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Automated Planning and Acting – Nondeterministic Models

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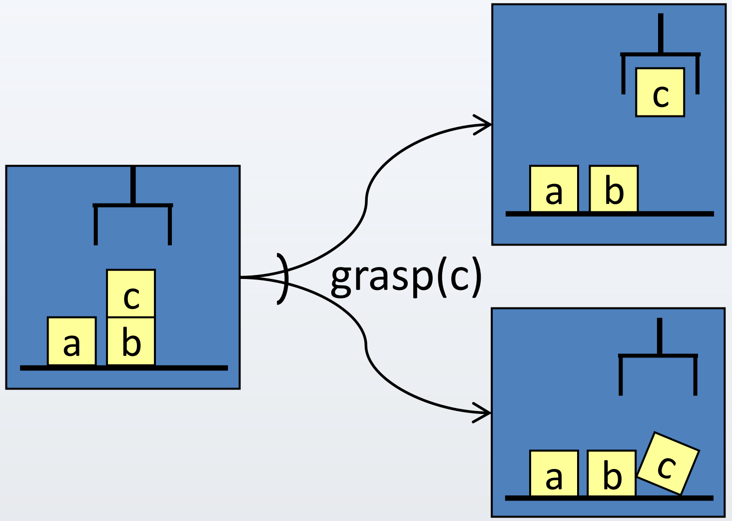
Motivation

- We have assumed action a in state s has just one possible outcome
  - y(s,a)
- Often more than one possible outcome
  - Unintended outcomes
  - Exogenous events
  - Inherent uncertainty



Content

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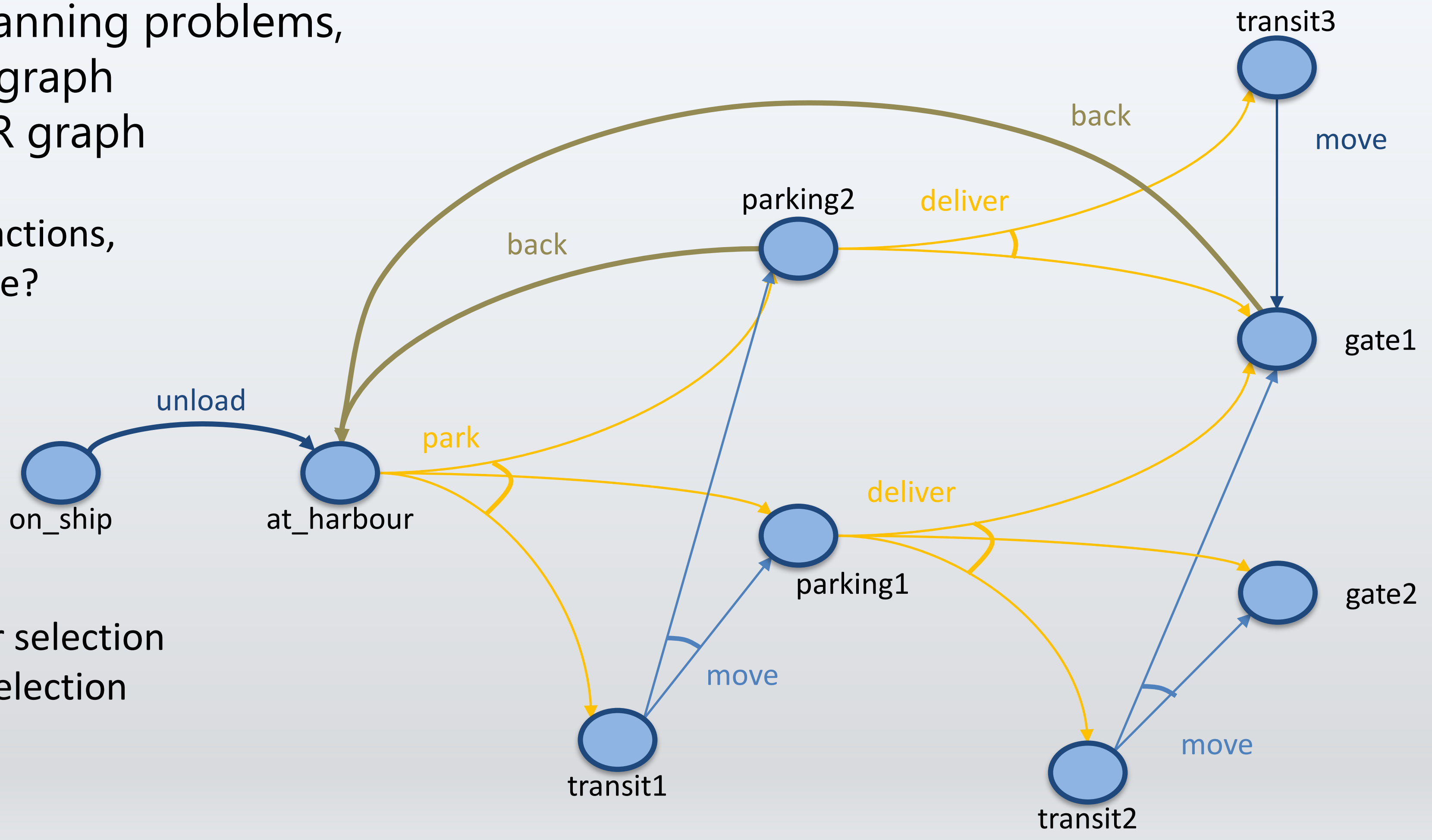
Nondeterministic Planning Domains

- 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 possible 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 $eff_1, eff_2, \ldots, eff_{2^k \triangleq n}$ effect lists
      - One for each possible combination of $e_1, e_2, \ldots, e_k$
  - 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: $e_{n1}, e_{n2}, \ldots$

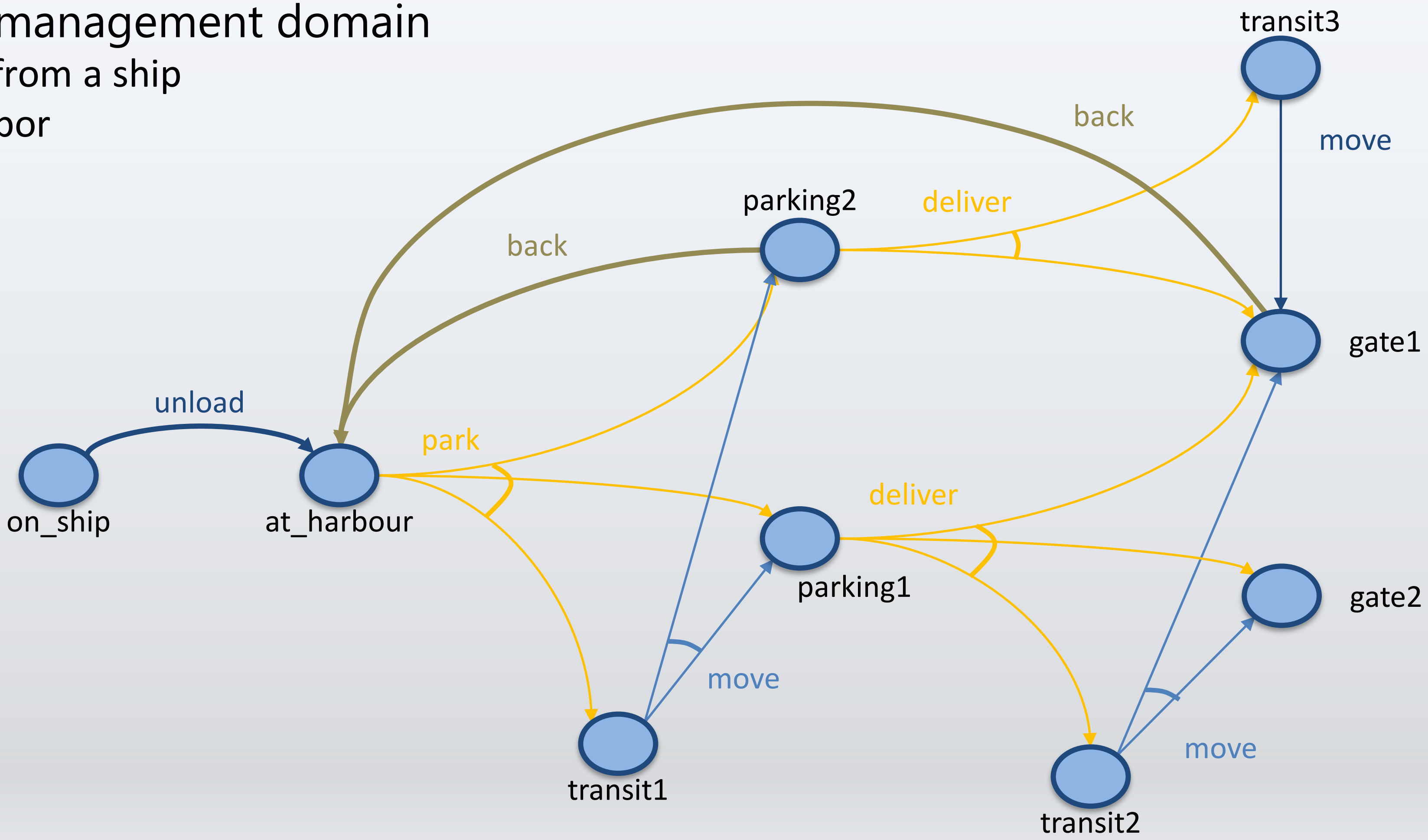
Nondeterministic Planning Domains

- 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 ⇔ resolver selection
  - *AND* branch ⇔ flaw selection



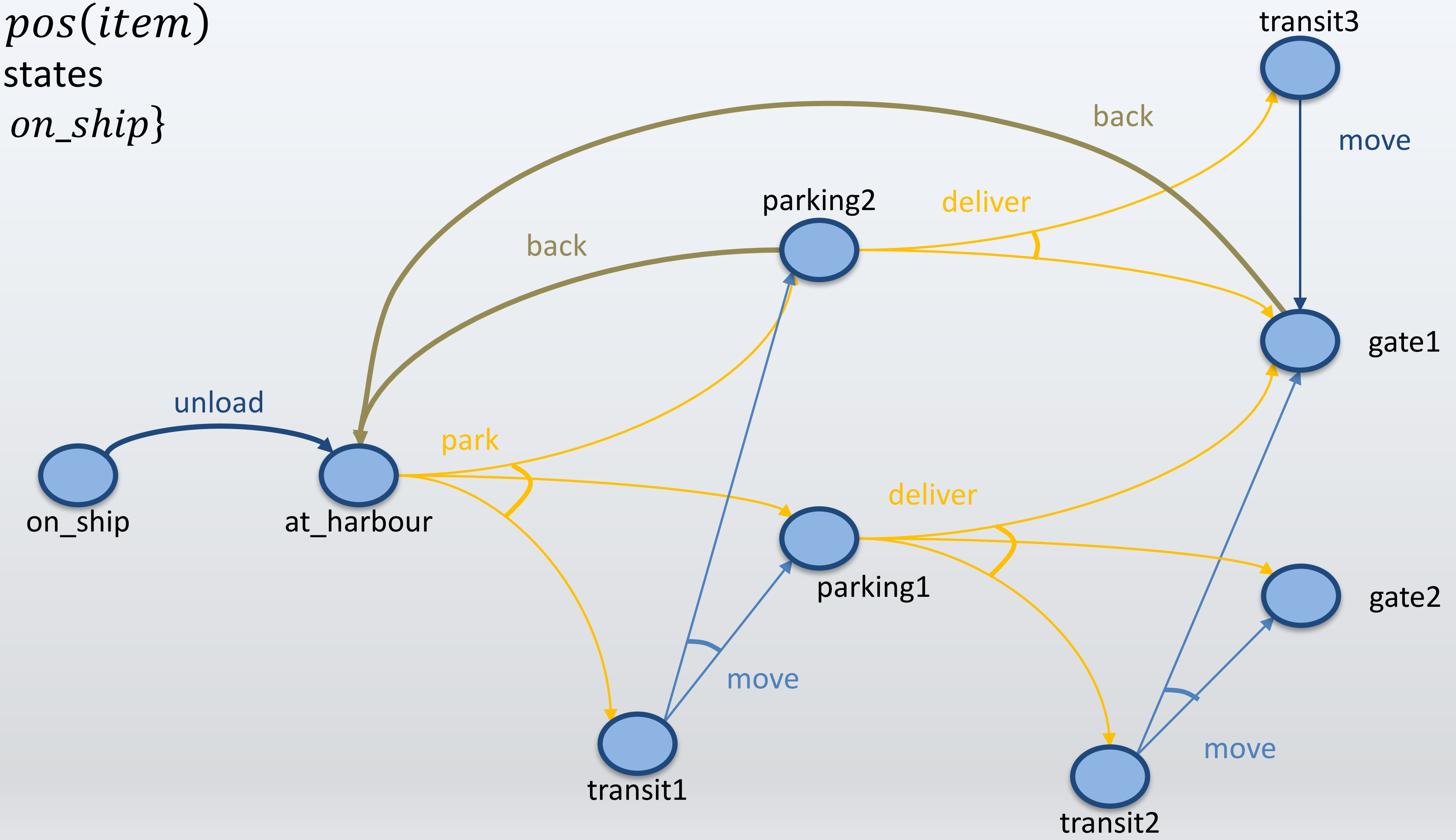
Example

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



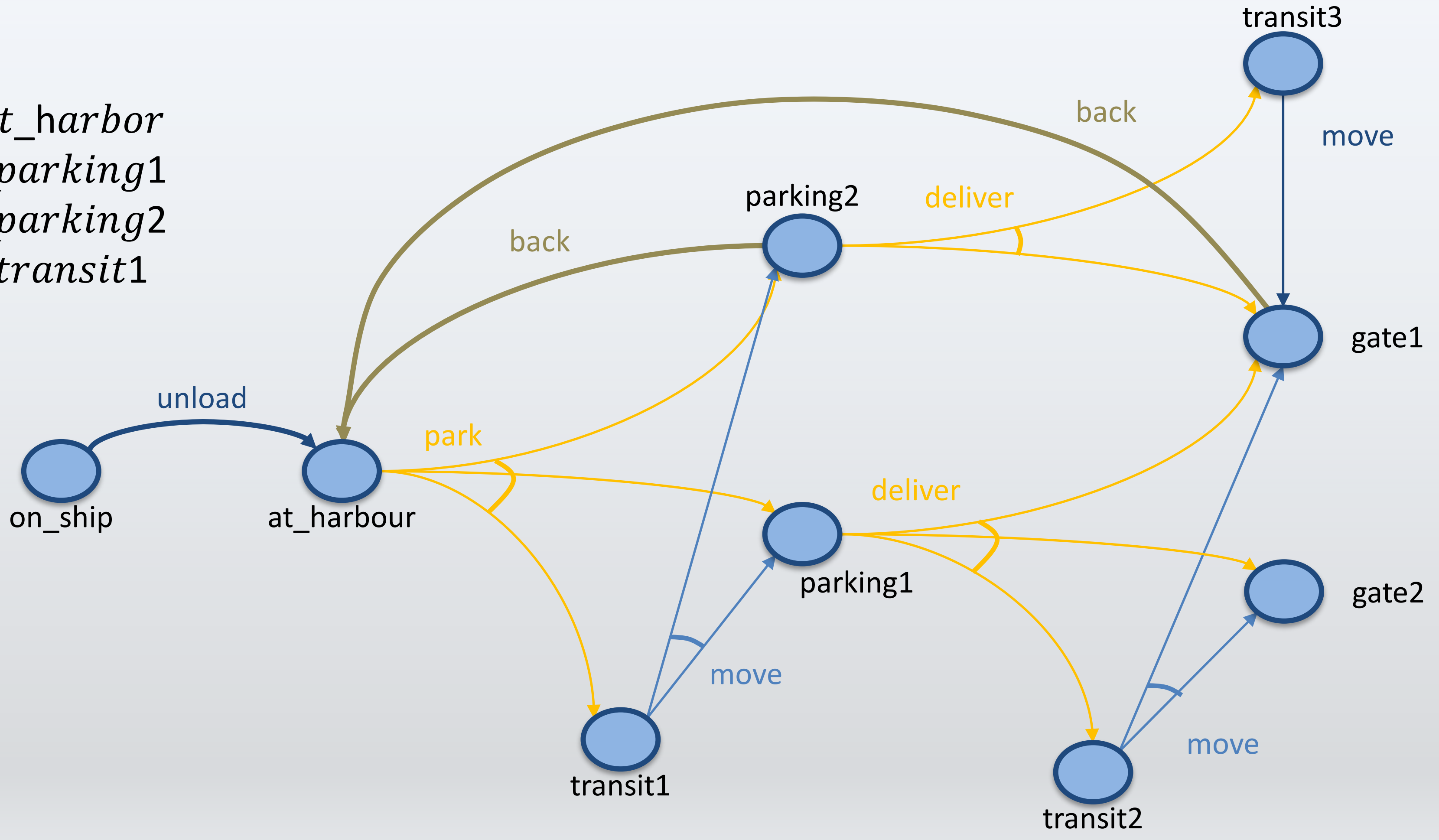
Example

- One state variable: $pos(item)$
  - Simplified names for states
    - For $\{pos(item) = on\_ship\}$ write on_ship
- Five actions
  - Deterministic:
    - $unload$
    - $back$
    - ($move$ in *transit3*)
  - Nondeterministic:
    - $park$,
    - $move$,
    - $deliver$



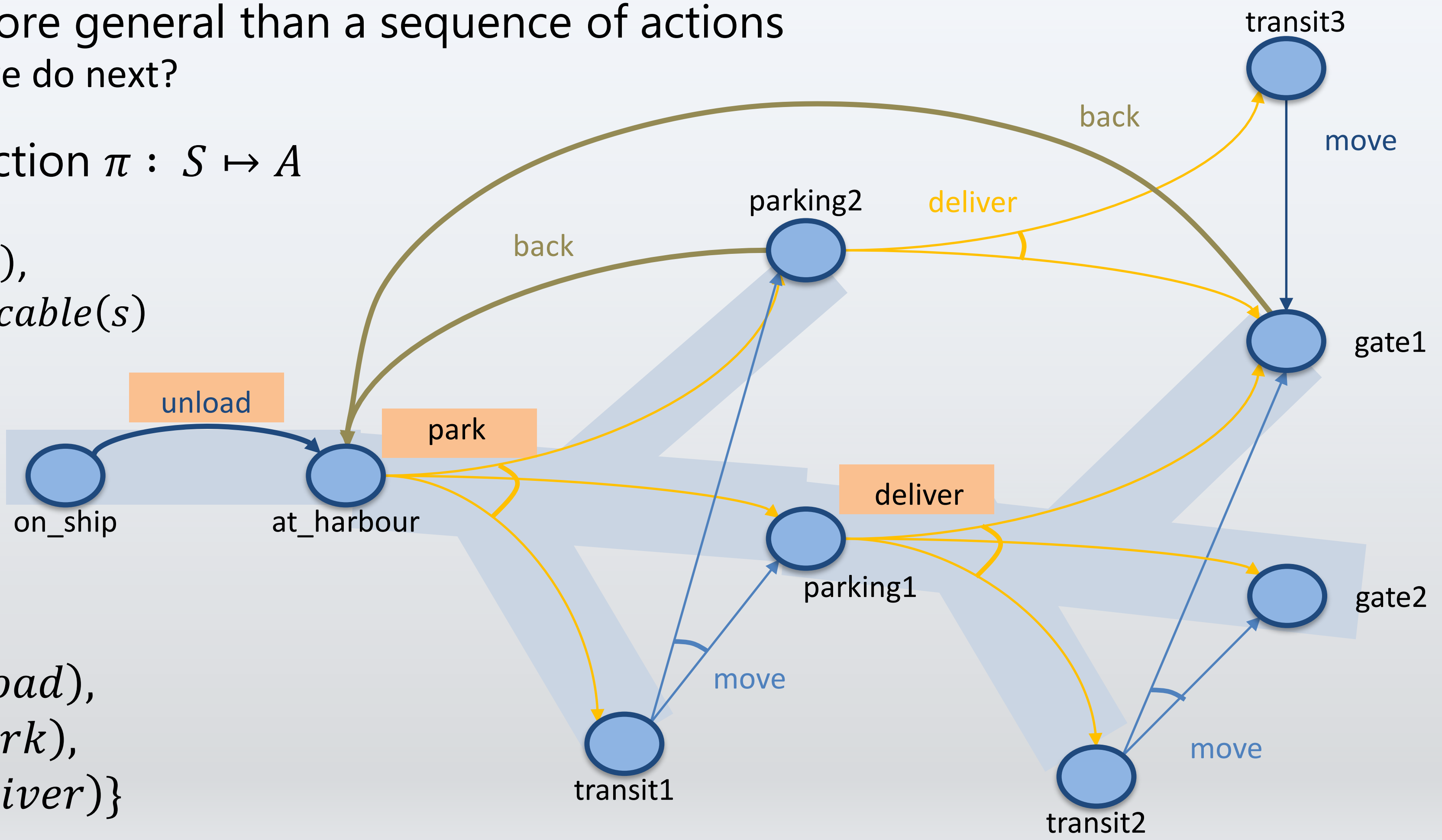
Actions

- Action example:
  - $park$
    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



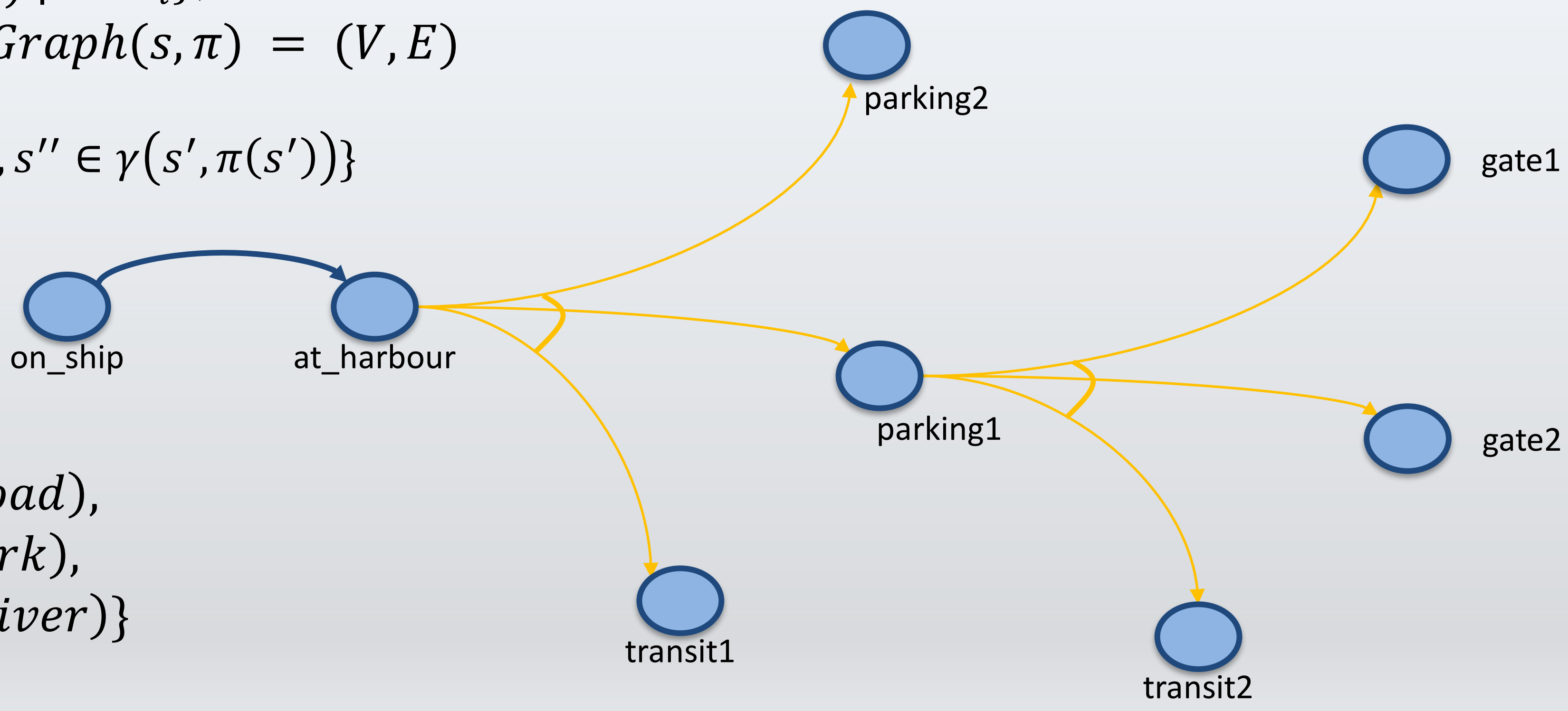
~~Plans~~ Policies

- 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

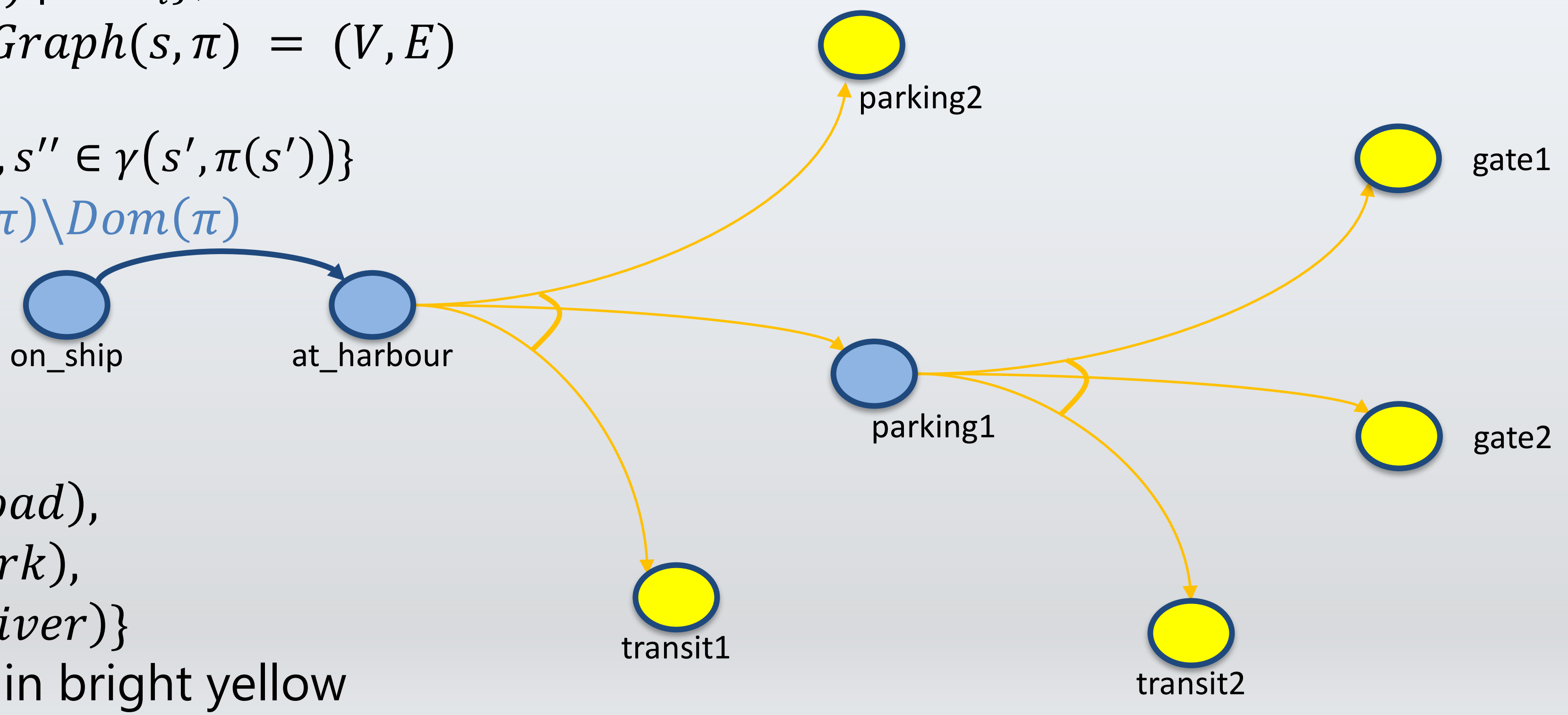
- Transitive closure $\hat{\gamma}(s,\pi)$ = {all states reachable from s using π}
  - $\hat{\gamma}(s,\pi) = S_0 \cup S_1 \cup S_2 \cup \cdots$
    - $S_0 = \{s\}$
    - $S_{i+1} = \bigcup\{\gamma(s,\pi(s)) \mid s \in S_i\}, i \geq 0$
- Reachability graph $Graph(s,\pi) = (V,E)$
  - $V = \hat{\gamma}(s,\pi)$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



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

Definitions Over Policies

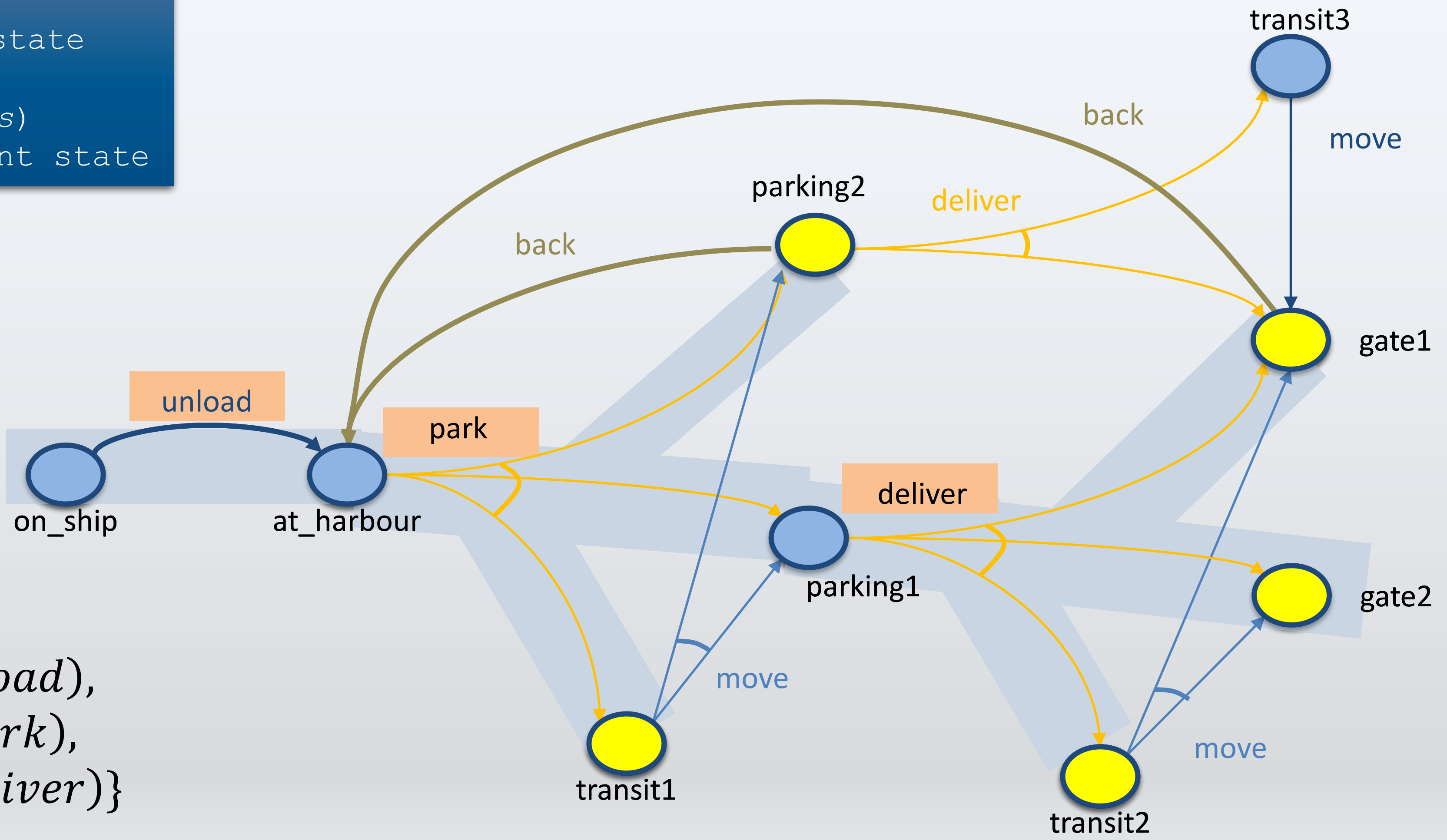
- Transitive closure $\hat{\gamma}(s,\pi)$ = {all states reachable from s using π}
  - $\hat{\gamma}(s,\pi) = S_0 \cup S_1 \cup S_2 \cup \cdots$
    - $S_0 = \{s\}$
    - $S_{i+1} = \cup\{\gamma(s,\pi(s)) \mid s \in S_i\}, i \geq 0$
- Reachability graph $Graph(s,\pi) = (V,E)$
  - $V = \hat{\gamma}(s,\pi)$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



