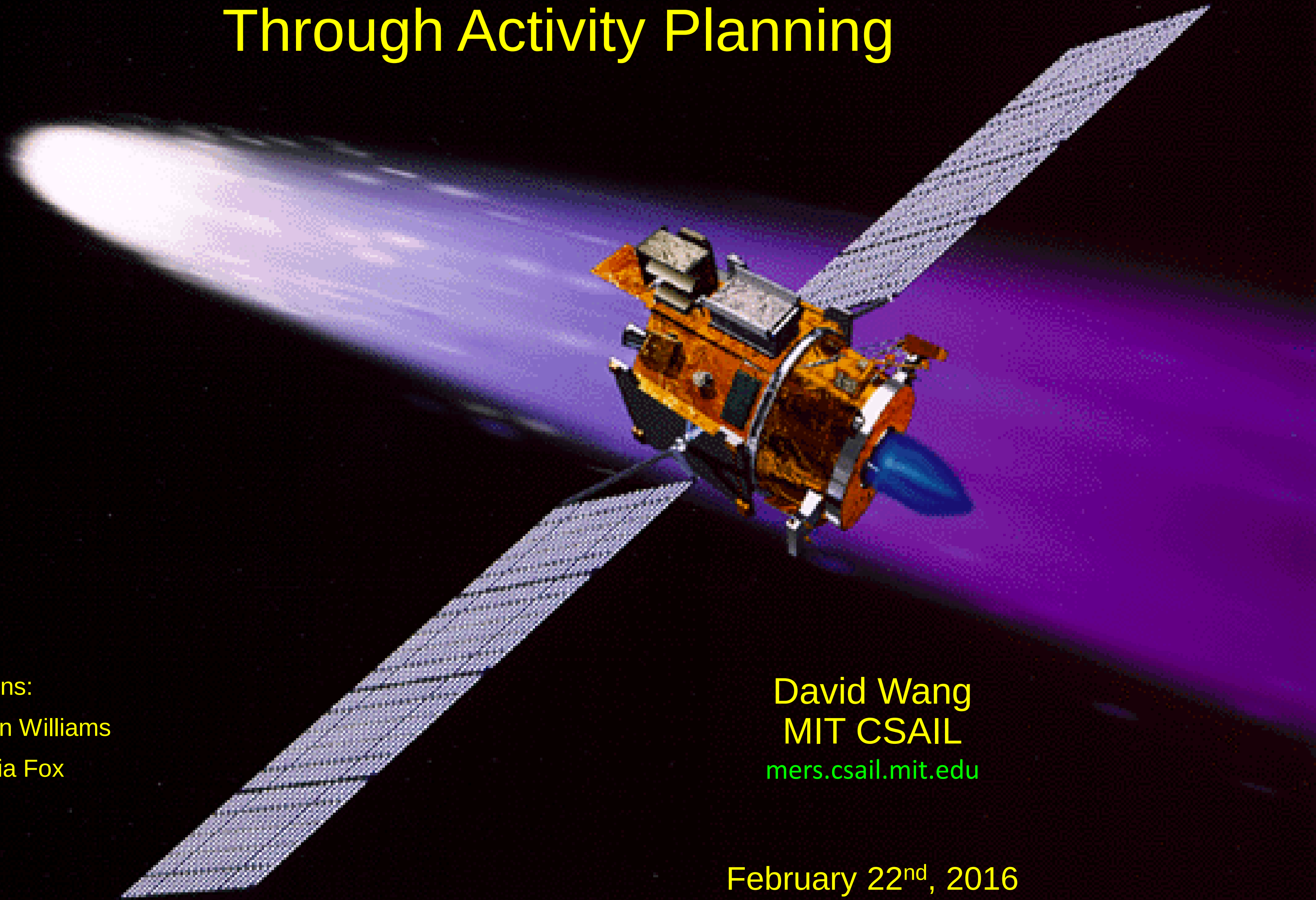
Creating Programs on State: Through Activity Planning



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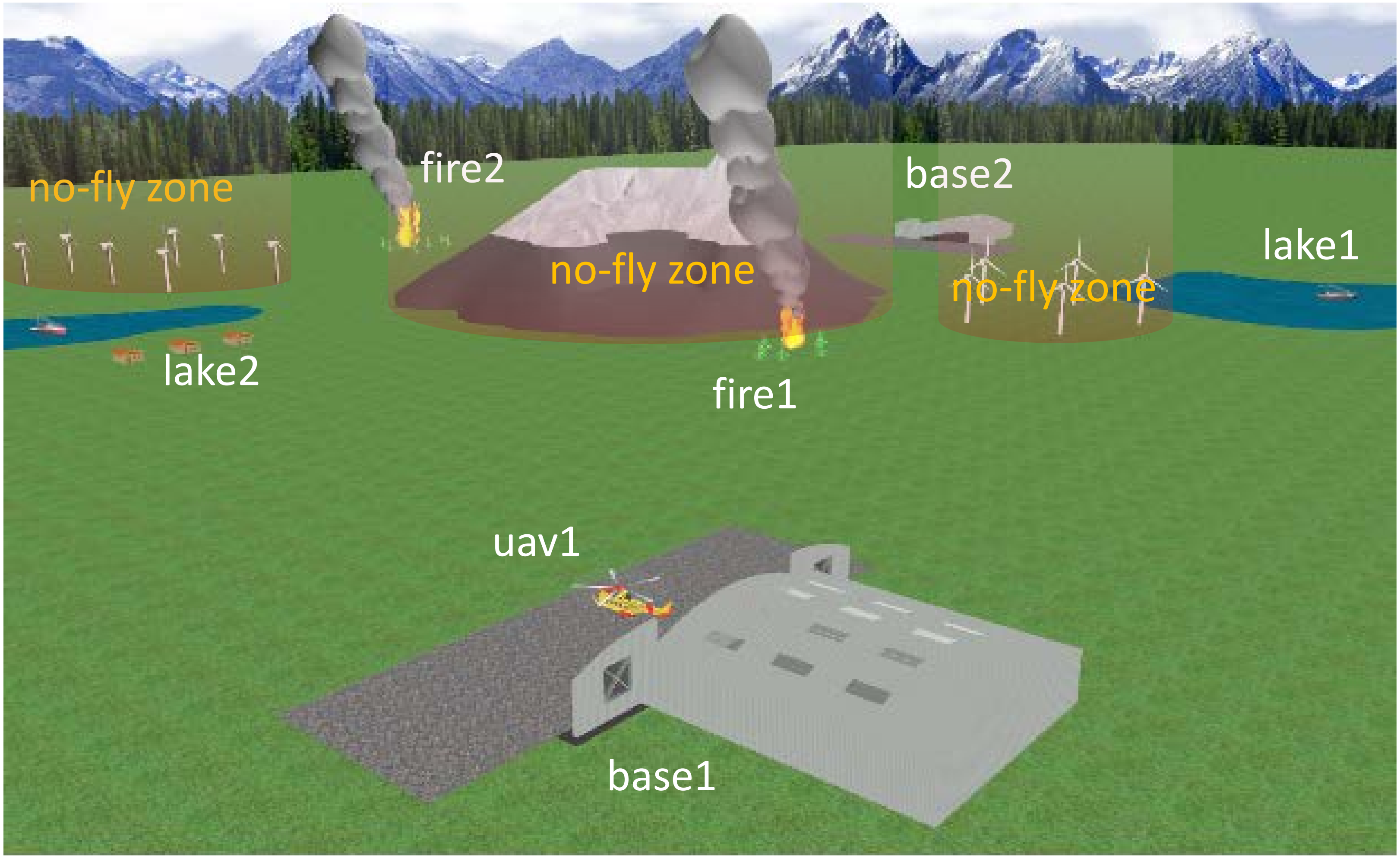
courtesy of JPL

The Firefighting Scenario

Objective: Put out all the fires using UAV1, avoid no-fly zones.



