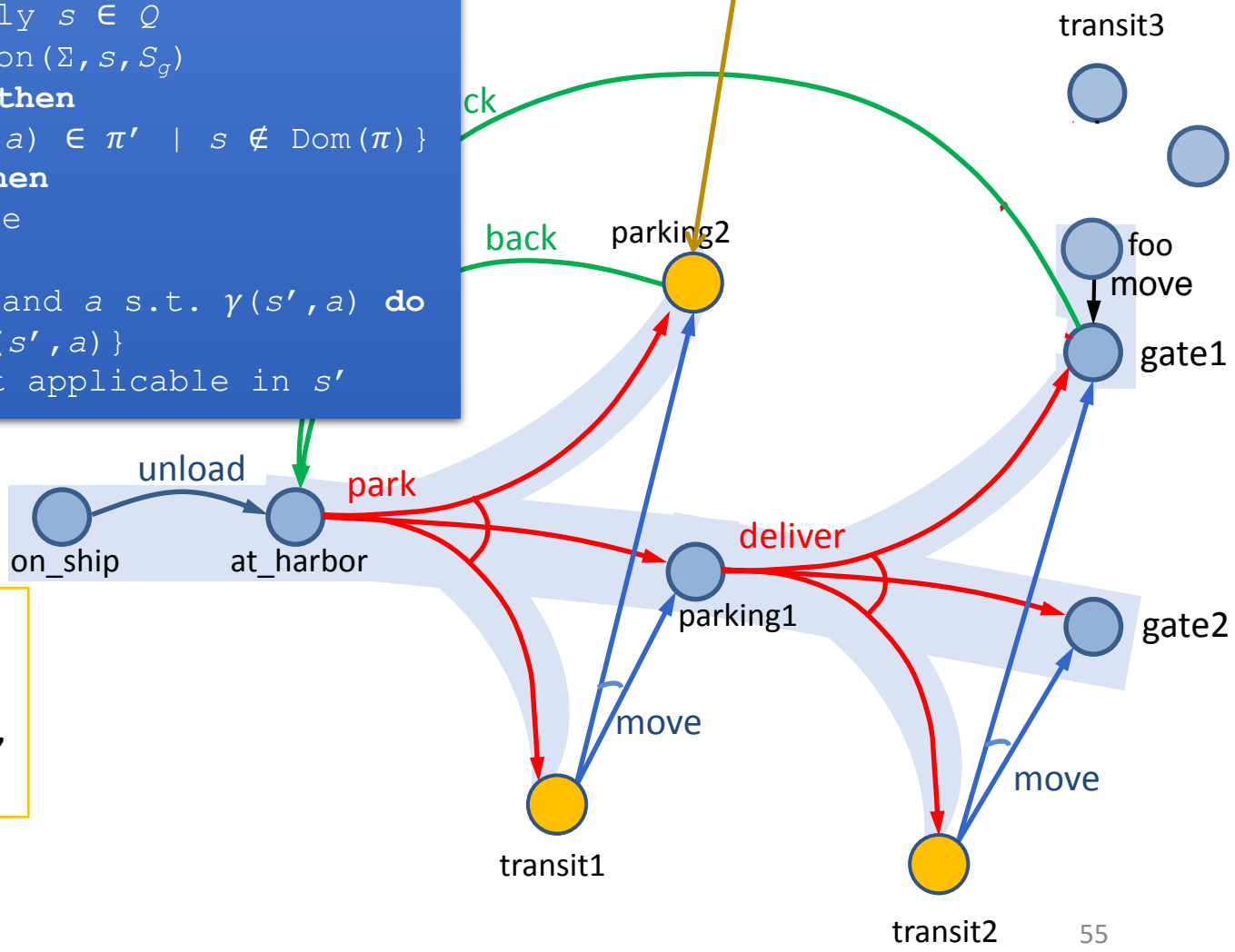


π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(foo, move)}

Example

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

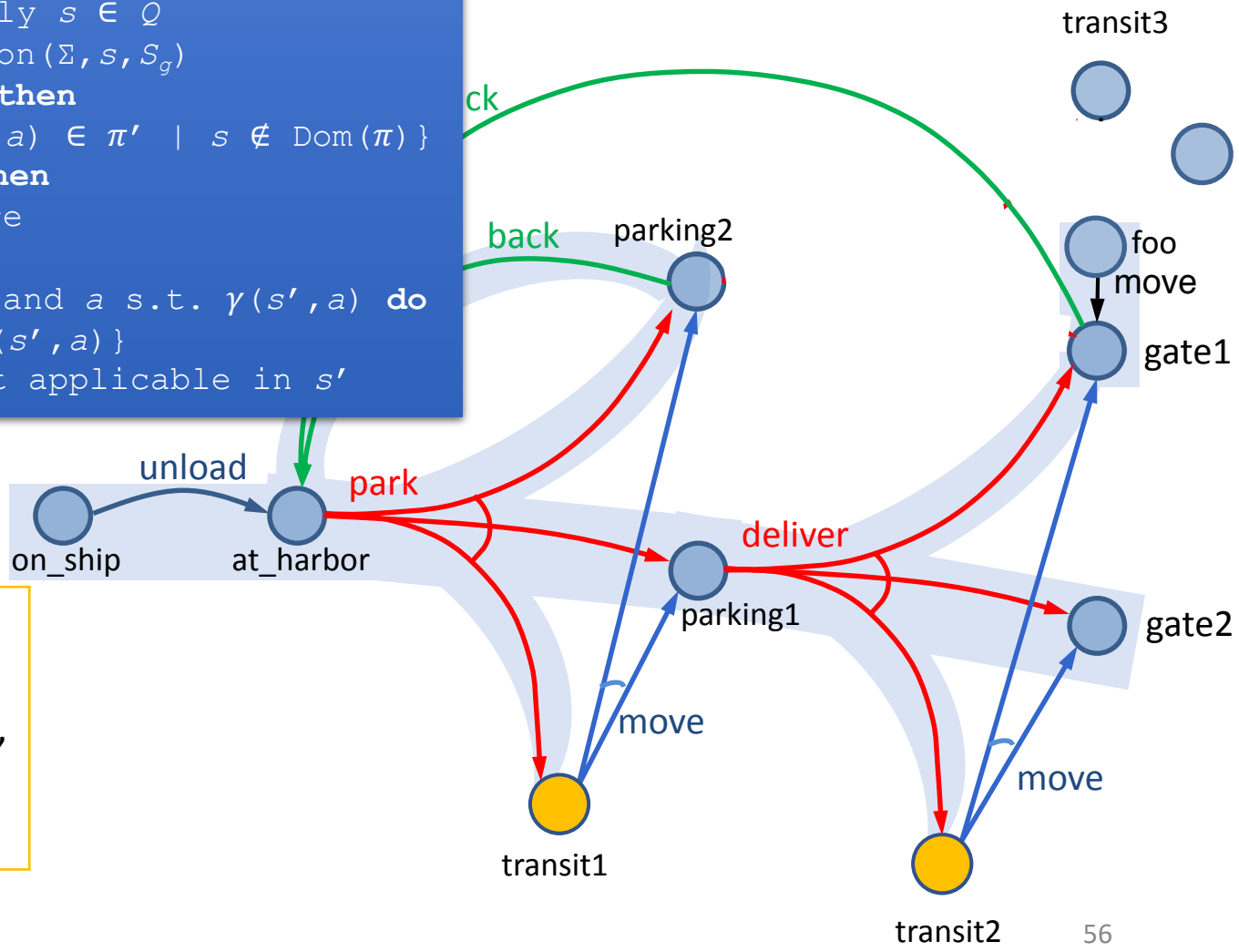
Modify Σ_d to make move inapplicable



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

Example

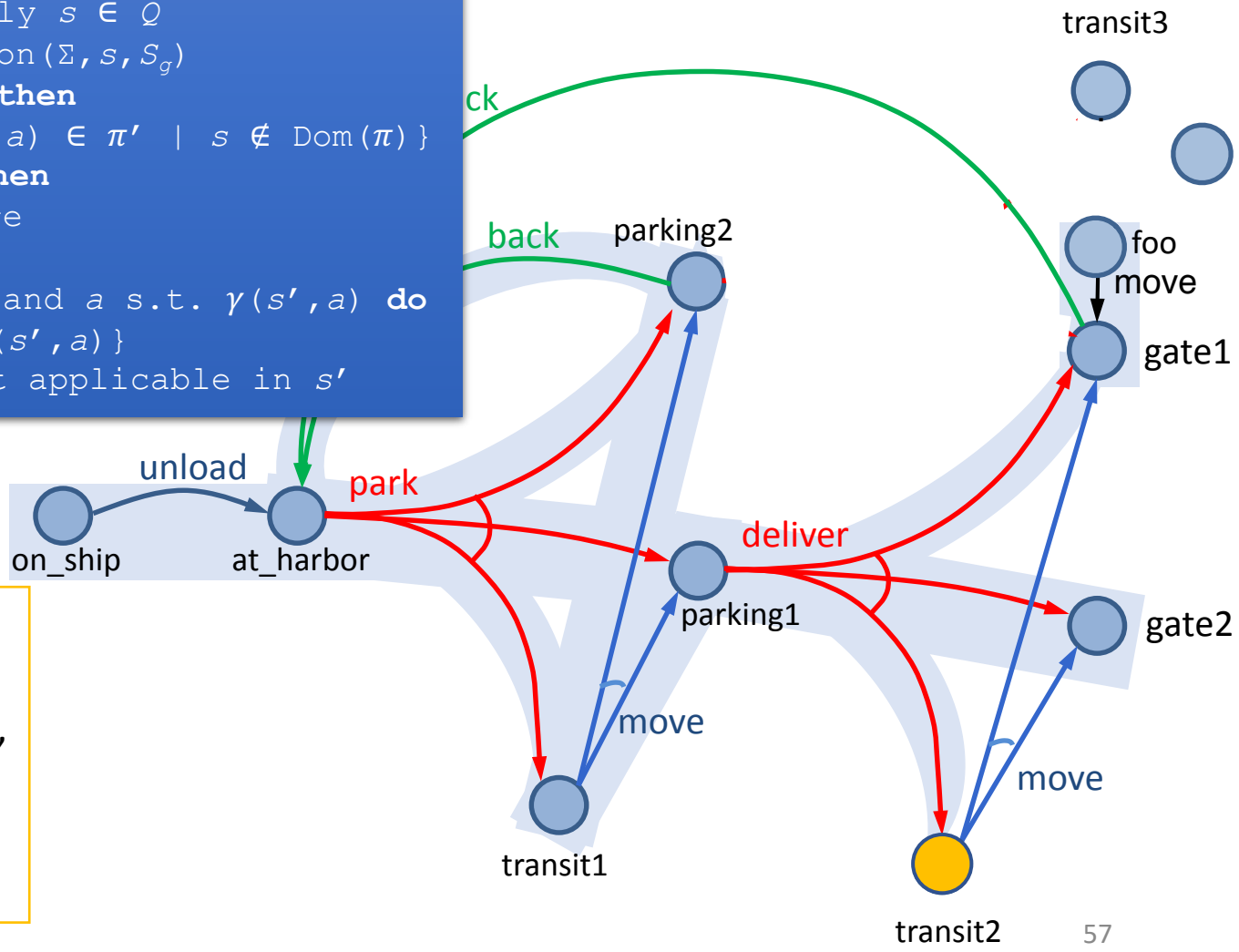
```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```



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

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

Example



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

```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    ...
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
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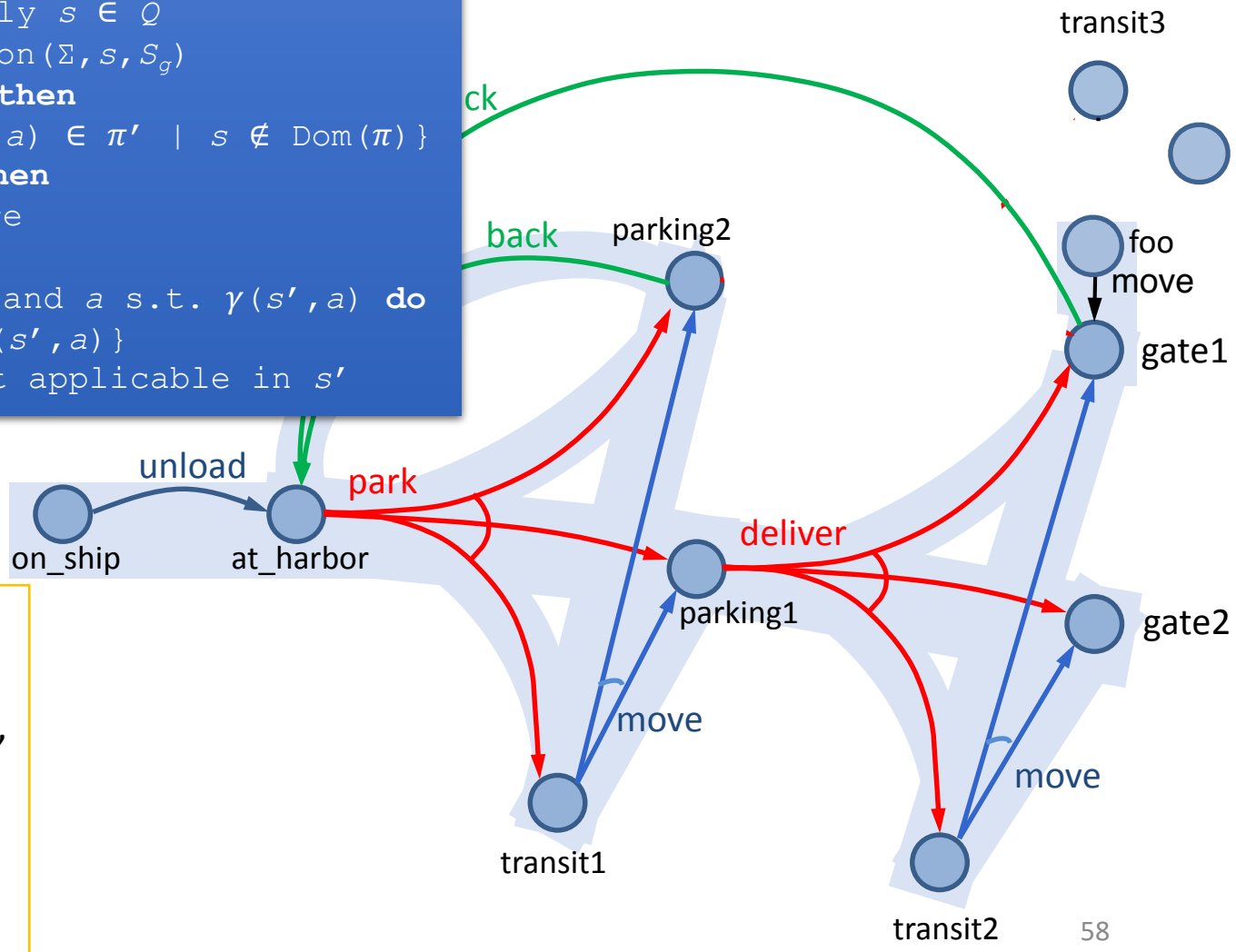
Example