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

Performing a Policy

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



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

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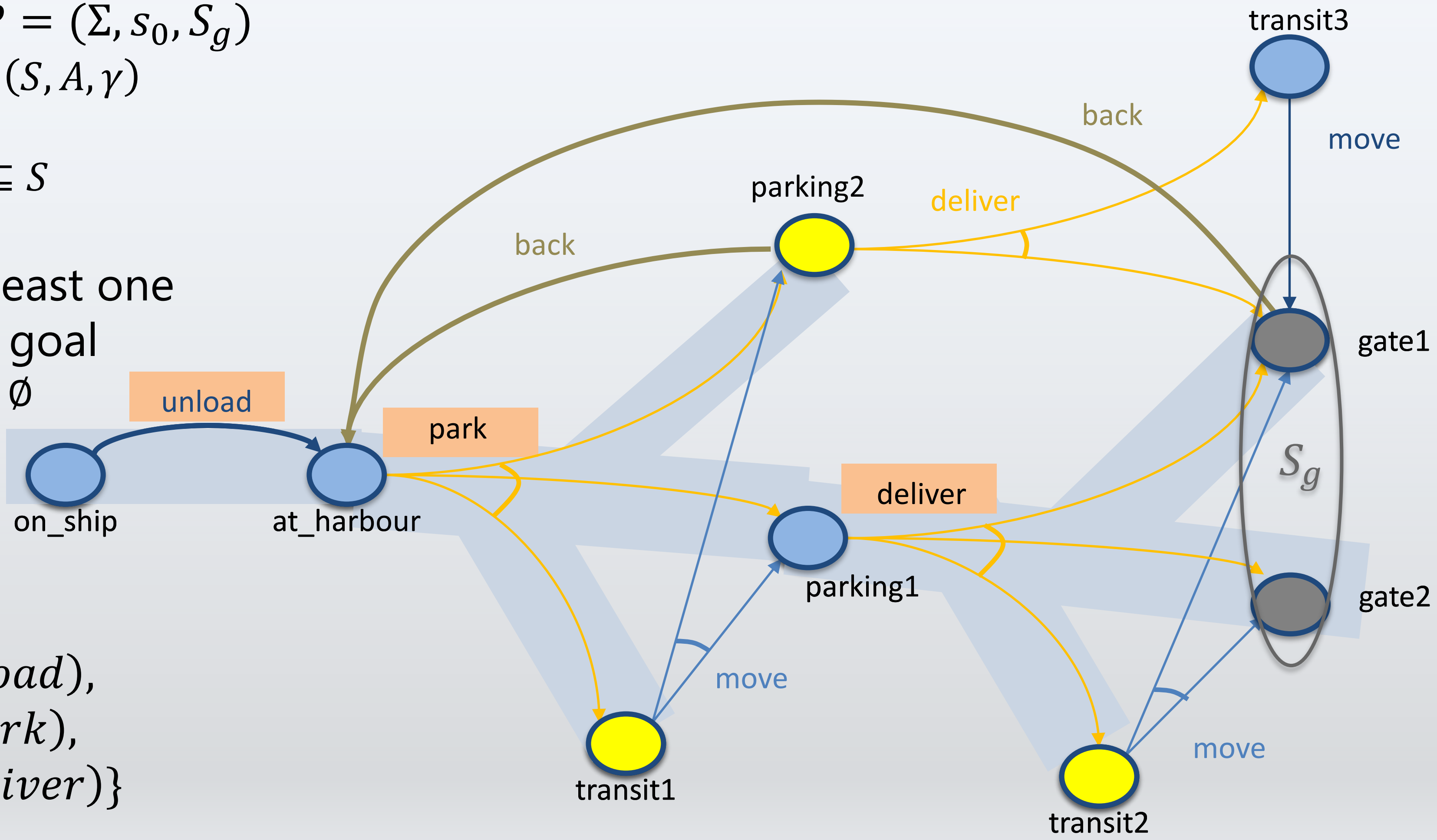
Planning Problems and Solutions

- 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 grey)
- π is a solution if at least one execution ends at a goal
  - $leaves(s_0, \pi) \cap S_g \neq \emptyset$

Is π_1 a solution?

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

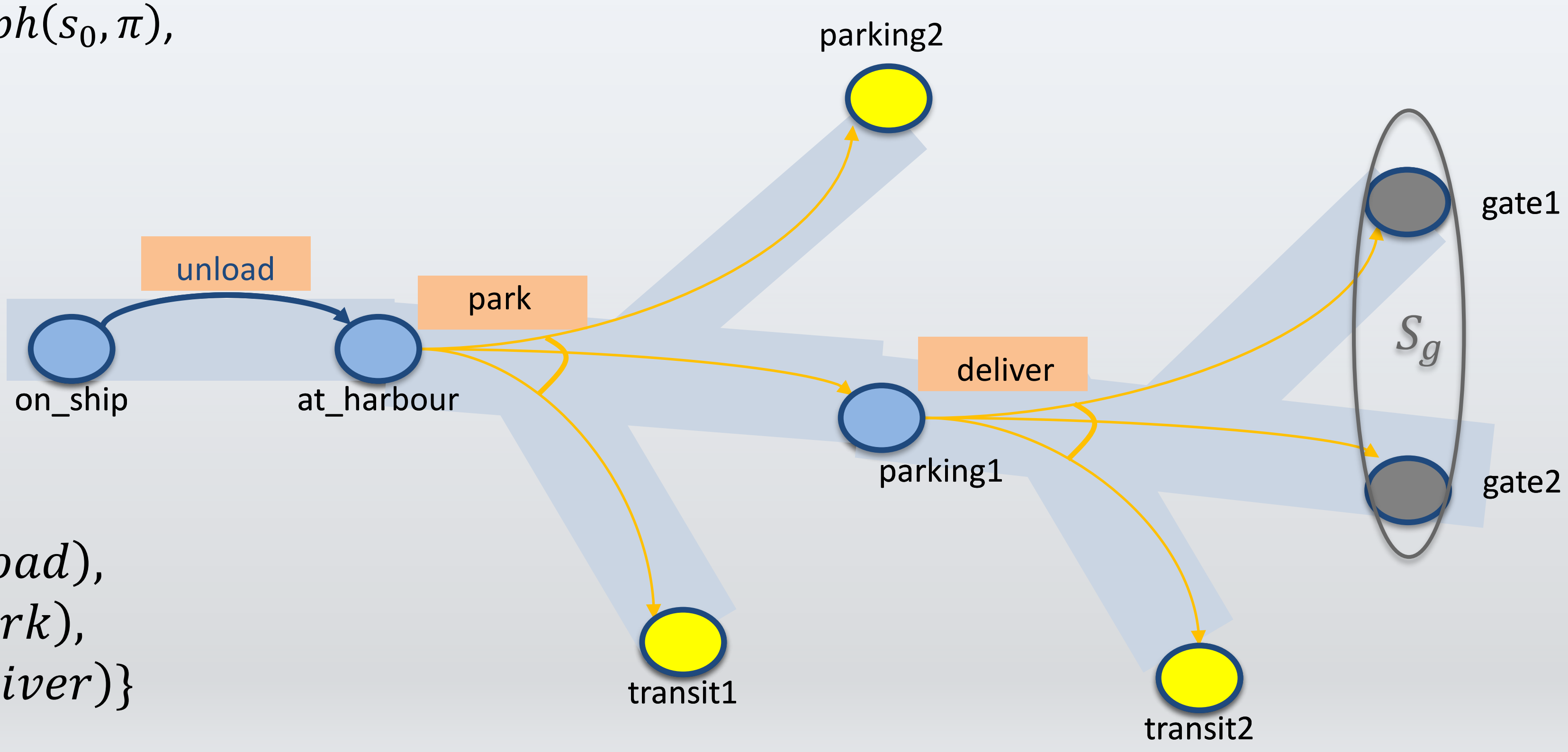


Safe Solutions

- A solution π is safe if
  $$\forall s \in \hat{\gamma}(s_0, \pi),$$
  $$leaves(s, \pi) \cap S_g \neq \emptyset$$
  - at every node of $Graph(s_0, \pi)$, the goal is *reachable*
- Otherwise, *unsafe*

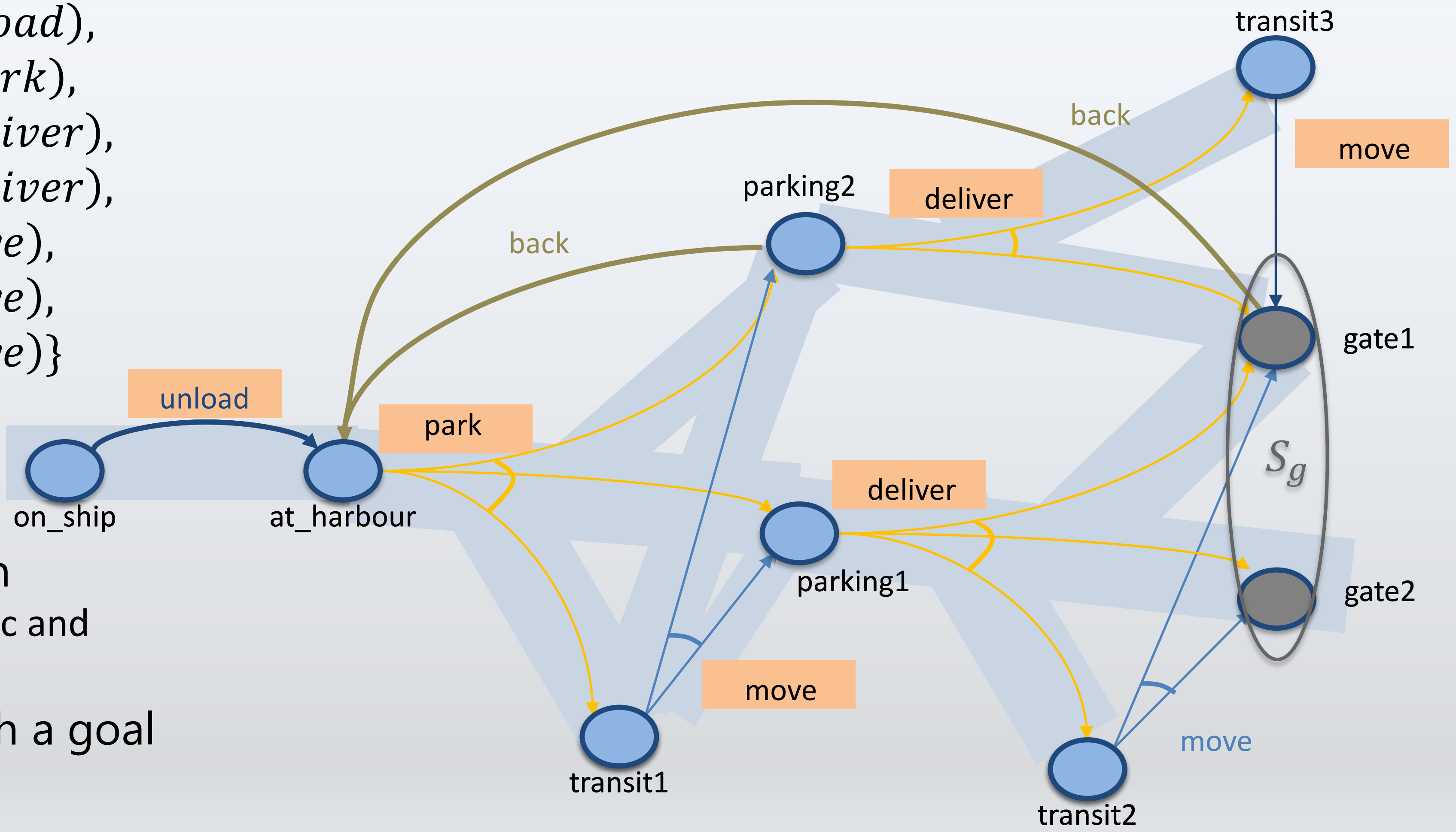
Is π_1 safe?

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



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

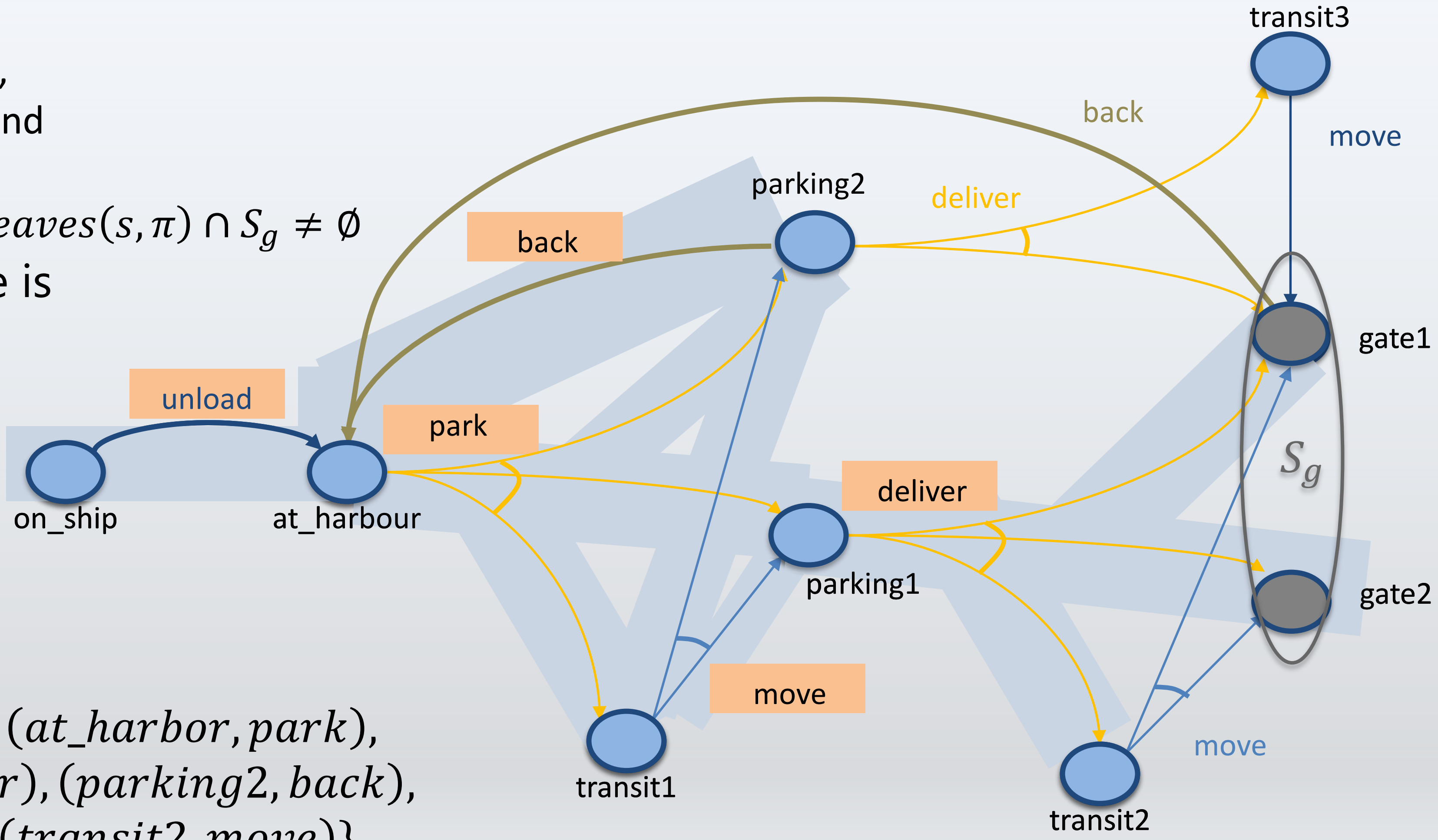
Safe Solutions

- Cyclic safe solution
  - $Graph(s_0, \pi)$ is cyclic,
  - $leaves(s_0, \pi) \subseteq S_g$, and
  - $\forall s \in \hat{\gamma}(s_0, \pi)$,

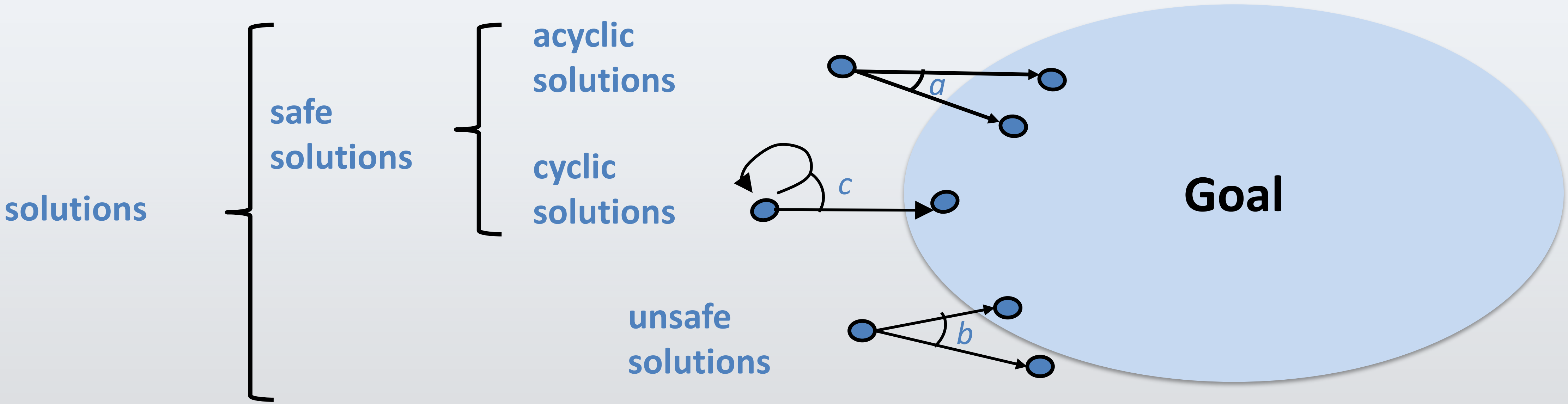
$$leaves(s, \pi) \cap S_g \neq \emptyset$$

- At every state, there is an execution path that ends at a goal
- Will never get caught in a dead end

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



Kinds of Solutions



Intermediate Summary

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

Finding (Unsafe) Solutions


```
Find-Solution(Σ,s0,Sg)
    s ← s0
    π ← ∅
    Visited ← {s0}
    loop
        if s ∈ Sg 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′
```

```
Forward-search(Σ,s0,g)
    s ← s0
    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
```