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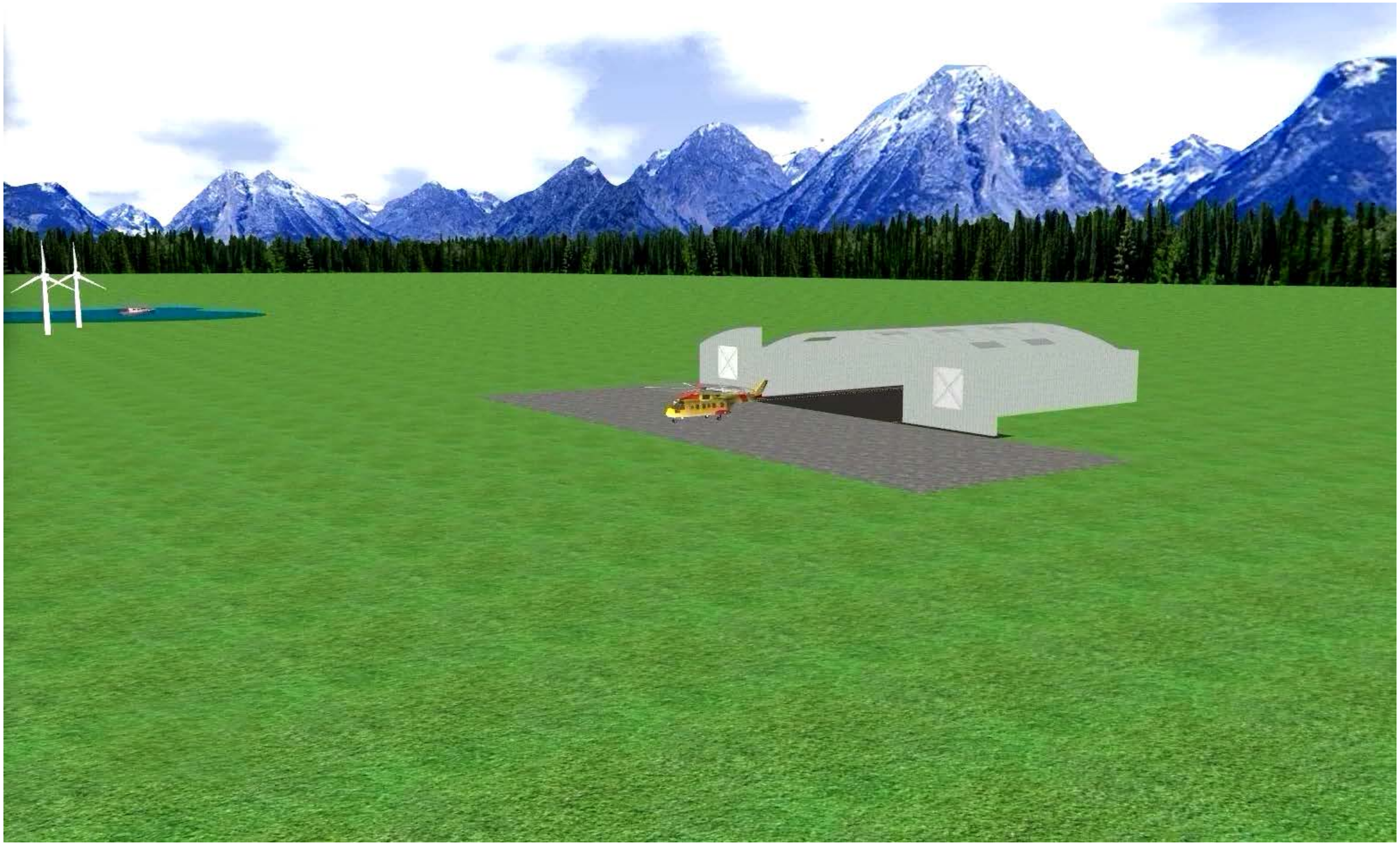

Traditional Solution:

Specify each activity (the usual programmatic way)

```
class Main{
  UAV uav1;
  Lake lake1;
  Lake lake2;
  Fire fire1;
  Fire fire2;
  // constructor
  Main (){
      uav1 = new UAV();
      uav1.location= base_1_location;
      uav1.flying = no;
      uav1.loaded = no;

      lake1 = new Lake();
      lake1.location = lake_1_location;

      lake2 = new Lake();
      lake2.location = lake_2_location;

      fire1 = new Fire();
      fire1.location = fire_1_location;
      fire1 = high;

      fire2 = new Fire();
      fire2.location = fire_2_location;
      fire2 = high;
  }
  // "main" method
 method run() {
    sequence{
      uav1.takeoff();
      uav1.fly(base_1_location,lake_2_location);
      uav1.load_water(lake2);
      uav1.fly(lake_2_location,fire_2_location);
      uav1.drop_water_high_altitude(fire2);
      … <13 additional activities> …
      uav1.land();
     }
  }
}
```

```
class UAV {
  Roadmap location;
  Boolean flying;
  Boolean loaded;

  primitive method takeoff()
    flying == no => flying == yes;

  primitive method land()
    flying == yes => flying == no;

  primitive method load_water(Lake lakespot)
    ((flying == yes) && (loaded == no)
      && (lakespot.location == location)) => loaded == yes;

  primitive method drop_water_high_altiture(Fire firespot)
    ((flying == yes) && (loaded == yes)
     && (firespot.location == location) && (firespot == high))
     => ((loaded == no) && (firespot == medium));

  primitive method drop_water_low_altiture(Fire firespot)
    ((flying == yes) && (loaded == yes)
     && (firespot.location == location) && (firespot == medium))
     => ((loaded == no) && (firespot == out));

  #MOTION_PRIMITIVES(location, fly, flying==yes)
}
```

These are the actions the UAV can take.

A program that specifies the exact sequence of activities.

State-based Solution:

Specify the desired states, let the computer plan the activities.

```
class Main{
  UAV uav1;
  Lake lake1;
  Lake lake2;
  Fire fire1;
  Fire fire2;
 // constructor
  Main (){
      uav1 = new UAV();
      uav1.location= base_1_location;
      uav1.flying = no;
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      lake1 = new Lake();
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      lake2 = new Lake();
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      fire1.location = fire_1_location;
      fire1 = high;

      fire2 = new Fire();
      fire2.location = fire_2_location;
      fire2 = high;
  }

 // "main" method
 method run() {
    sequence{
       (fire1 == out);
       (fire2 == out);
       (uav1.flying == no &&
       uav1.location == base_1_location);
    }
  }
}
```

A program that specifies the desired states.

```
class UAV {
  Roadmap location;
  Boolean flying;
  Boolean loaded;

  primitive method takeoff()
    flying == no => flying == yes;

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    flying == yes => flying == no;

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}
```

These are the actions the UAV can take.

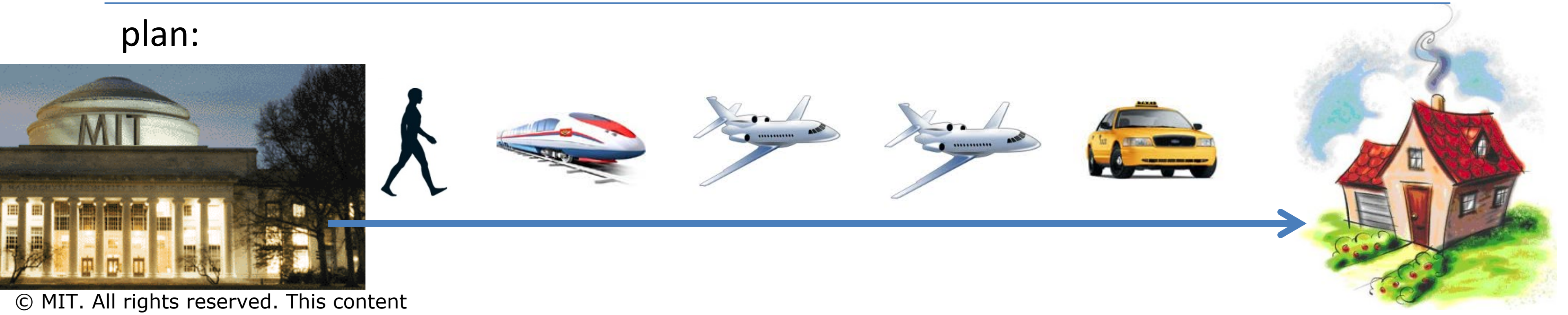
Activity Planning

initial state:

goals:

operators:

plan:



Activity Planning Maps Desired States to Actions

Initial State

```
class Main{
  UAV uav1;
  Lake lake1;
  Lake lake2;
  Fire fire1;
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 // constructor
  Main (){
      uav1 = new UAV();
      uav1.location= base_1_location;
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      fire1 = high;

      fire2 = new Fire();
      fire2.location = fire_2_location;
      fire2 = high;
  }
```

Goal[s]

```
 // "main" method
 method run() {
    sequence{
       (fire1 == out);
       (fire2 == out);
       (uav1.flying == no &&
       uav1.location == base_1_location);
    }
  }
}
```