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Guided-Find-Safe-Solution(Σ, s_0, S_g)
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        Q ← leaves(s_0, π) \ S_g
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        else
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                π ← π \ {(s',a)}
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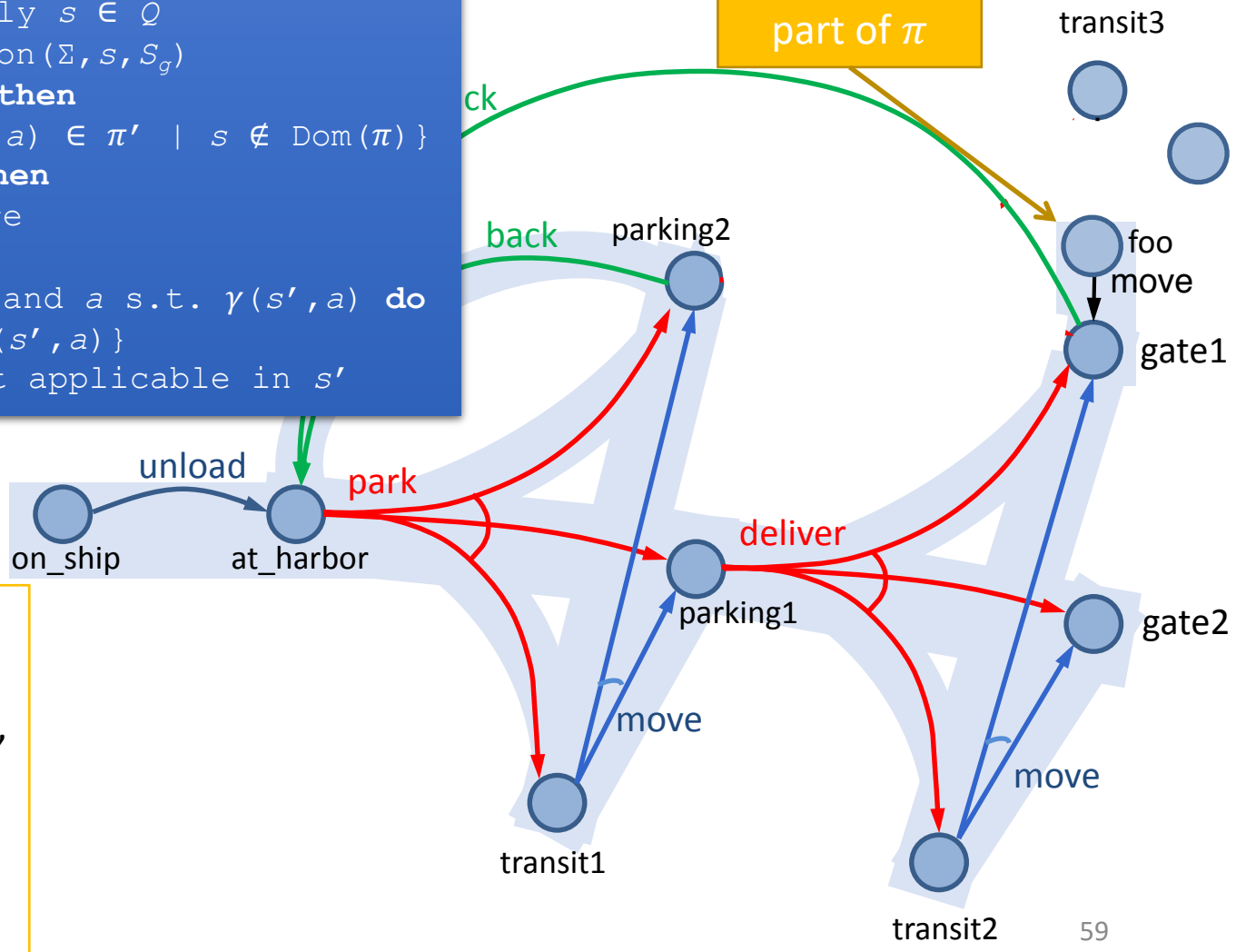
```

Example

Remove unreachable part of π



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

Determinisation

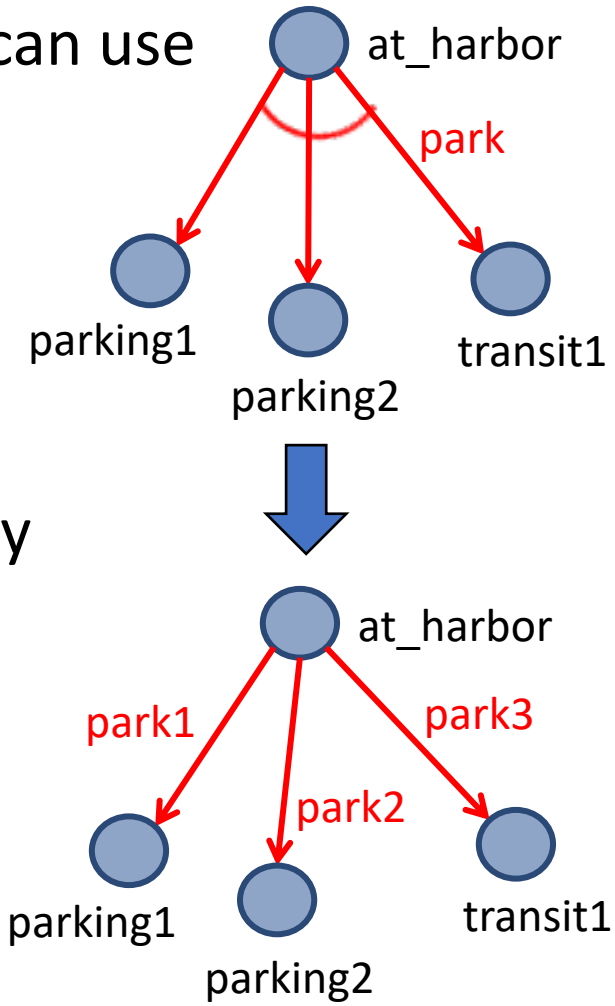
```
Guided-Find-Safe-Solution(Σ, s_0, S_g)
    if s_0 ∈ S_g then
        return ∅
    if Applicable(s_0) = ∅ then
        return failure
    π ← ∅
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ, s, S_g)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

- How to implement it?
  - Need implementation of `Find-Solution`
  - Need it to be very efficient
    - Called many times
- Idea: instead, use a classical planner
  - Any algorithm from Chapter 2
  - Efficient algorithms, search heuristics
- For that, determinise actions

Determinisation

- Convert the nondeterministic actions into something the classical planner can use
- Determinise
  - 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
  - $\{(s_0, \boldsymbol{a}_1), (s_1, \boldsymbol{a}_2), \ldots, (s_{n-1}, \boldsymbol{a}_n)\}$

  where
  - each $\boldsymbol{a}_i$ is the nondeterministic action whose determinisation includes a_i
  - $s_i \in \gamma(s_{i-1}, \boldsymbol{a}_i)$



Determinisation

- Nondeterministic planning problem $P = (\Sigma, s_0, S_g)$
- Determinisation $P_d = (\Sigma_d, s_0, S_g)$
- Classical planner returns a solution for P_d
  - 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
  - $\{(s_0, \boldsymbol{a}_1), (s_1, \boldsymbol{a}_2), \ldots, (s_{n-1}, \boldsymbol{a}_n)\}$

  where
  - each $\boldsymbol{a}_i$ is the nondeterministic action whose determinisation includes a_i
  - each $s_i \in \gamma(s_{i-1}, \boldsymbol{a}_i)$

```
Plan2policy(p=⟨a_1,...,a_n⟩,s)
    π ← ∅
    for i from 1 to n do
        π ← π ∪ {s,det2nondet(a_i)}
        s ← γ_d(s,a_i)
    return π
```

Guided-Find-Safe-Solution

```
Find-Safe-Solution-by-Determinisation(Σ, s_0, S_g)
    if s_0 ∈ S_g then
        return ∅
    if Applicable(s_0) = ∅ then
        return failure
    π ← ∅
    Σ_d ← mk-deterministic(Σ)
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σ_d, s, S_g)
        if p' ≠ fail then
            π ← Plan2policy(p', s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s', a) do
                π ← π \ {(s', a)}
                make the actions in the
                        determinisation not
                        applicable in s'
```

Same as Guided-Find-Safe-Solution.

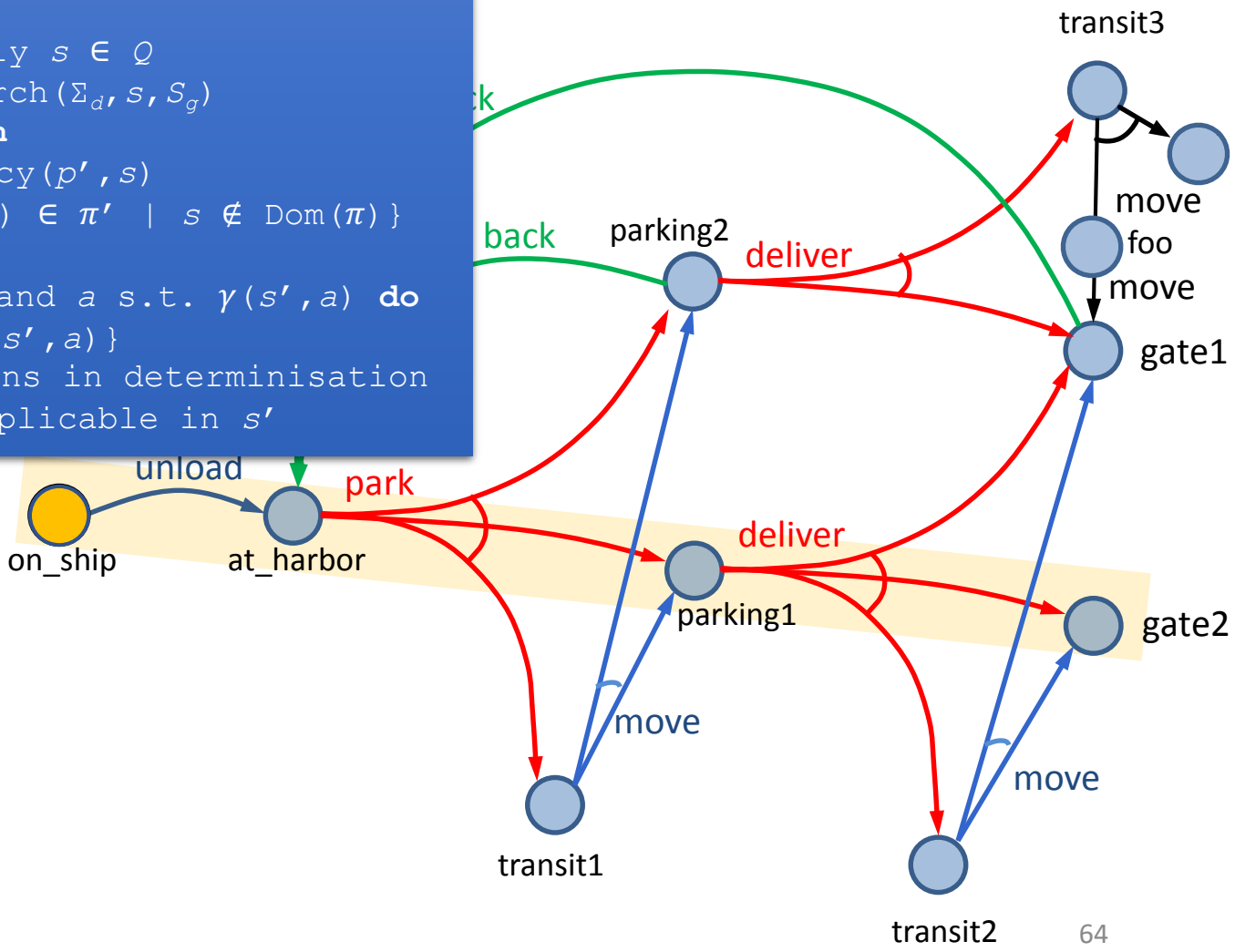
Any classical planner that does not return cyclic plans.

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 will never use a at s'.