For comparison: Forward-search with deterministic models

Decide which state to plan for

Cycle-checking

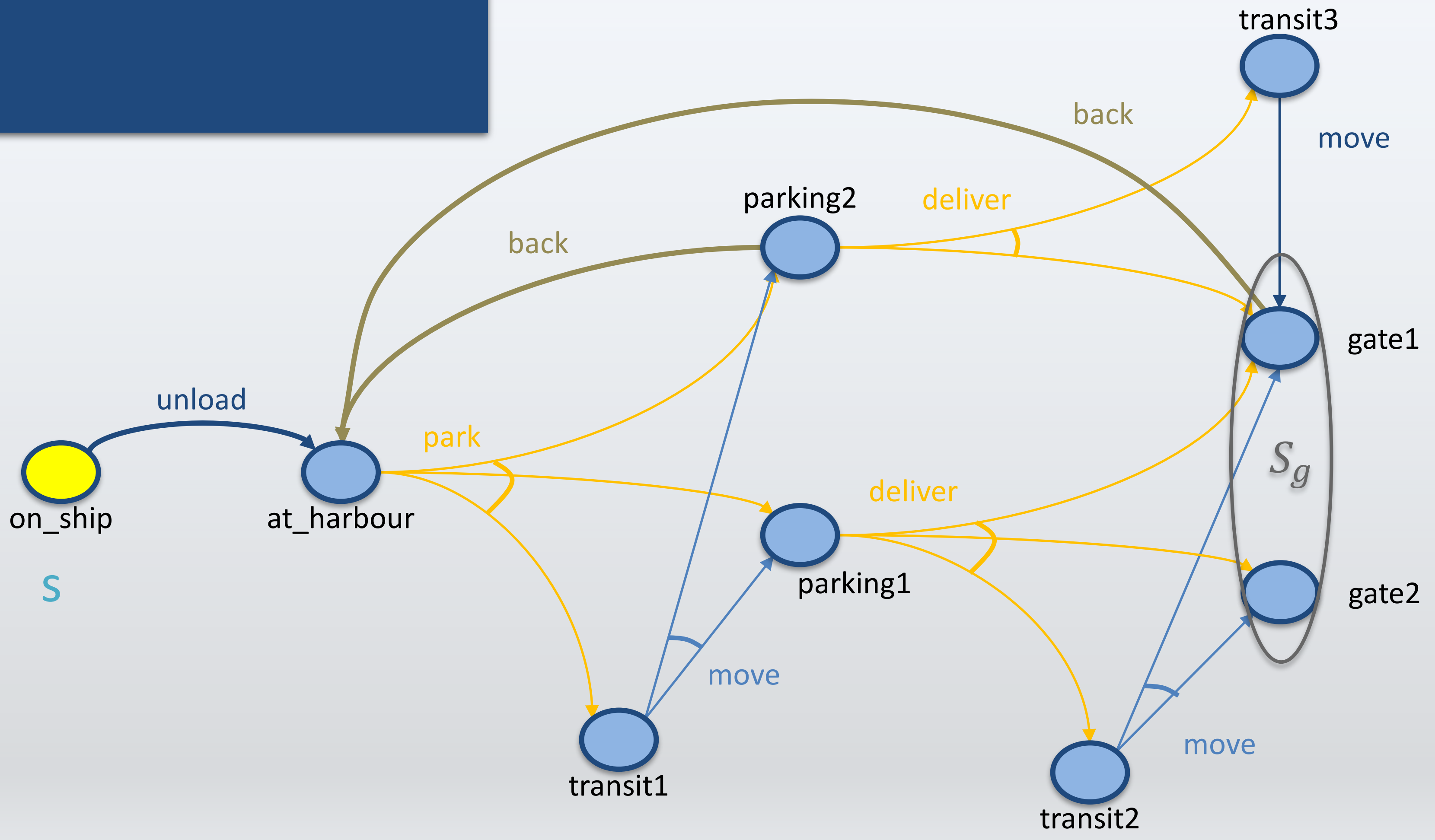
Example


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

s = on_ship

$\pi = \{\}$

$Visited = \{$on_ship$\}$



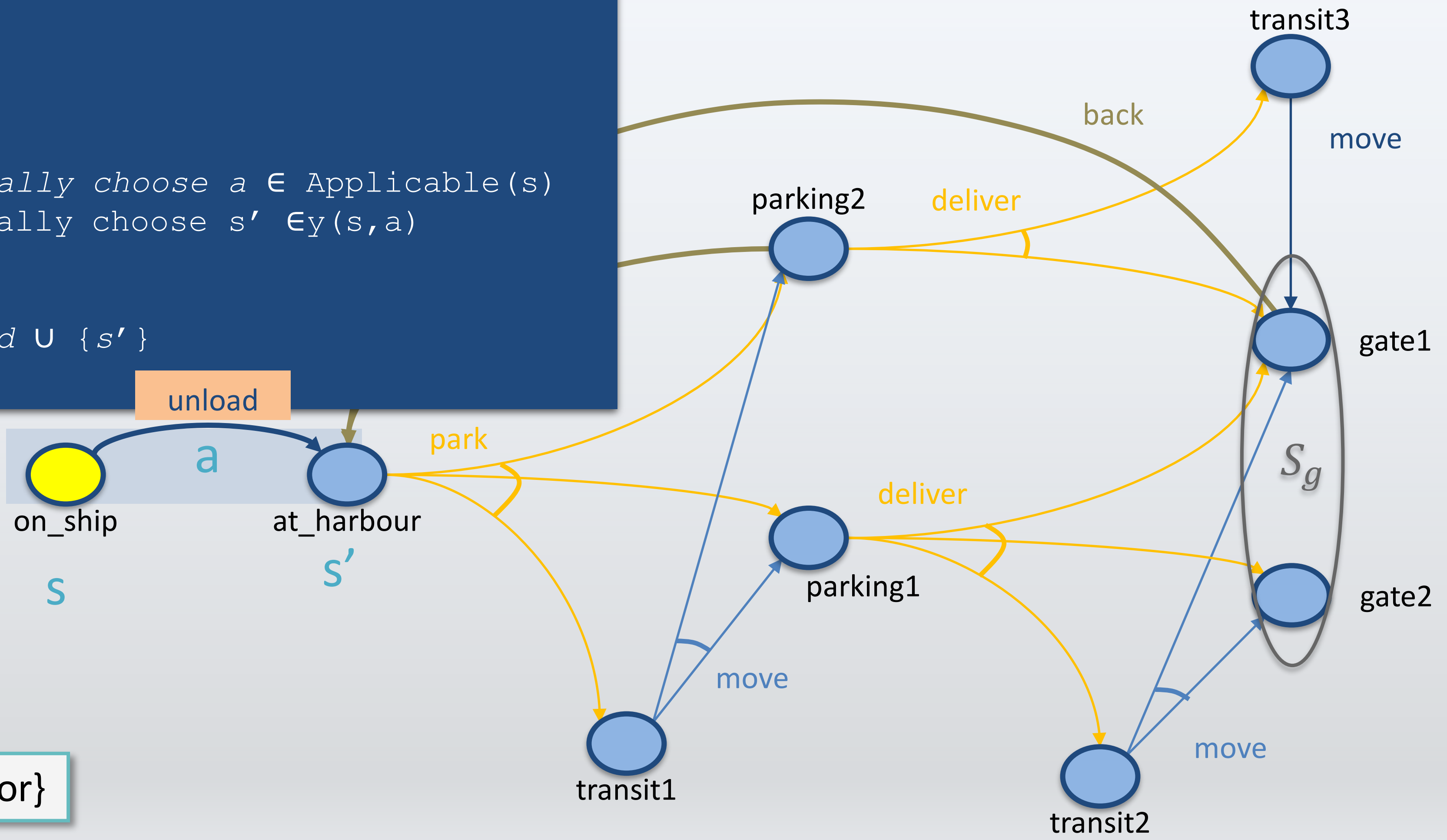
Example

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

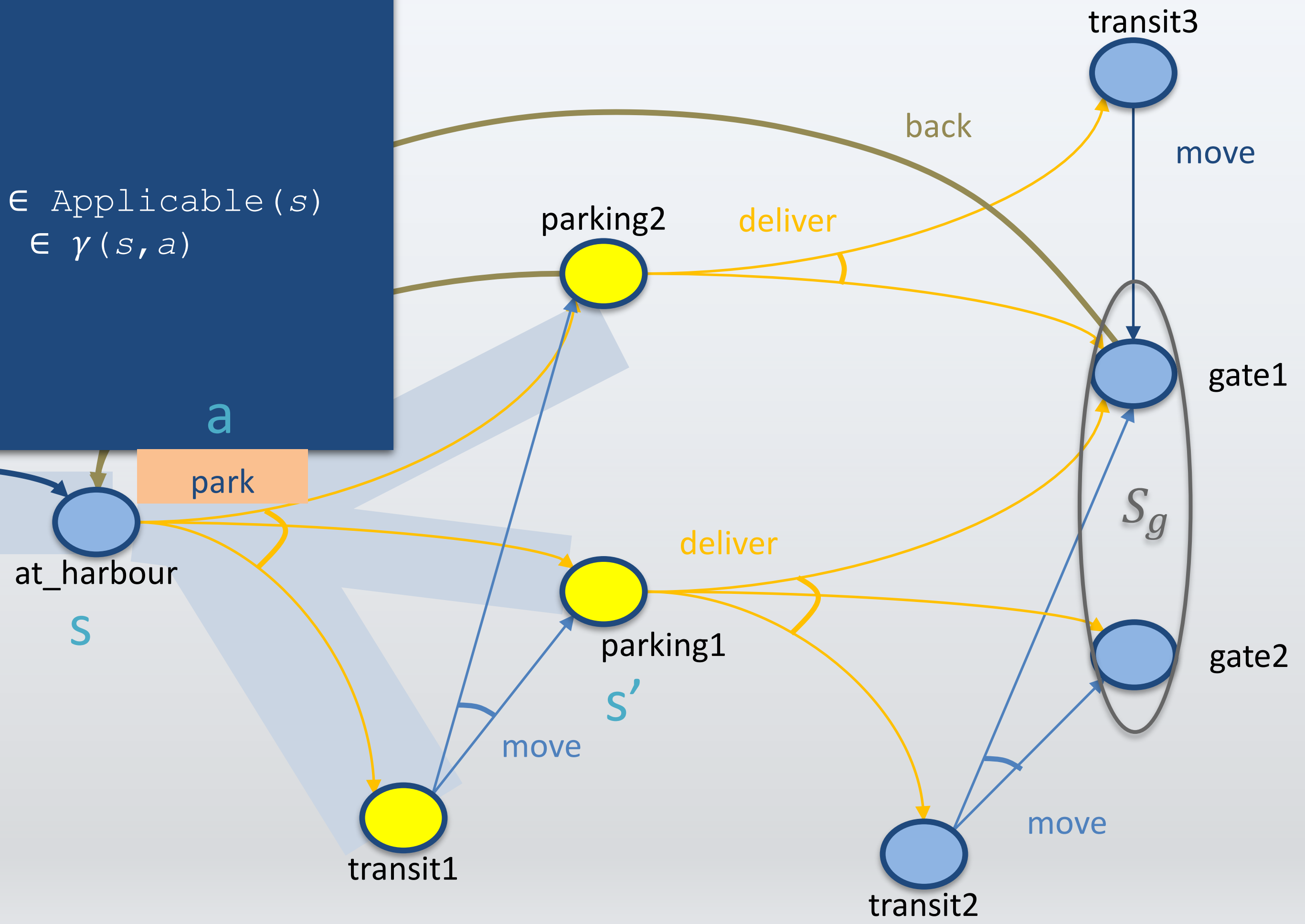
π = {(on_ship, unload)}

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′
```



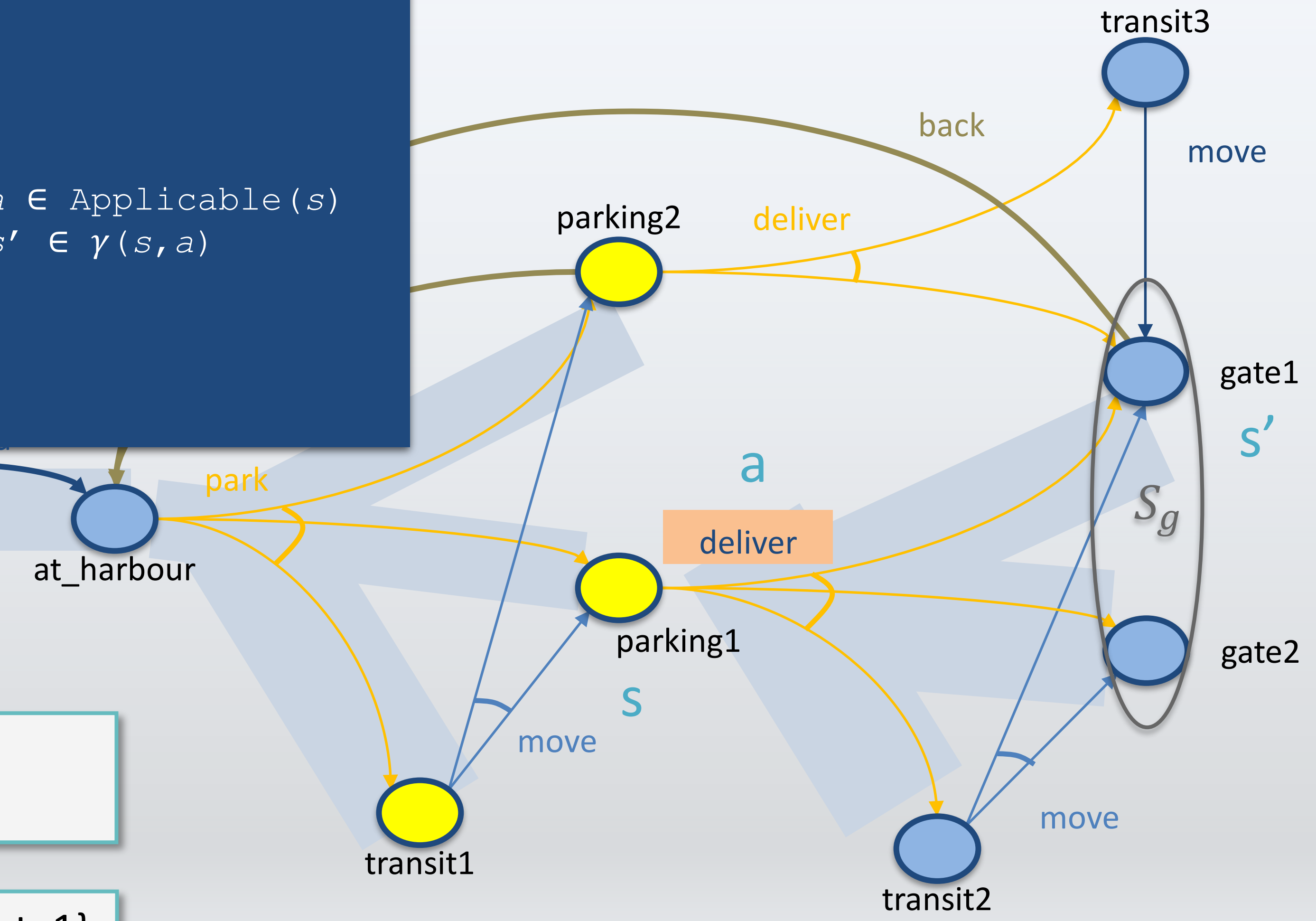
s = at_harbor, a = park
$\gamma(s,a)$ = {parking1, parking2, transit1}
s' = parking1

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

Visited = {on_ship, at_harbor, parking1}

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

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

Visited = {on_ship, at_harbor, parking1, gate1}

Example

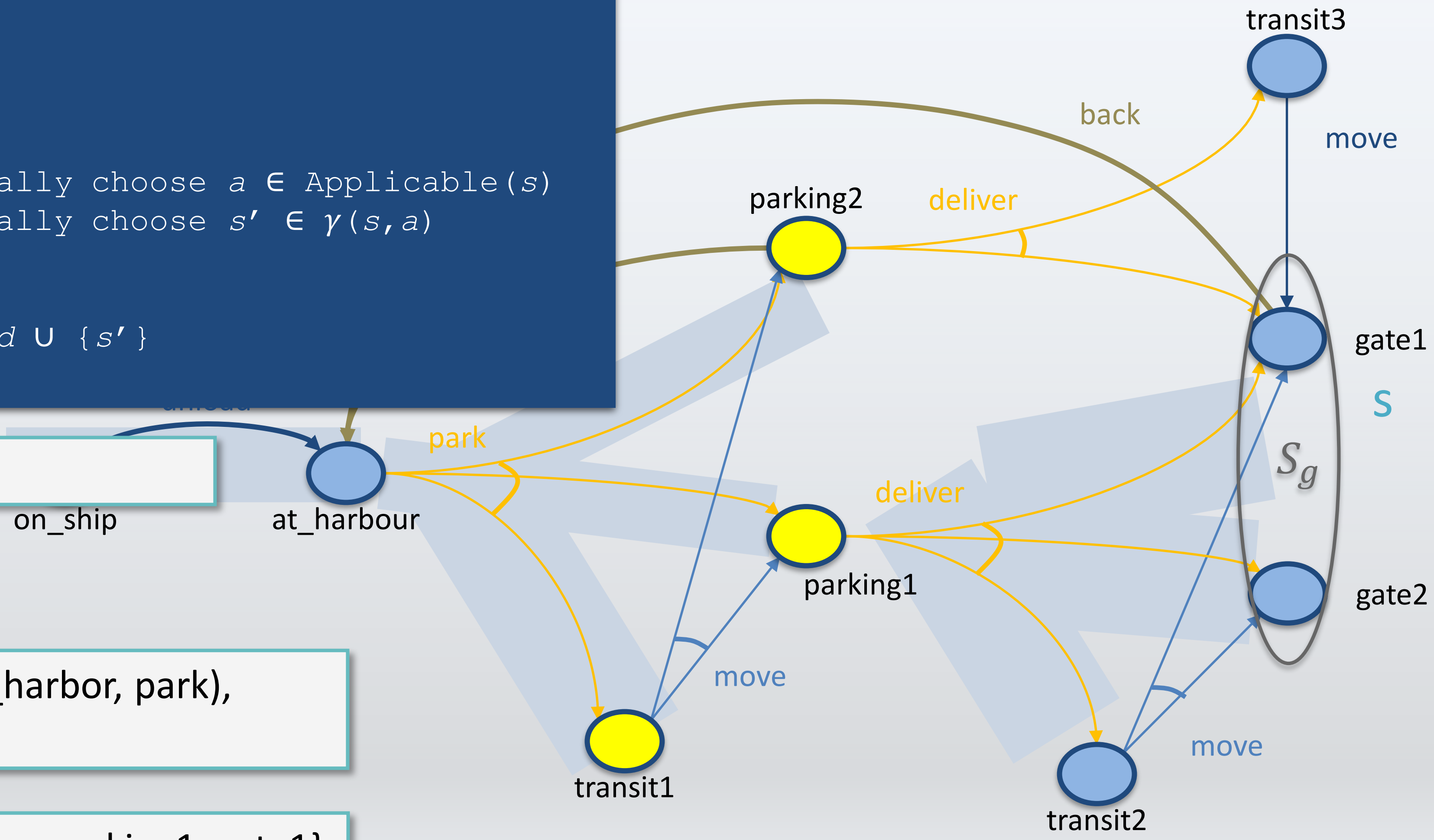
```
Find-Solution(Σ,s0,Sg)
    ...
    loop
        if s ∈ Sg then
            return π
        ...
        nondeterministically choose a ∈ Applicable(s)
        nondeterministically choose s′ ∈ γ(s,a)
        ...
        π(s) ← a
        Visited ← Visited ∪ {s′}
        s ← s′
```

s = 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,s0,Sg)
   π ← ∅
   Frontier ← {s0}
   for every s ∈ Frontier \ Sg 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 in A*

Add all outcomes that π does not already handle

Cycle-checking

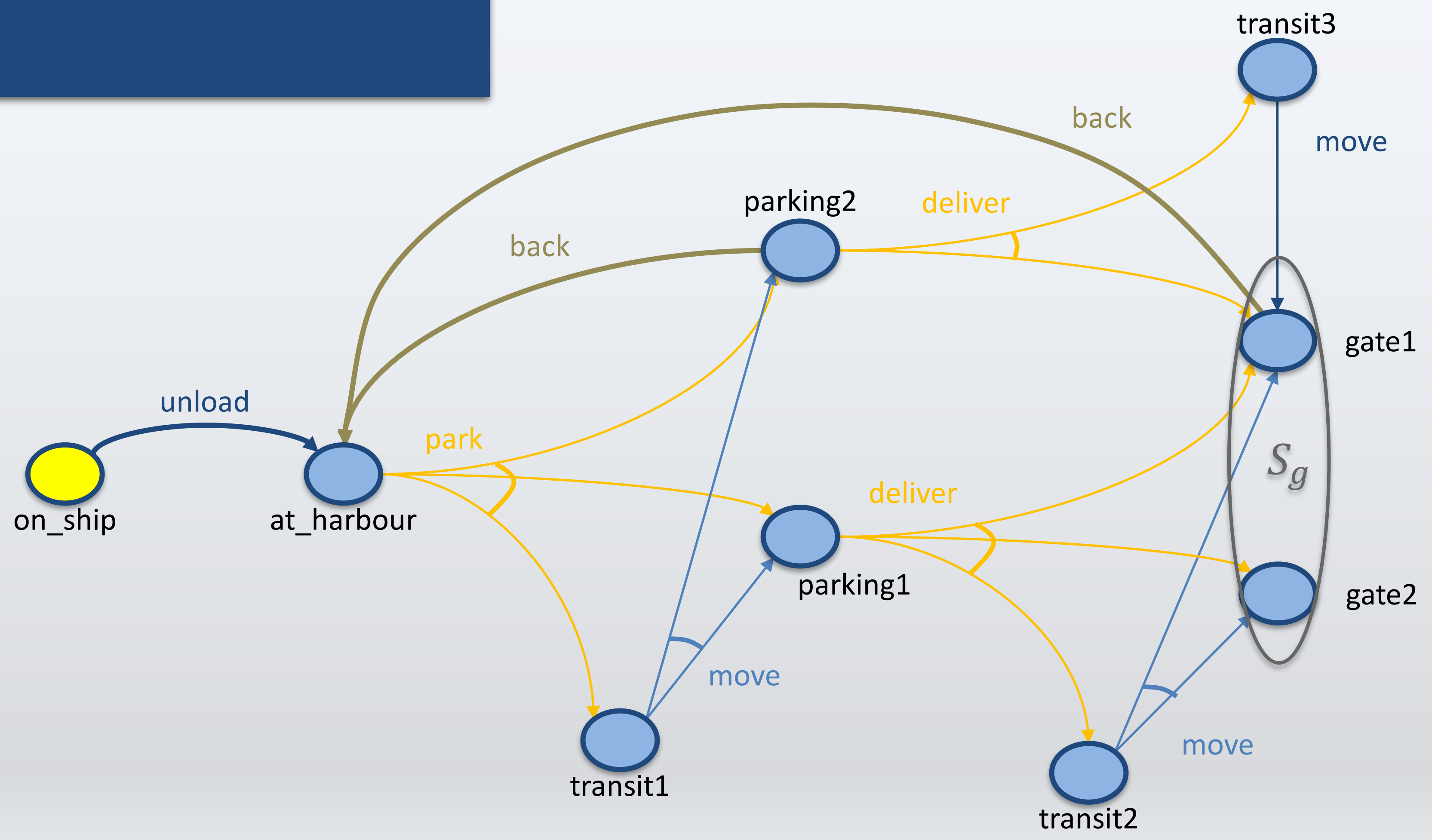
- Check for cycles
  - For each $s' \in \left(\gamma(s,a) \cap Dom(\pi)\right)$
    - Is $s' \in \hat{\gamma}(s',\pi)$?
  - Formally, $has{-}loops(\pi, s, Frontier)$ iff
    - $\exists s' \in \left(\gamma(s,a) \cap Dom(\pi)\right) :\ s' \in \hat{\gamma}(s',\pi)$
  - I.e., a state s' is reachable from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

Example

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

$Frontier \setminus S_g$ = {on_ship}

$\pi = \{\}$



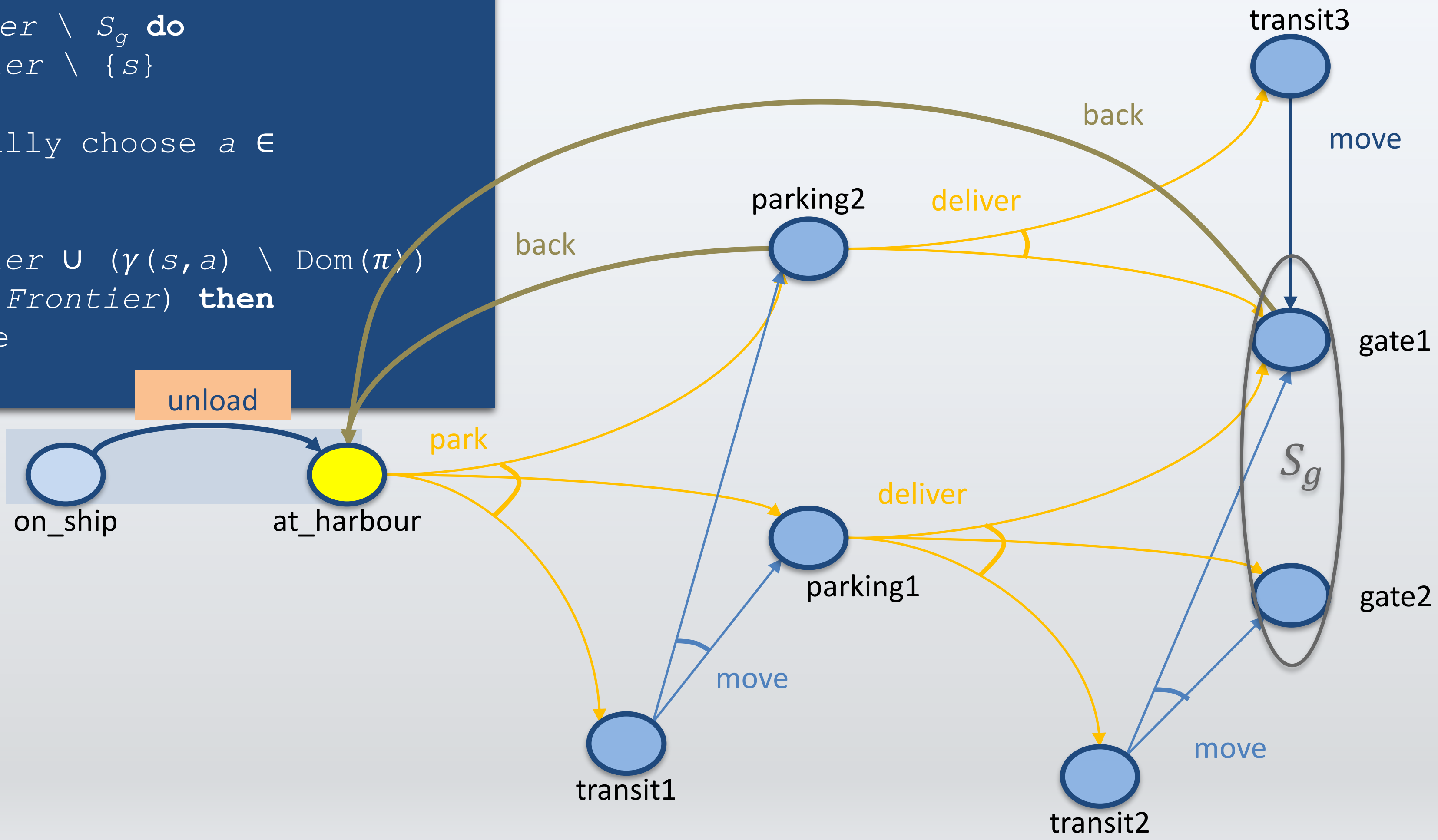
Example

```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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 = on_ship

$Frontier \setminus S_g$ = {at_harbor}

π = {(on_ship, unload)}



Example

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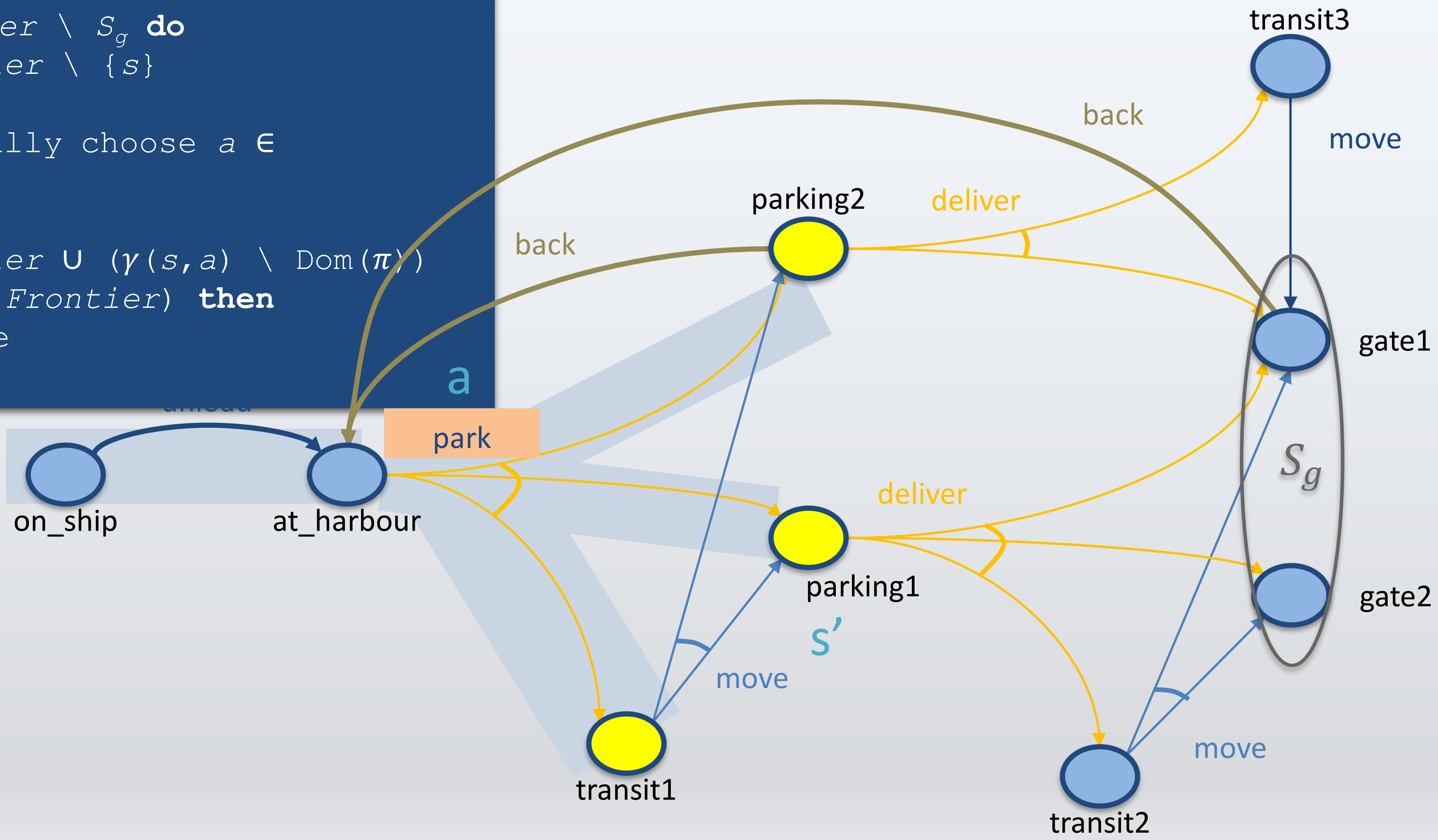
```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈
Applicable(s)
        π ← π ∪ (s,a)
        Frontier ← Frontier ∪ (γ(s,a) \ Dom(π))
        if has-loops(π,s,Frontier) then
            return failure
    return π
```



s = at_harbor

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

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

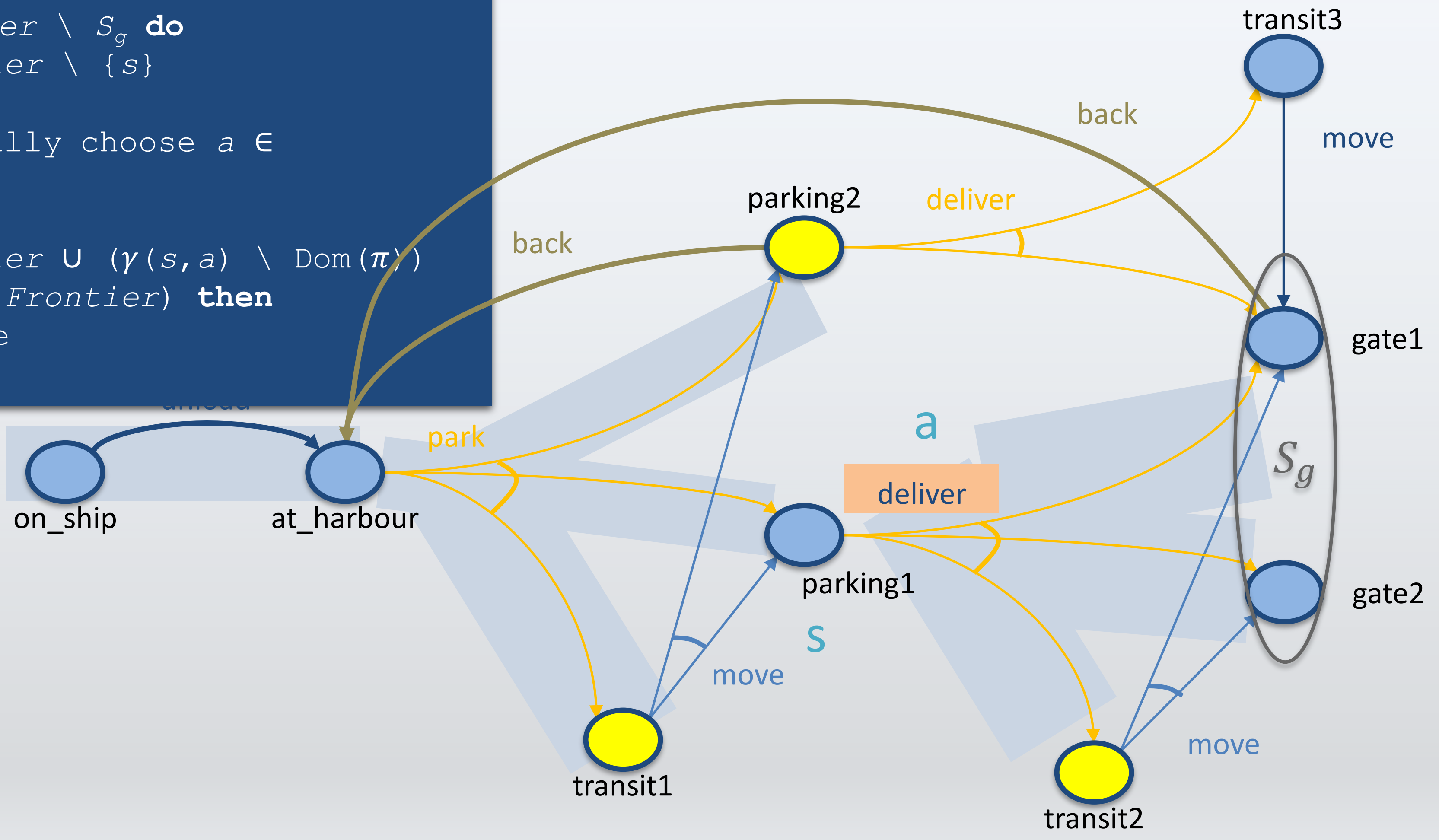
Example

```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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
```

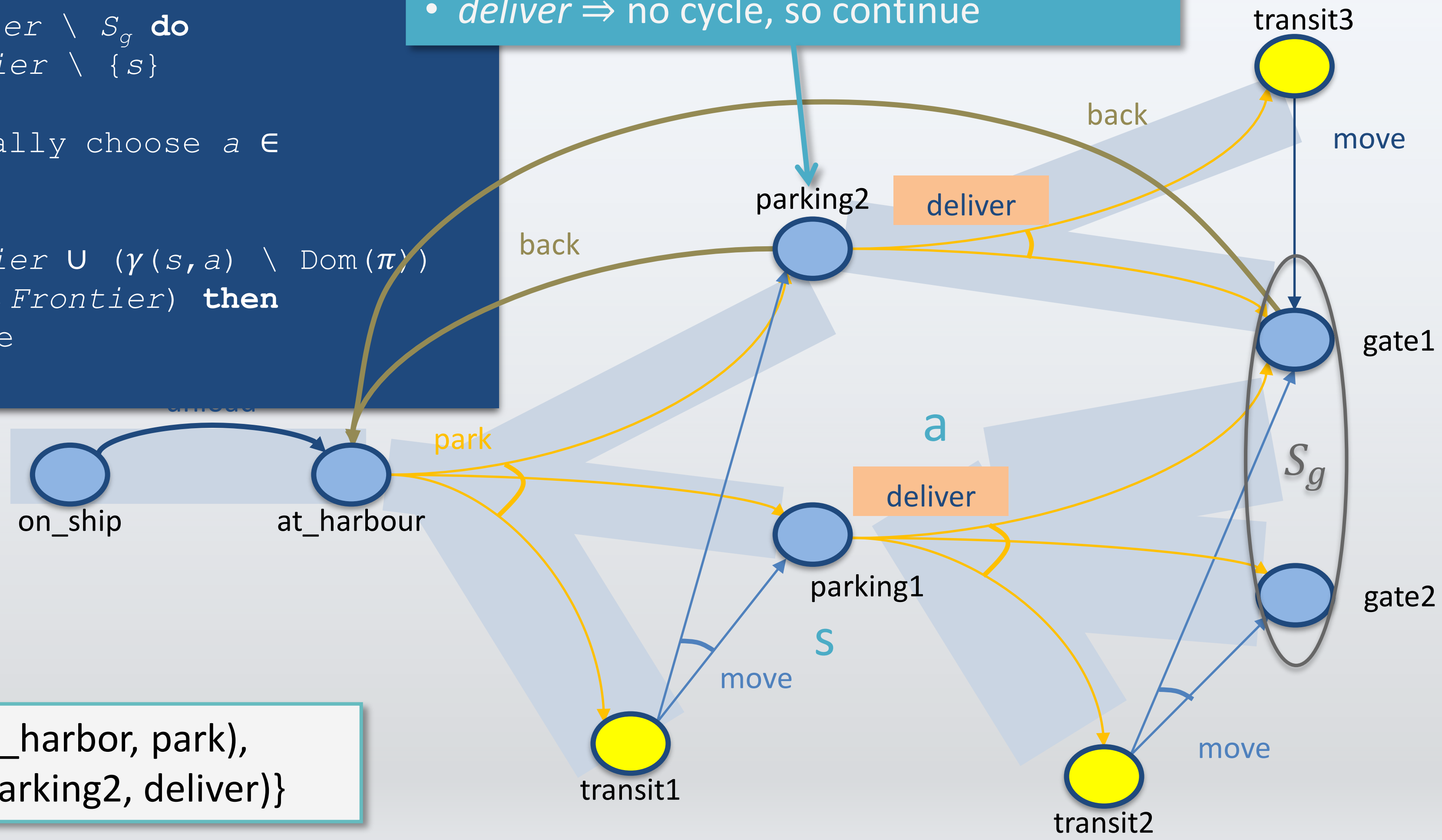
nondeterministically choose *back* or *deliver*