Actions (aka Operators)

```
class UAV {
  Roadmap location;
  Boolean flying;
  Boolean loaded;

  primitive method takeoff()
    flying == no => flying == yes;

  primitive method land()
    flying == yes => flying == no;

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  #MOTION_PRIMITIVES(location, fly, flying==yes)
}
```

Activity Planner

Plan

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// "main" method
method run() {
   sequence{
     uav1.takeoff();
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     uav1.drop_water_high_altitude(fire2);
     … <13 additional activities> …
     uav1.land();
   }
 }
}
```

Outline

- Programming on State with Activity Planning
- Classic Planning Problem
- Planning as Heuristic Forward Search (Fast Forward Planner)
  - Enforced Hill Climbing
  - Fast Forward Heuristic
- Planning with Time (Crikey 3 Planner)
  - Temporal Planning Problem
  - Temporal Relaxed Plan Graph

Plan Representation

Many ways of expressing planning problems.

All include:

Inputs:

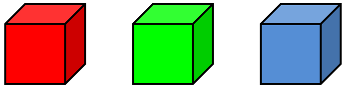
- initial state – a set of **facts** about the world
- goal – **subset** of **facts** that must appear in the goal state.
- actions – a set of named **precondition** and **effect** pairs.

Outputs:

- plan – a schedule of actions (i.e. a sequence or list of actions).

“Classic” Representation (PDDL)

Action Model:

Objects (things): 

Predicates (used to create true or false statements about the world, “facts”):

(On A, B)

(Clear A)

Actions (used to change truth of predicates):

(Clear A)
(Clear B)

preconditions

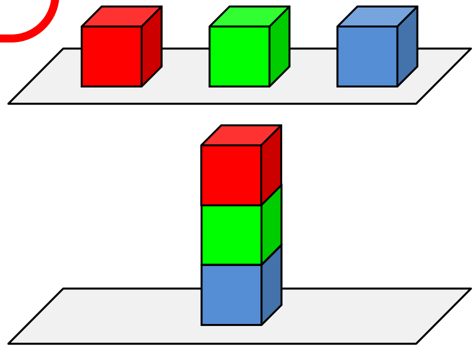
→ **Stack** →

¬(Clear B)
(On A, B)

effects

Initial: (Clear) (Clear) (Clear)

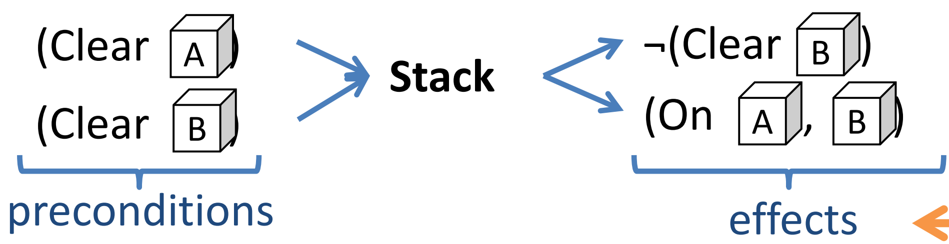
Goal: (On ,) (On)



“Classic” Planning Actions

Preconditions – a conjunction of statements that must be true **before** the action is applied.