Example

```
Find-Safe-Solution-by-Determinisation(Σ, s_0, S_g)
    ...
    Σ_d ← mk-deterministic(Σ)
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σ_d, s, S_g)
        if p' ≠ fail then
            π ← Plan2policy(p', s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```



Example

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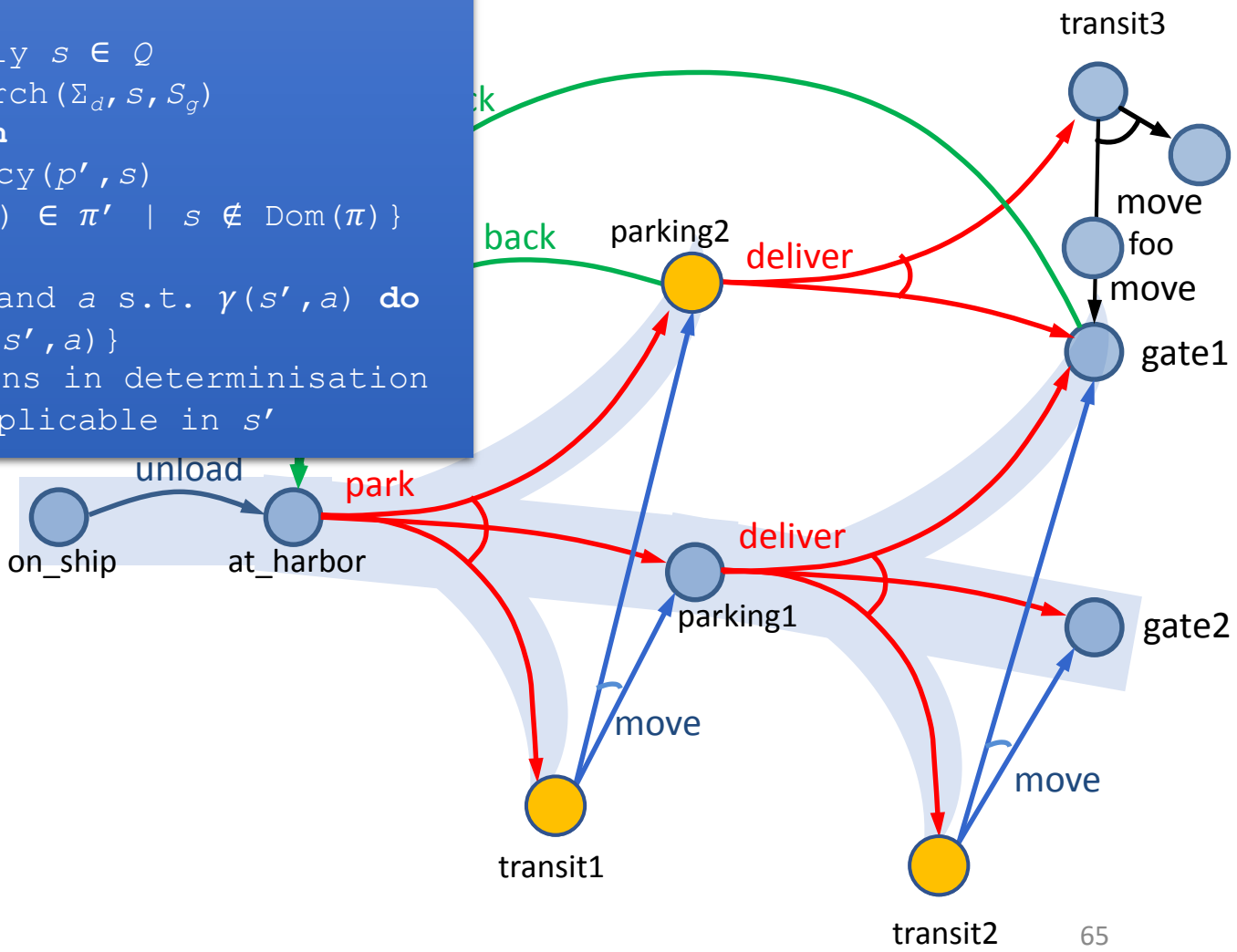

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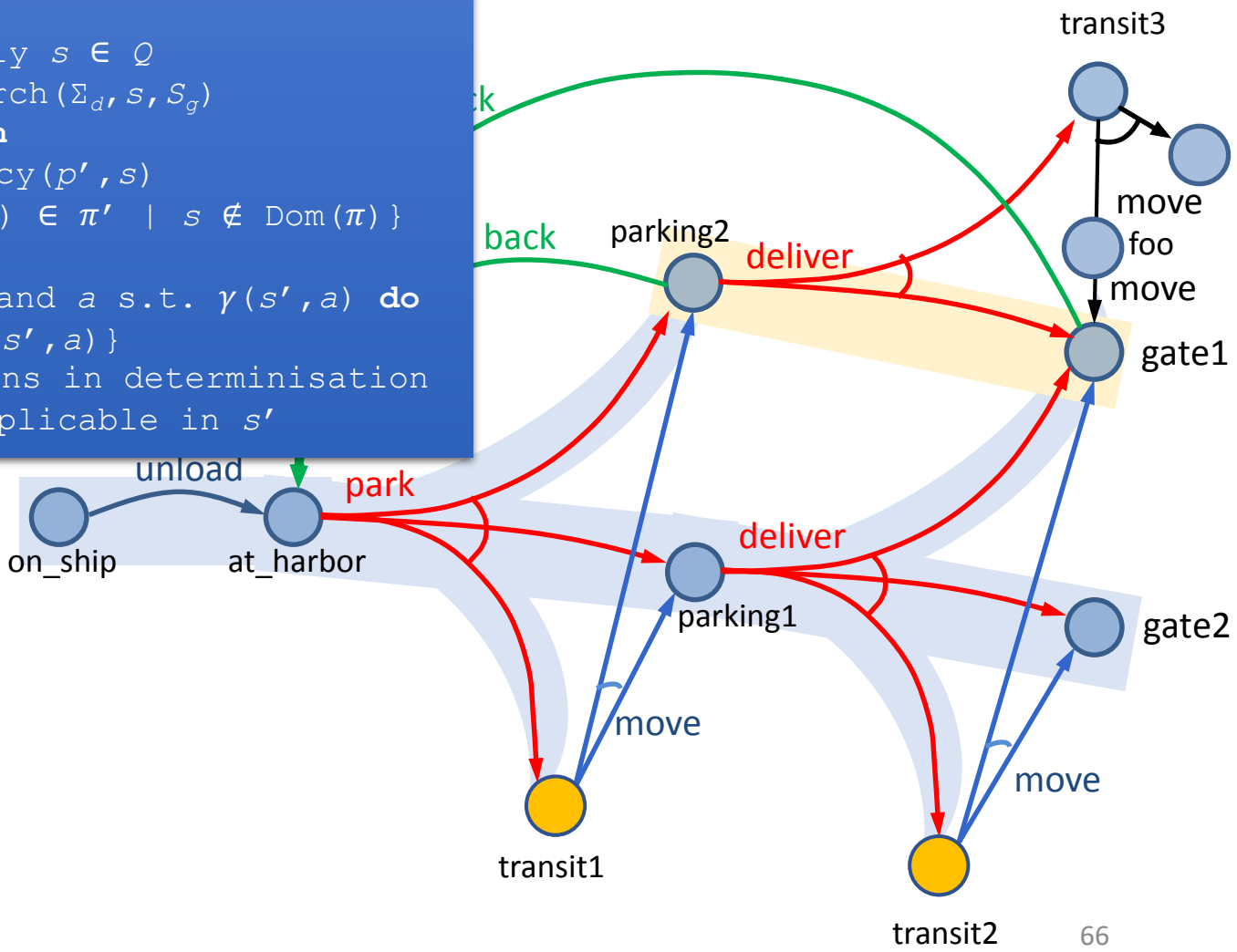

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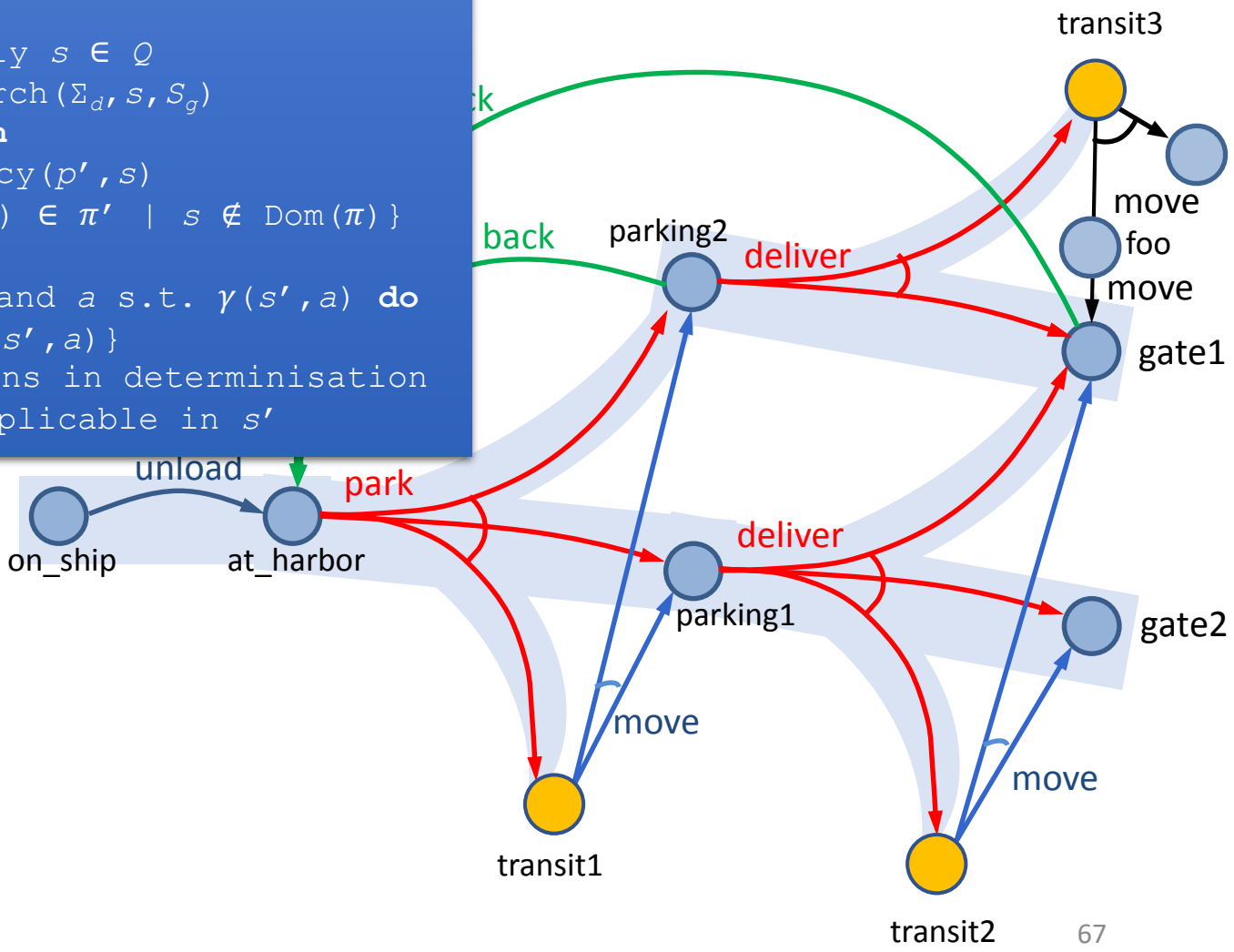

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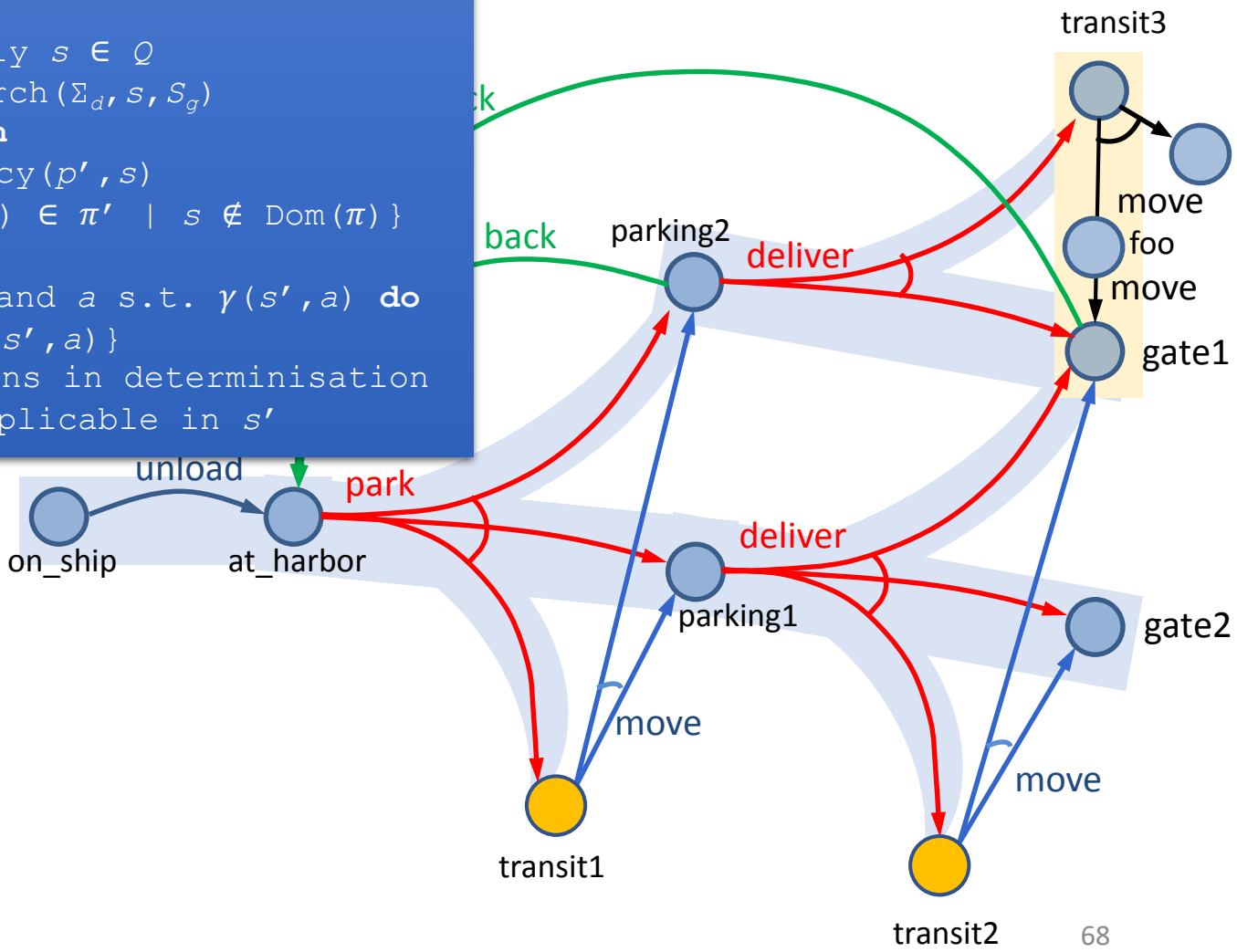
```