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

s = parking2

Frontier \ S_g = {transit1, transit2, transit3}

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



Example

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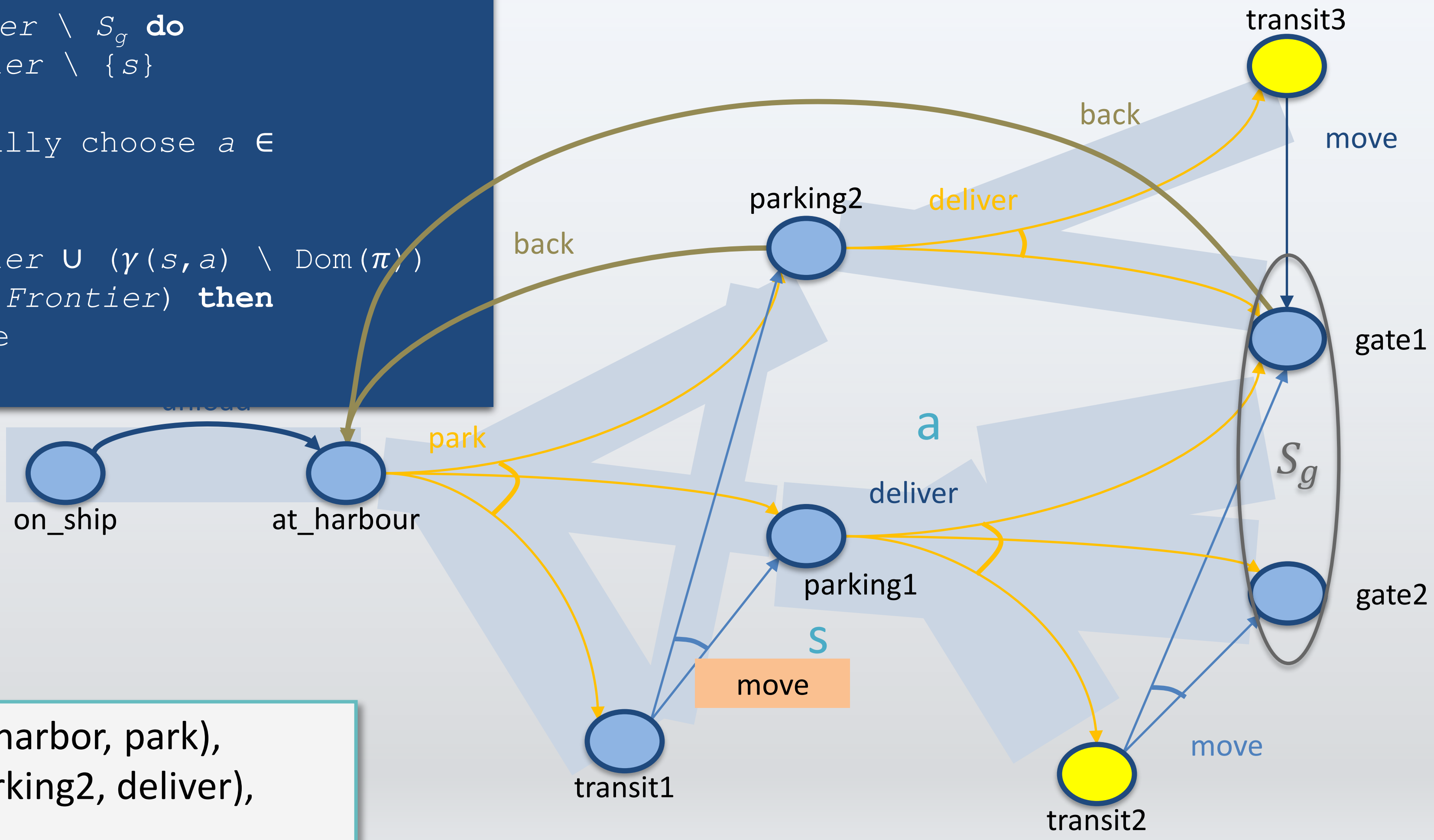
```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈
Applicable(s)
        π ← π ∪ (s,a)
        Frontier ← Frontier ∪ (γ(s,a) \ Dom(π))
        if has-loops(π,s,Frontier) then
            return failure
    return π
```

s = transit1

Frontier \ S_g = {transit2, transit3}

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

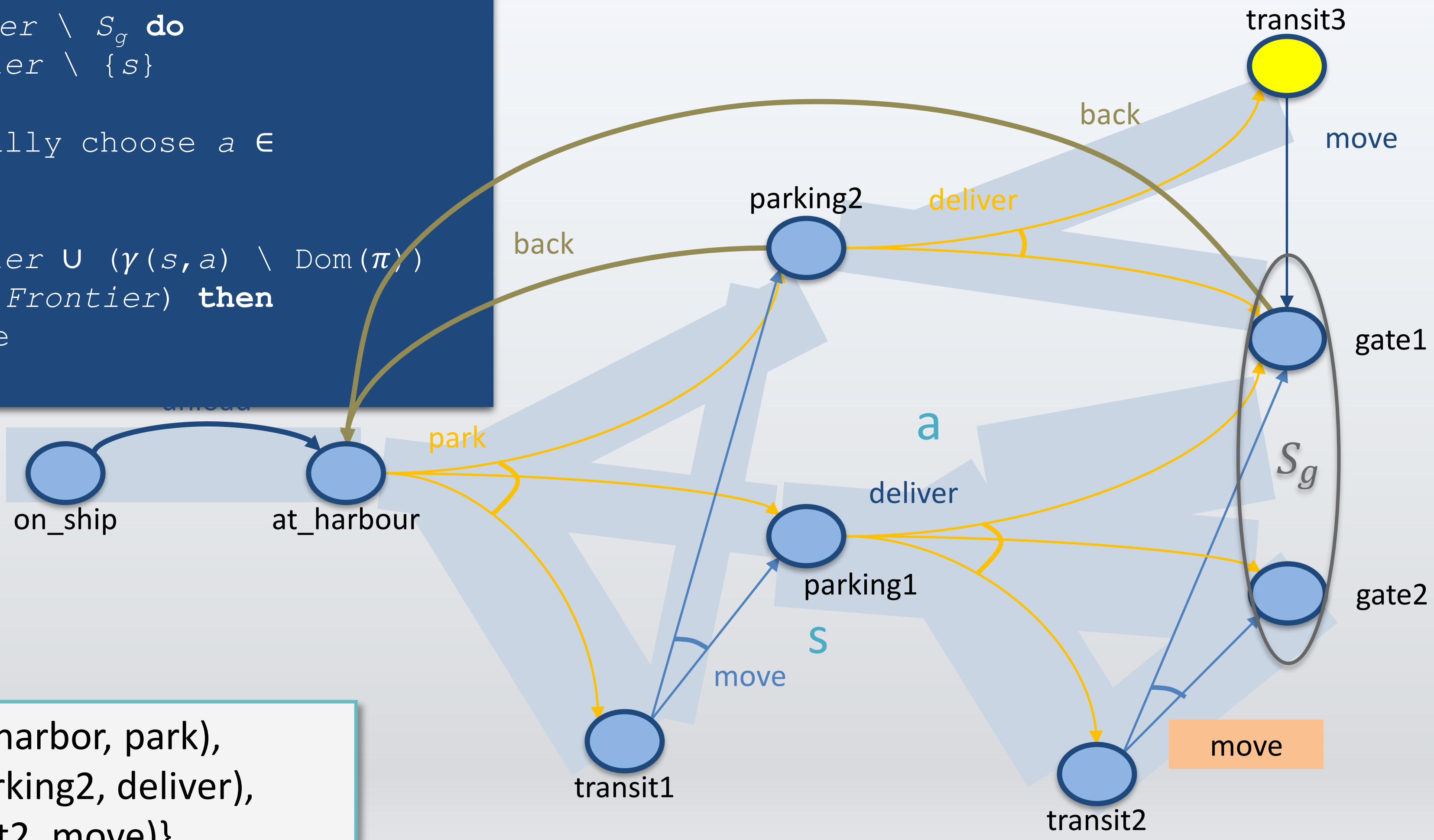


Example

```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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 = transit2

$Frontier \setminus S_g$ = {transit3}



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

Example

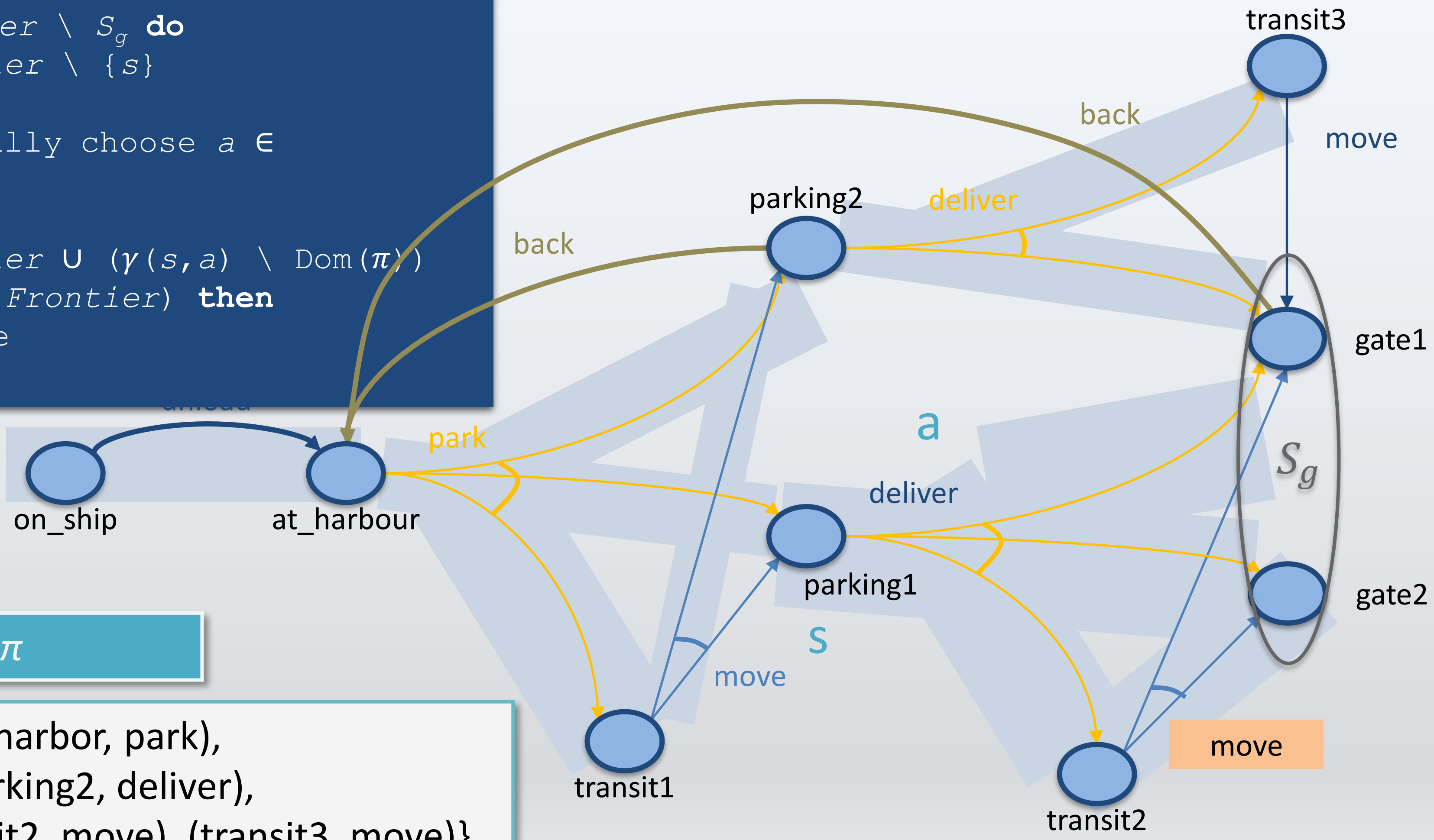
```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈
Applicable(s)
        π ← π ∪ (s,a)
        Frontier ← Frontier ∪ (γ(s,a) \ Dom(π))
        if has-loops(π,s,Frontier) then
            return failure
    return π
```

s = 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,s0,Sg)
   π ← ∅
   Frontier ← {s0}
   for every s ∈ Frontier \ Sg 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

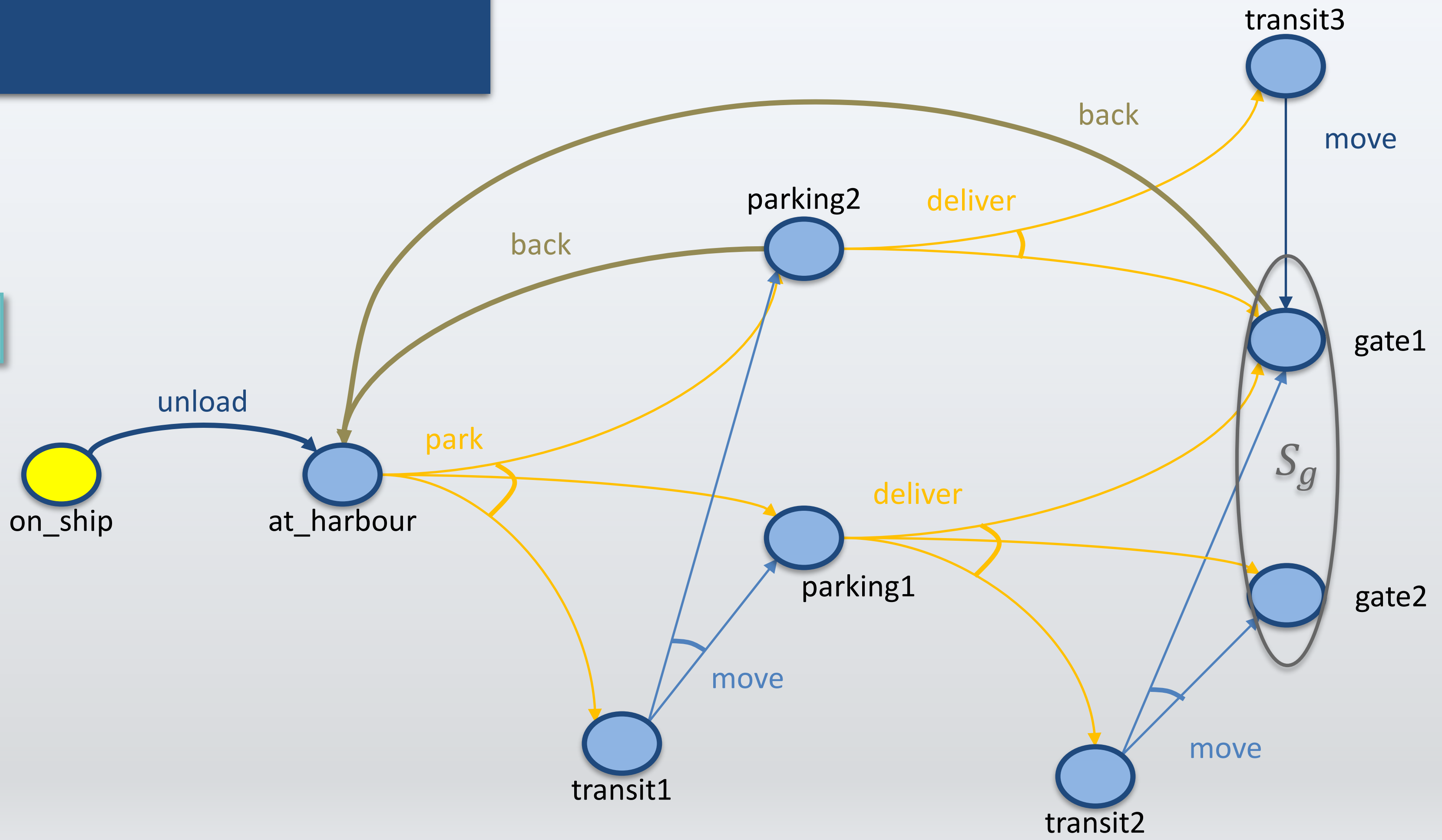
- Same as `Find-Acyclic-Solution` except for cycle-checking
- `has-unsafe-loops` instead of `has-loops`
- Check if π contains any cycles that cannot be escaped:
  - For each $s' \in \left(\gamma(s,a) \cap Dom(\pi)\right)$
    - Is $\hat{\gamma}(s',\pi) \cap Frontier = \emptyset$?
  - Formally, $has{-}unsafe{-}loops(\pi,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

Example

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

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

$\pi = \{\}$



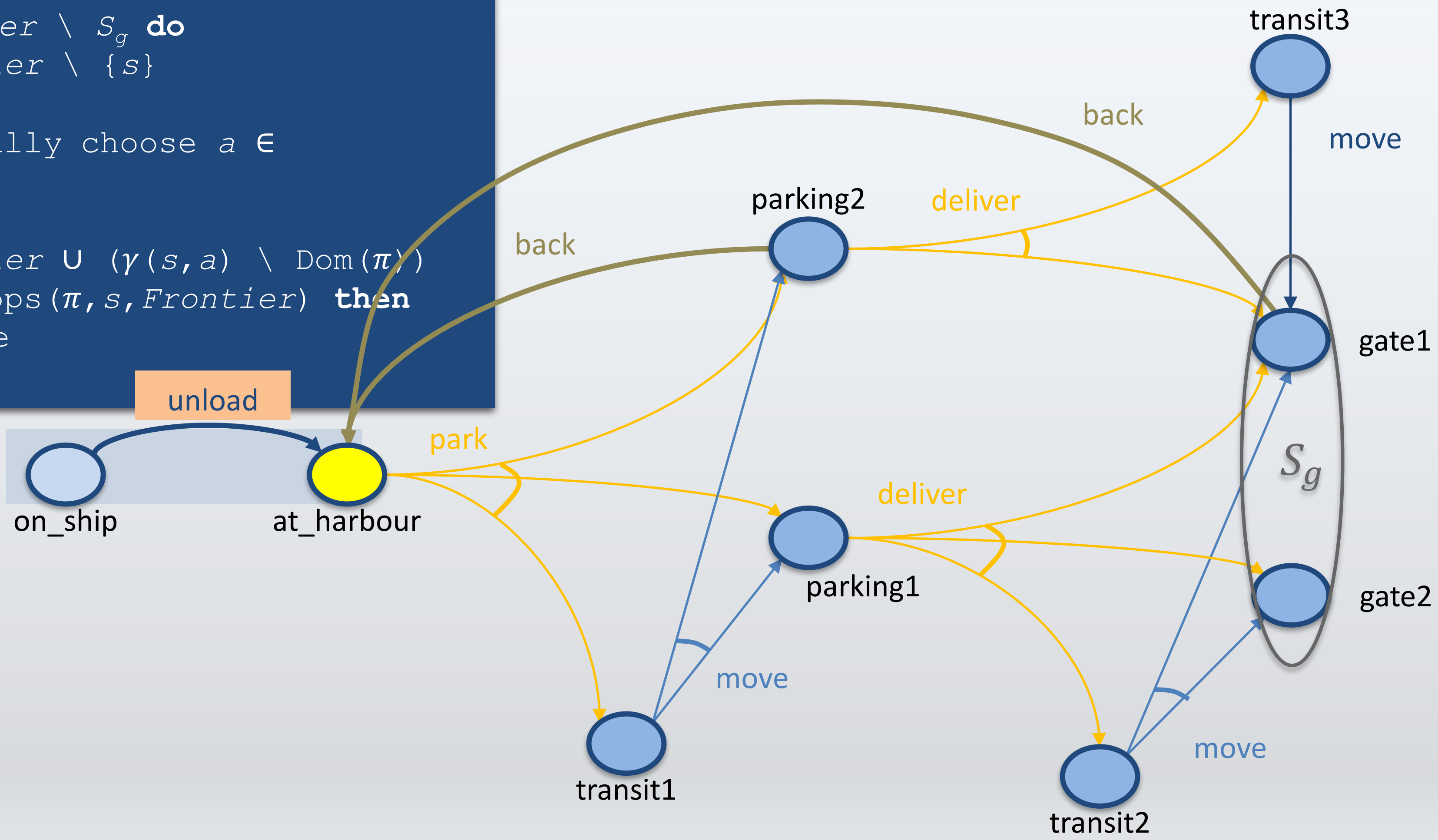
Example

```
Find-Safe-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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)}



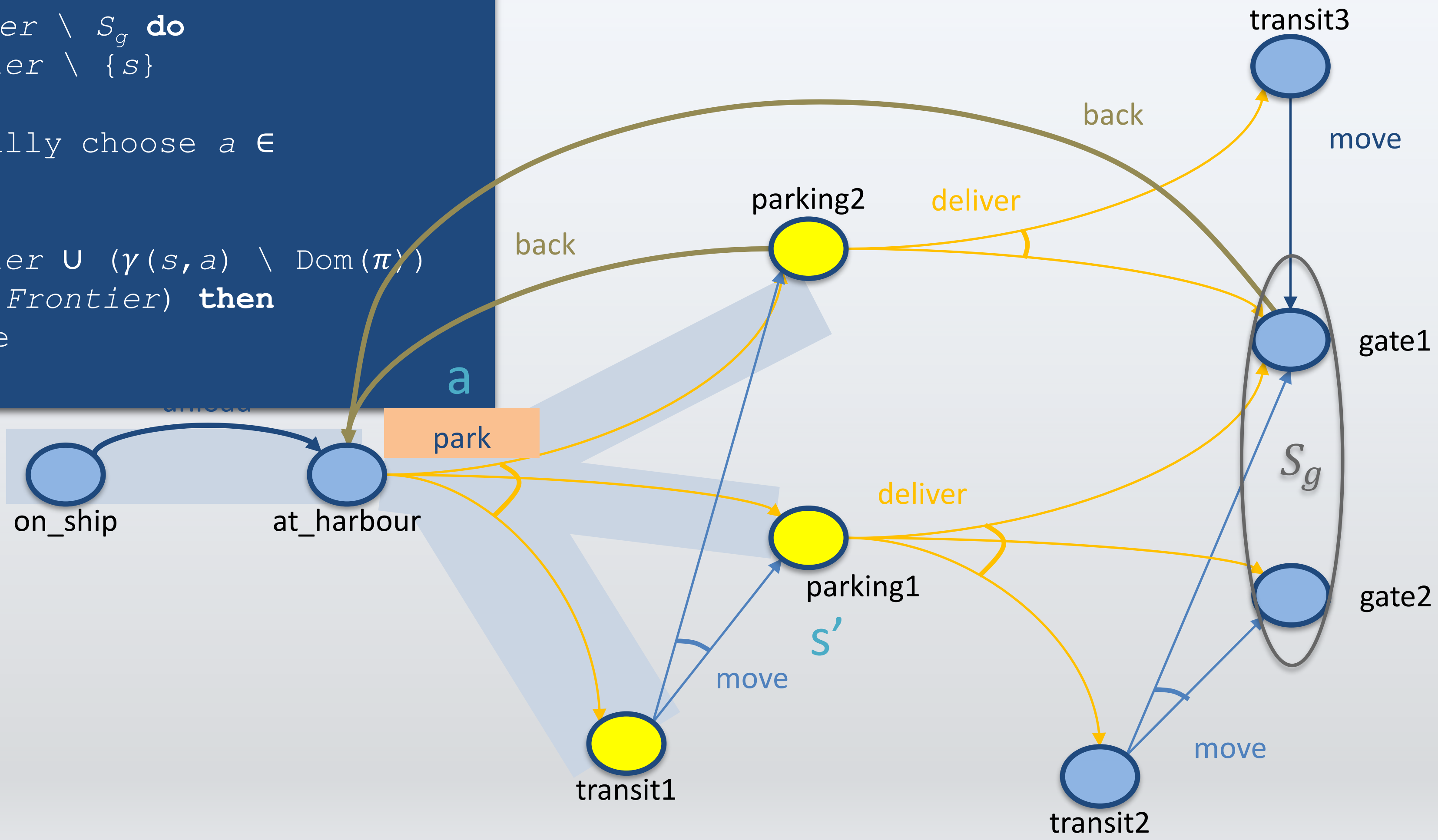
Example

```
Find-Acyclic-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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 = at_harbor

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

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



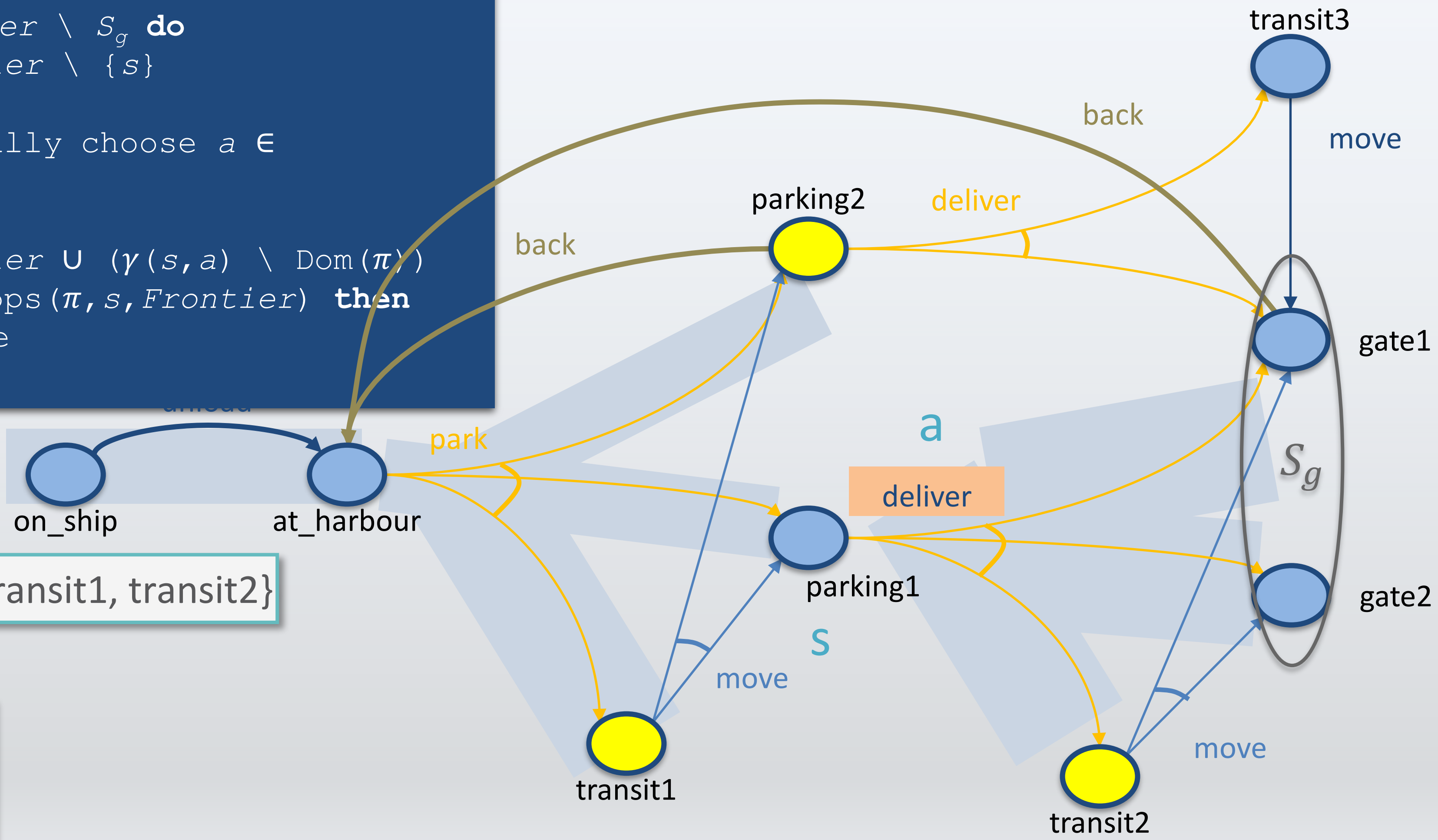
Example


```
Find-Safe-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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
```

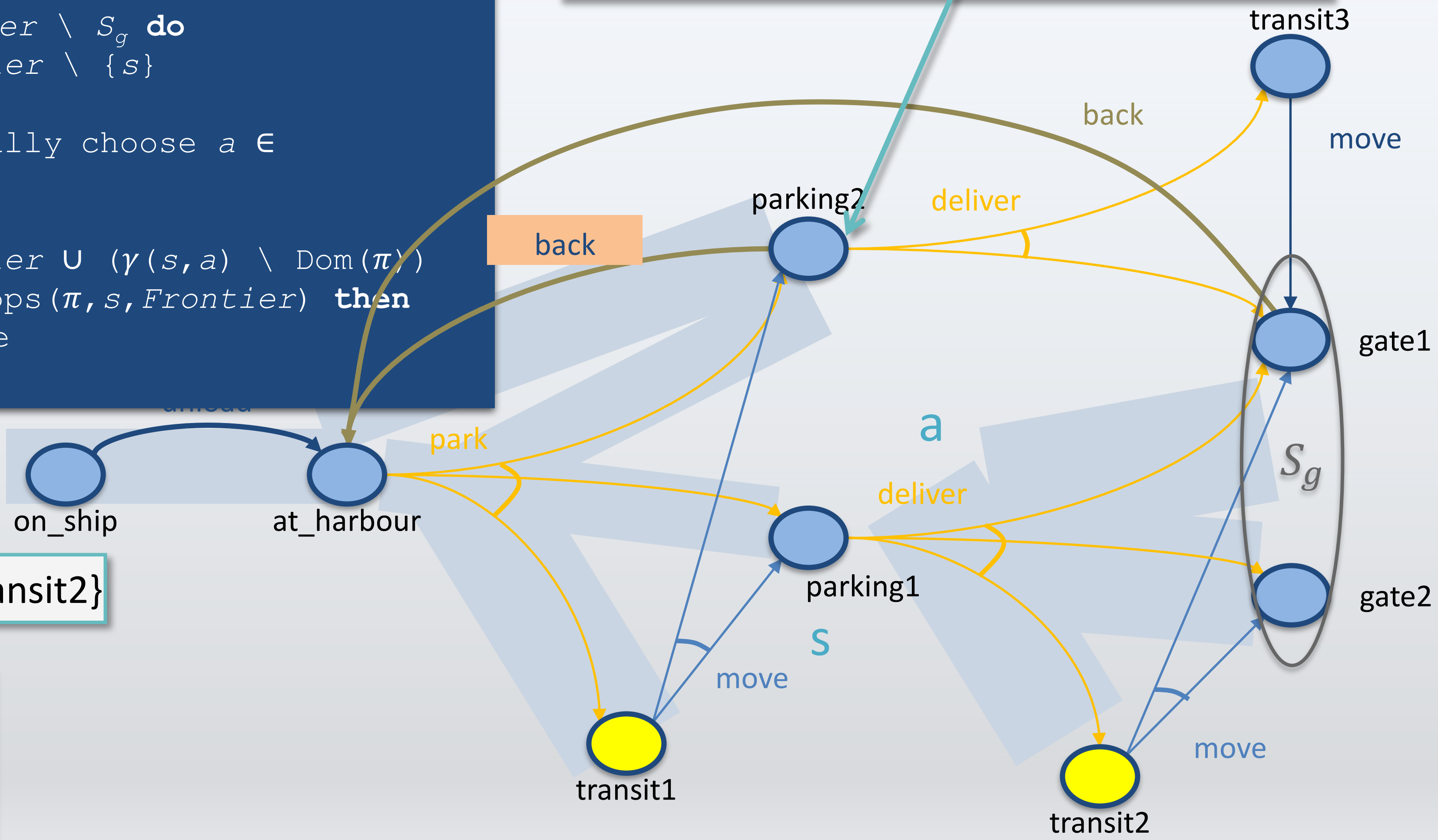
nondeterministically choose *back* or *deliver*

- *back* is okay: escapable cycle

s = parking2

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

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



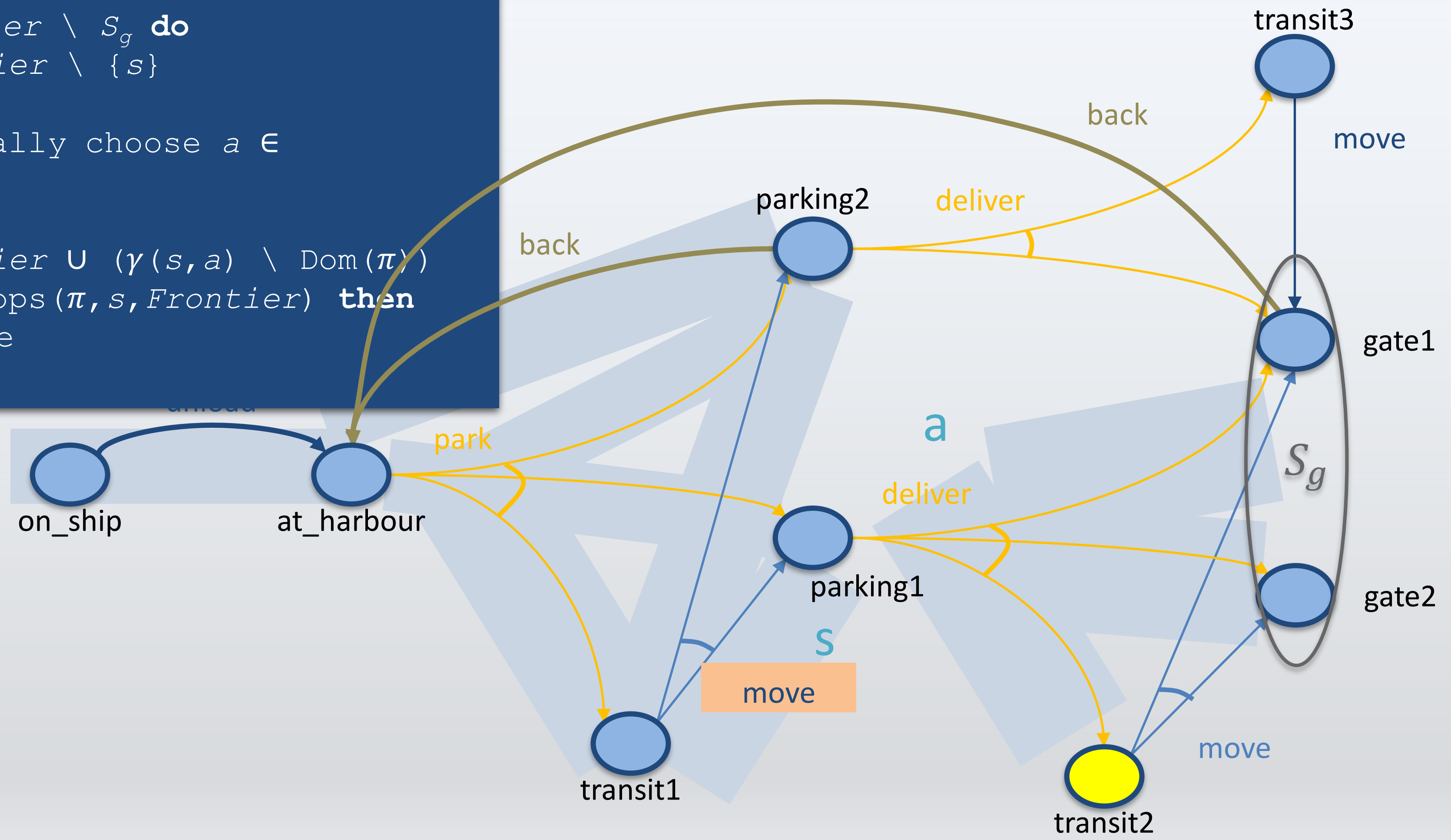
Example

```
Find-Safe-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg 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)}