Actions (used to change truth of predicates):



Effects – a conjunction of statements that must be true **after** the action is applied.

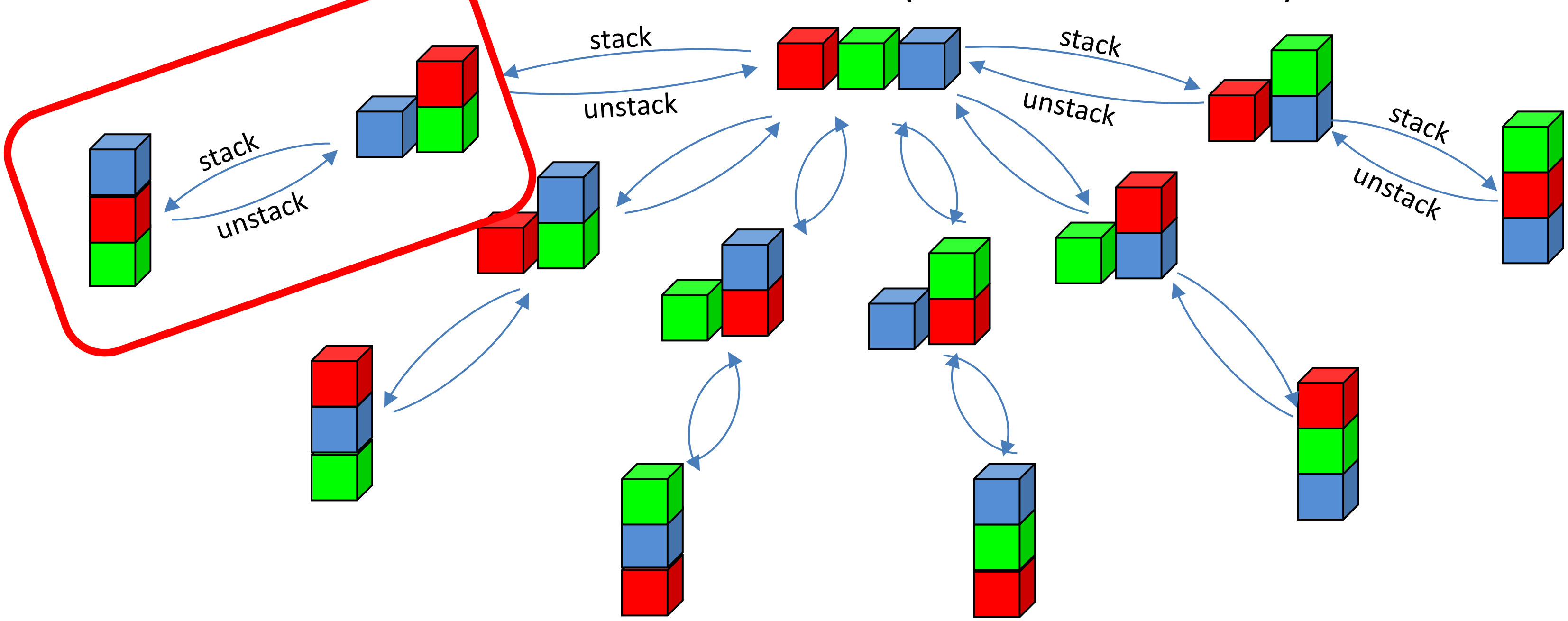
“Delete” Effects – statements that must NOT be true.

“Add” Effects – statements that must be true.

Automata Representation

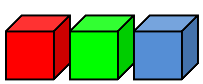
Action/model:

Concurrent Constraint Automata (like a state-machine):

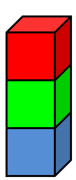


Note: This is a very simple example, there are usually many automata, and guards on the transitions.

Initial:



Goal:



Algorithms exist to map between the two representations.

What is the difference between Path and Activity Planning?

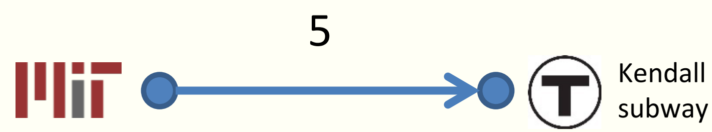
For a Path Planner:

State = a location

Kendall
subway

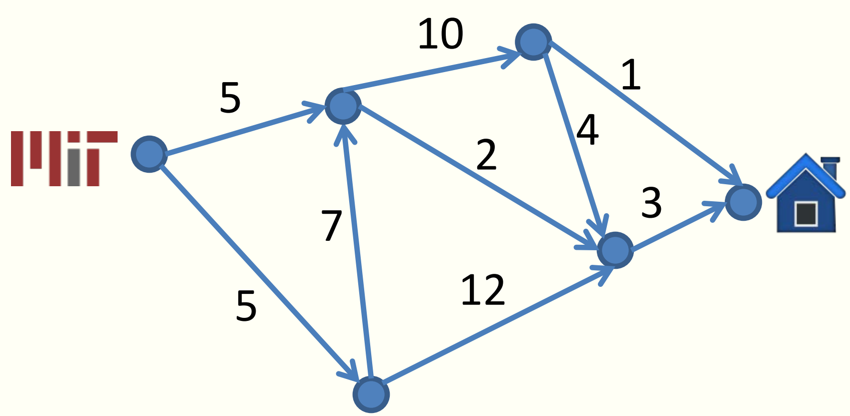
(identified by name)

Operator = a weighted edge



The start and end states uniquely identify where this operator can be applied.

State Space = a map



Formulating Activity Planning as Search

Search needs a State Space, constructed from States and Operators:

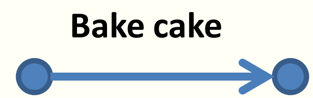
State = a set of facts

- I'm hungry
- I want cake
- I have flour
- I have sugar

(identified by the set of statements)

Operator = an action

- I have flour
- I have sugar
- I have milk
- I have eggs

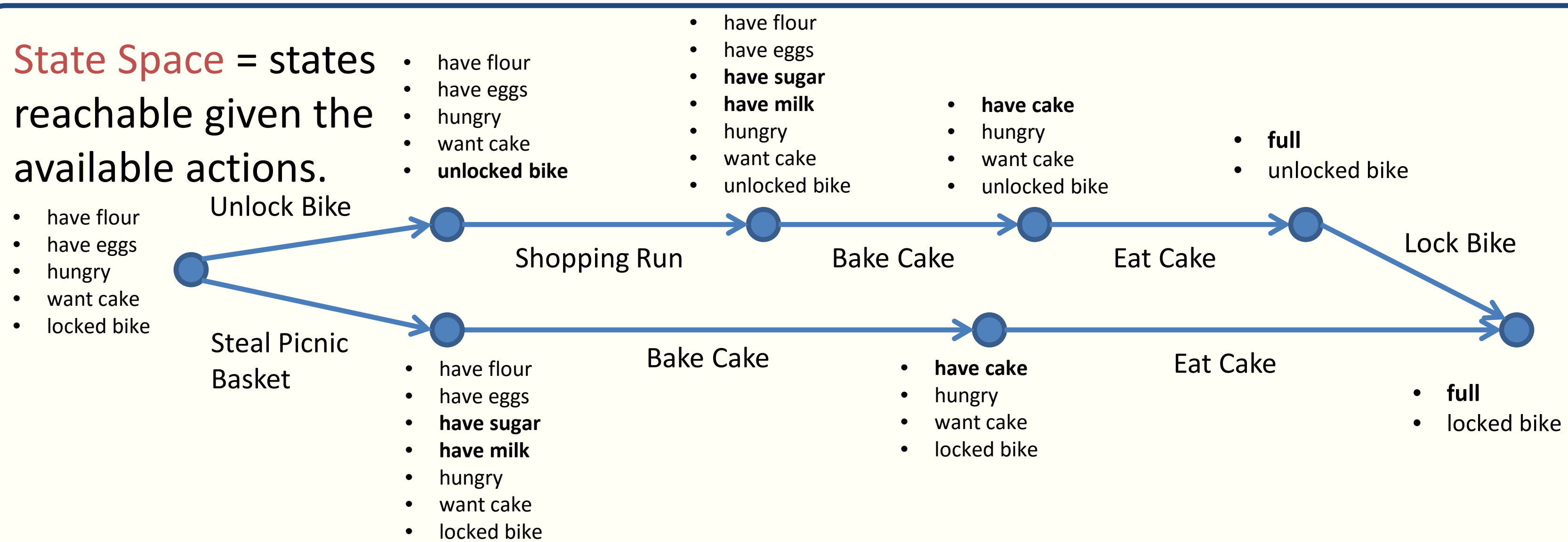


- I have cake
- I do NOT have flour.
- I do NOT have sugar.
- I do NOT have milk.
- I do NOT have eggs.

Precondition:
Statements that must be a subset of the starting state.

Effect:
Statements that will be true in ending state.

State Space = states reachable given the available actions.

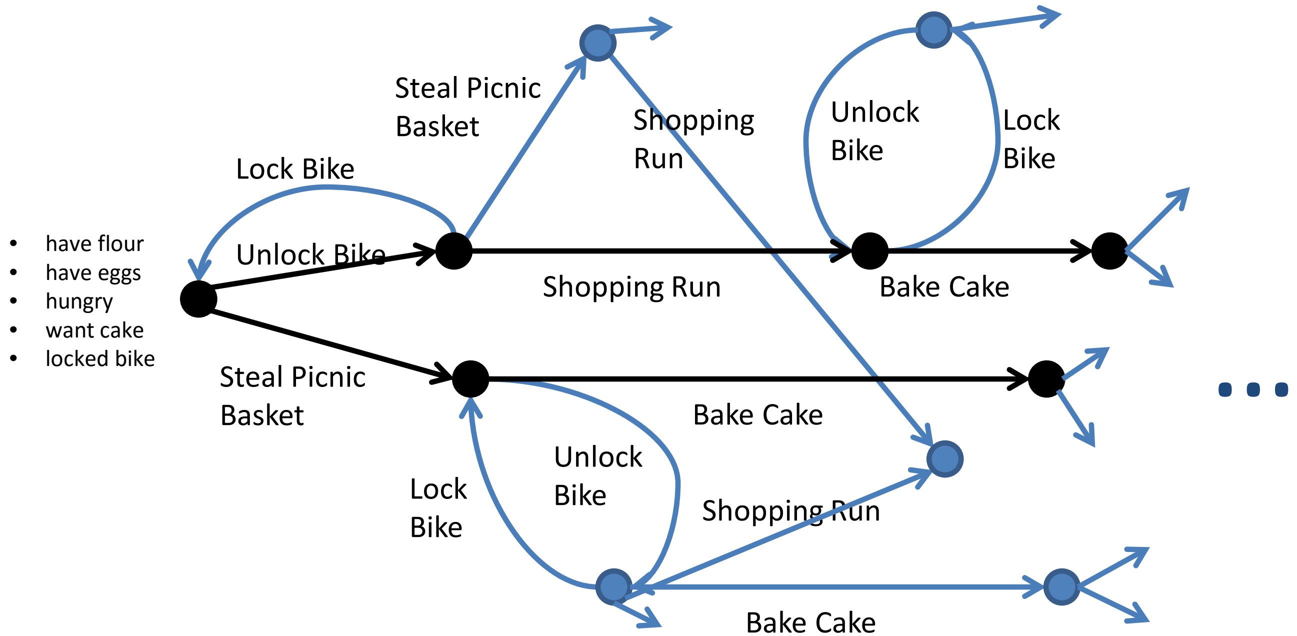


Activity Planning as Search

- Providing a "map" will all possible actions is too large and time-consuming.
- Instead, we provide a set of actions...