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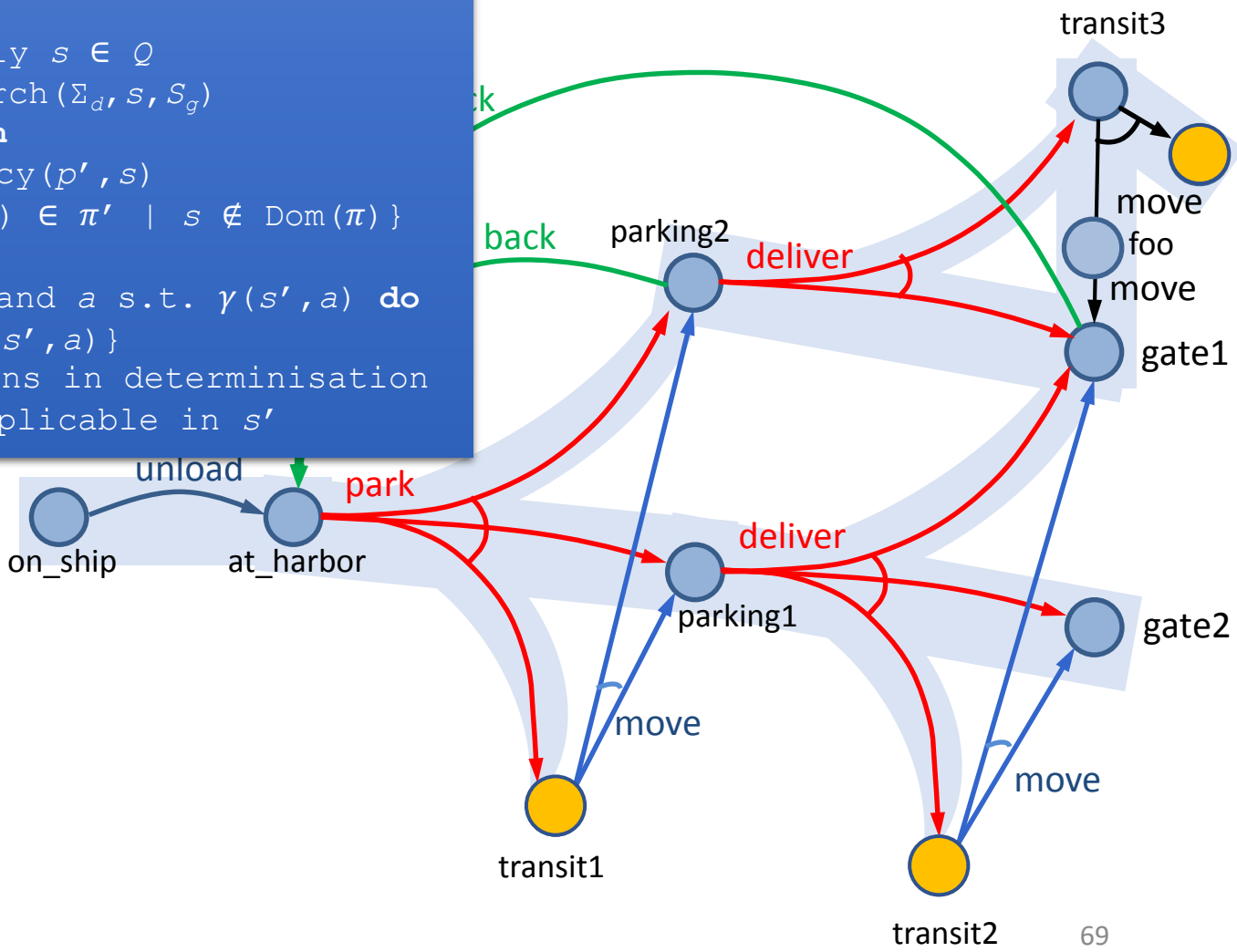

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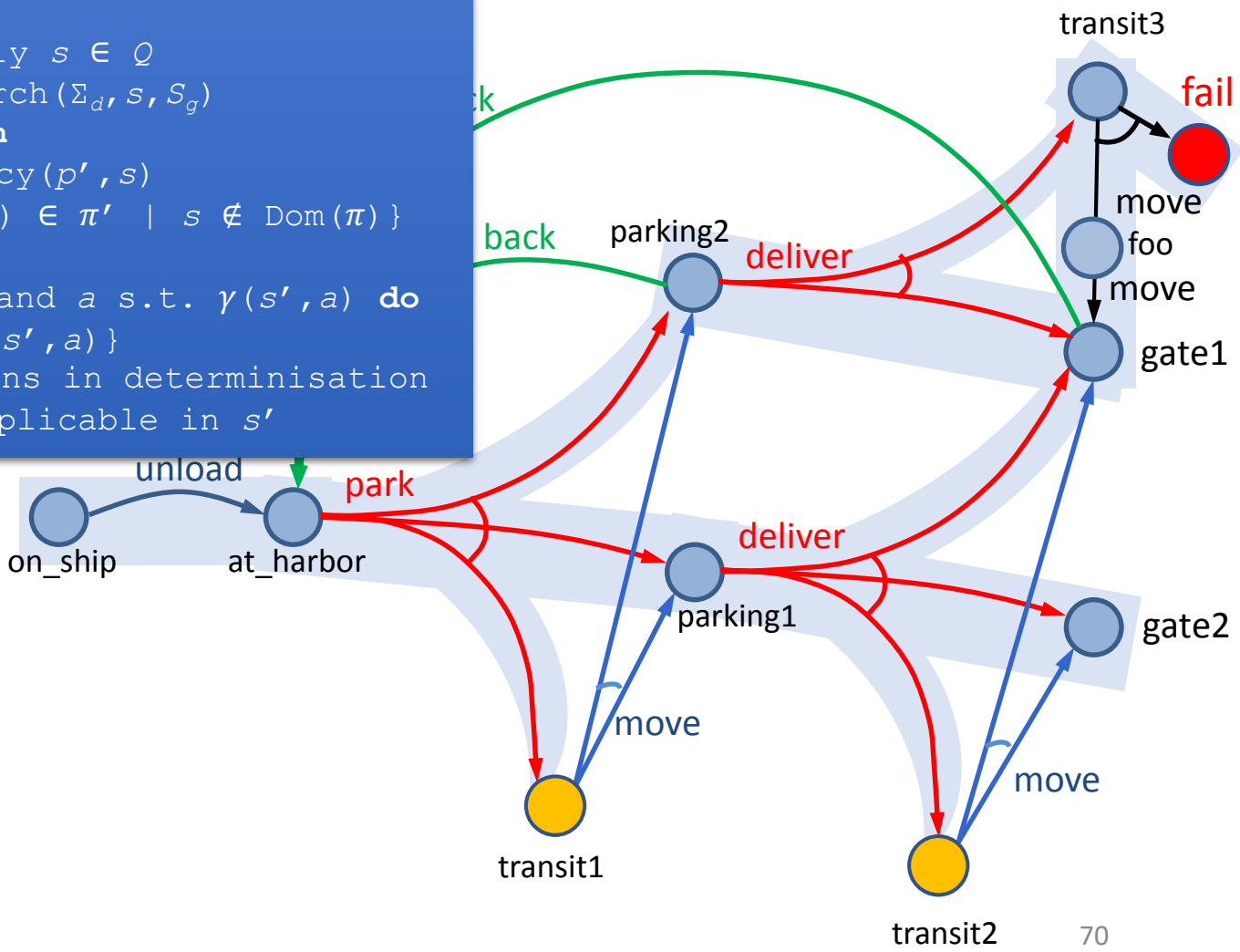