Example

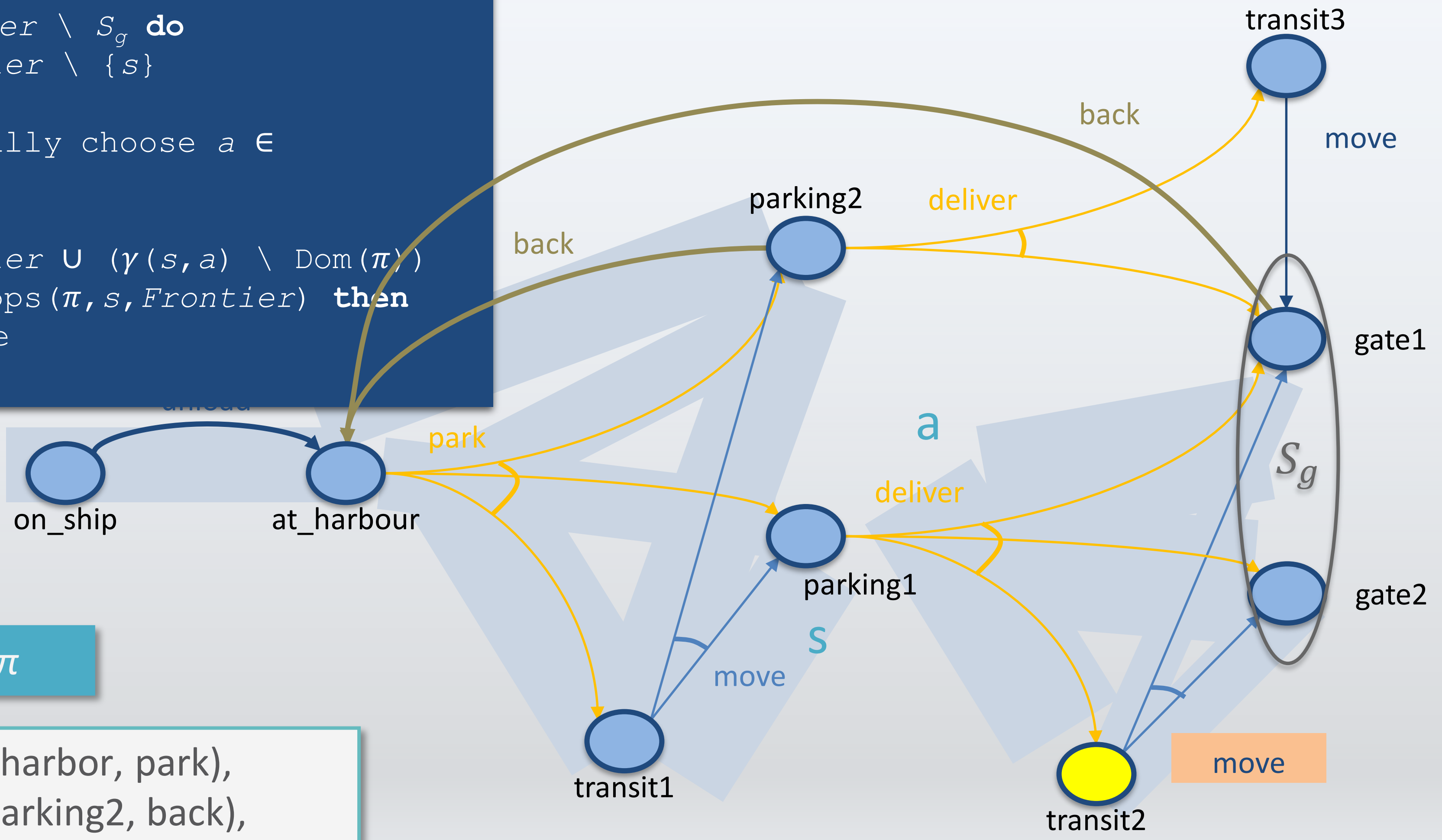
```
Find-Safe-Solution(Σ,s0,Sg)
    ...
    for every s ∈ Frontier \ Sg do
        Frontier ← Frontier \ {s}
        ...
        nondeterministically choose a ∈
Applicable(s)
        π ← π ∪ (s,a)
        Frontier ← Frontier ∪ (γ(s,a) \ Dom(π))
        if has-unsafe-loops(π,s,Frontier) then
            return failure
    return π
```

s = 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
  - Analogue to forward search in deterministic models
  - Algorithms for each type of solution
    - Unsafe
    - Cyclic safe
    - Acyclic safe

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,s0,Sg)
    if s0 ∈ Sg then
        return ∅
    if Applicable(s0) = ∅ then
        return failure
    π ← ∅
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        arbitrarily select s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then          <-Not in the book
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

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

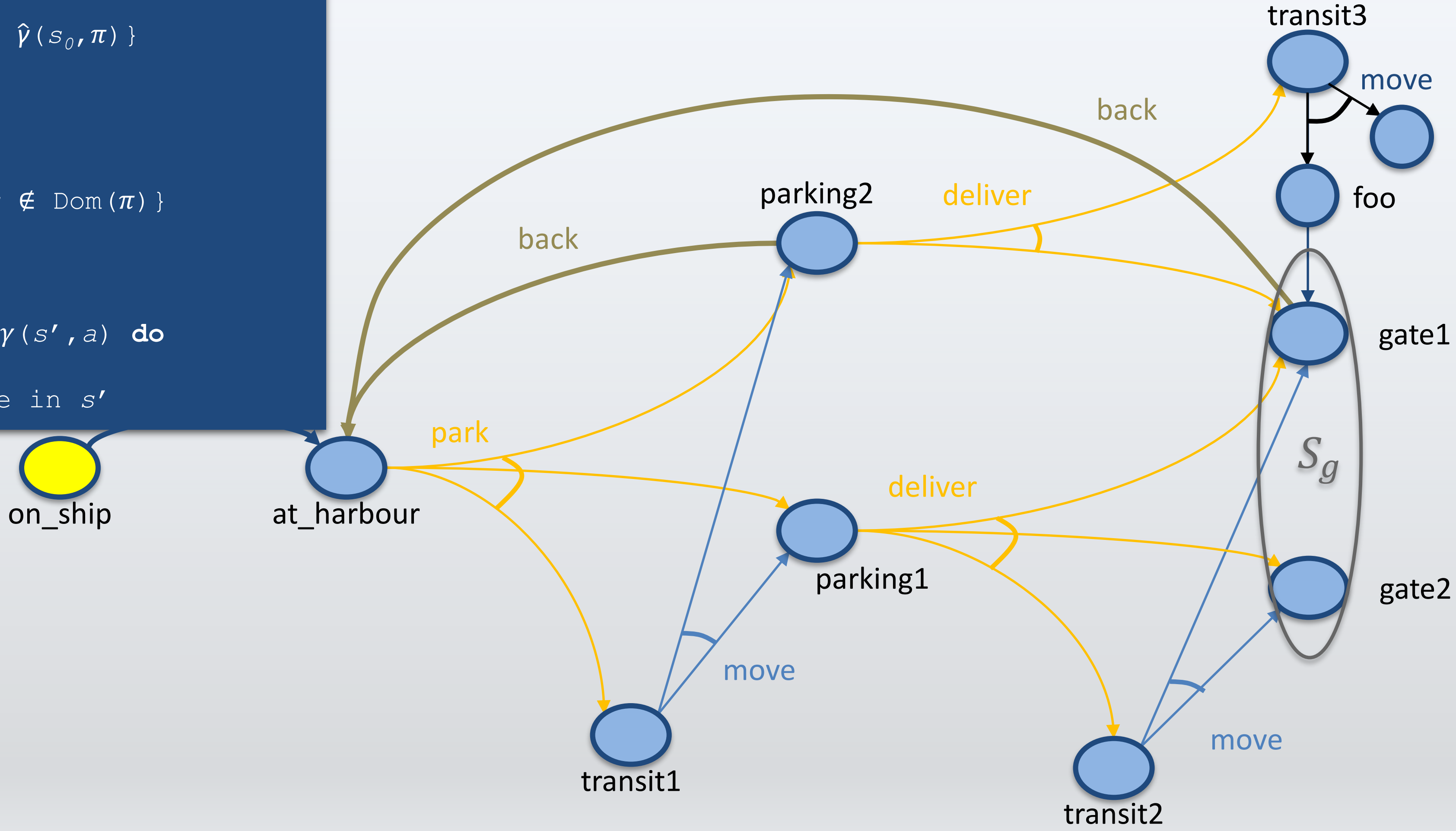
Choose any leaf s that is not a goal. Find a solution π' for s.

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'

Example

```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

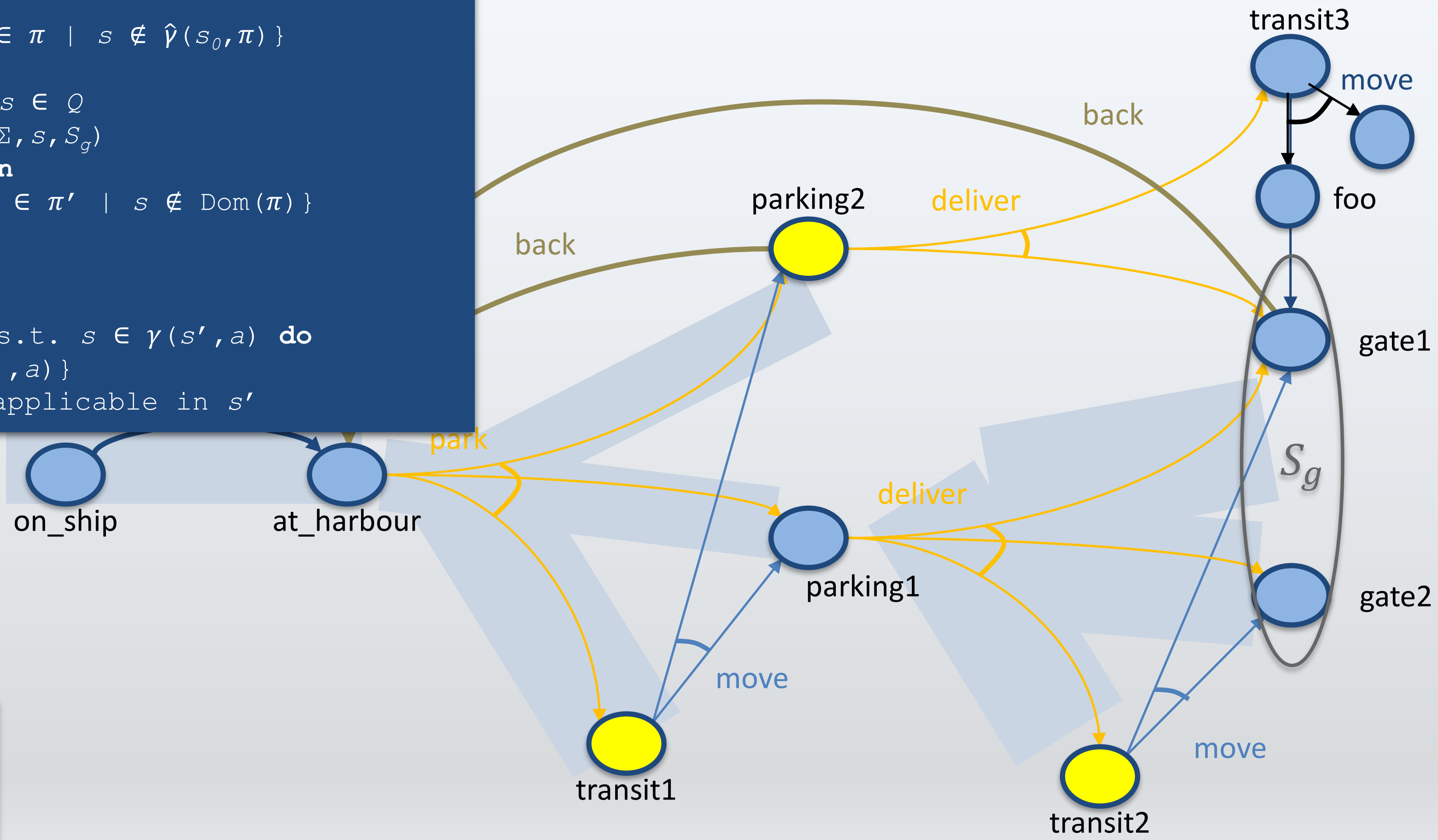


$s_0 = \text{on\_ship}$

$\pi = \{\}$

Example

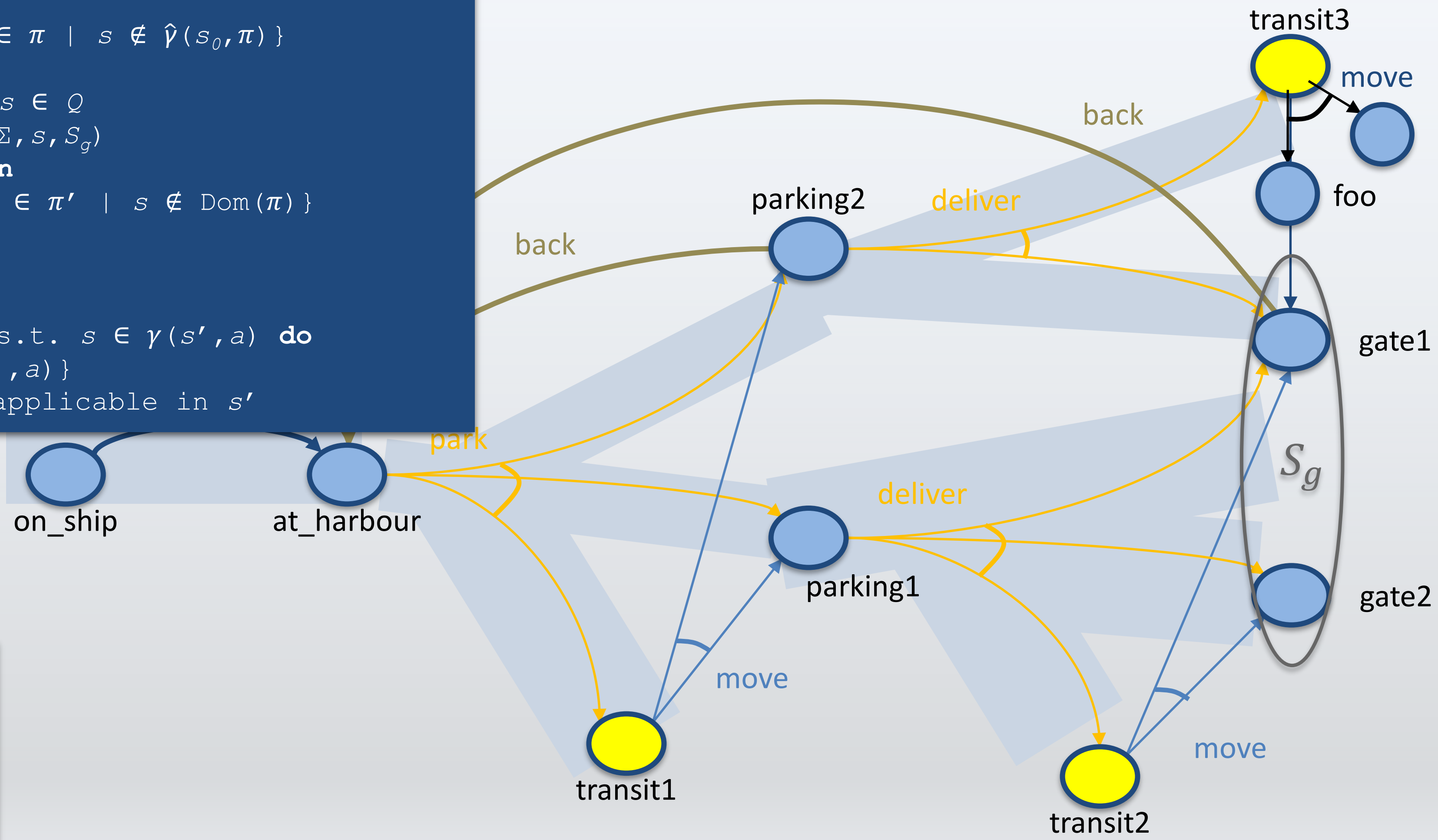
```
Guided-Find-Safe-Solution(Σ,s_0,S_g)
    ... loop
        Q ← leaves(s_0,π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s_0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,S_g)
        if π' ≠ failure then
             π ← π ∪ {(s,a)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



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

Example

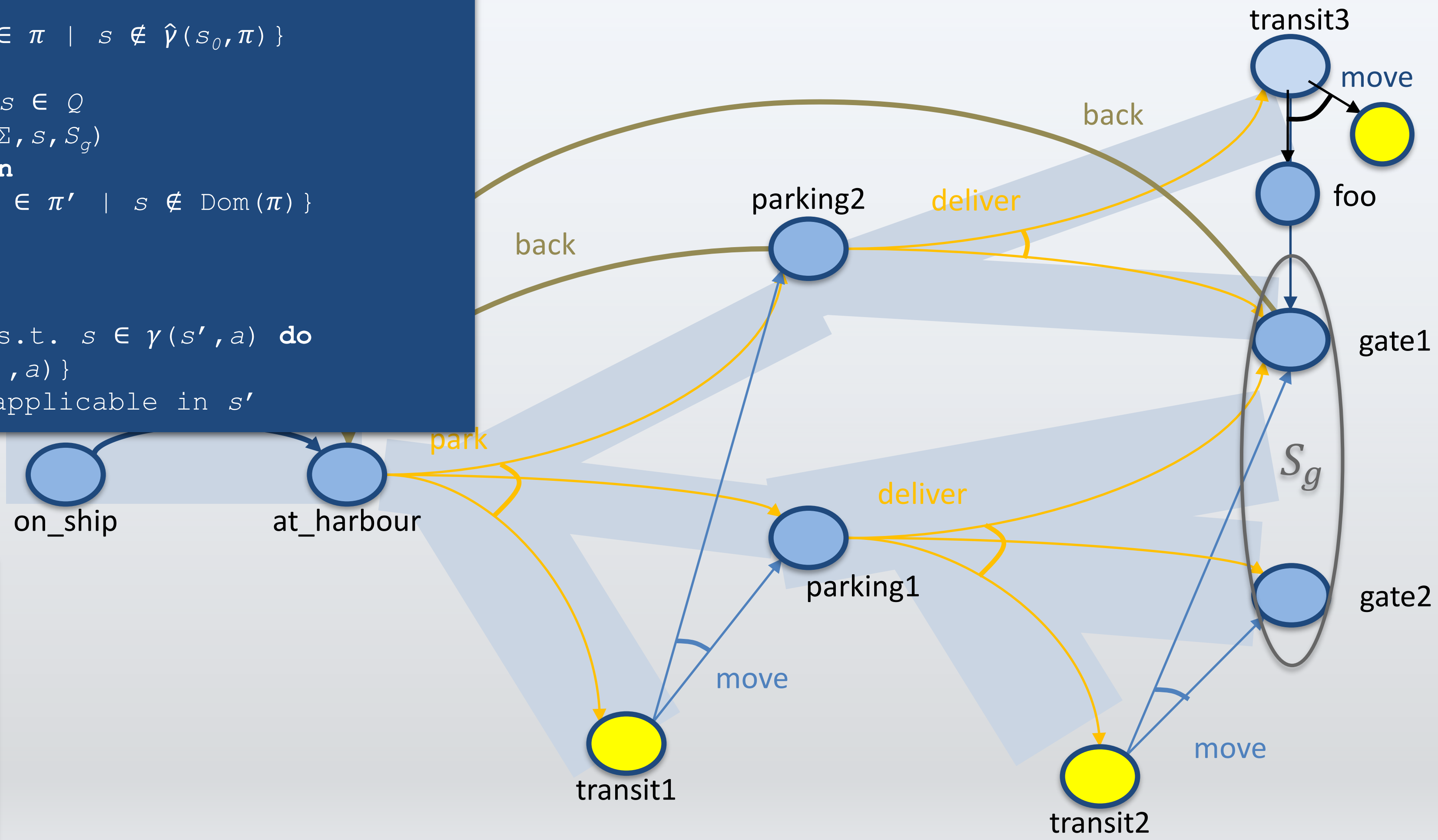

```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```



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

Example

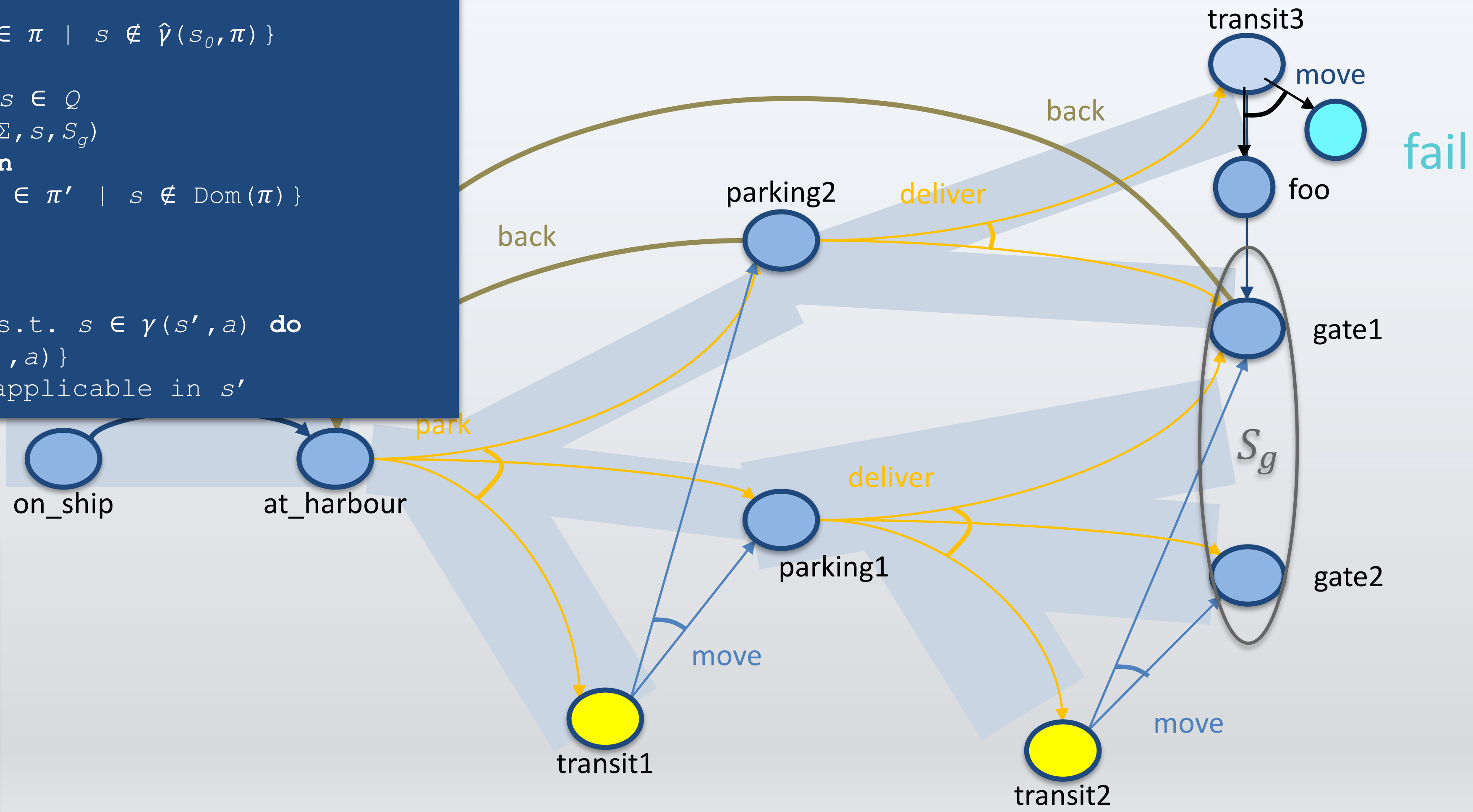
```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```



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

Example

```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

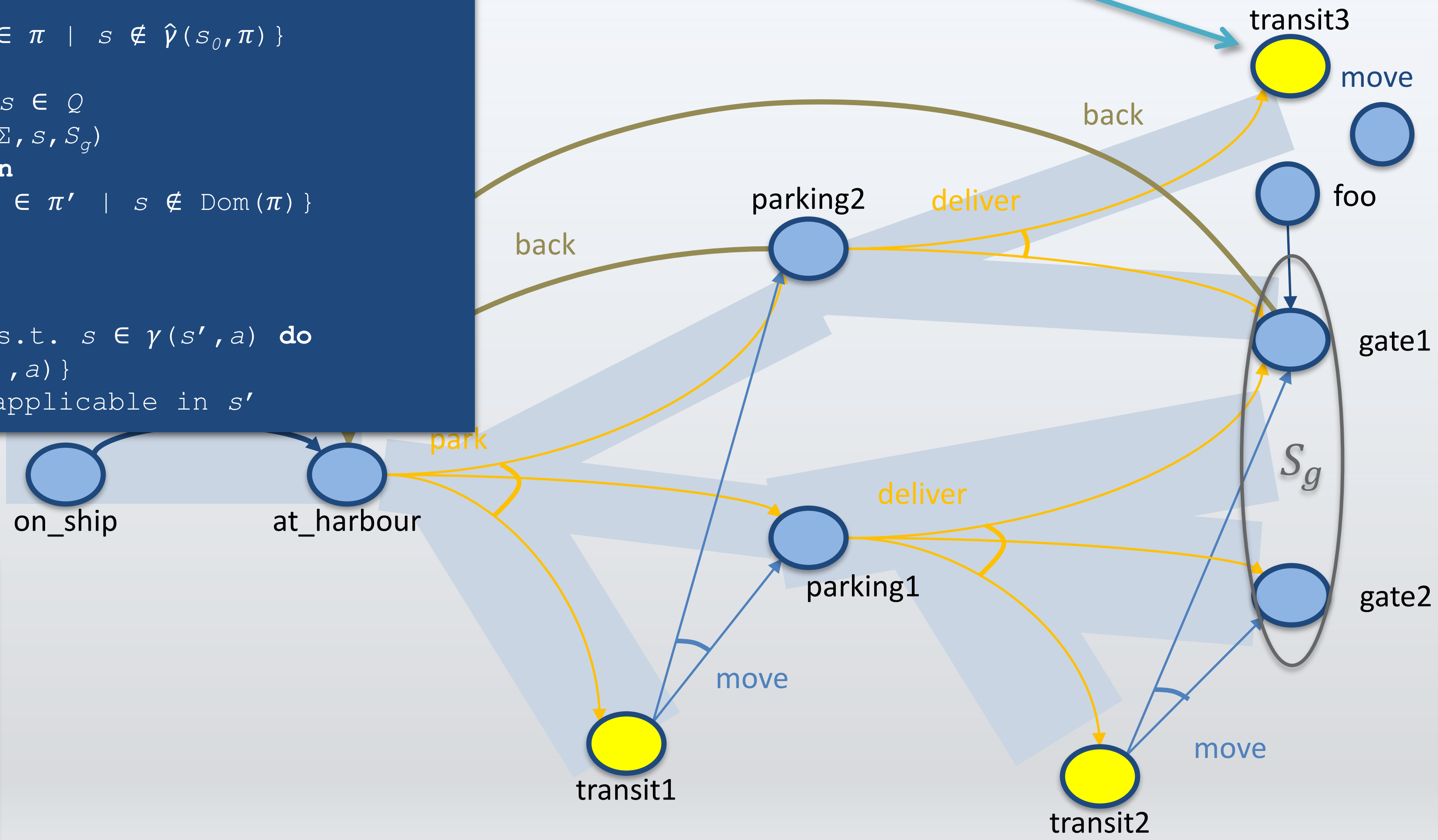


π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(transit3, move),
(foo, move)}

Example

```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

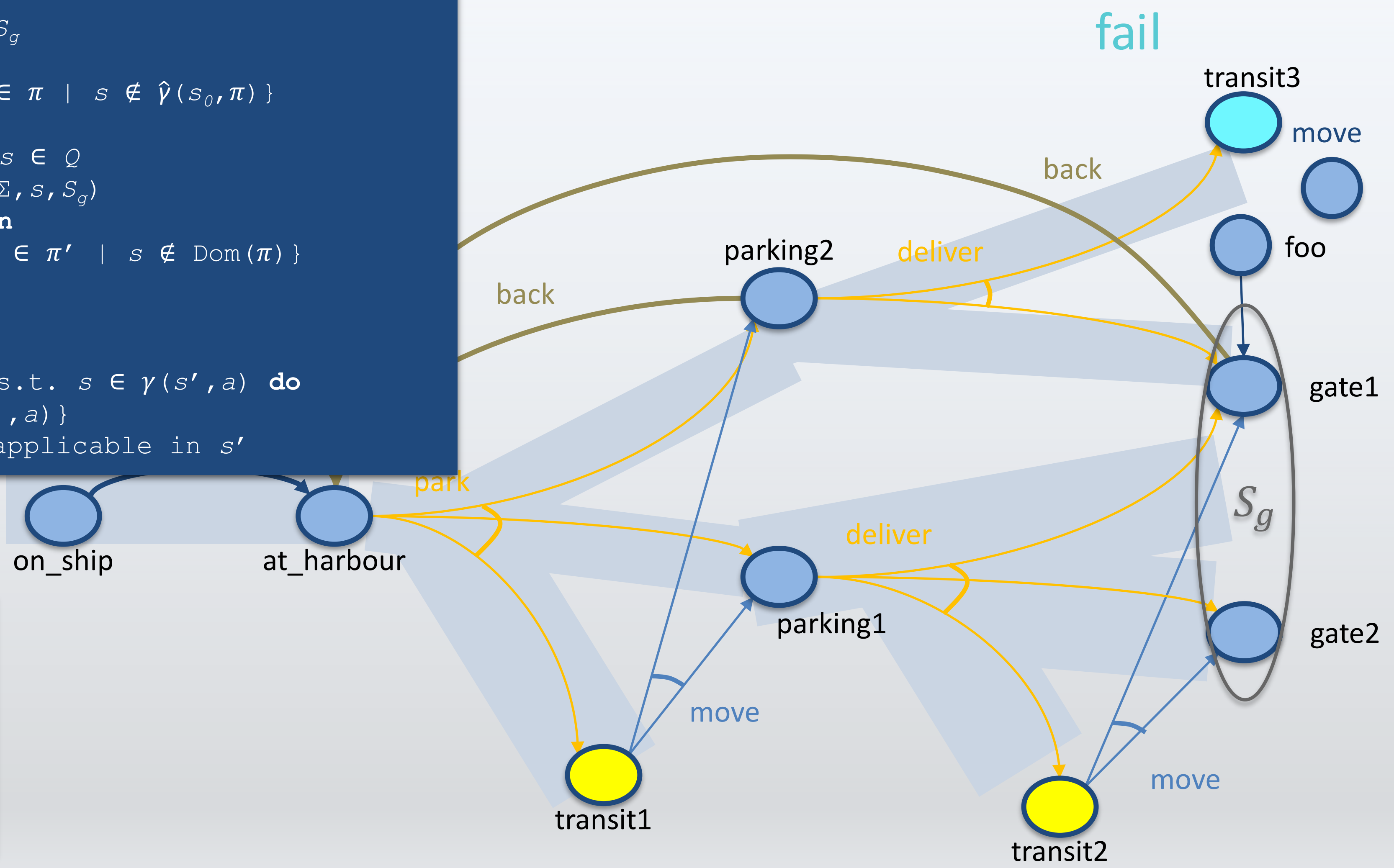
Modify Σ to make *move* inapplicable



π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
~~(transit3, move),~~
(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',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