Actions = { Unlock Bike, Lock Bike, Shopping Run,
Steal Picnic Basket, Bake Cake, Eat Cake }

and expect the planner to build the "map" as needed.



How Hard is Activity Planning?

The "map" is usually not provided in activity planning, but we can imagine how hard the planning problem is relative to depth first search.

Complexity of Depth First Search: $O(b^d)$

Planning Problem with:

- 10 actions
- 10 statements = 1024 possible states (not necessarily all reachable)

Scenario 1: Lets assume our expected plan is 10 actions long

if b = 10 actions, d = 10 states

b^d = 10,000,000,000

Scenario 2: A few actions are applied over and over again in different orders, visiting all possible states.

if b = 10 actions, d = 1024 states

b^d > atoms in the universe (3.0×10^{23})

Note: We talked about the runtime complexity of the algorithm, but we can also talk about the complexity of the problem itself. The "Single Source Single Destination Shortest Path Problem" is Linear(#Edges+#Vertices). The "Plan Existence Problem" (aka planning) is PSpace(#Actions).

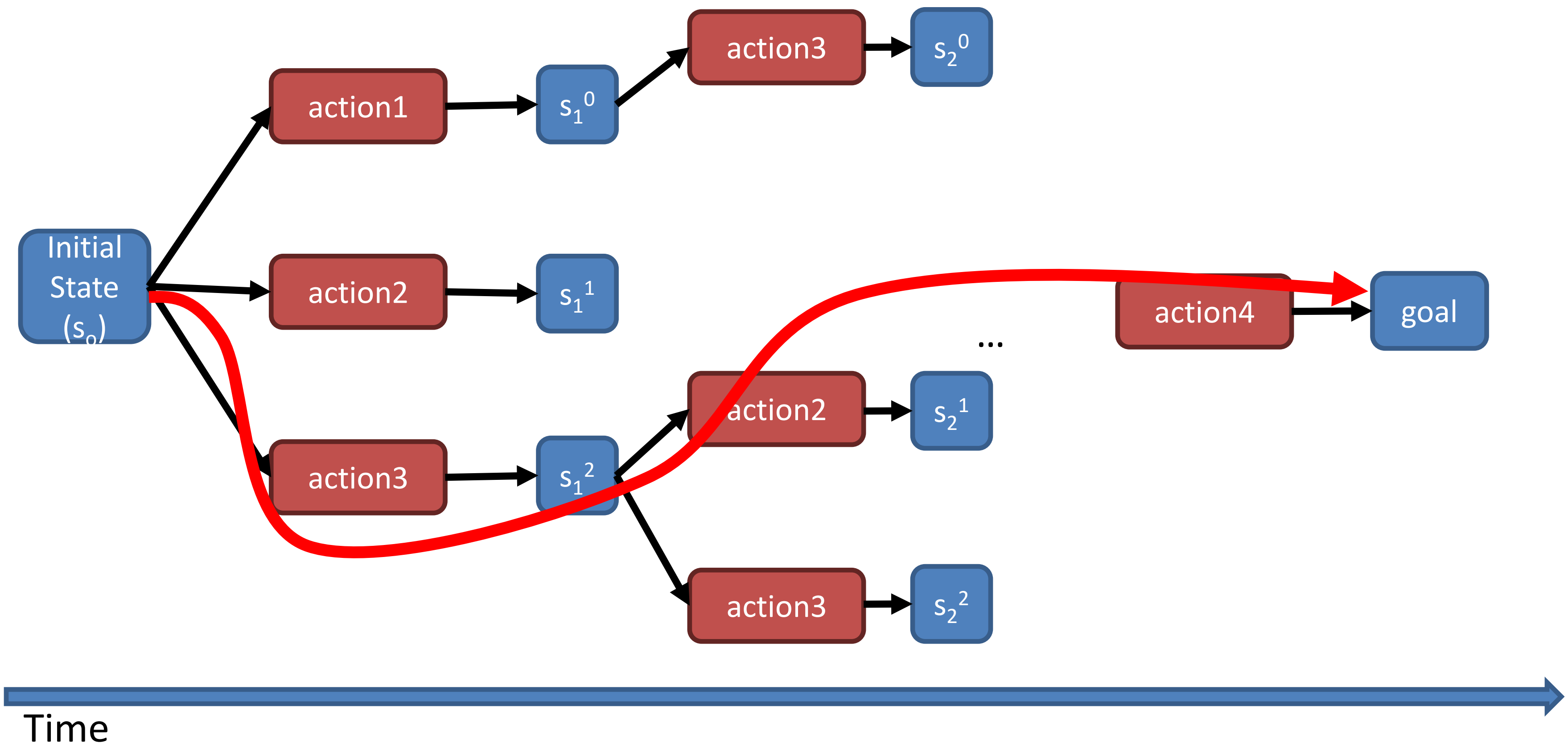
Activity Planning Search Strategies

The **order** we search for actions matters a lot . . .

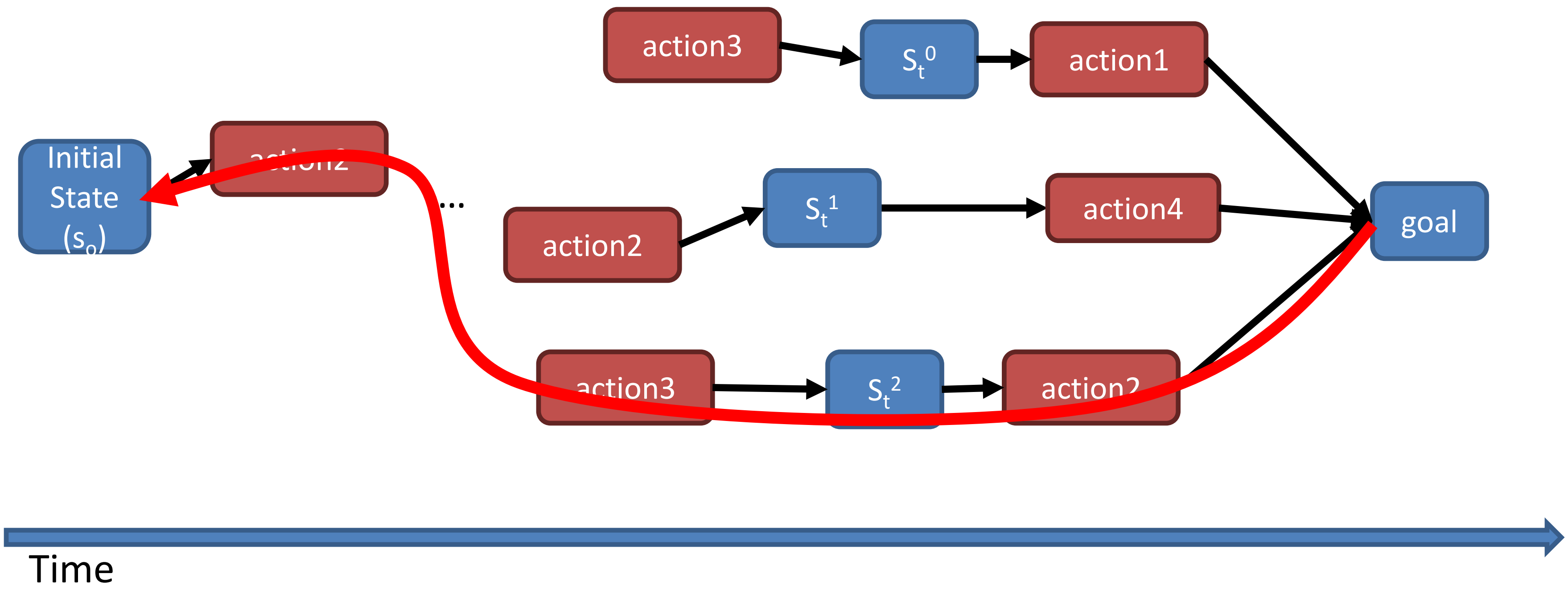
- **Forward search** – start at beginning; 'simulate' forward, with all states grounded.
  - **Heuristic Forward Search* (Enforced Hill Climbing)**
- **Goal-regression search** – start with goals; ask "what actions are needed to achieve each goal?"
- **Constraint Satisfaction** – encode as constraint problem; solver exploits tightest constraints.

** Very popular right now.*

Forward Search



Goal-Regression Search



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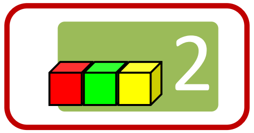
Enforced Hill-Climbing Search

(i.e., greedy with-out backup)

Basic Enforced Hill-Climbing Algorithm