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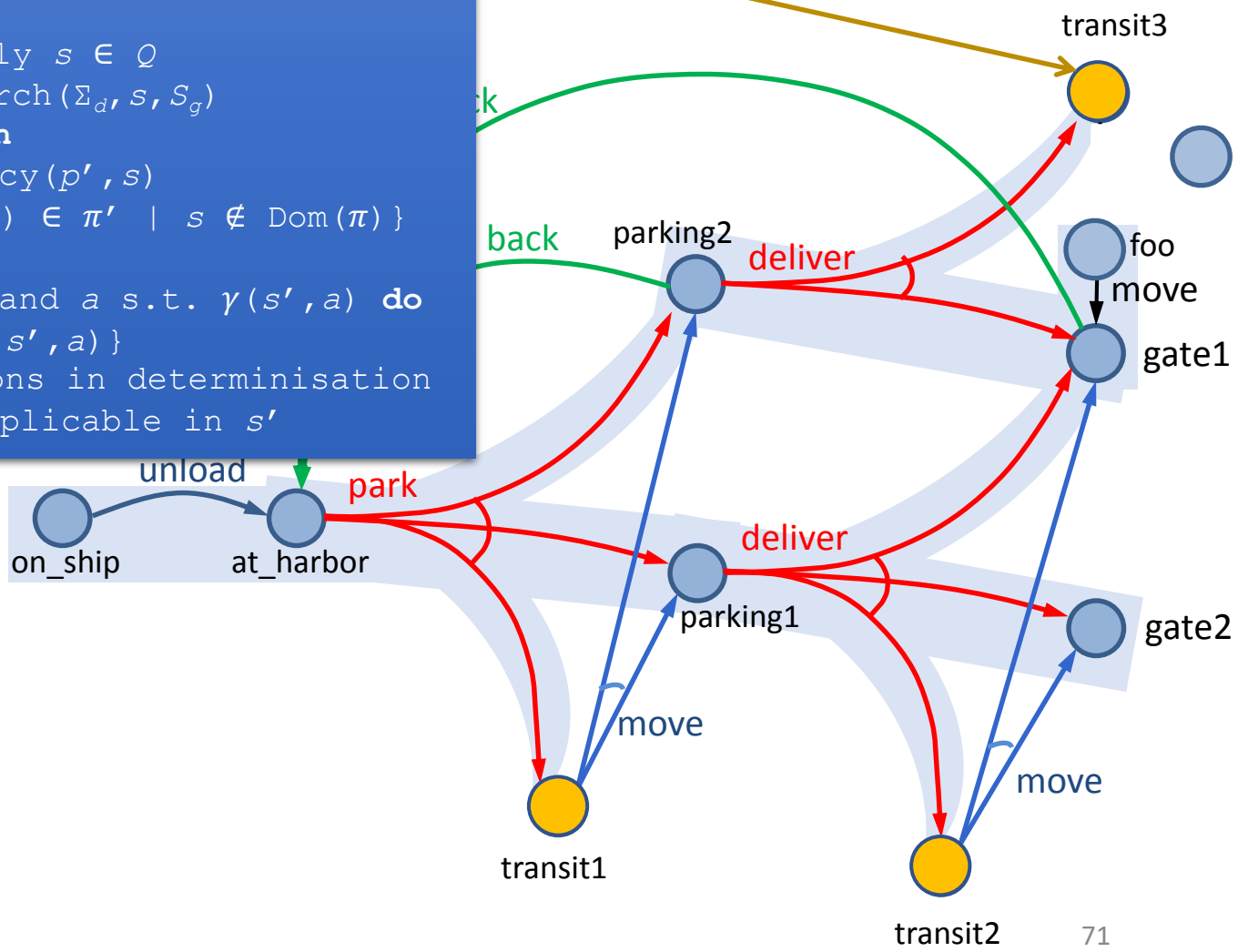
```

Modify Σ_d to make move inapplicable



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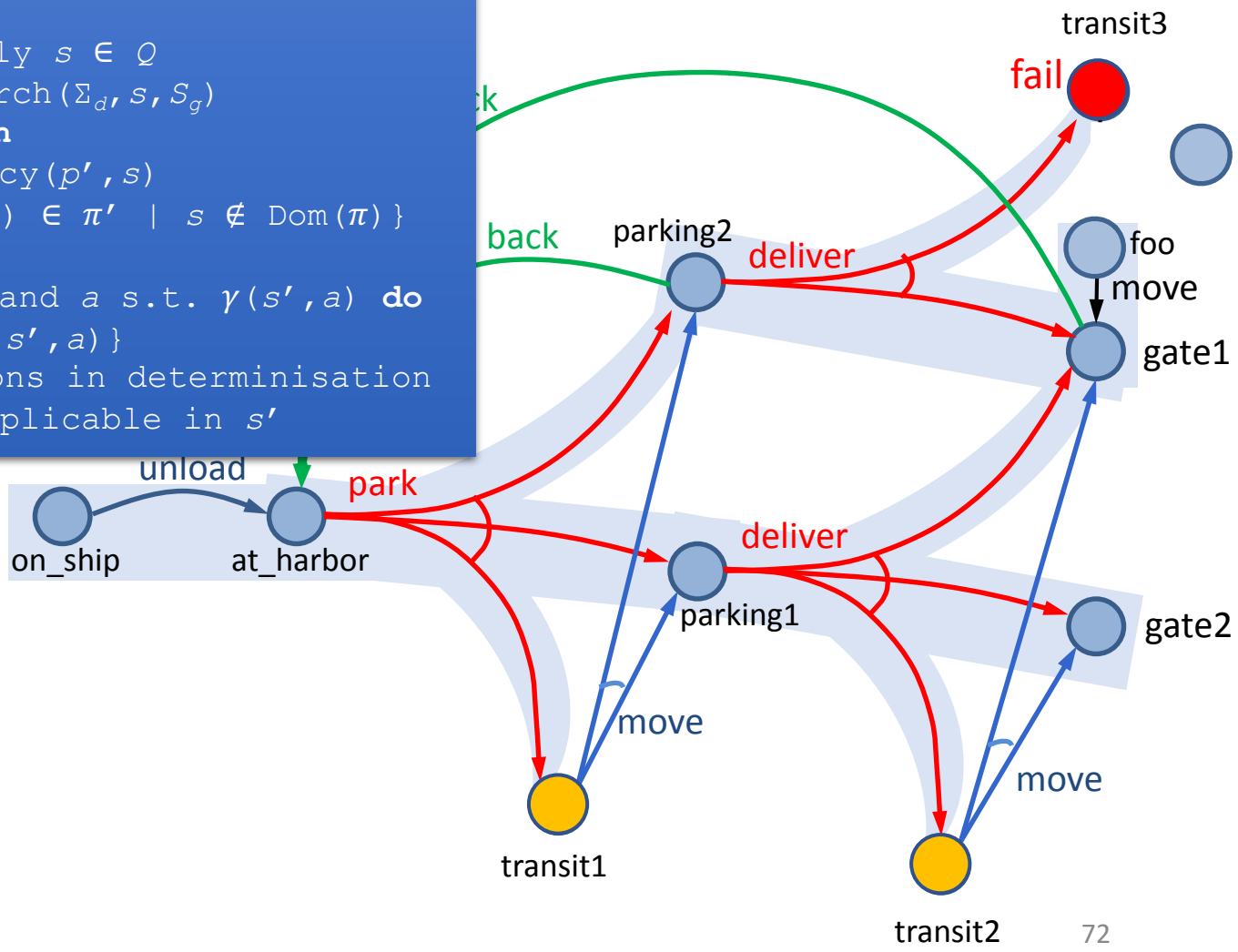

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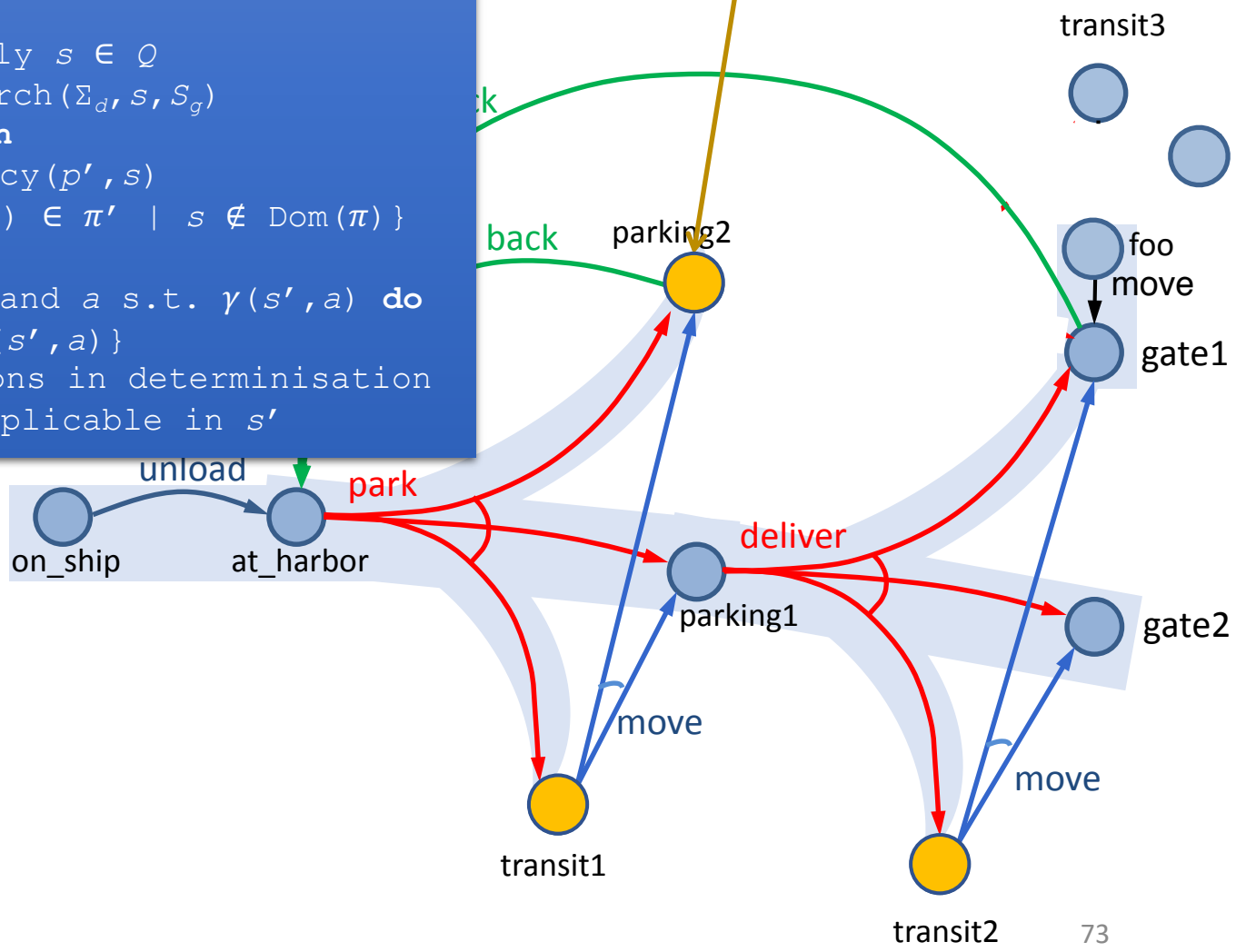

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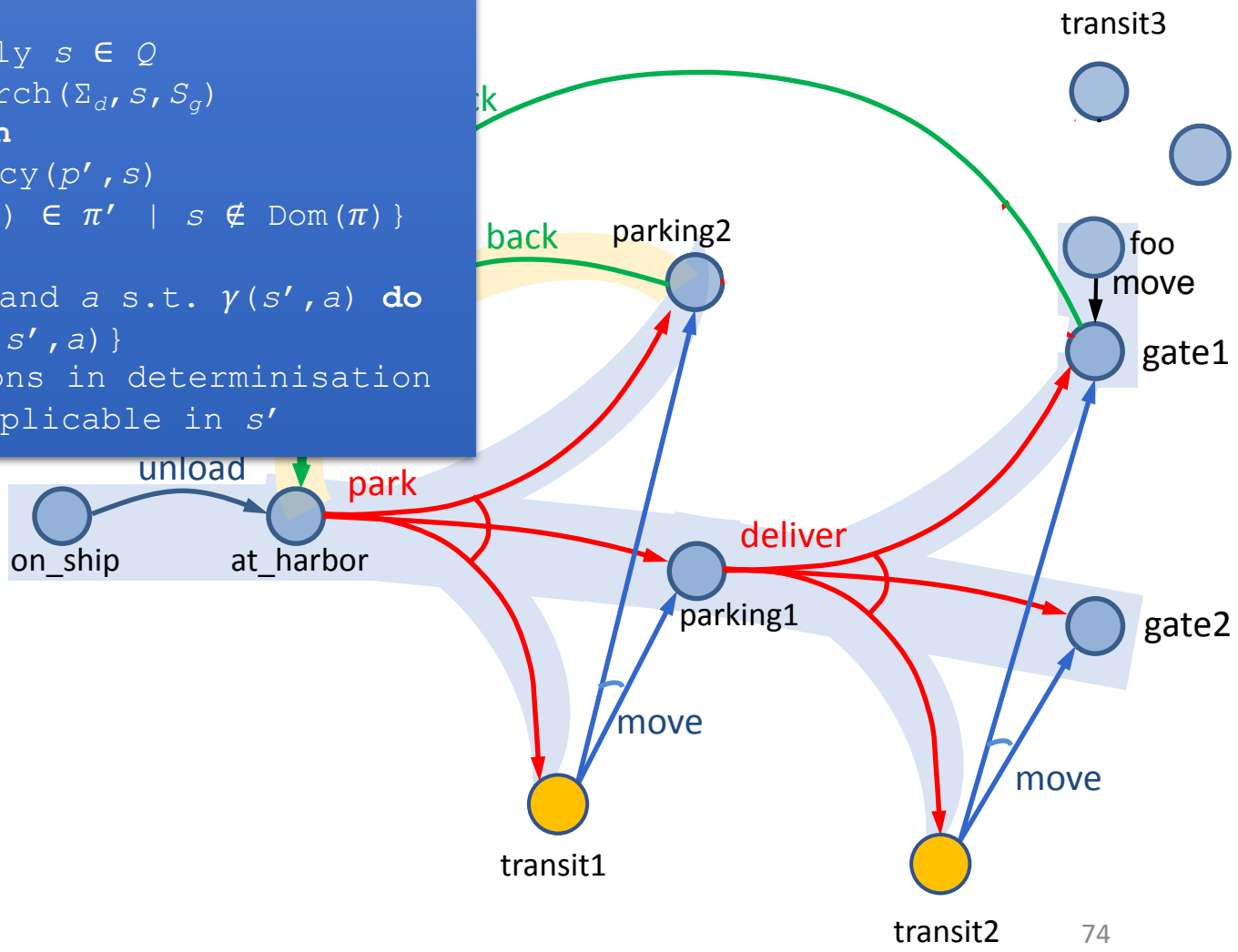

Example

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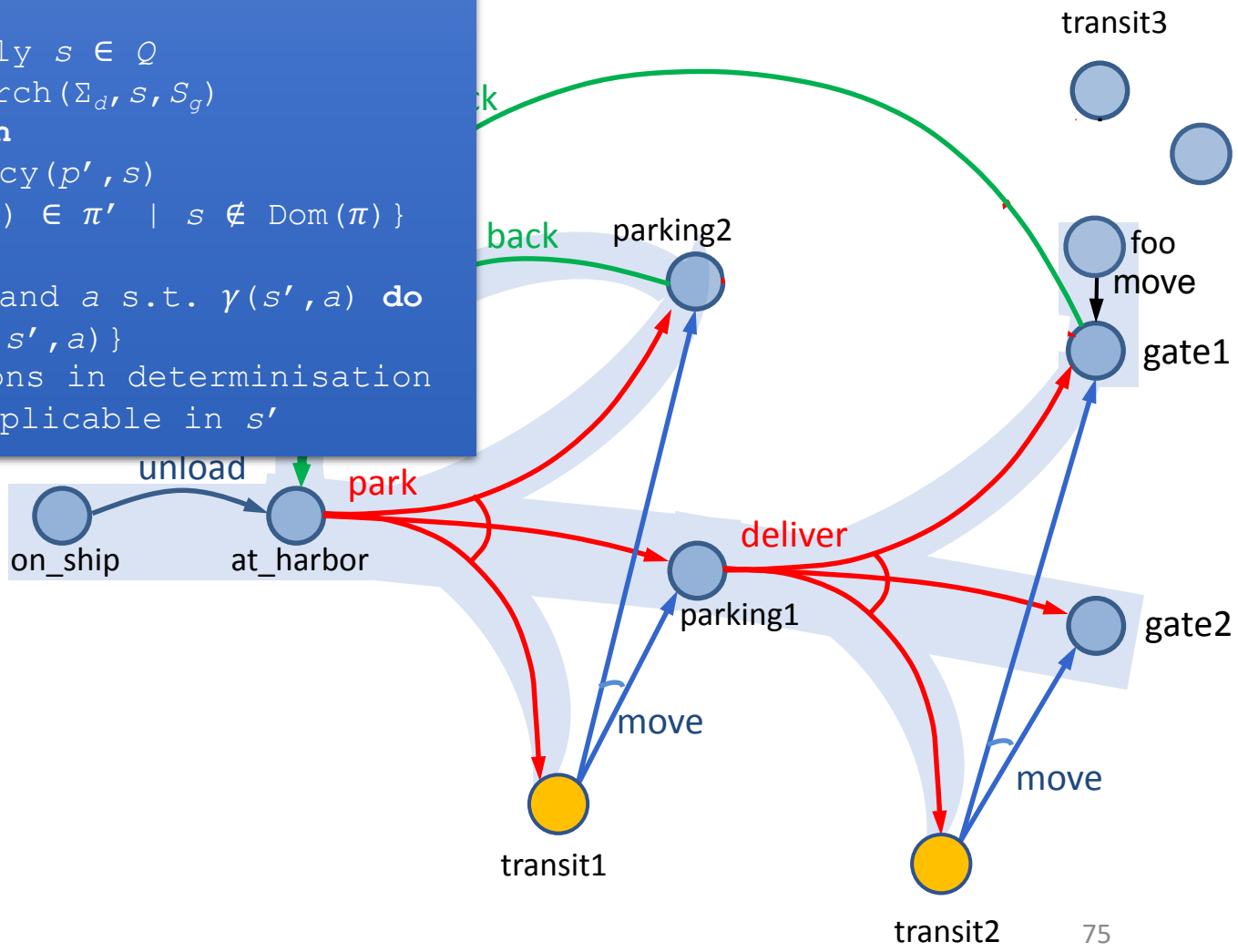

Example

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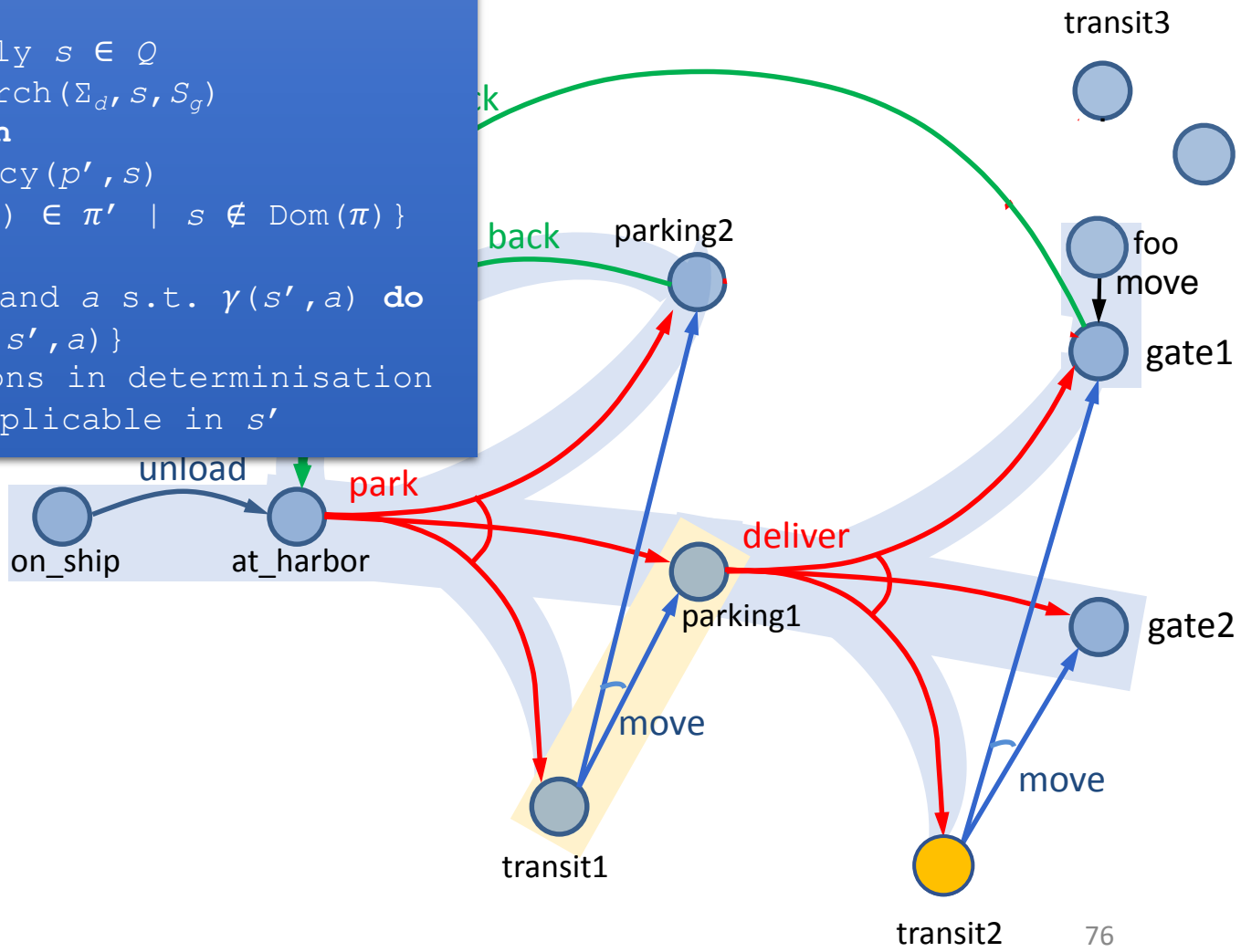

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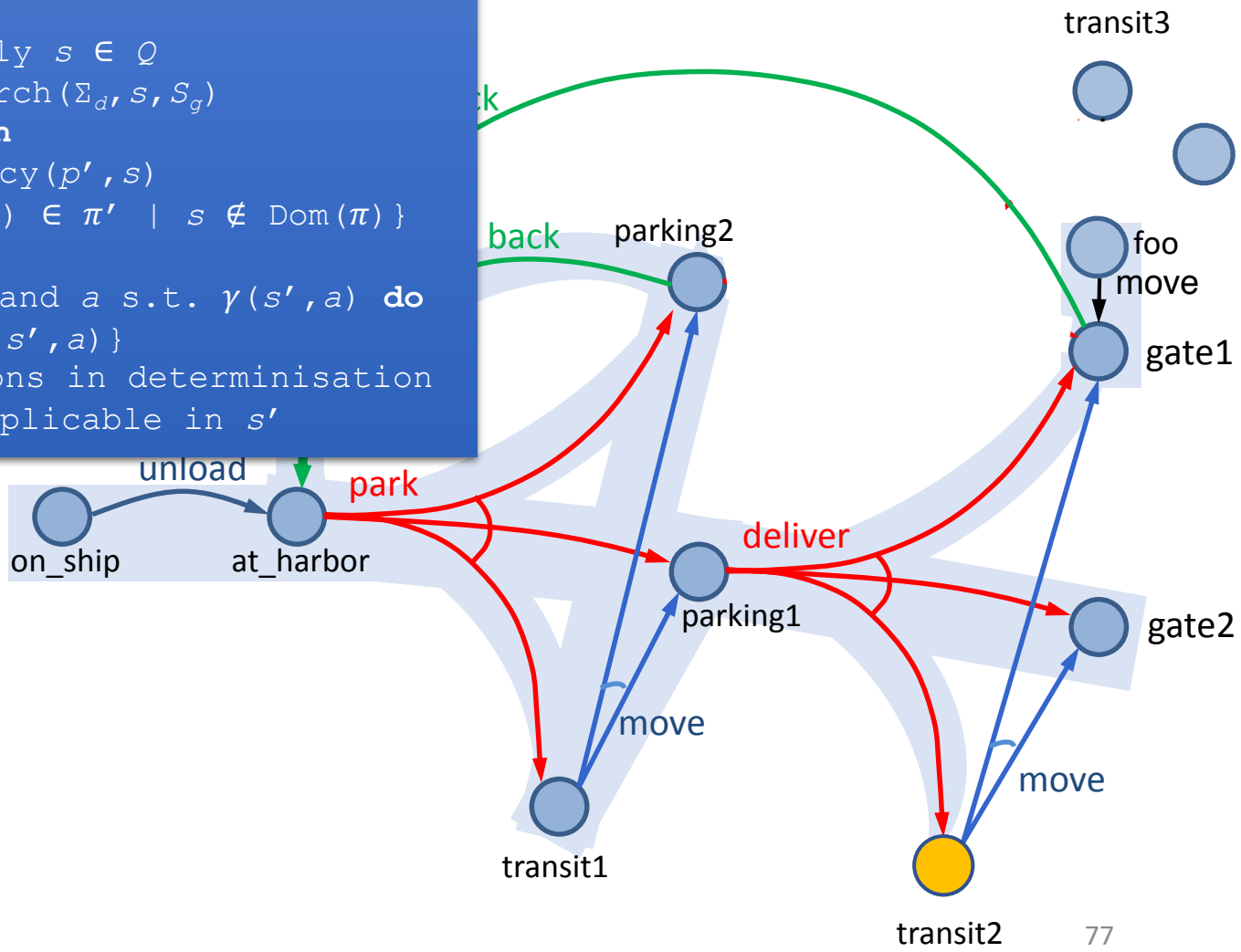

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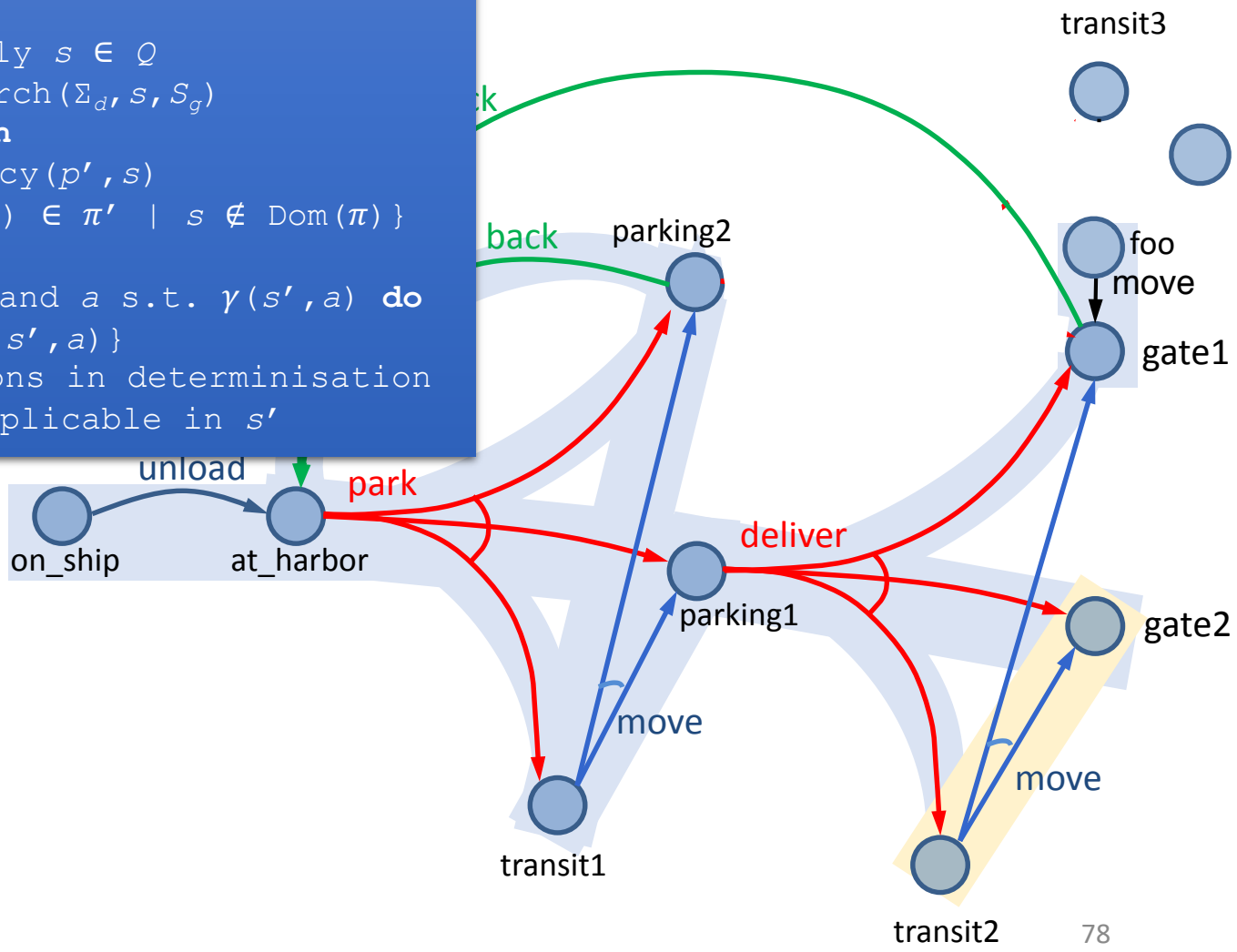
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σ_d, s, S_g)
        if p' ≠ fail then
            π ← Plan2policy(p', s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```



Example