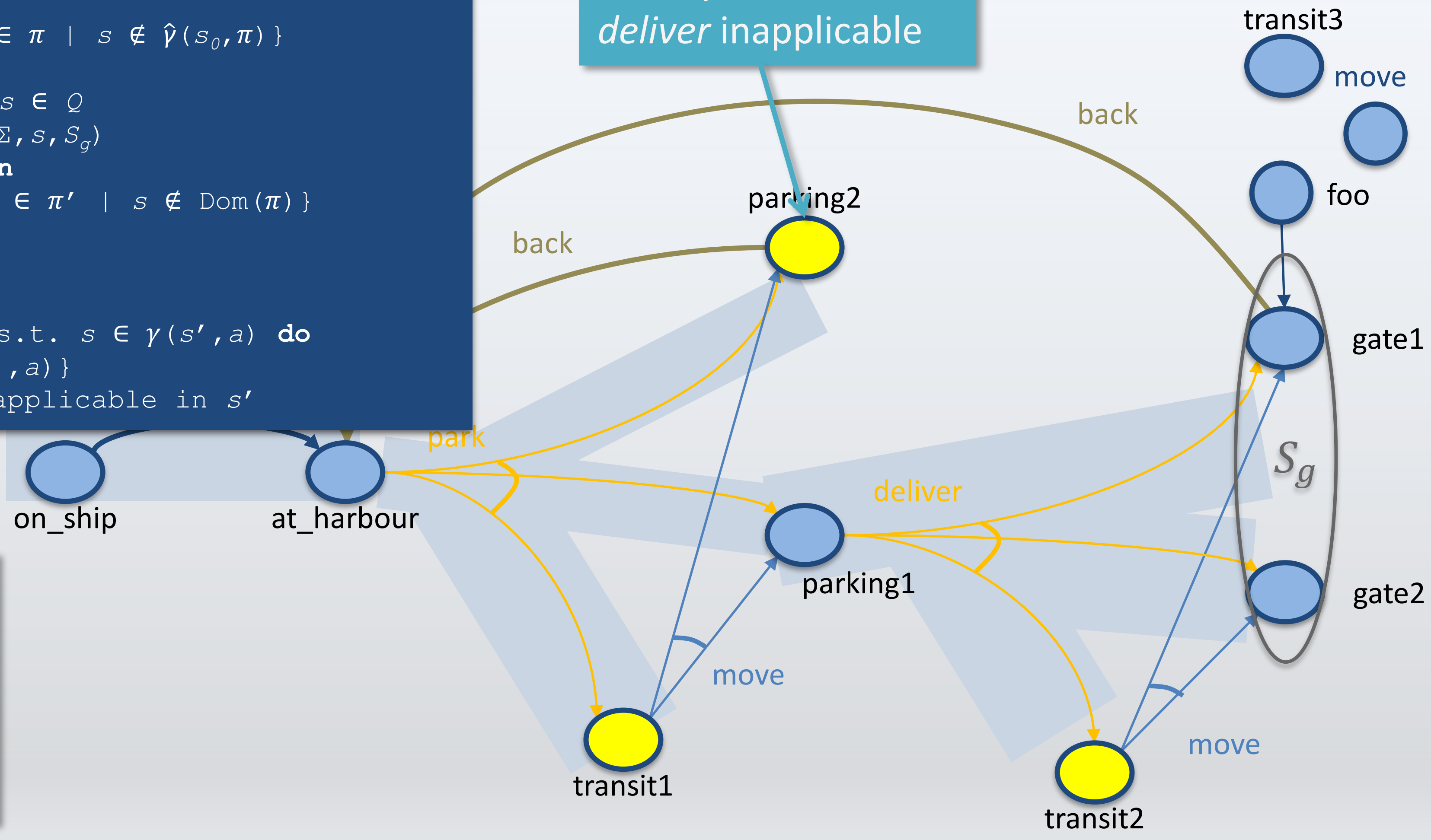


π = {(on_ship, unload),
(at_harbor, park),
(parking1, deliver),
(parking2, deliver),
(foo, move)}

Example

```
Guided-Find-Safe-Solution(Σ,s₀,S_g)
    ... loop
        Q ← leaves(s₀,π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s₀,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 = s₀ then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

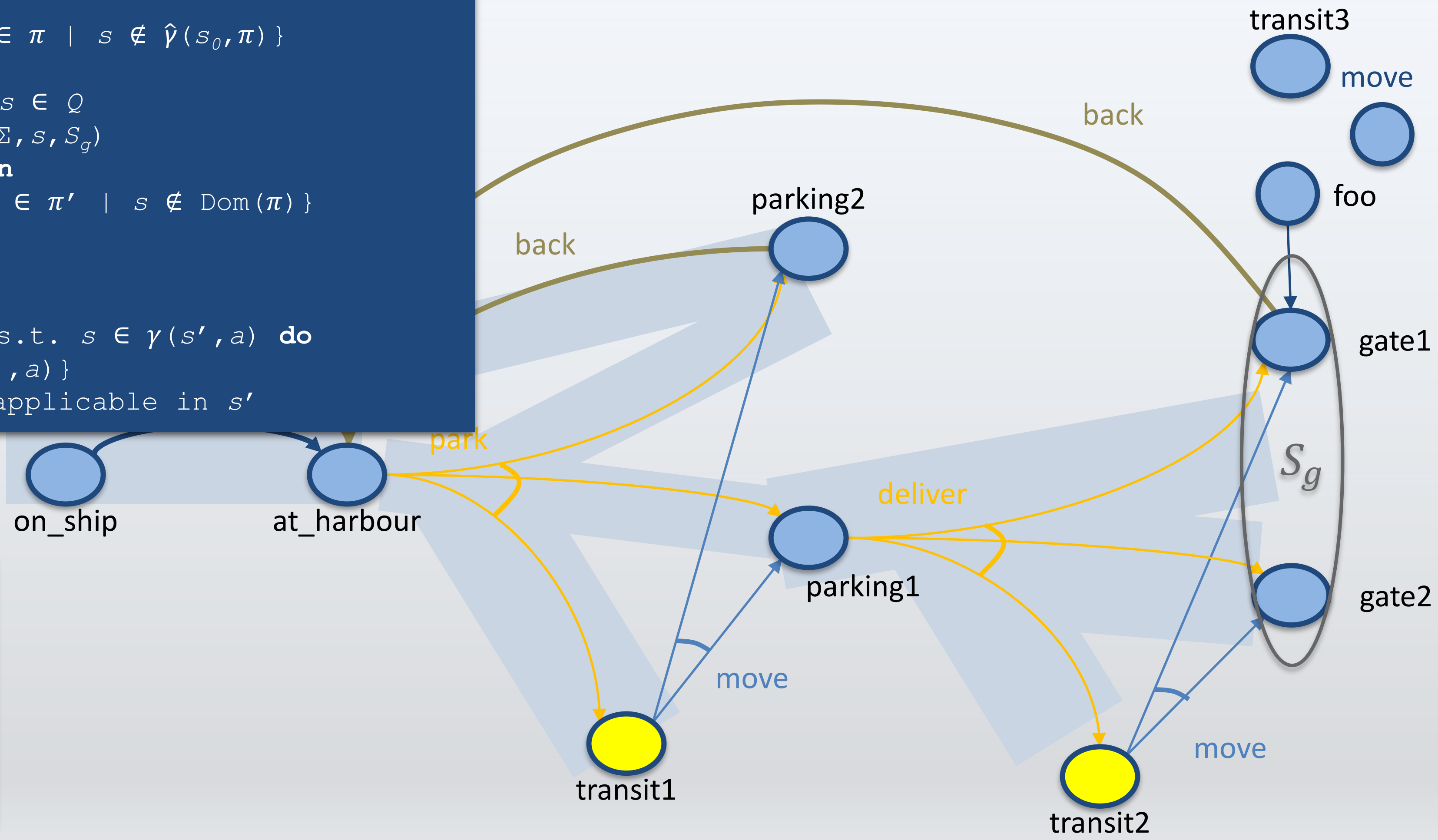
Modify Σ to make *deliver* inapplicable



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

Example

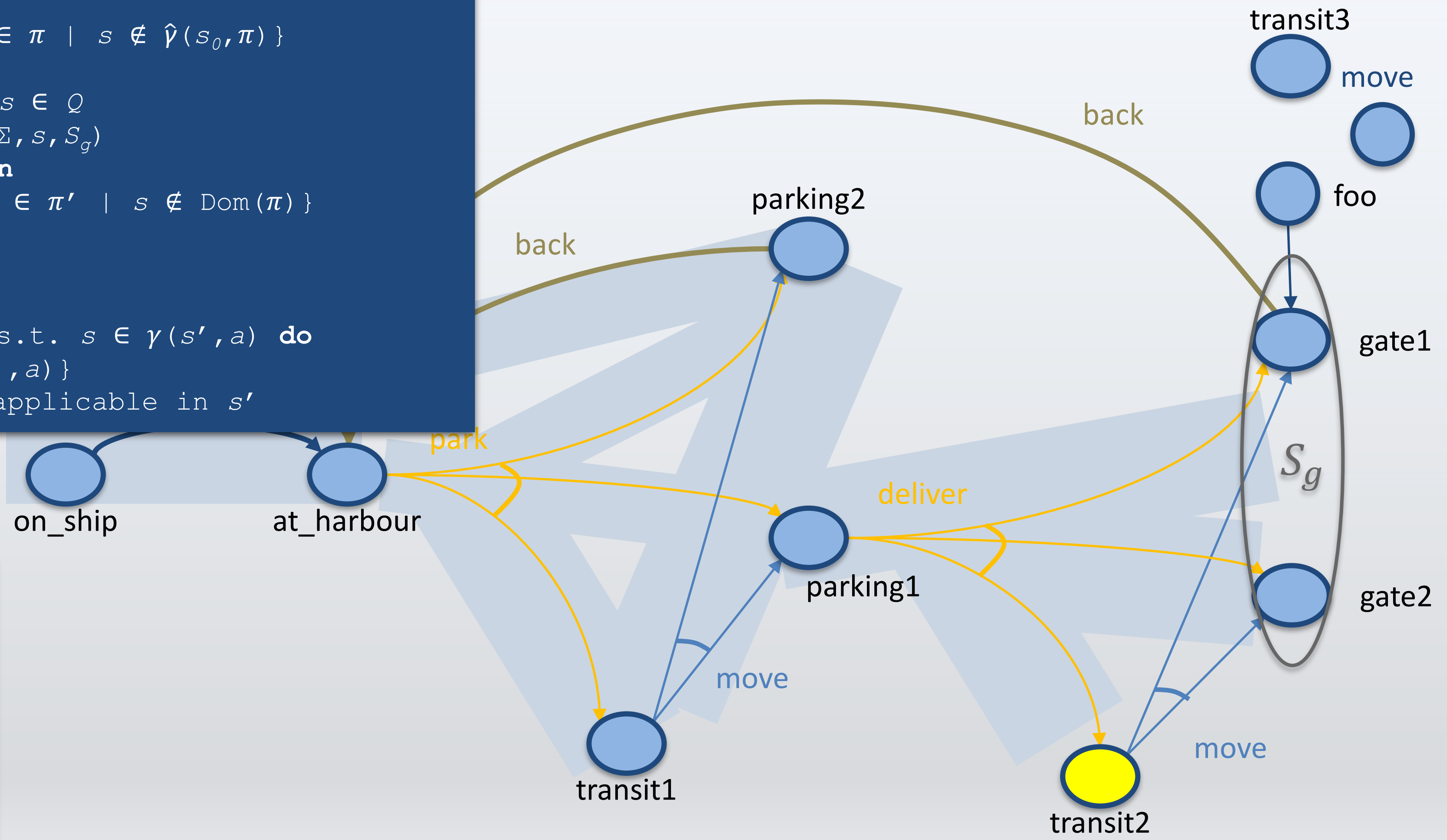
```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π′ | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s′,a s.t. s ∈ 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)}

Example

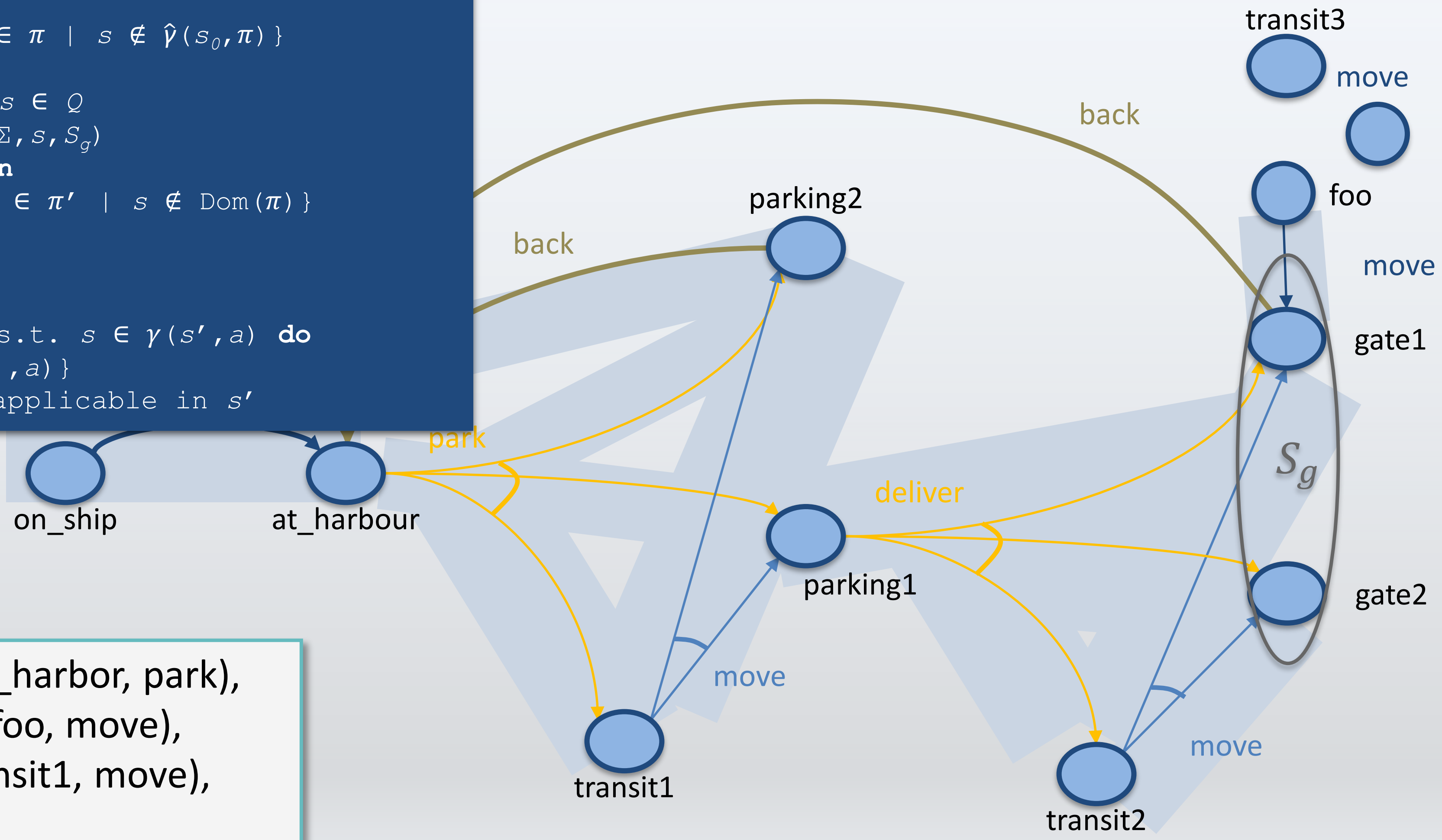
```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π′ | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s′,a s.t. s ∈ 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),
(transit1, move)}

Example

```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
             π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

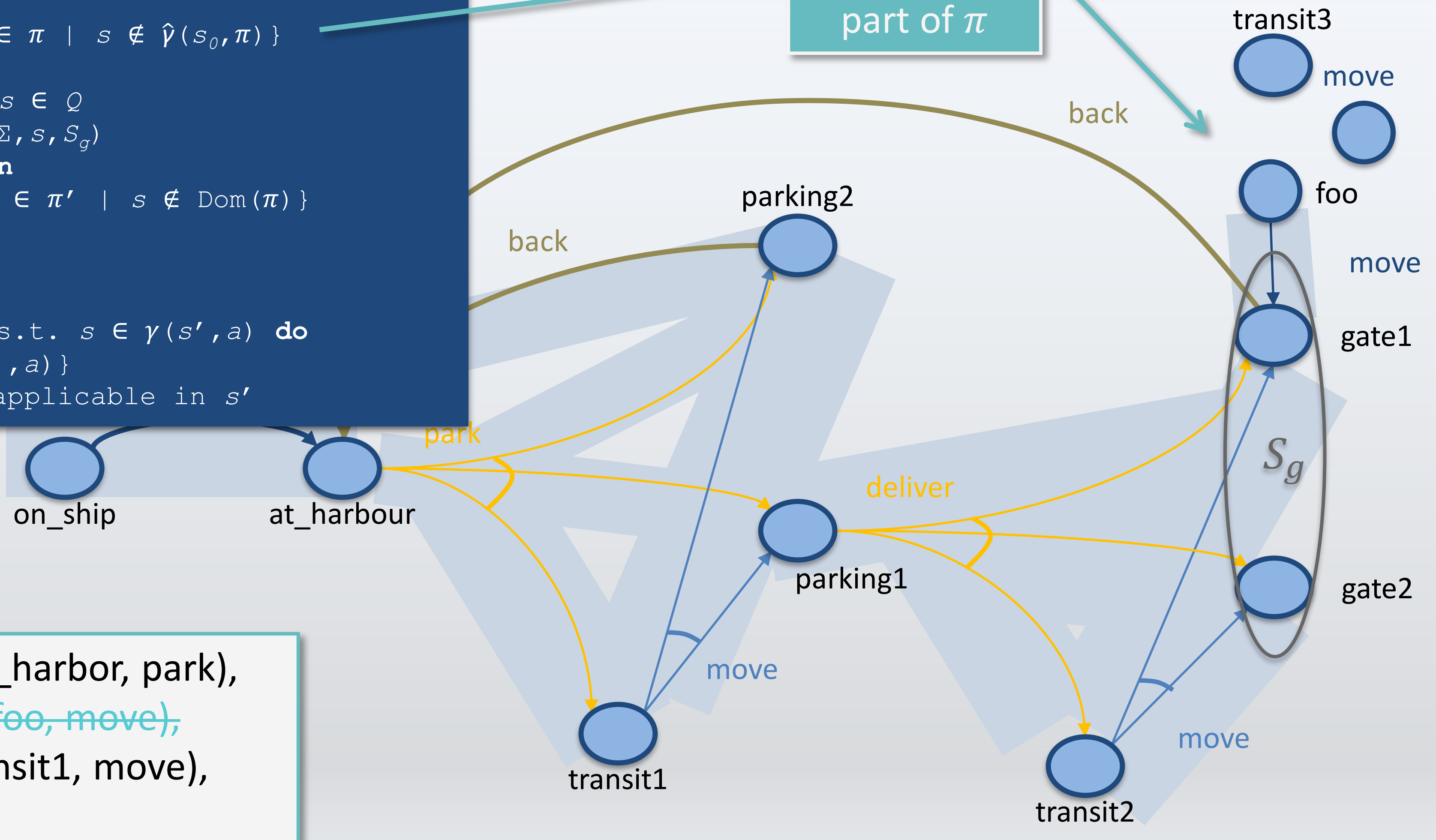


π = {(on_ship, unload), (at_harbor, park),
(parking1, deliver), (foo, move),
(parking2, back),(transit1, move),
(transit2, move)}

Example

```
Guided-Find-Safe-Solution(Σ,s0,Sg)
    ... loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        π' ← Find-Solution(Σ,s,Sg)
        if π' ≠ failure then
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s',a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make a not applicable in s'
```

Remove unreachable part of π



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

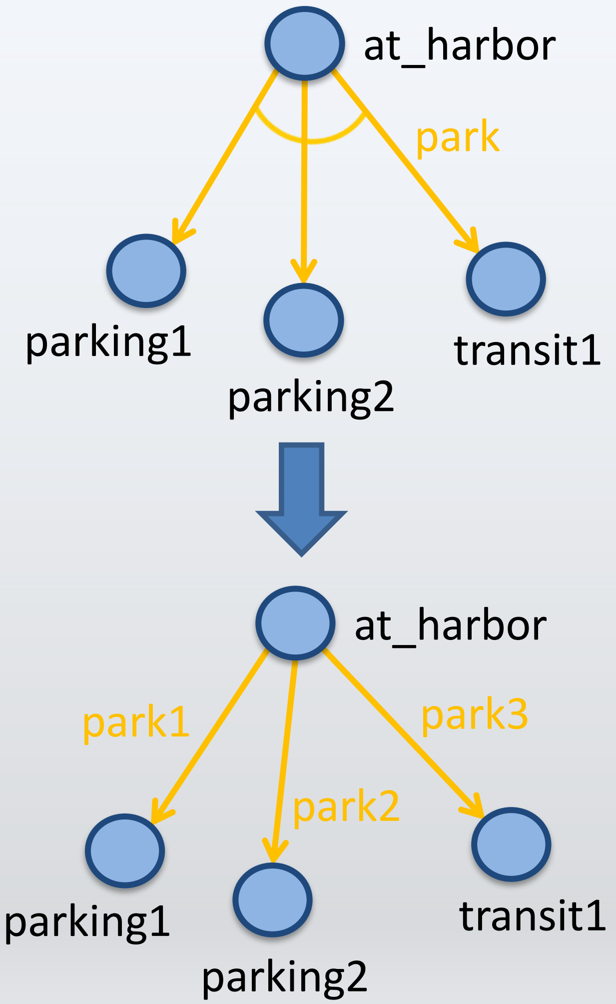
Determinisation


```
Guided-Find-Safe-Solution(Σ,s₀,S_g)
    if s₀ ∈ S_g then
        return ∅
    if Applicable(s₀) = ∅ then
        return failure
    π ← ∅
    loop
        Q ← leaves(s₀,π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s₀,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 = s₀ then
            return failure
        else
            for every s',a s.t. s ∈ 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 Ch. 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 K possible outcomes
  - K deterministic actions $a_i^k, k \in \{1, \dots, K\}$, one for each outcome
  - Given nondeterministic domain $\Sigma = (S, A, \gamma)$, determinised domain $\Sigma_d = (S, A_d, \gamma_d)$
    - $A_d = \bigcup_{a_i \in A, a_i \text{ deterministic}} \{a_i\}$
      $\cup \bigcup_{a_i \in A, a_i \text{ nondeterministic}} \bigcup_{k=1}^{K} \{a_i^k\}$
    - γ_d defined as γ with determinised inputs s, a_i^k yielding a state with effects according to k
- Classical planner returns a plan $p = \langle a_1, a_2, \dots, a_n \rangle$
  - If p is acyclic, can convert it to a policy



Determinisation

- Nondeterministic planning problem $P = (\Sigma, s_0, S_g)$
- Determinisation $P_d = (\Sigma_d, s_0, S_g)$
  - As on previous slide
- Classical planner returns a solution for P_d
  - A plan $p = \langle a_1, a_2, \dots, a_n \rangle$
- If p is acyclic, can convert it to an (unsafe) solution for P
  - $\{(s_0, \boldsymbol{a}_1), (s_1, \boldsymbol{a}_2), \dots, (s_{n-1}, \boldsymbol{a}_n)\}$
  - where
  - each $\boldsymbol{a}_i$ is the nondeterministic action whose determinisation includes a_i
    - Function `det2nondet` returns exactly this
  - each $s_i \in \gamma_d(s_{i-1}, a_i)$

```
Plan2policy(p=⟨a1,...,an⟩,s)
    π ← ∅
    for i from 1 to n do
        π ← π ∪ {s,det2nondet(ai)}
        s ← γd(s,ai)
    return π
```

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    if s0 ∈ Sg then
        return ∅
    if Applicable(s0) = ∅ then
        return failure
    π ← ∅
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p′ ← Forward-search(Σd,s,Sg)
        if p′ ≠ fail then
            π ← Plan2policy(p′,s)
            π ← π ∪ {(s,a) ∈ π′ | s ∉ Dom(π)}
        else if s = s0 then
            return failure
        else
            for every s′, a s.t. s ∈ γ(s′,a) do
                π ← π \ {(s′,a)}
                make the actions in the
                     determinisation not
                     applicable in s′
```

Same as Guided-Find-Safe-Solution.

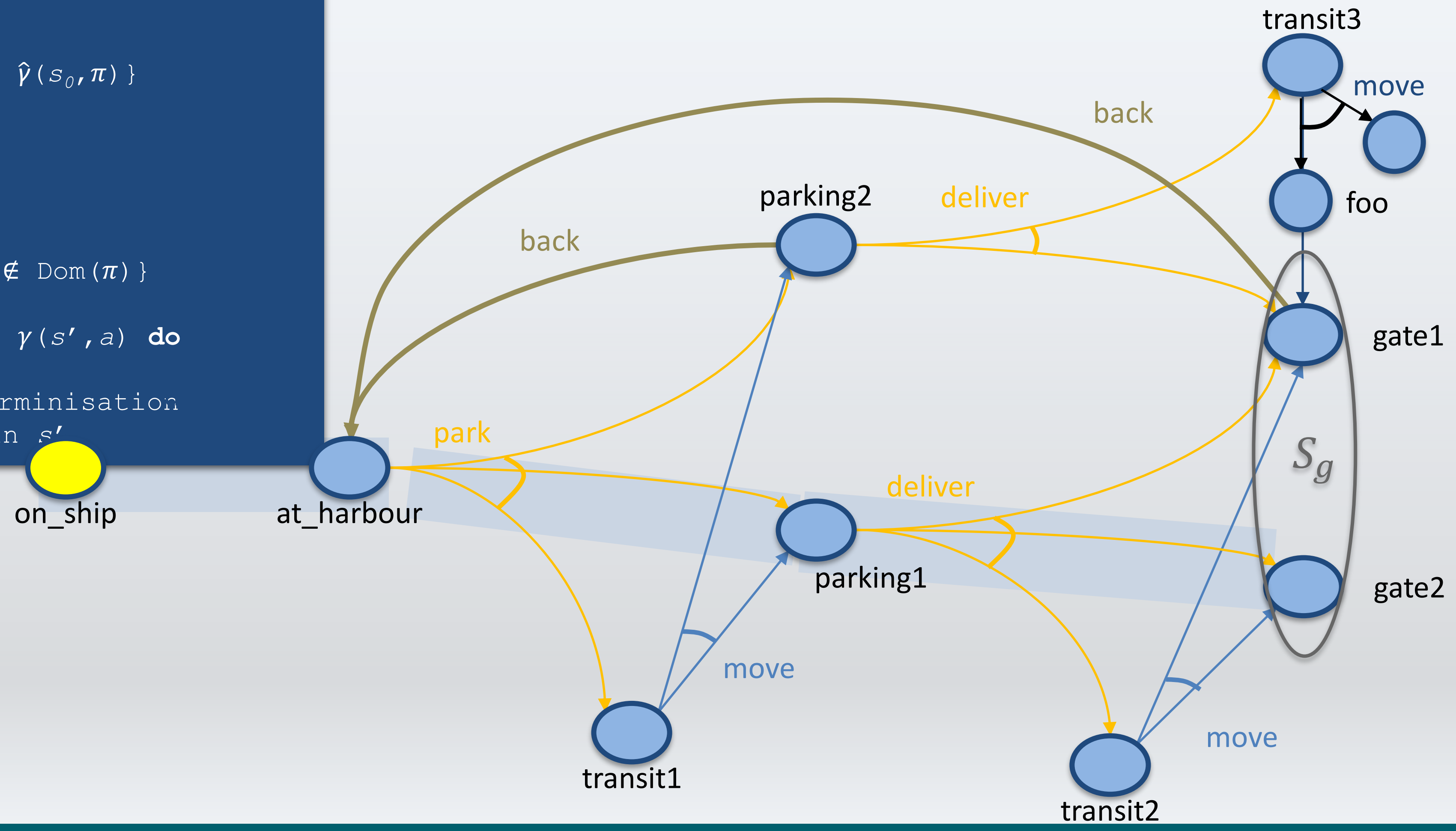
Any classical planner that does not return cyclic plans.