```
Start with the initial state.
If the state is not the goal:
1.  Identify applicable actions.
2.  Obtain heuristic estimate of the value of
    the next state for each action considered.
3.  Select action that transitions to a state with
    better heuristic value than the current state.
4.  Move to the better state.
5.  Append action to plan head and repeat.
(Never backtrack over any choice.)
```



Legend: s, h(s)

Time

Used by FF (Hoffmann, IJCAI, 2000) , FastDownward (Helmert, JAIR, 2006) and many others.

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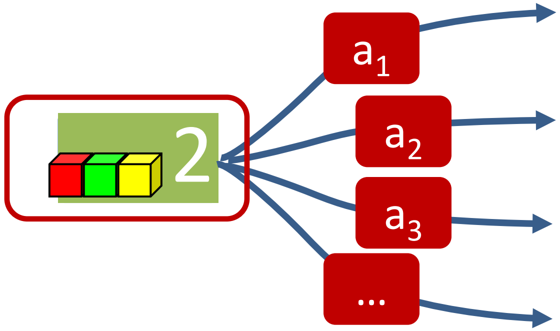

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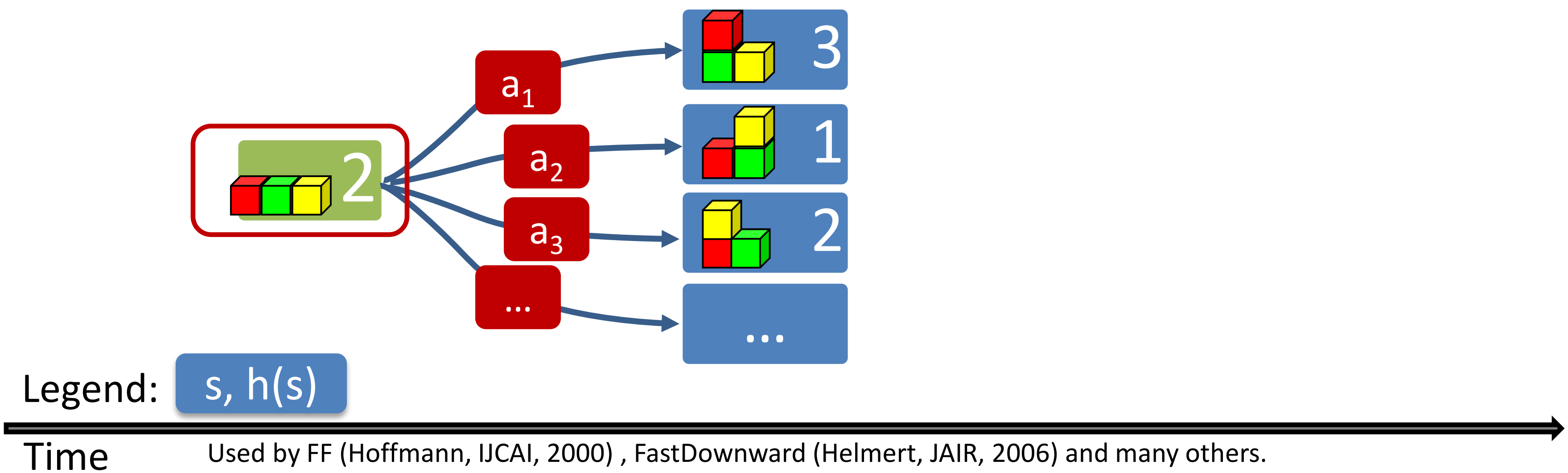

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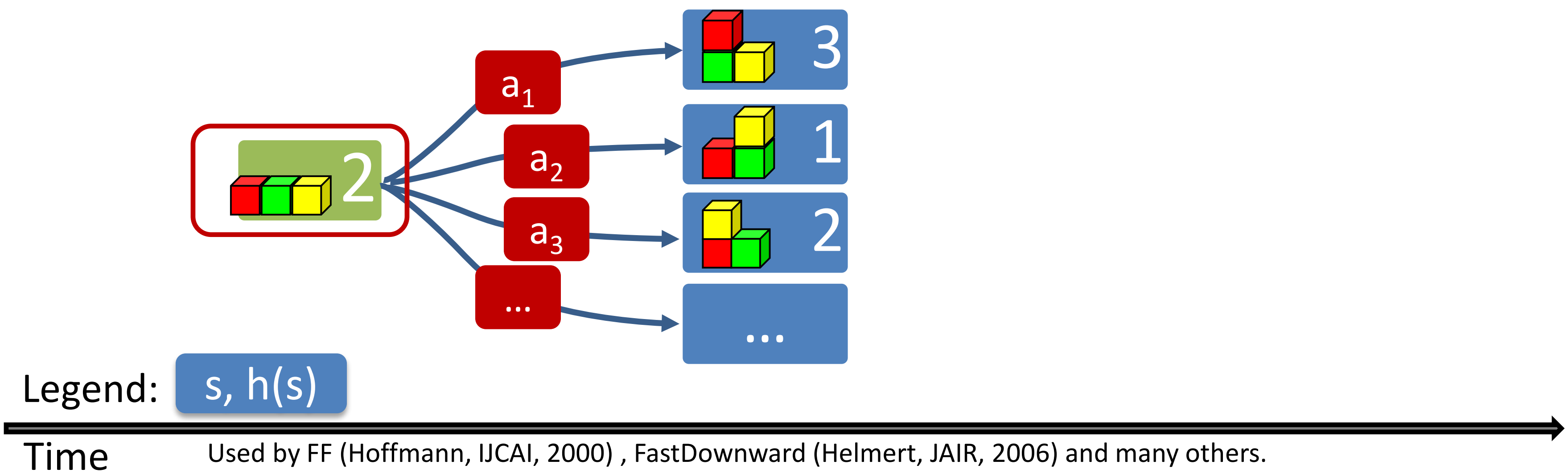

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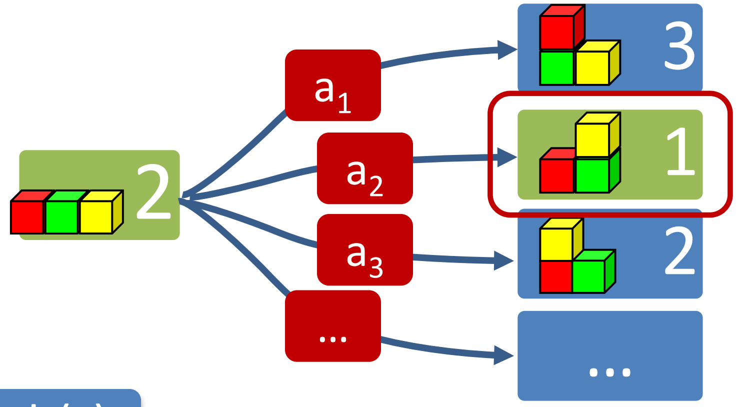

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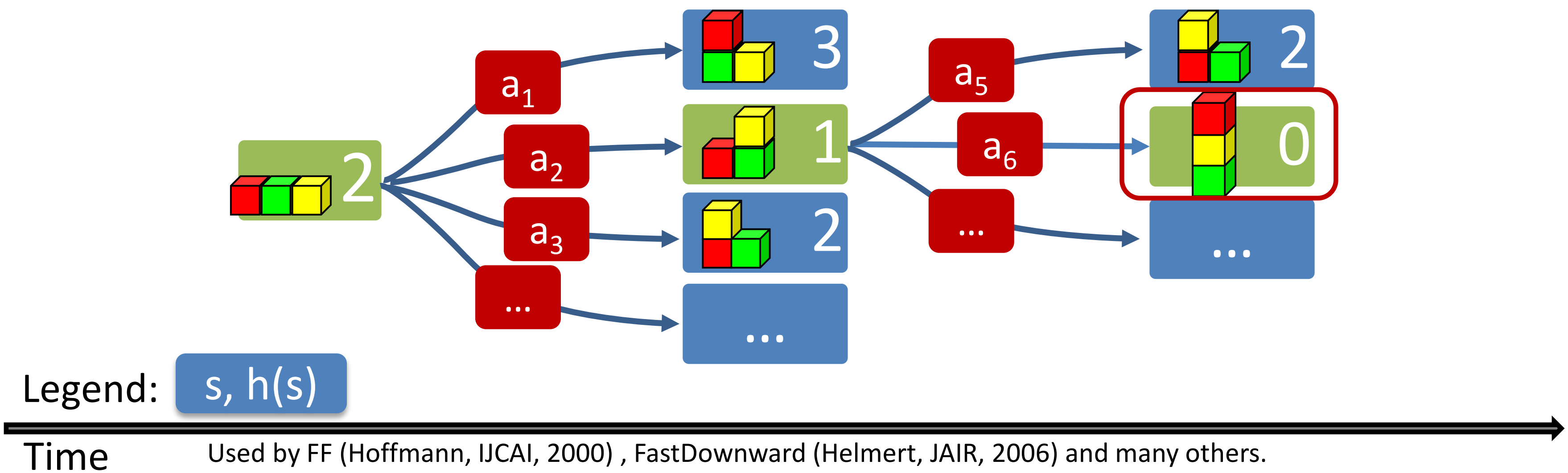

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5.  Append action to plan head and repeat.
(Never backtrack over any choice.)
```
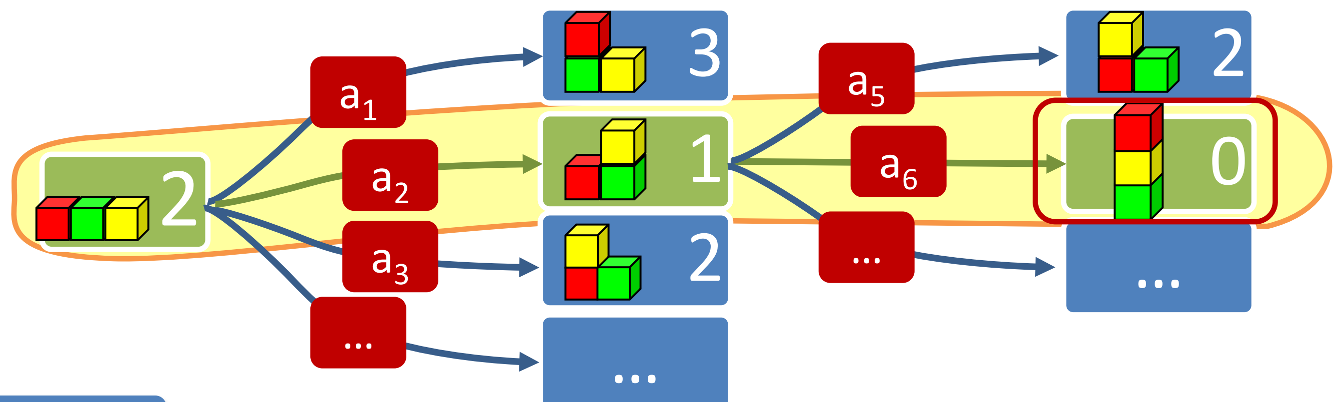