```
Find-Safe-Solution-by-Determinisation(Σ, s_0, S_g)
    ...
    Σ_d ← mk-deterministic(Σ)
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σ_d, s, S_g)
        if p' ≠ fail then
            π ← Plan2policy(p', s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
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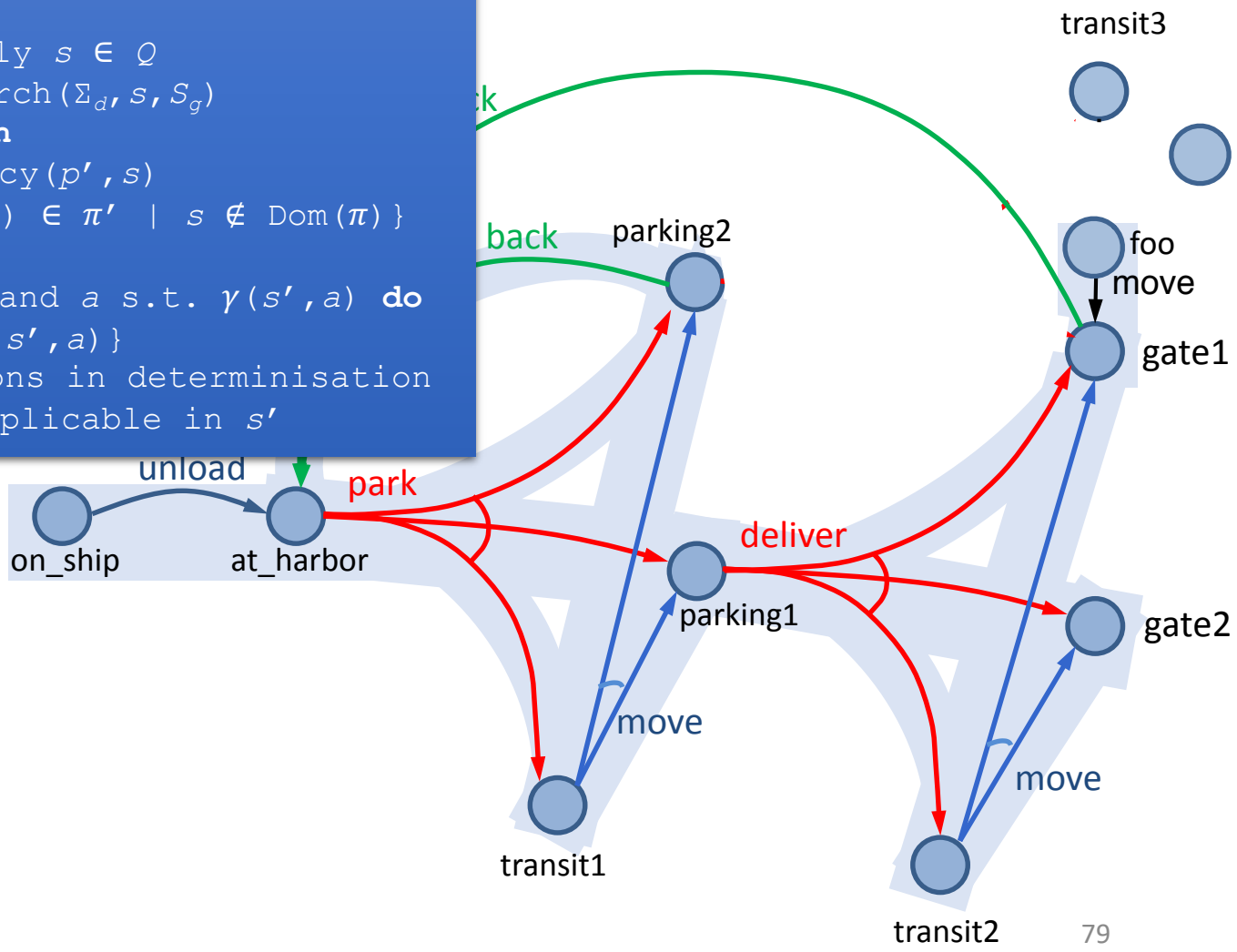