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

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

Determinisation


```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

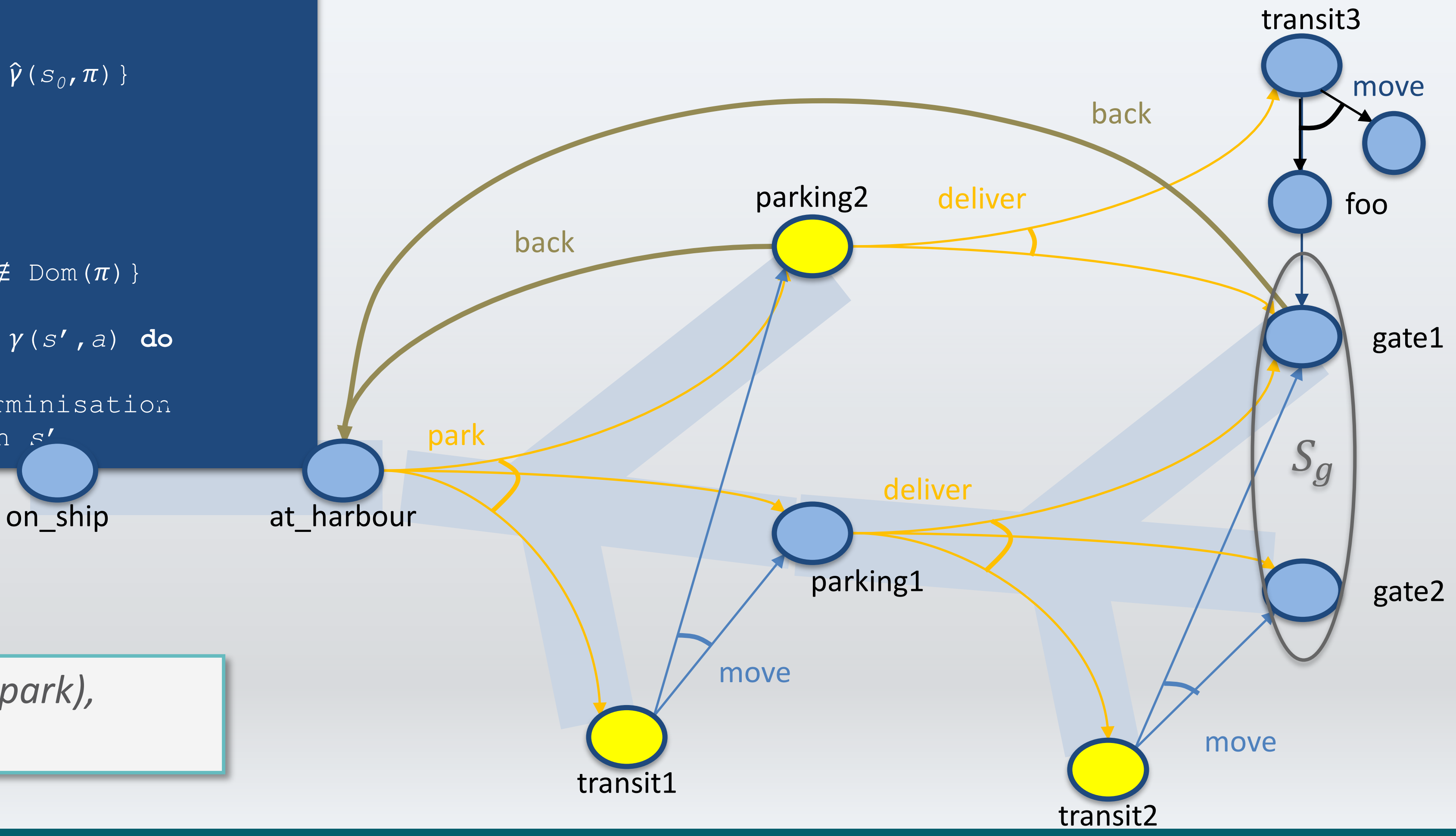


$p' = \langle$unload, park$_2$, deliver$_2\rangle$

$\pi = \{\}$

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                     not applicable in s'
```

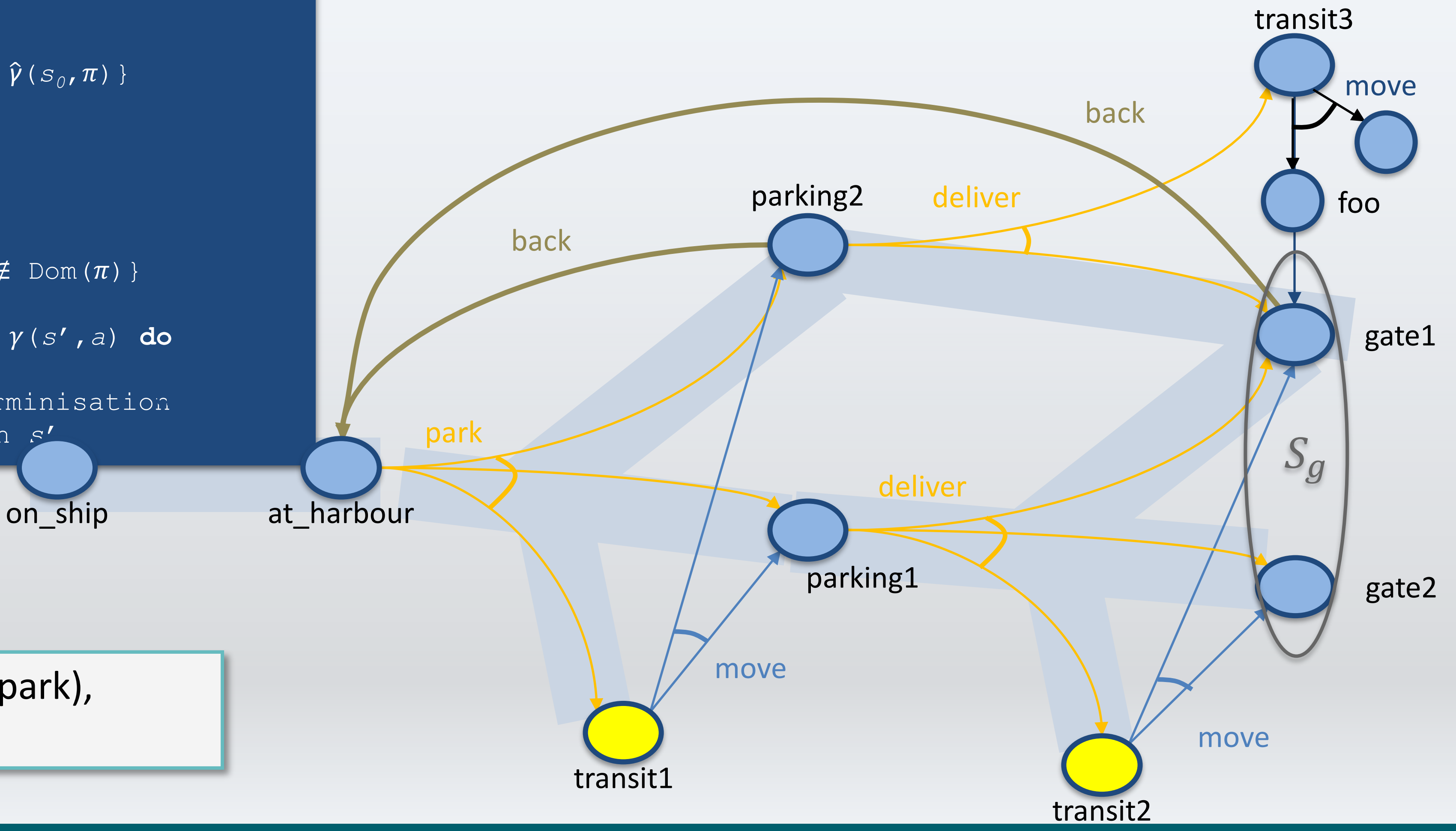


$p' = \langle$unload, park$_2$, deliver$_2\rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

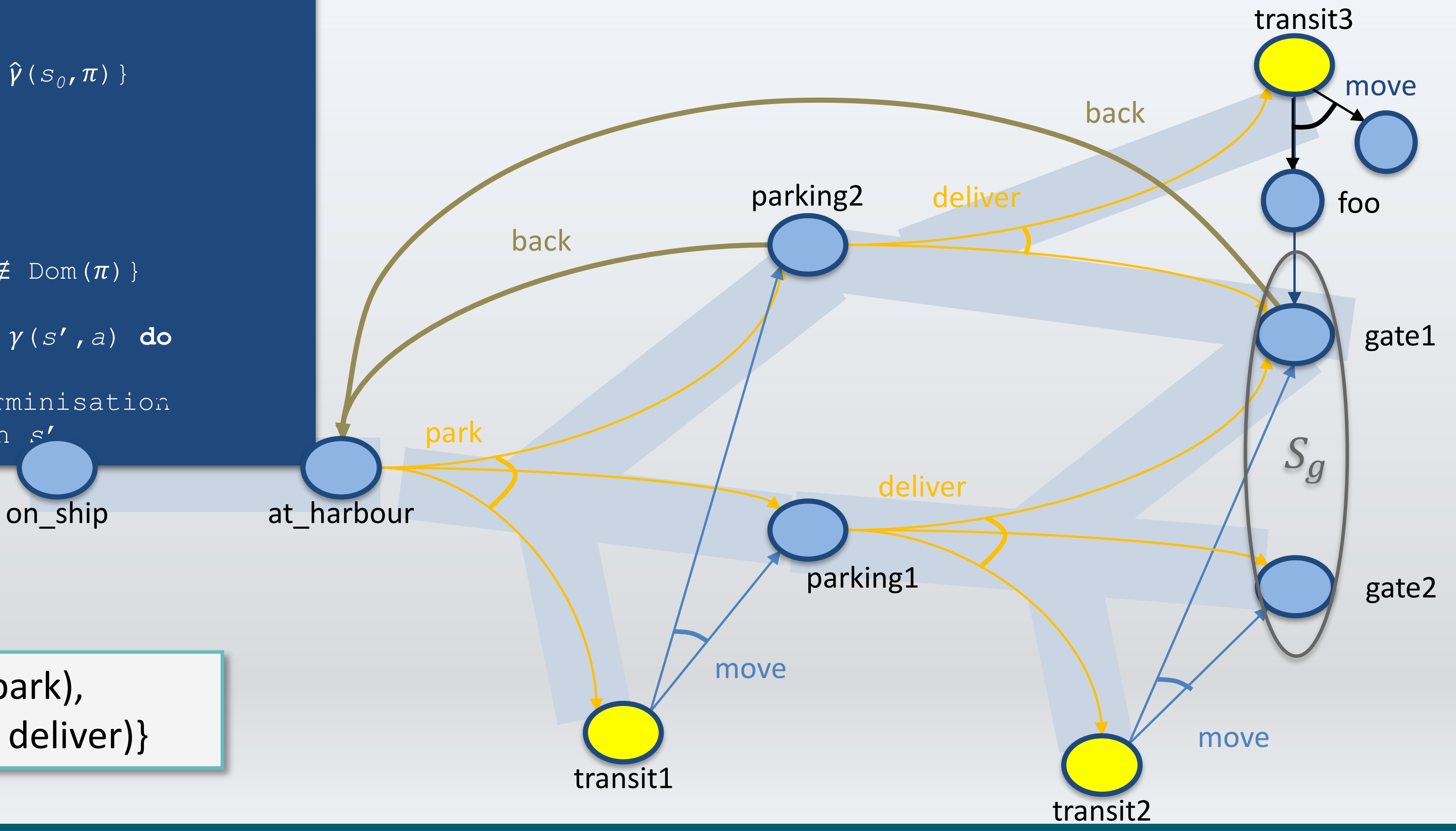


$p' = \langle \text{deliver}_2 \rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

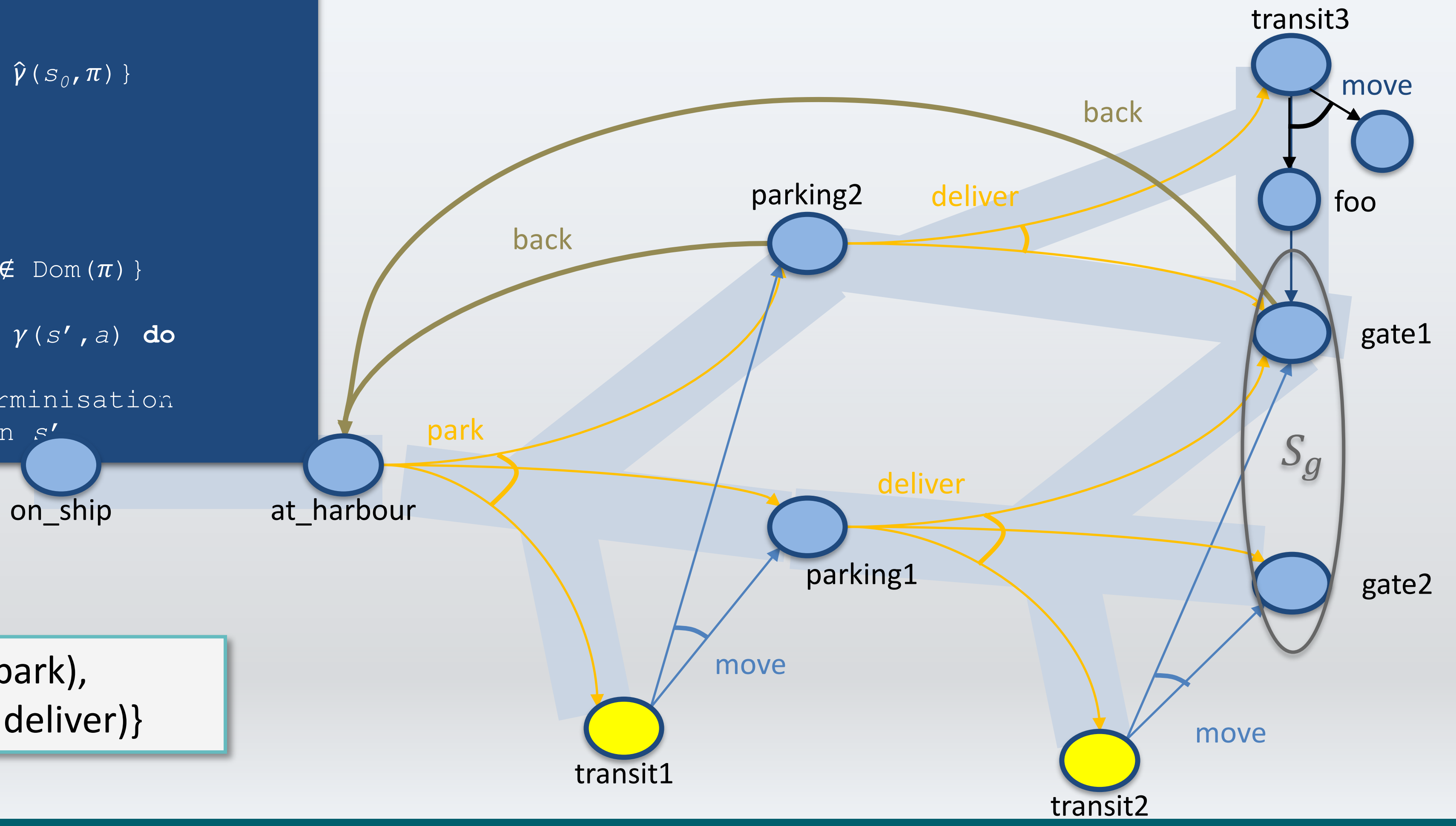


$p' = \langle deliver_2 \rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

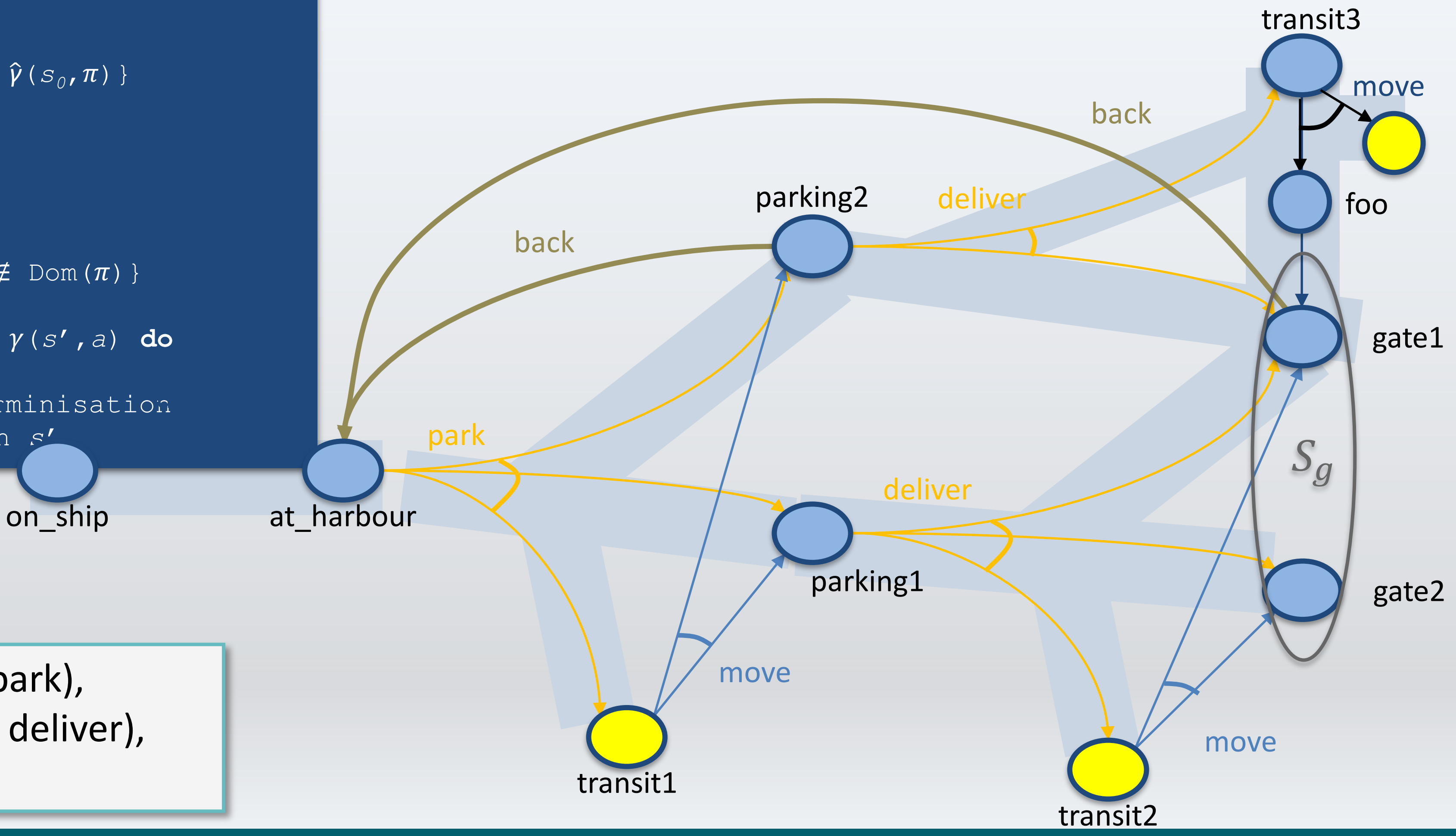


$p' = \langle \text{move}_2, \text{move} \rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

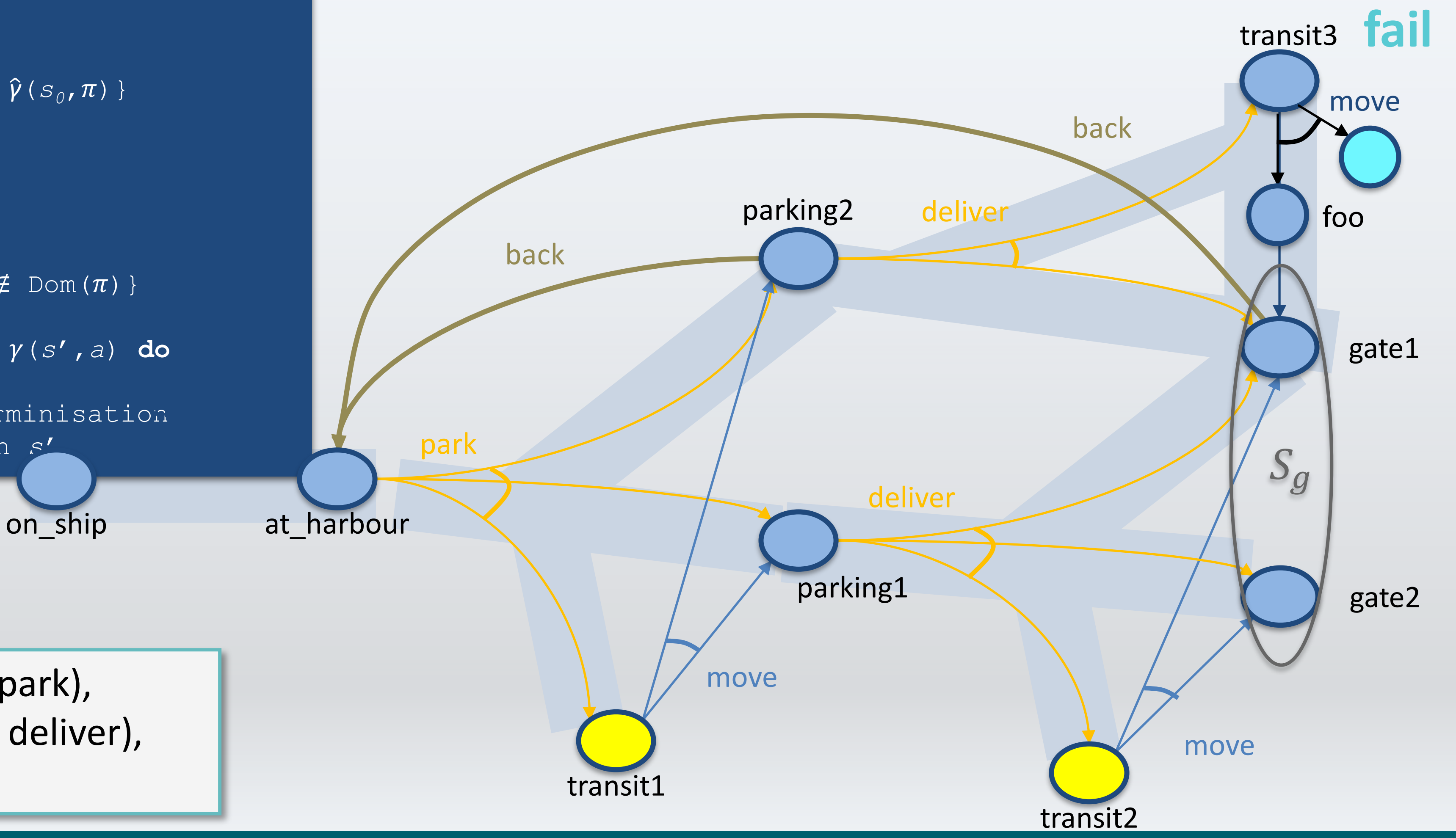


$p' = \langle \text{move}_2, \text{move} \rangle$

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

Determinisation


```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```



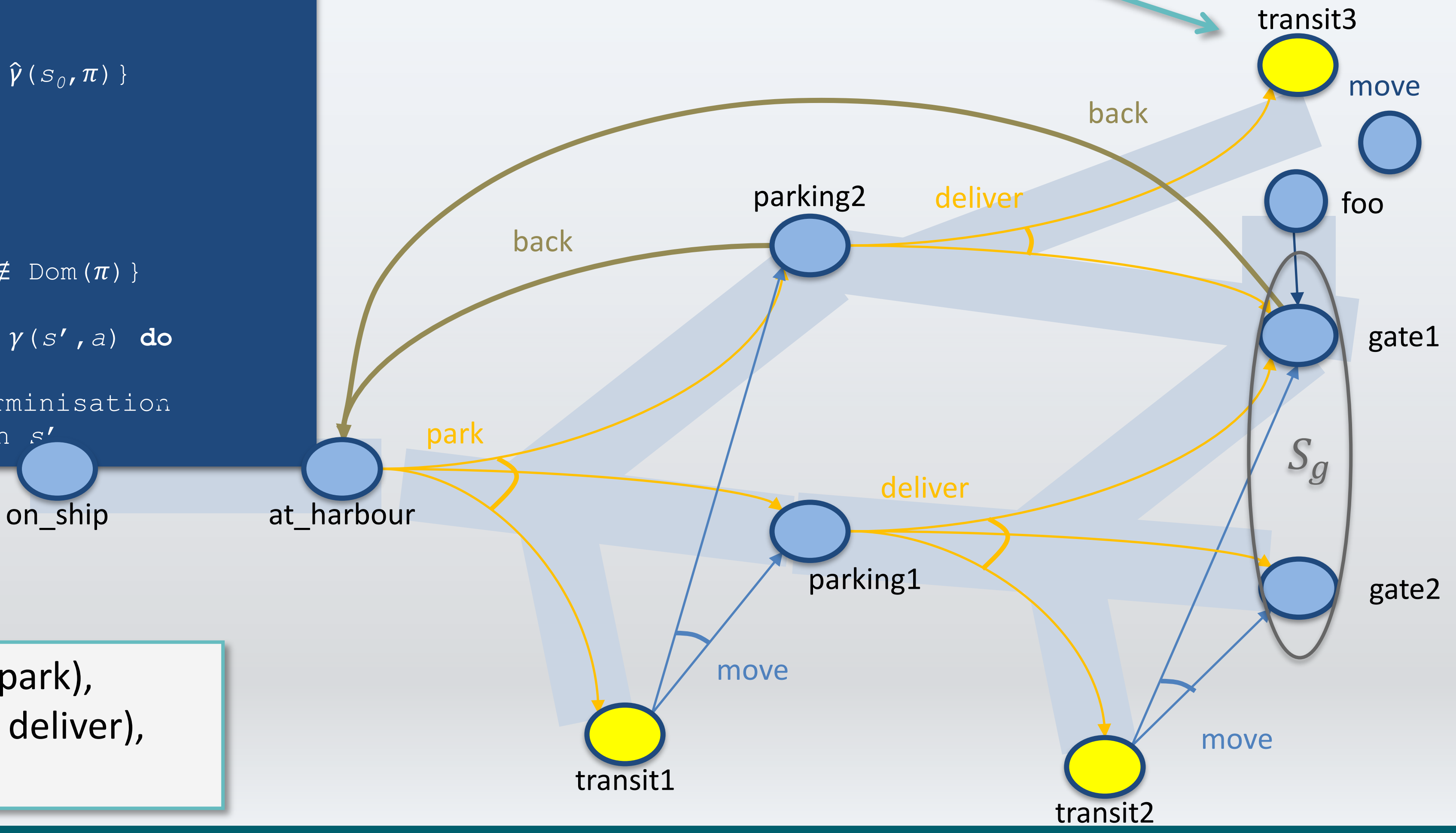
p' = *fail*

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

Modify Σ_d to make *move* inapplicable

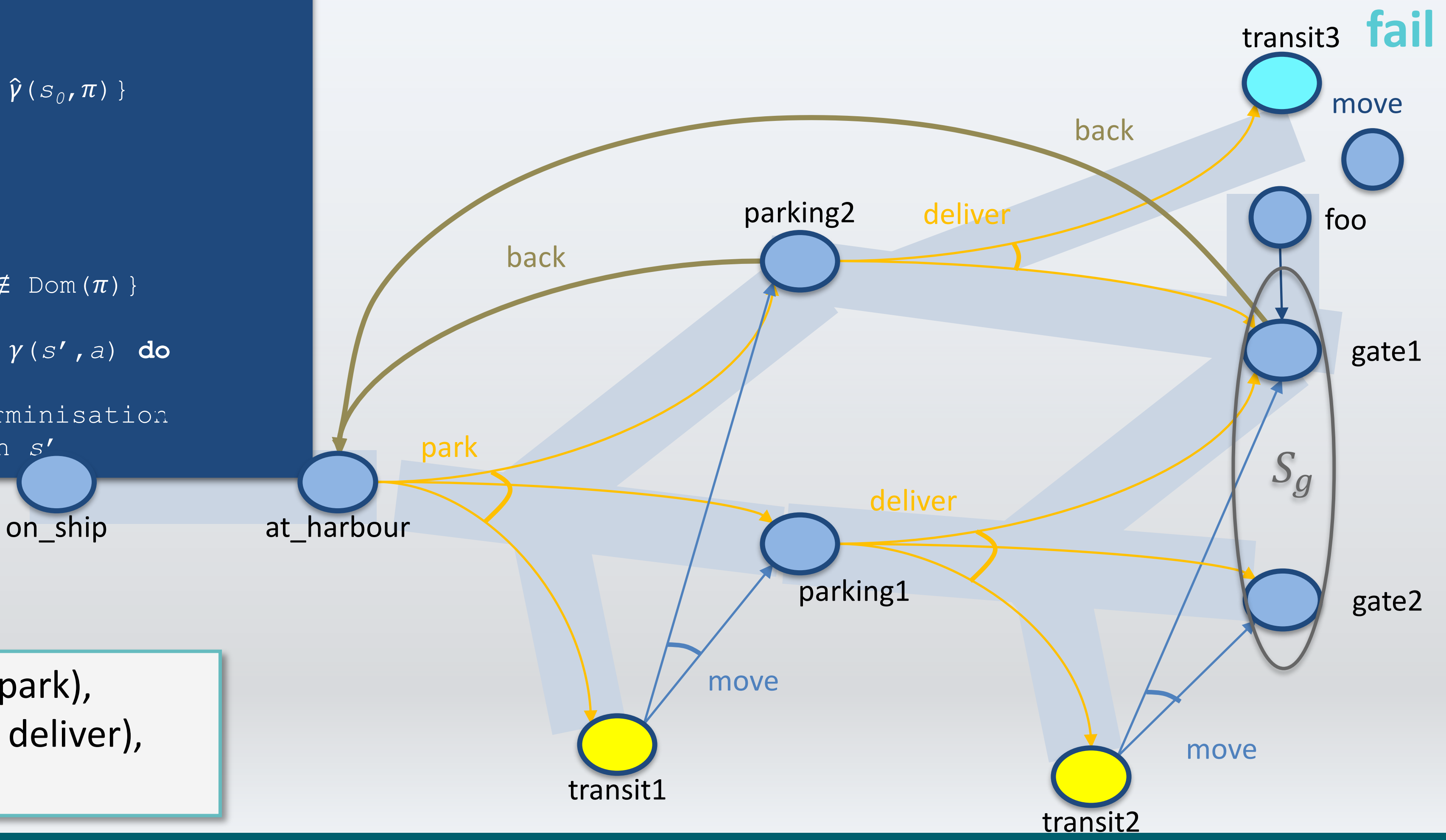


p' = fail

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

Determinisation