Done!

Search finishes when the current state contains the goal. The actions along the path form the plan.



Legend: s, h(s)

Resulting Plan: $\{a_2, a_6\}$

Time

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Enforced Hill-Climbing (EHC) Pseudo Code

The basic Enforced Hill-Climbing algorithm, shown before,
is conceptually easy to understand but hides interesting details.

```
open_list = [initial_state];
best_heuristic = heuristic value of initial_state;
while open_list not empty do
    current_state = pop state from head of open_list;
    successors = the list of states reachable from current_state;
    while successors is not empty do
        next_state = remove a state from successors;
        h = heuristic value of next_state;
        if next_state is a goal state then
            return next_state;
        end if
        if h better than best_heuristic then
            clear successors;
            clear open_list;
            best_heuristic = h;
        end if
        place next_state at back of open_list;
    end while
end while
Recover Plan (i.e. by using and walking backwards over parent pointers)
```

EHC uses a queue to remember states to expand.

The queue is cleared when a better state is found, effectively enforcing the search to only consider the best state.

If there are no successor states with better heuristic value, EHC expands the current state in a breadth first manner.

Planning as Enforced Hill-Climbing (cont.)

- Success depends on an informative heuristic.
  - Fast Forward uses Delete-Relaxation heuristic, which is informative for a large class of bench mark planning domains.
- Strategy is suboptimal.
  - Heuristic may over estimate.
- Strategy is incomplete.
  - Never backtracking means some parts of the search space are lost.
- If Enforced Hill-Climbing fails (ends without reaching a goal state), the Fast Forward planner switches to best-first search.
  - (e. g., Greedy search with Backup or A* search).

Where does this Heuristic come from?

- Numerous heuristics have emerged over 15 years.

- Many heuristics solve an **easier**, **relaxed**, problem by:
  - Ignoring information or constraints.
  - Being optimistic.

- The FF heuristic applies the previous fastest planner, Graph Plan, to a relaxed problem.

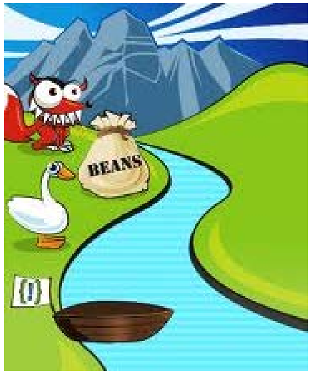
Fast Forward Heuristic, $h_{ff}(s)$

- Observation:
  - Actions complicate planning by "deleting" the progress made by other actions.
  - If actions can never undo effects, planning is simple.

- Idea: Delete Relaxation
  - Ignore "delete" effects of actions.
  - Generate simplified plan using relaxed actions.
  - The heuristic counts the actions in that simplified plan.

- Example: The Farmer, Fox Goose and grain
  - A farmer must use a boat to move a fox, goose, and bag of grain across a river two-at-a-time.
  - If left alone, the fox will eat the goose and the goose will eat the bag of grain.
  - What is the plan?

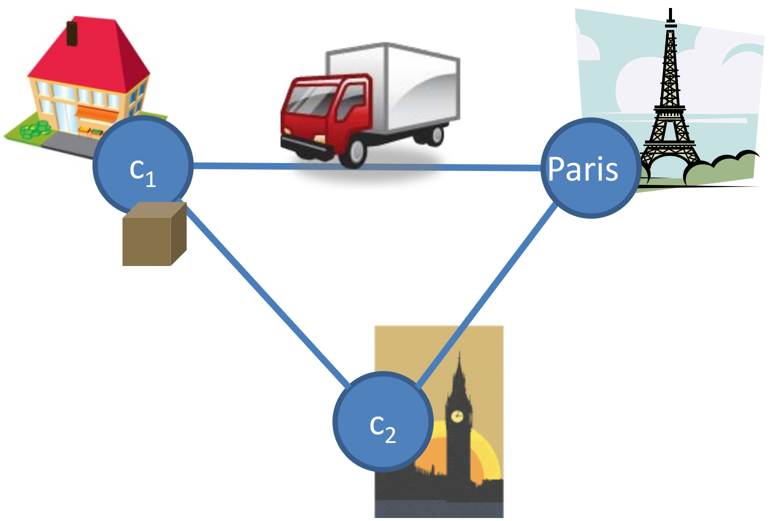
  - For the relaxed heuristic: ignore eating each other.



B. Nebel, The FF Planning System: Fast Plan Generation Through Heuristic Search, in: Journal of Artificial Intelligence Research, Volume 14, 2001, Pages 253 - 302.

Simple Planning Problem

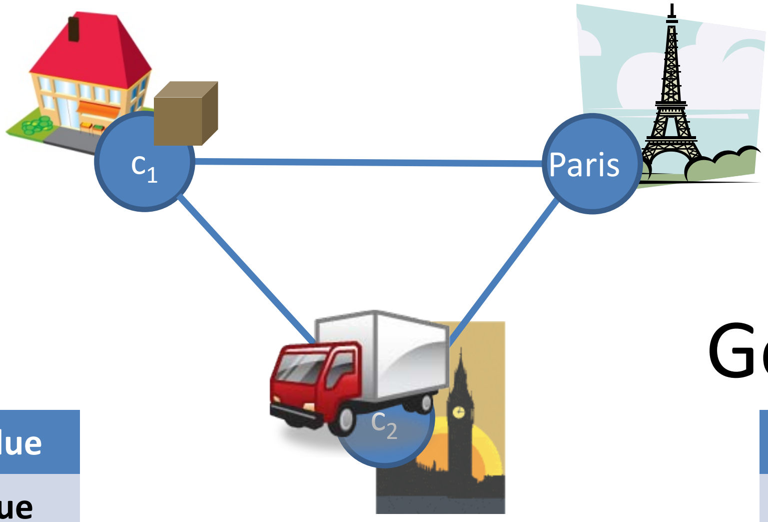
Actions:



Action	Preconditions	Add Effects	Delete Effects
Load(b, t, c)	BoxIn(b, c), TruckIn(t, c)	BoxOn(b, t)	BoxIn(b, c)
Unload(b, t, c)	BoxOn(b, t), TruckIn(t, c)	BoxIn(b, c)	BoxOn(b, t)
Drive(t, c, c’)	TruckIn(t, c)	TruckIn(t, c’)	TruckIn(t, c)

Simple Planning Problem

Problem: "Get the box to Paris"



Initial:

Atom	Value
BoxIn(b, c_1)	**True**
BoxIn(b, c_2)	False
BoxIn(b, Paris)	False
BoxOn(b, t)	True
TruckIn(t, c_1)	False
TruckIn(t, c_2)	**True**
TruckIn(t, Paris)	False

Goal:

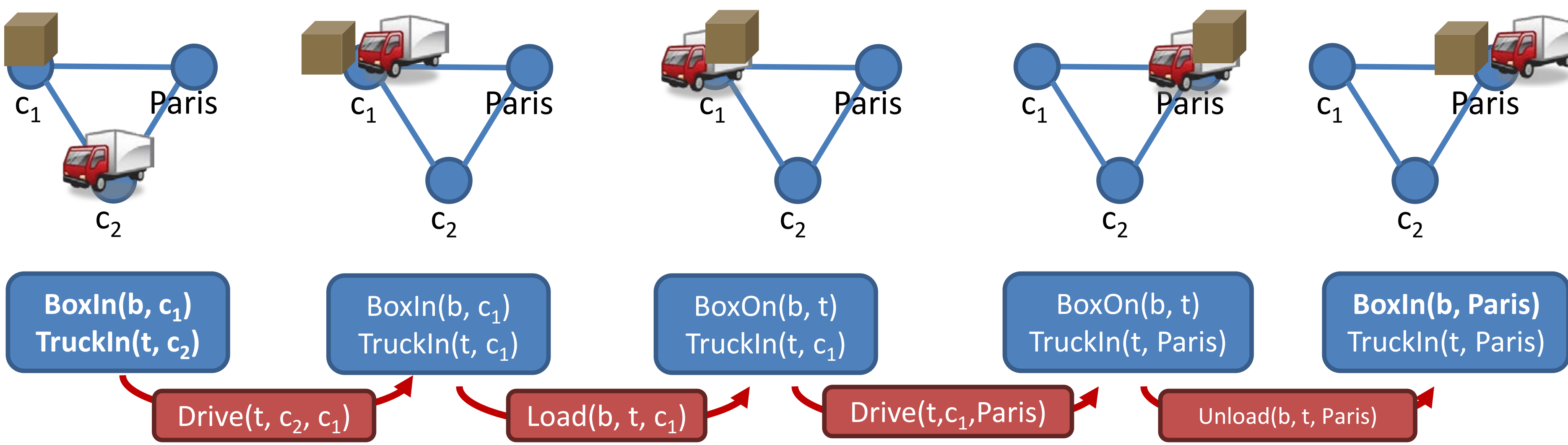
Atom	Value
BoxIn(b, c_1)	*
BoxIn(b, c_2)	*
BoxIn(b, Paris)	**True**
BoxOn(b, t)	*
TruckIn(t, c_1)	*
TruckIn(t, c_2)	*
TruckIn(t, Paris)	*