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Find-Safe-Solution-by-Determinisation(Σ, s_0, S_g)
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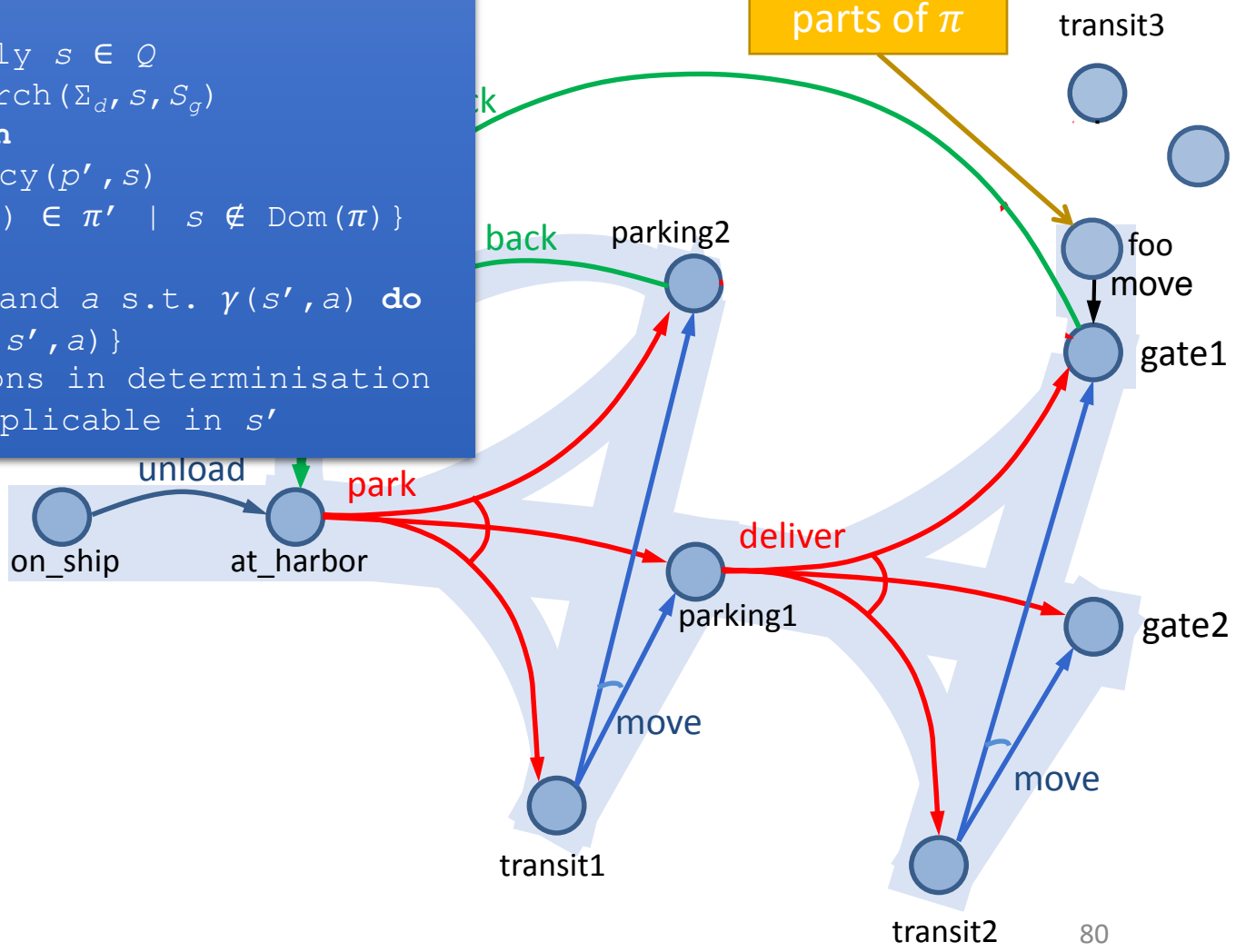
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σ_d, s, S_g)
        if p' ≠ fail then
            π ← Plan2policy(p', s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s' and a s.t. γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

Remove unreachable parts of π



Making Actions Inapplicable

```
Find-Safe-Solution-by-Determinisation(Σ, s_0, S_g)
    if s_0 ∈ S_g then
        return ∅
    if Applicable(s_0) = ∅ then
        return failure
    π ← ∅
    Σ_d ← mk-deterministic(Σ)
    loop
        Q ← leaves(s_0, π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0, π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σ_d, s, S_g)
        if p' ≠ fail then
            π ← Plan2policy(p', s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s_0 then
            return failure
        else
            for every s' and a s.t. γ(s', a) do
                π ← π \ {(s', a)}
                make the actions in the
                        determinisation 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) s.t. $s \in \gamma(s', a)$,

    $Bad[s'] \leftarrow Bad[s']$
    $\cup\ determinization(a)$
  - Modify classical planner to take the table as an argument
    - if s is current state, only choose actions in $Applicable(s) \setminus Bad(s)$

Intermediate Summary

- Determinisation Techniques
  - 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

Outline per the Book

5.2 Planning Problem

- Planning domains
- Plans as policies
- Planning problems and solutions

5.3 And/Or Graph Search

- Planning by forward search

5.5 Determinisation Techniques

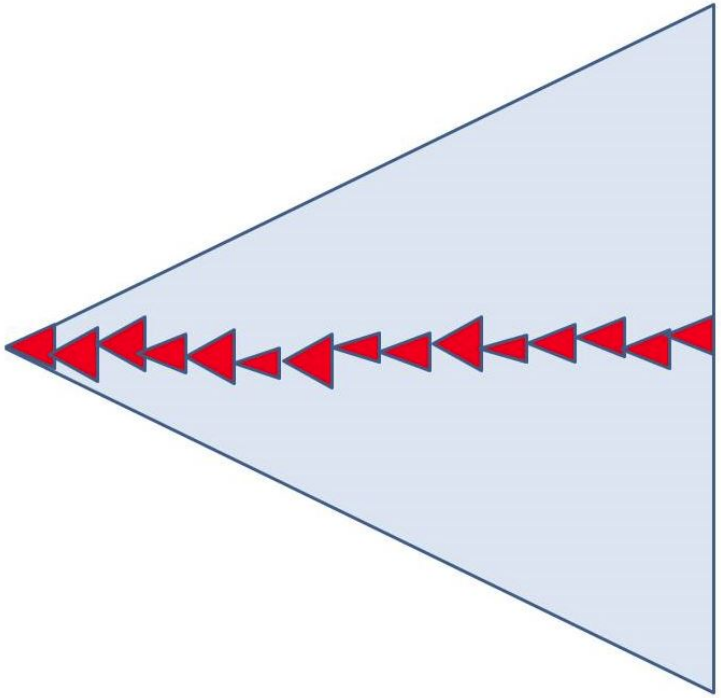
- Guided planning for safe solutions
- Planning for safe solutions by determinisation

5.6 Online Approaches

- Lookahead
- Lookahead by Determinisation
- Lookahead with a bounded number of steps

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 reachable from all situations
- Other domains contain dead-ends, partial planning will not 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

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
  - θ context-dependent vector of parameters to restrict in some way the search for a solution

```
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
            perform partial plan π
            s ← observe current state
```

FS-Replan

- Adaptation of Run-Lookahead (Ch. 2)
- Calls Forward-Search (Ch. 2) on determinized domain, converts to a policy
  - Unsafe solution

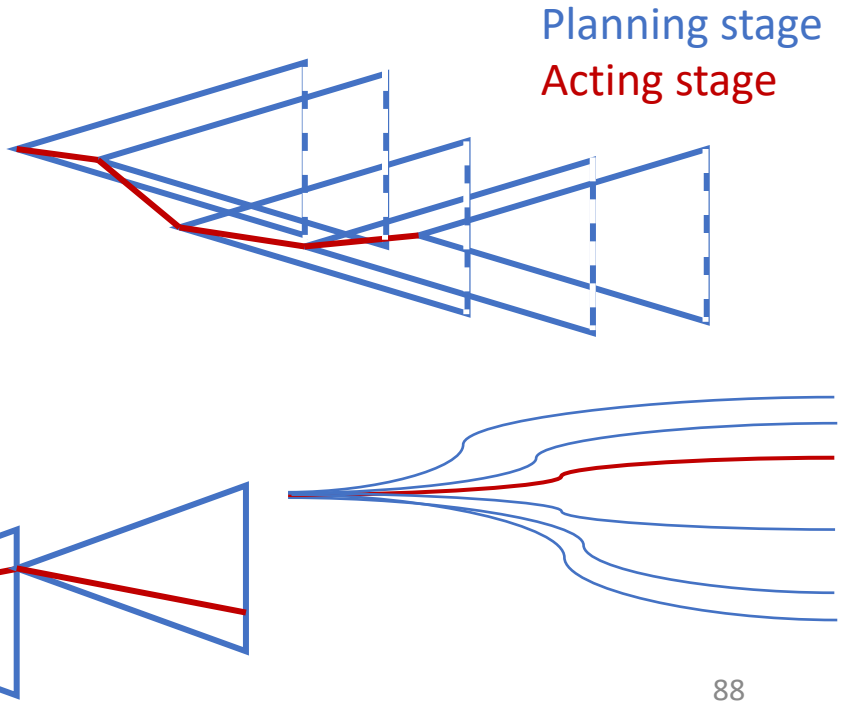
```
FS-Replan(Σ, s, S_g)
    π_d ← ∅
    while s ∉ S_g and Applicable(s) ≠ ∅ do
        if π_d undefined for s then
            π_d ← Plan2policy(Forward-search(Σ_d, s, S_g), s)
            if π_d = failure then
                return failure
        perform action π_d(s)
        s ← observe resulting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

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

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

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



Possibilities for Lookahead (ct'd)

- 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

```
T ← i elements
        of γ(s,a) \ Dom(π)
Frontier ← Frontier ∪ T
```

```
Find-Acyclic-Solution(Σ,s_0,S_g)
    π ← ∅
    Frontier ← {s_0}
    for every s ∈ Frontier \ S_g do
        Frontier ← Frontier \ {s}
        if Applicable(s) = ∅ then
            return failure
        nondeterministically choose a ∈ Applicable(s)
        π ← π ∪ (s,a)
        Frontier ← Frontier ∪ (γ(s,a) \ Dom(π))
        if has-loops(π,s,Frontier) then
            return failure
    return π
```

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?

Min-Max LRTA*

Assumes each action has cost 1
Can easily be modified to use cost ≠ 1

```
Min-Max-LRTA*(Σ, s_0, S_g)
    s ← s_0
    while s ∉ S_g and Applicable(s) ≠ ∅ do
        a ← argmin_{a∈Applicable(s)} max_{s'∈γ(s,a)} h(s')
        h(s) ← max{h(s), 1 + max_{s'∈γ(s,a)} h(s')}
        perform action a
        s ← the current state
```

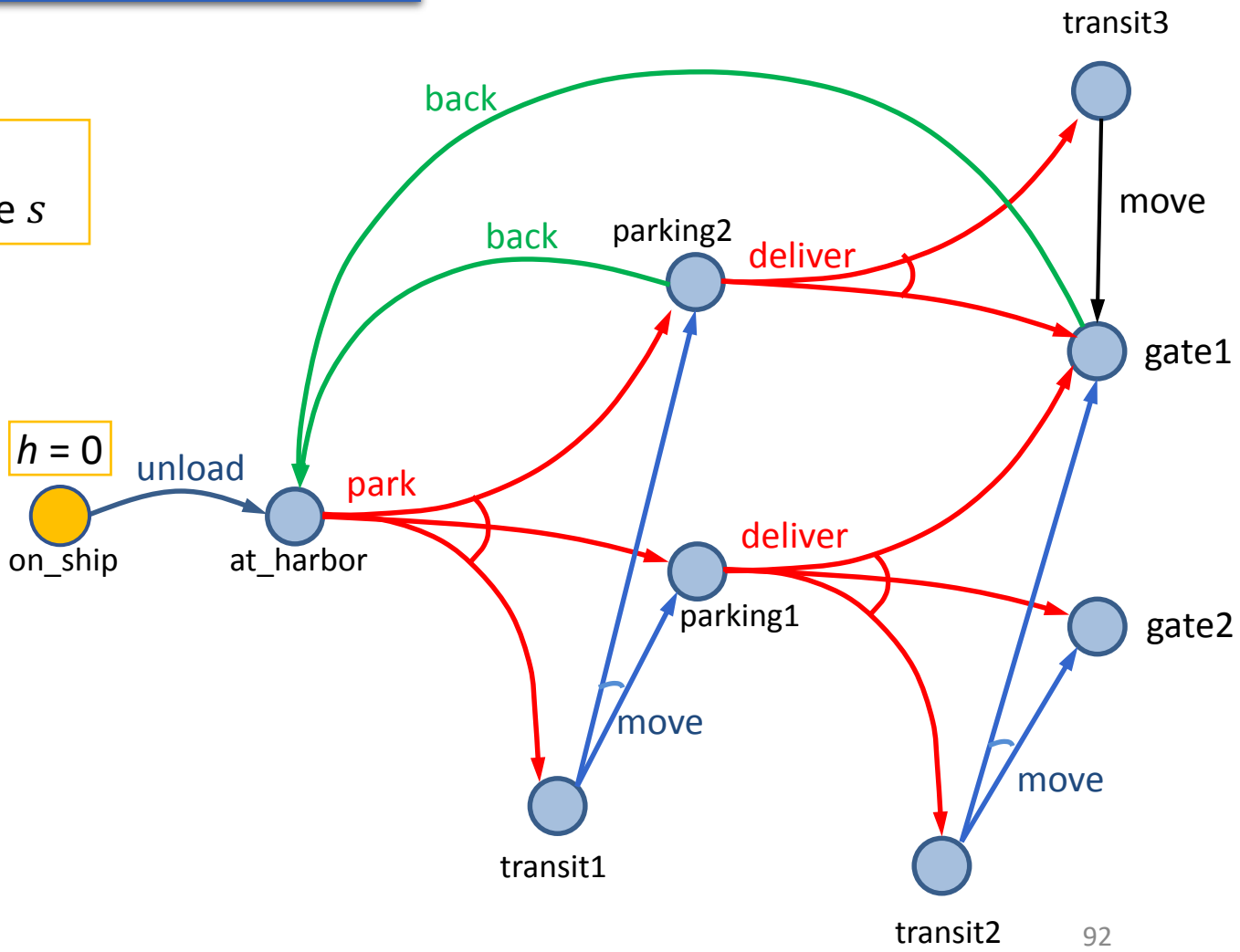
- Loop
  - choose an action a that (according to h) has optimal worst-case cost
    - Update $h(s)$ to use a's worst-case cost
    - Perform a
- In safely explorable domains with no "unfair" executions, guaranteed to reach a goal