```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```



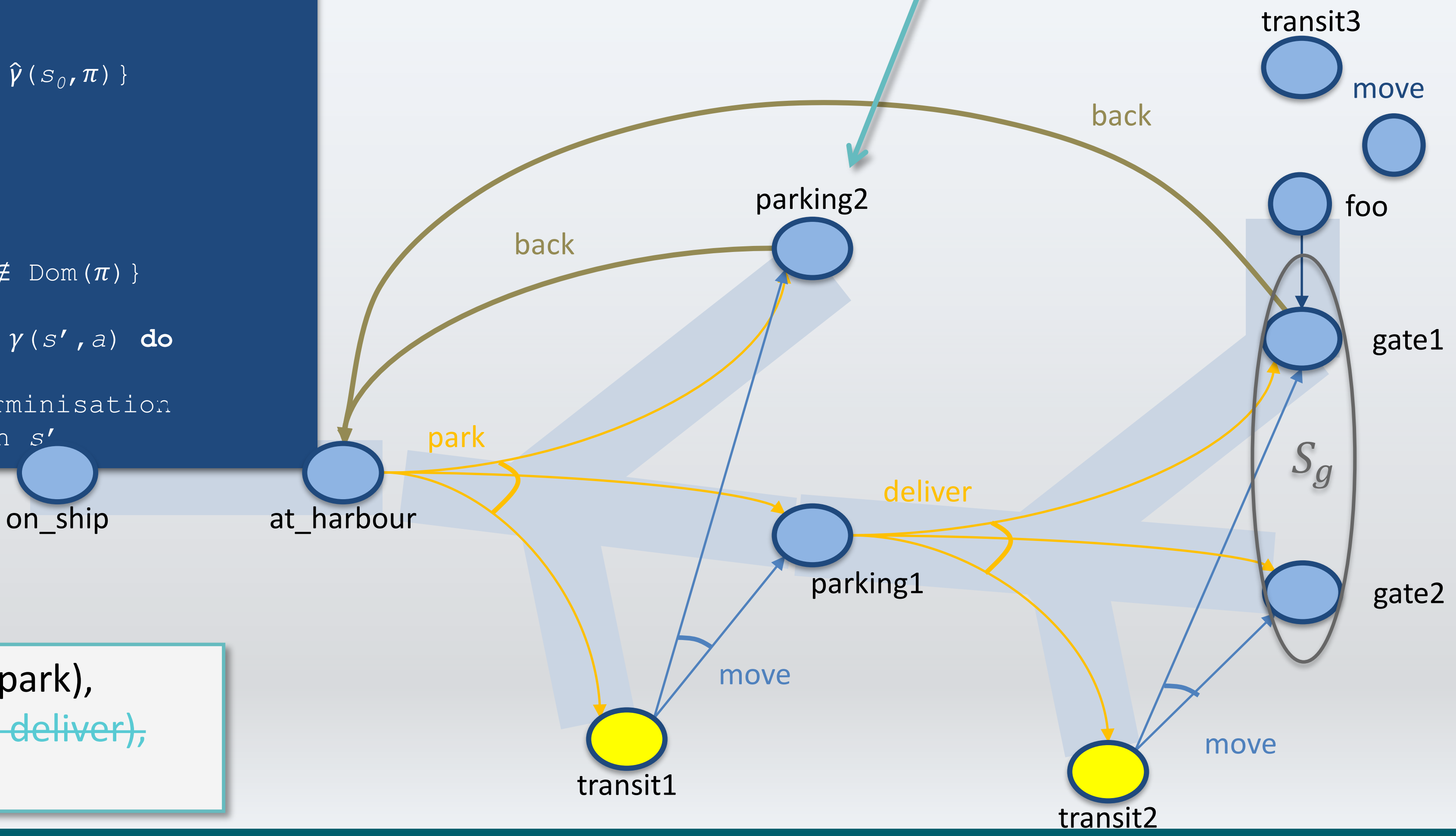
p' = *fail*

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

Determinisation


```
Find-Safe-Solution-by-Determinisation(Σ,s₀,S_g)
    ...
    Σ_d ← mk-deterministic(Σ)
    loop
        Q ← leaves(s₀,π) \ S_g
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s₀,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', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

Modify Σ_d to make *deliver* inapplicable

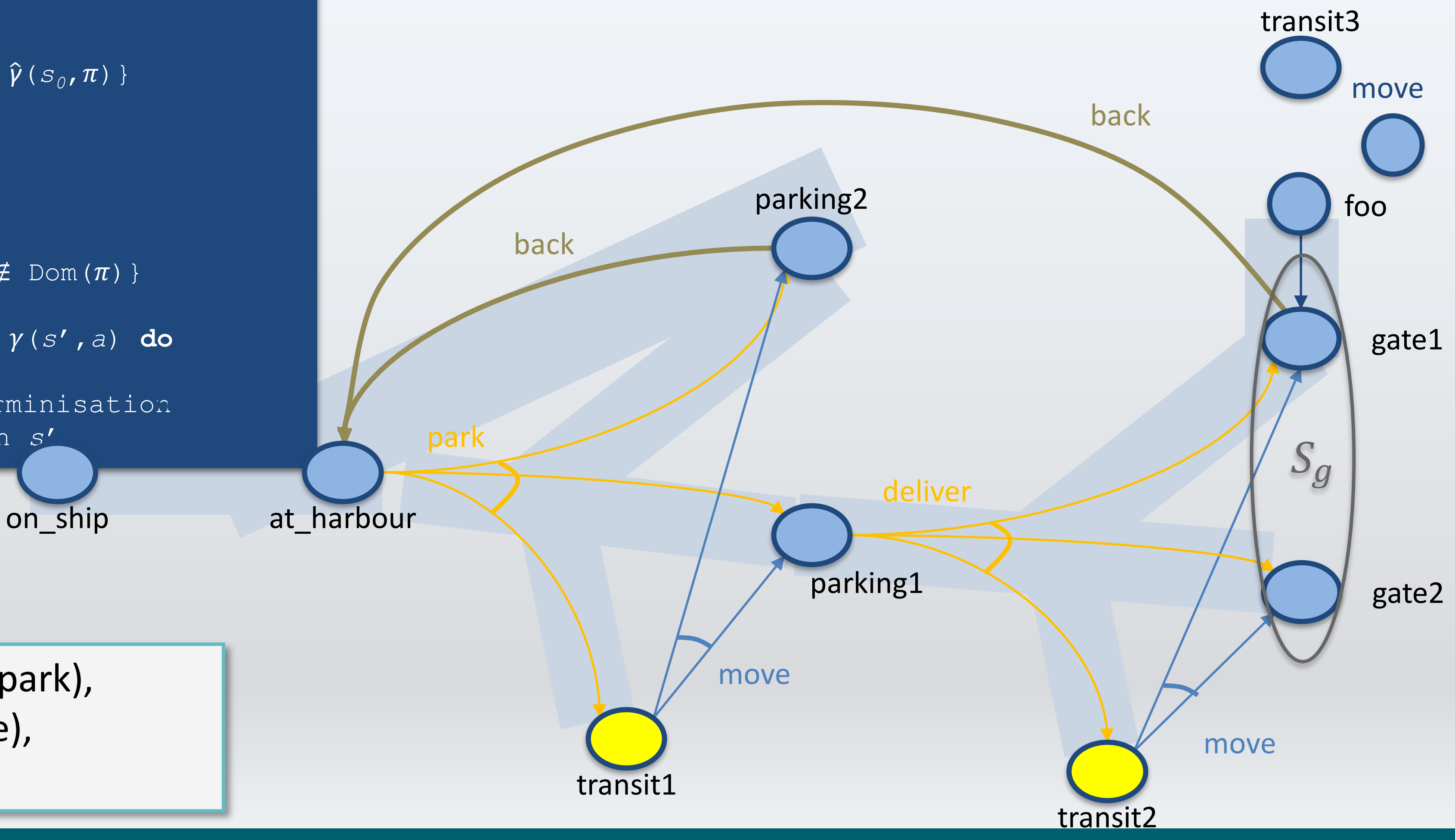


p’ = fail

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```



$p' = \langle \text{back}, \text{park}_2, \text{deliver}_1 \rangle$

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

Determinisation

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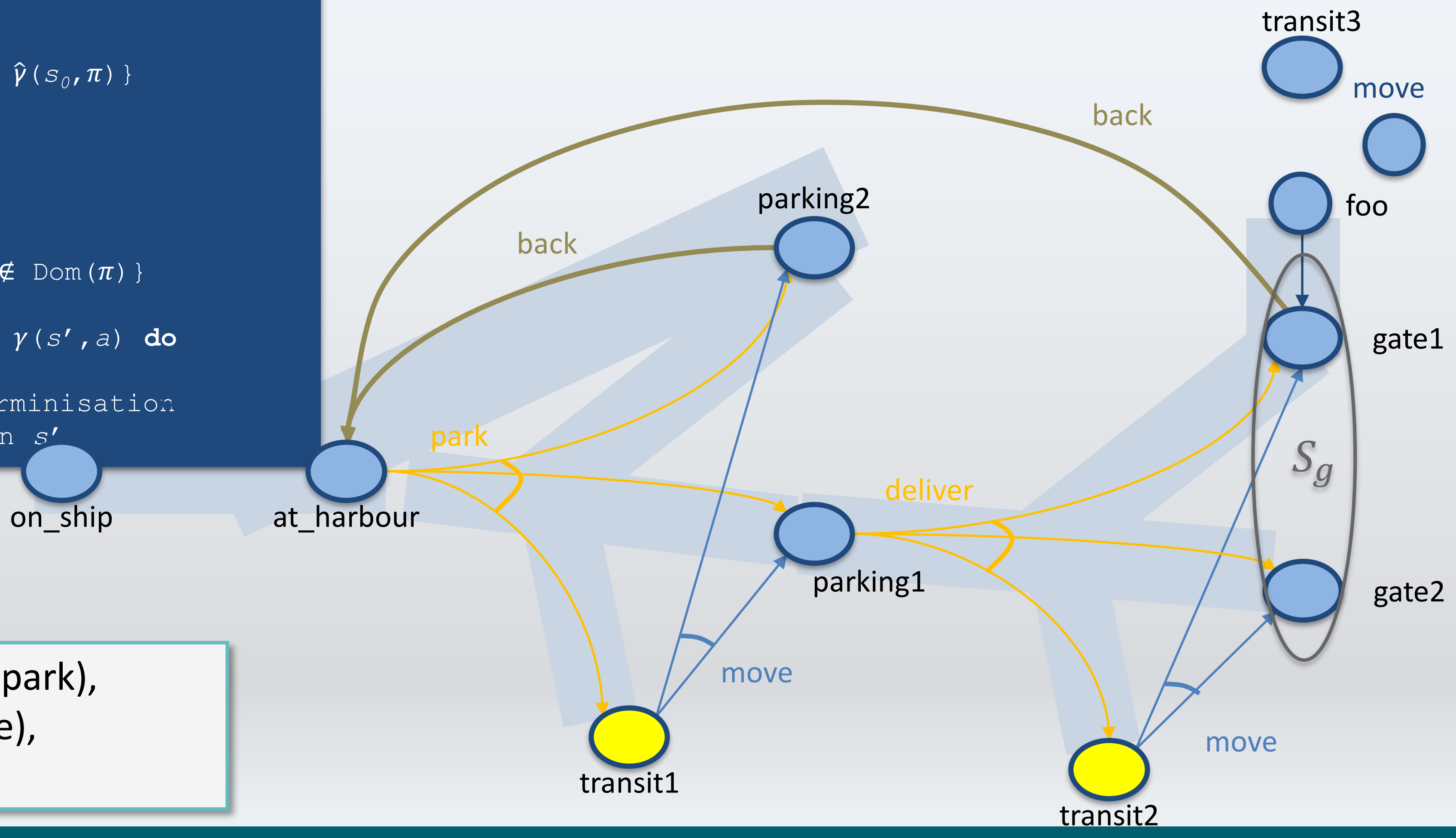
```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

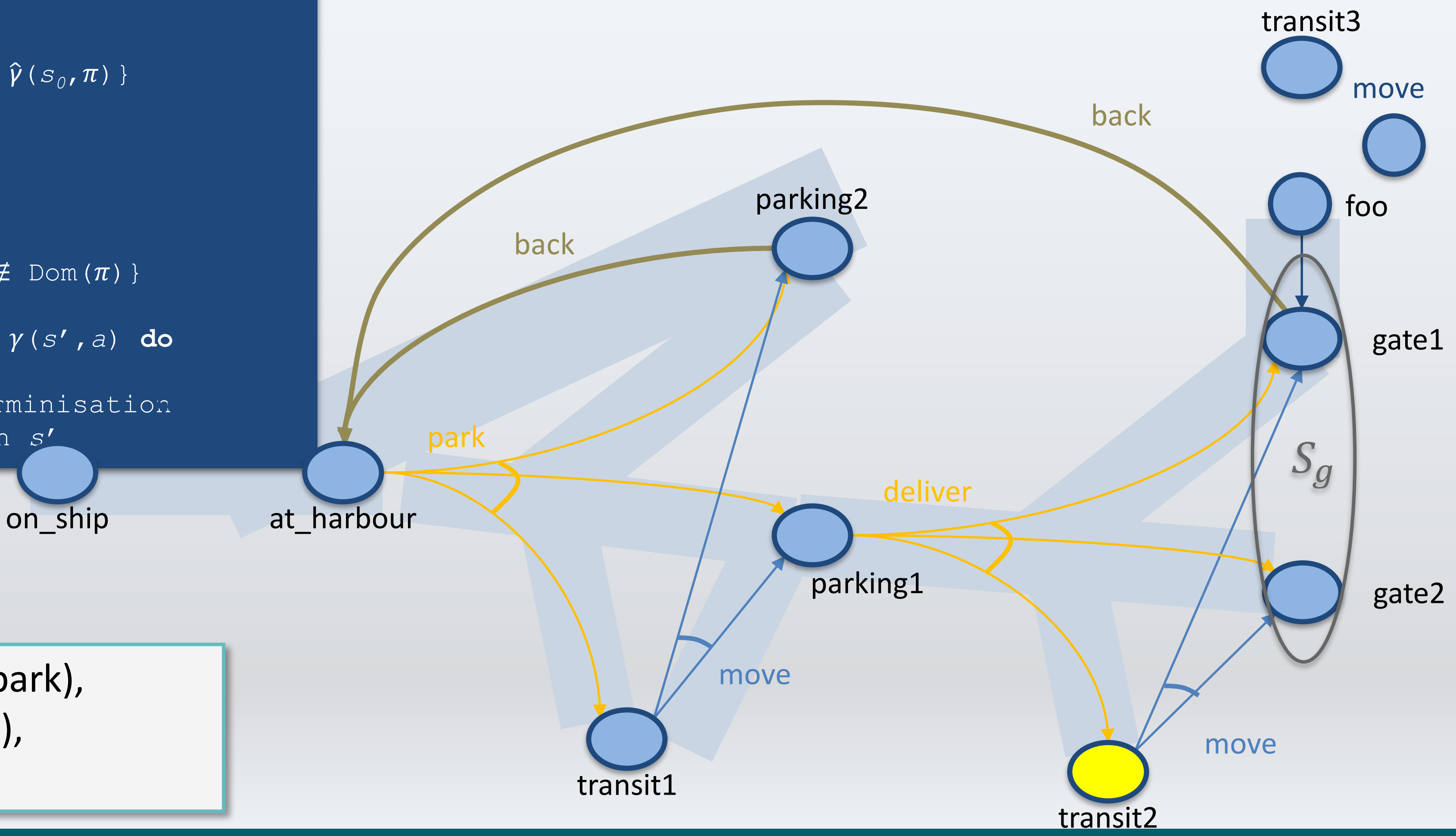


$p' = \langle move_2, deliver_1 \rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

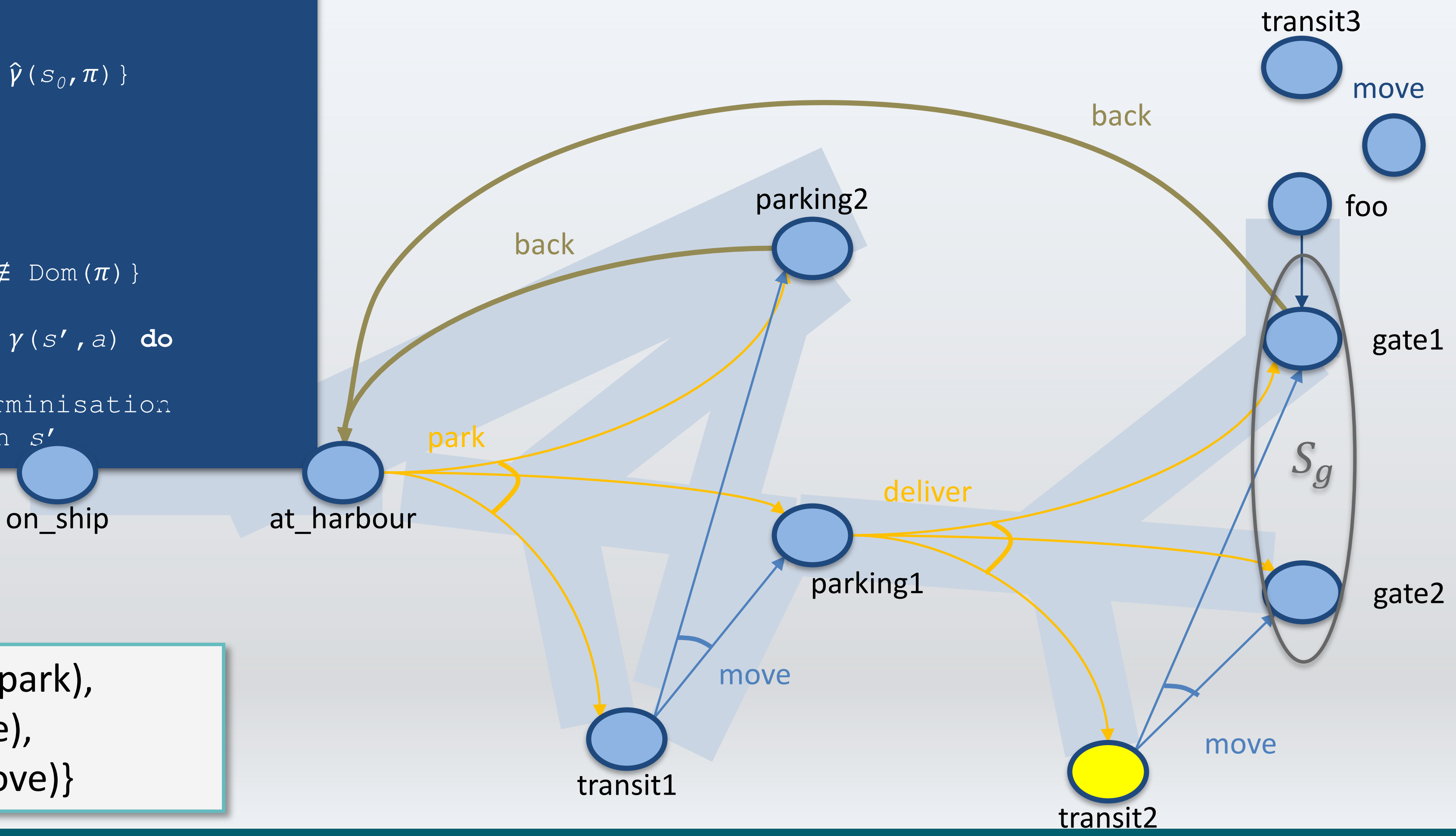


$p' = \langle move_2, deliver_1 \rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

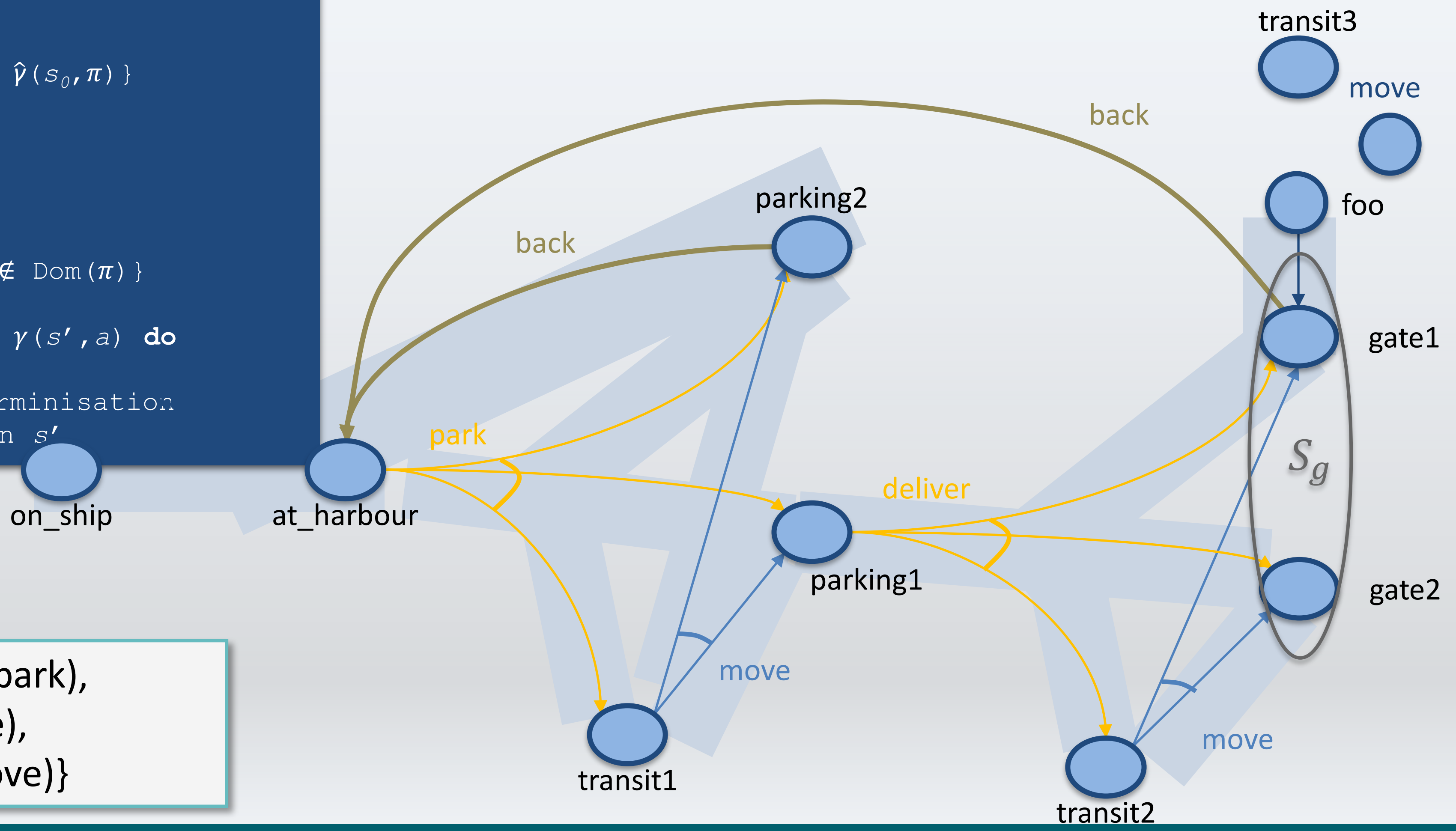


$p' = \langle move_2, deliver_1 \rangle$

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

Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```



$p' = \langle move_2 \rangle$

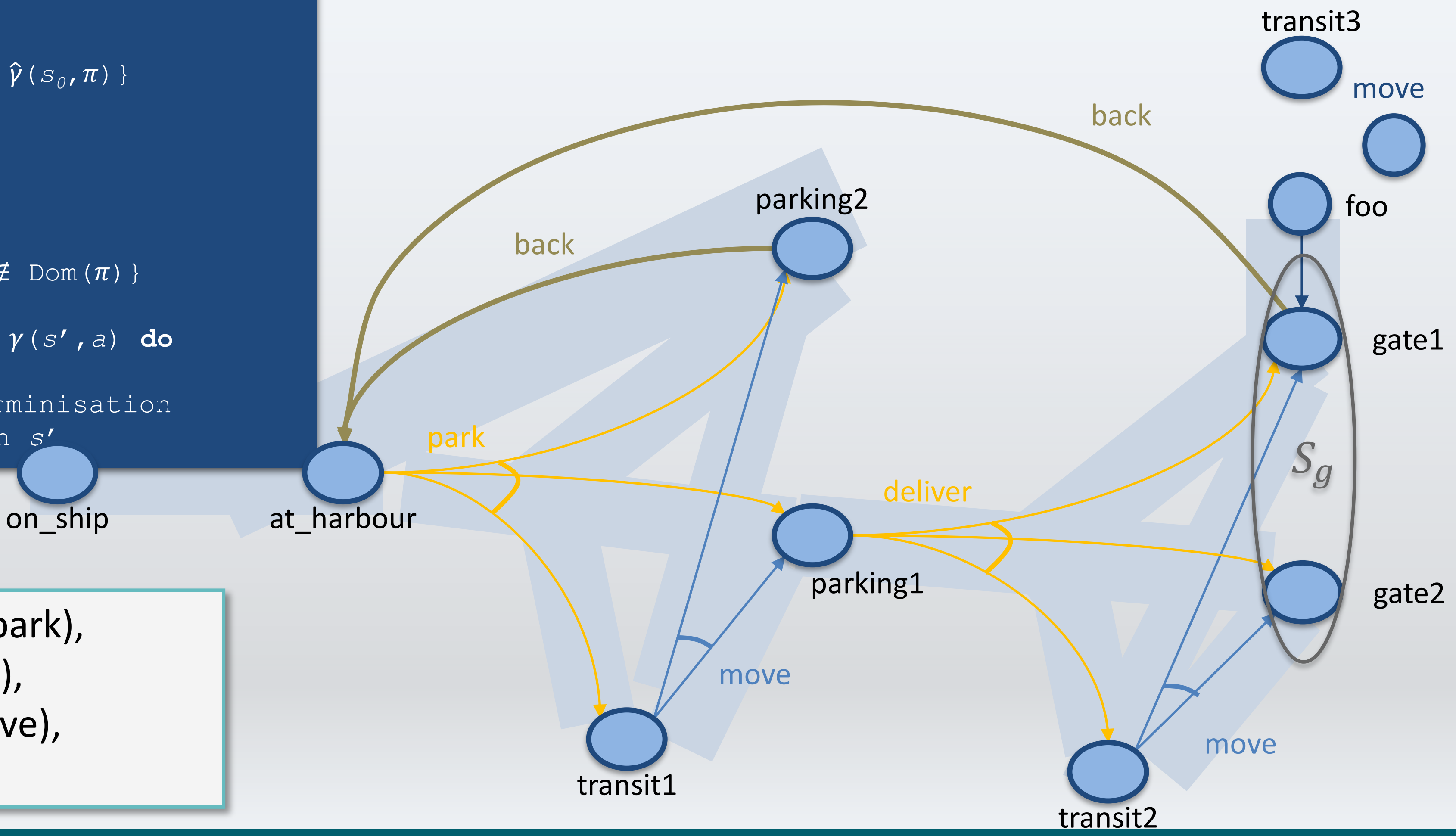
π = {(on_ship, unload),(at_harbor, park),
(parking1, deliver),(foo, move),
(parking2, back),(transit1, move)}

Determinisation

```
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', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

$p' = \langle move_2 \rangle$

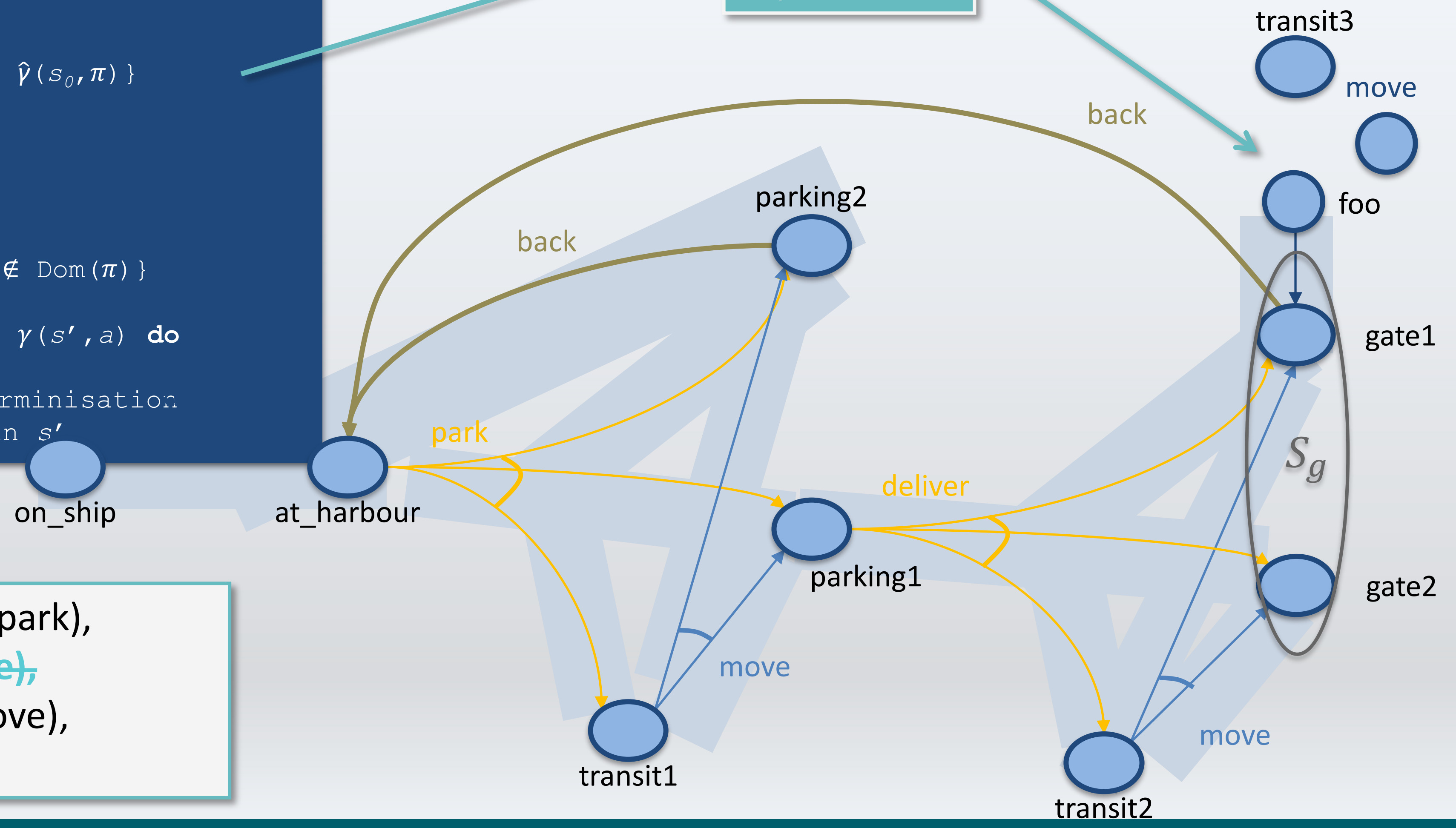
π = {(on_ship, unload),(at_harbor, park),
(parking1, deliver),(foo, move),
(parking2, back),(transit1, move),
(transit2, move)}



Determinisation

```
Find-Safe-Solution-by-Determinisation(Σ,s0,Sg)
    ...
    Σd ← mk-deterministic(Σ)
    loop
        Q ← leaves(s0,π) \ Sg
        if Q = ∅ then
            π ← π \ {(s,a) ∈ π | s ∉ γ̂(s0,π)}
            return π
        select arbitrarily s ∈ Q
        p' ← Forward-search(Σd,s,Sg)
        if p' ≠ fail then
            π ← Plan2policy(p',s)
            π ← π ∪ {(s,a) ∈ π' | s ∉ Dom(π)}
        else if … else
            for every s', a s.t. s ∈ γ(s',a) do
                π ← π \ {(s',a)}
                make actions in determinisation
                    not applicable in s'
```

Remove unreachable part of π



$p' = \langle move_2 \rangle$

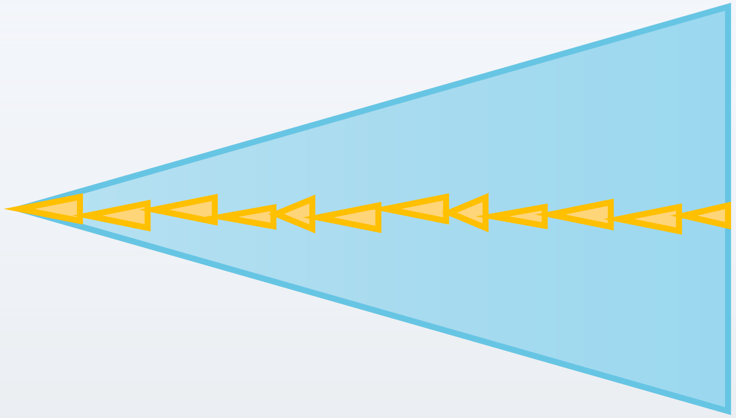
π = {(on_ship, unload),(at_harbor, park),
(parking1, deliver~~),(foo, move),~~
(parking2, back),(transit1, move),
(transit2, move)}

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

Online Approaches

- Motivation
  1. Planning models are approximate – execution seldom works out as planned
  2. 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 cannot come back up
    - Applicable actions, but caught in a loop
      - Robot goes into a collection of rooms from which there is no exit
  - However, partial planning can still make success more likely

Lookahead-Partial-Plan

- Adaptation of
  Run-Lazy-Lookahead (Ch. 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,s₀,S_g,θ)
    s ← s₀
    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

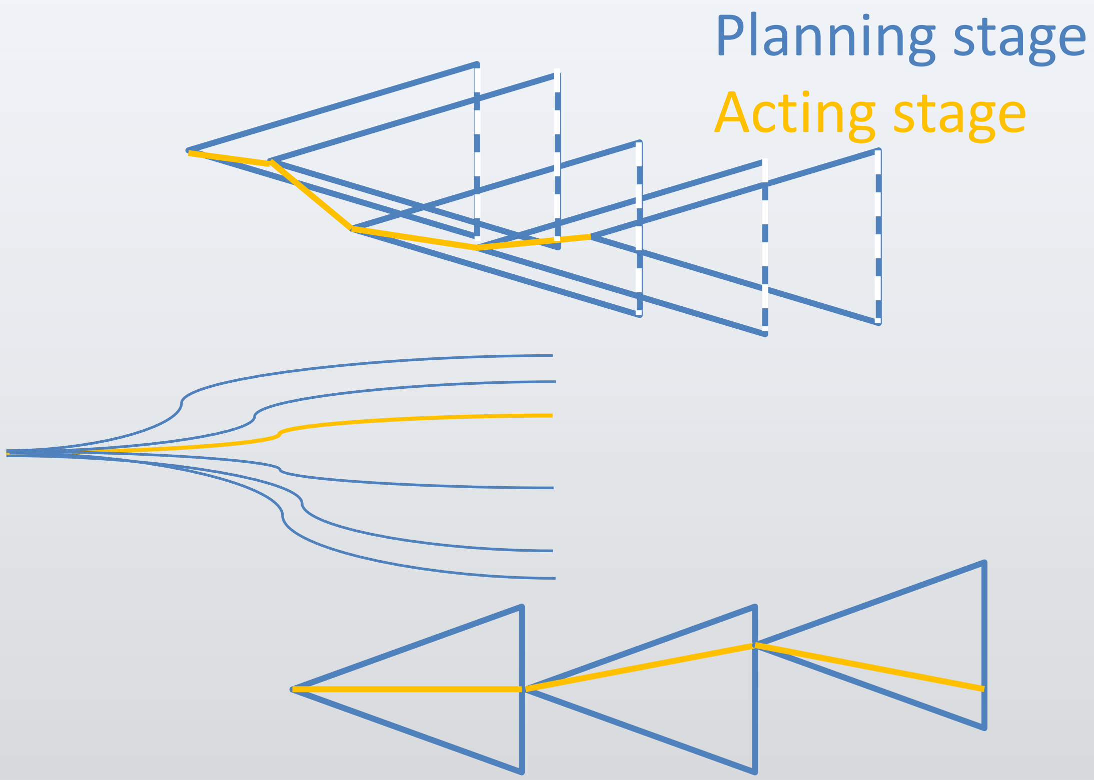
- Adaptation of Run-Lookahead (Ch. 2)
- Calls Forward-Search (Ch. 2) on determinised domain, converts to a policy
  - Unsafe solution
- Generalisation:
  - Lookahead can be any planning algorithm that returns a policy π

```
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
```

```
Generalised-FS-Replan(Σ,s,S_g,θ)
    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 does not have time to run to completion?
  - Can use the same techniques, we discussed earlier
    - Receding horizon
    - Sampling
    - Subgoaling
    - Iterative Deepening



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Possibilities for Lookahead (cont'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 $i = 1$, increase i 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,s0,Sg)
    π ← ∅
    Frontier ← {s0}
    for every s ∈ Frontier \ Sg 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
    - No dead ends

- In a safely explorable domain,
  - Using Lookahead-Partial-Plan or FS-Replan
    - Lookahead never returns failure
    - Then we will eventually reach a goal

What about picking a random action?

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

Can also adapt
Run-Concurrent-Lookahead

Can put bounds on both depth and breadth