Min-Max-LRTA*(Σ, s_0, S_g)

$s \leftarrow s_0$
while $s \notin S_g$ and Applicable(s) $\neq \emptyset$ **do**
  $a \leftarrow \text{argmin}_{a \in \text{Applicable}(s)} \max_{s' \in \gamma(s,a)} h(s')$
  $h(s) \leftarrow \max\{h(s), 1 + \max_{s' \in \gamma(s,a)} h(s')\}$
  perform action a
  $s \leftarrow$ the current state

Example

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



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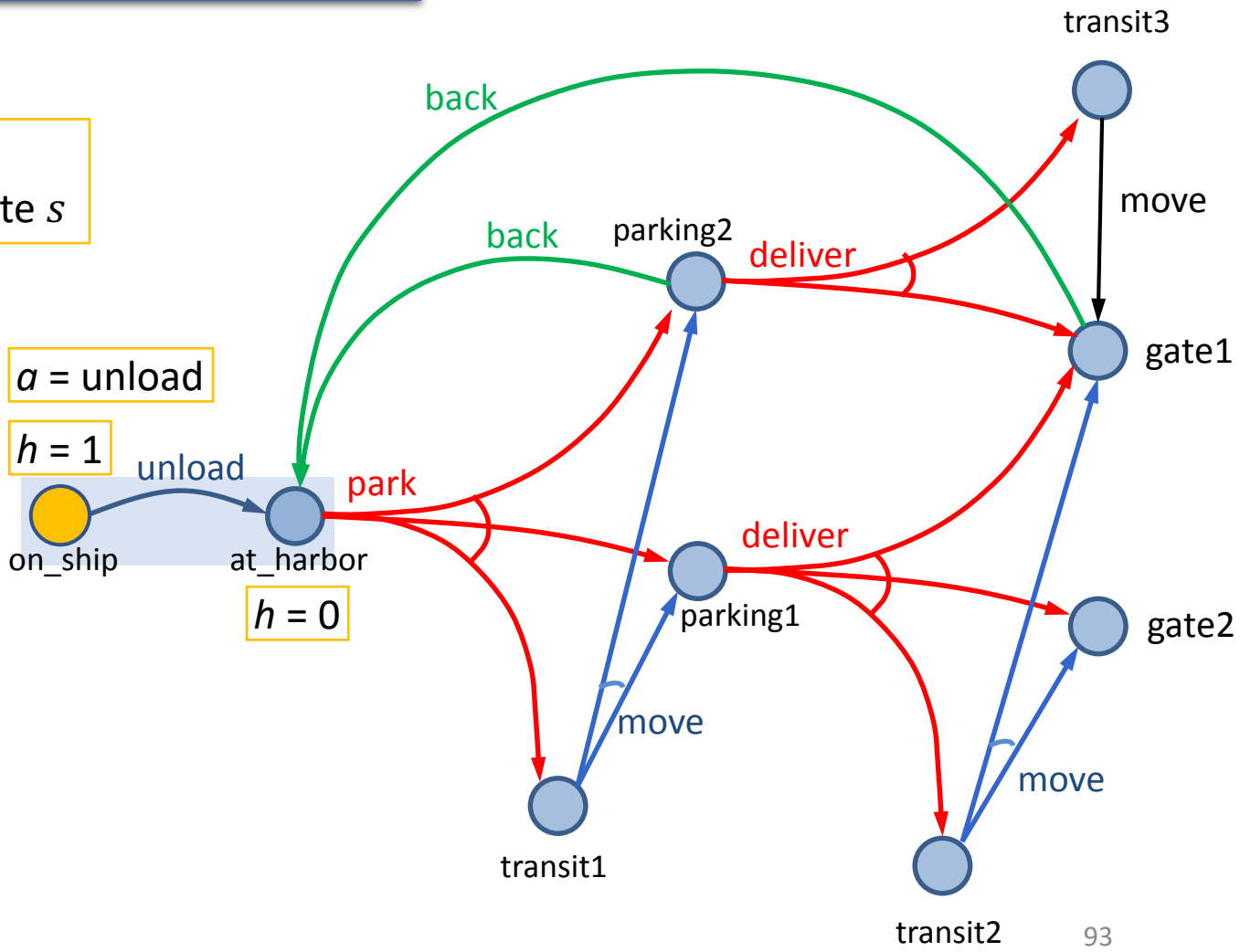

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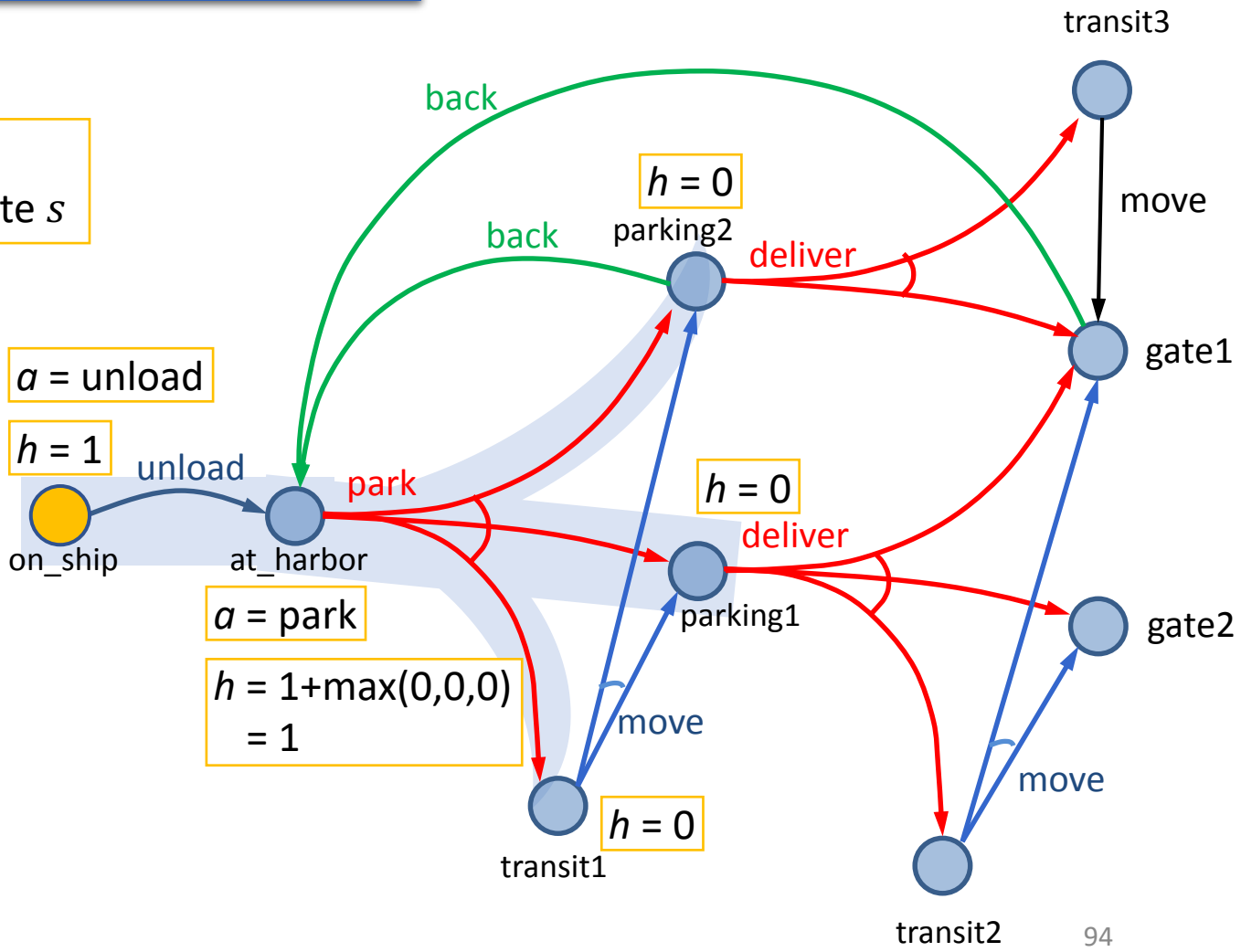

Min-Max-LRTA*(Σ, s_0, S_g)

$s \leftarrow s_0$
while $s \notin S_g$ and Applicable(s) $\neq \emptyset$ **do**
  $a \leftarrow \text{argmin}_{a \in \text{Applicable}(s)} \max_{s' \in \gamma(s,a)} h(s')$
  $h(s) \leftarrow \max\{h(s), 1 + \max_{s' \in \gamma(s,a)} h(s')\}$
  perform action a
  $s \leftarrow$ the current state

Example

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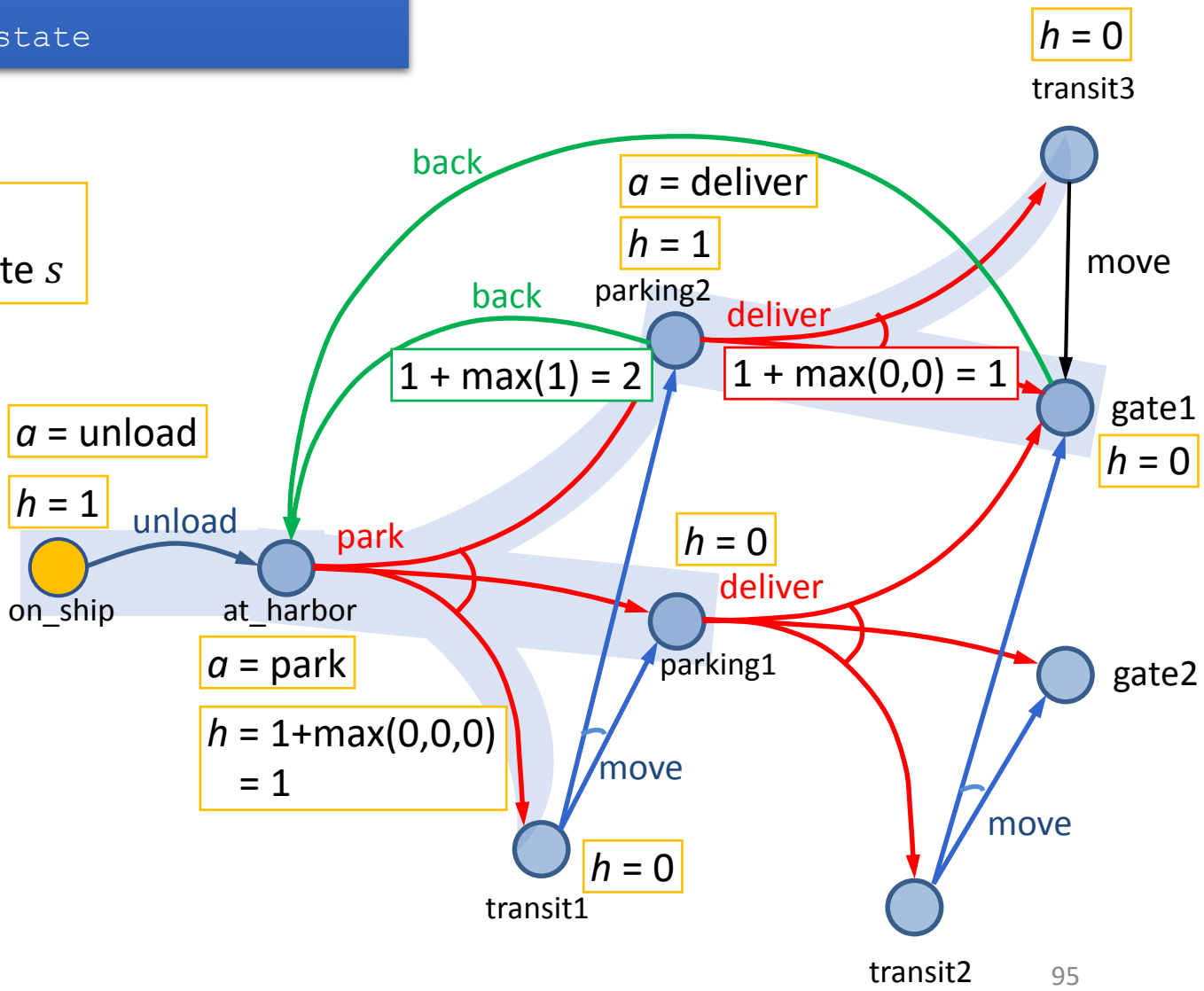

Intermediate Summary

- 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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$\Longrightarrow$ Next: Making Simple Decisions