* Indicates unassigned (don't care)

Getting to Paris the *Correct* Way

Initial:

Goal:



Original Actions:

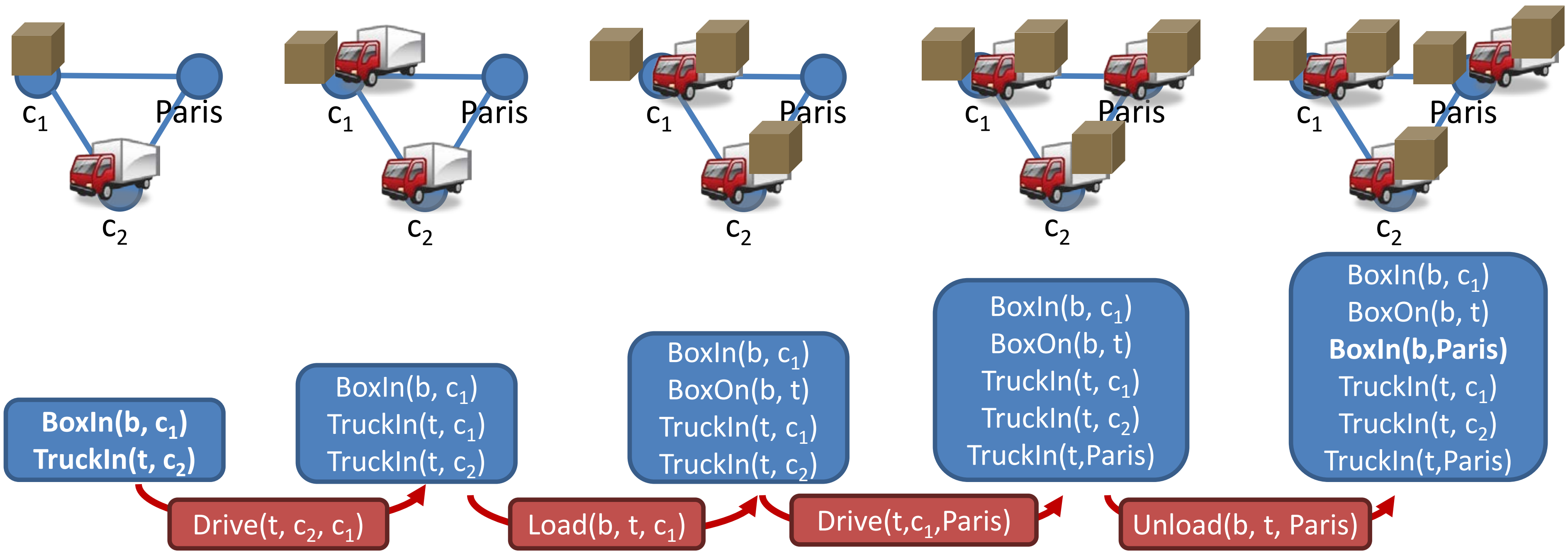
Action	Preconditions	Add Effects	Delete Effects
Load(b, t, c)	BoxIn(b, c), TruckIn(t, c)	BoxOn(b, t)	BoxIn(b, c)
Unload(b, t, c)	BoxOn(b, t), TruckIn(t, c)	BoxIn(b, c)	BoxOn(b, t)
Drive(t, c, c')	TruckIn(t, c)	TruckIn(t, c')	TruckIn(t, c)

Getting to Paris the ***Relaxed*** Way

Simple Idea: Ignore Delete Effects

Initial:

Goal:

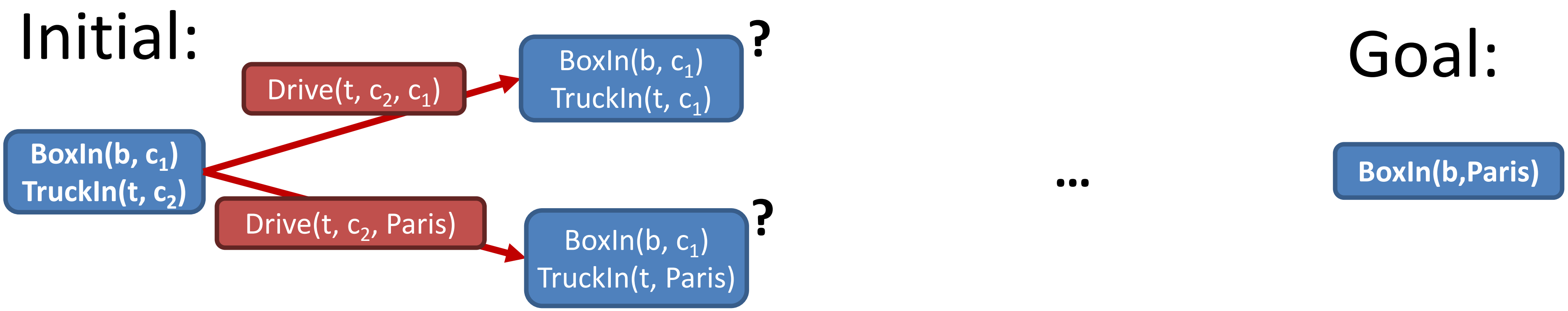


Relaxed Actions:

Action	Preconditions	Add Effects	Delete Effects
Load(b, t, c)	BoxIn(b, c), TruckIn(t, c)	BoxOn(b, t)	~~BoxIn(b, c)~~
Unload(b, t, c)	BoxOn(b, t), TruckIn(t, c)	BoxIn(b, c)	~~BoxOn(b, t)~~
Drive(t, c, c')	TruckIn(t, c)	TruckIn(t, c')	~~TruckIn(t, c)~~

The Fast Forward Heuristic, in Practice

Enforced Hill Climbing: searches for the **correct** plan…



For each possible next state,

while the Fast Forward Heuristic:

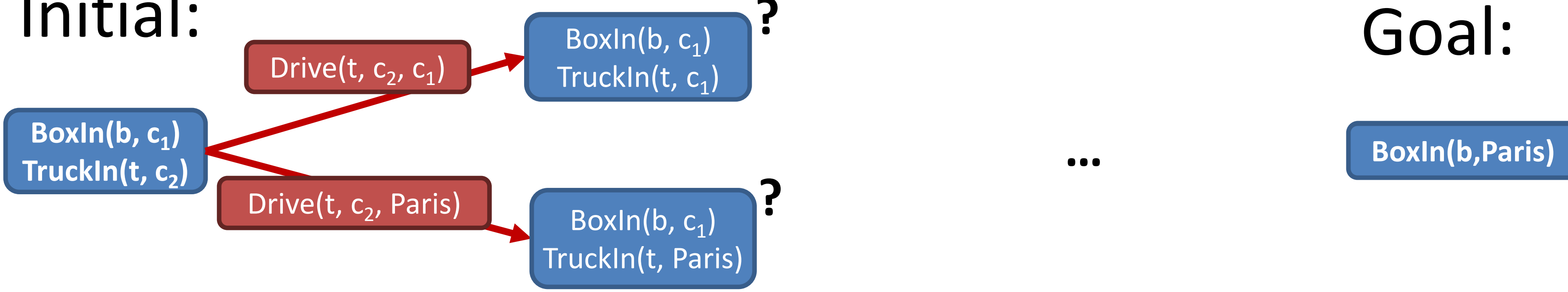
searches for the **relaxed** plan…

The Fast Forward Heuristic, in Practice

Enforced Hill Climbing searches for the **correct** plan…

Initial:

Goal:



For each possible next state,

while the Fast Forward Heuristic searches for the **relaxed** plan…

How do we efficiently find this relaxed plan?
Solution: Use a **Relaxed Plan Graph**

1. Create Relaxed Plan Graph that Encodes All Plans

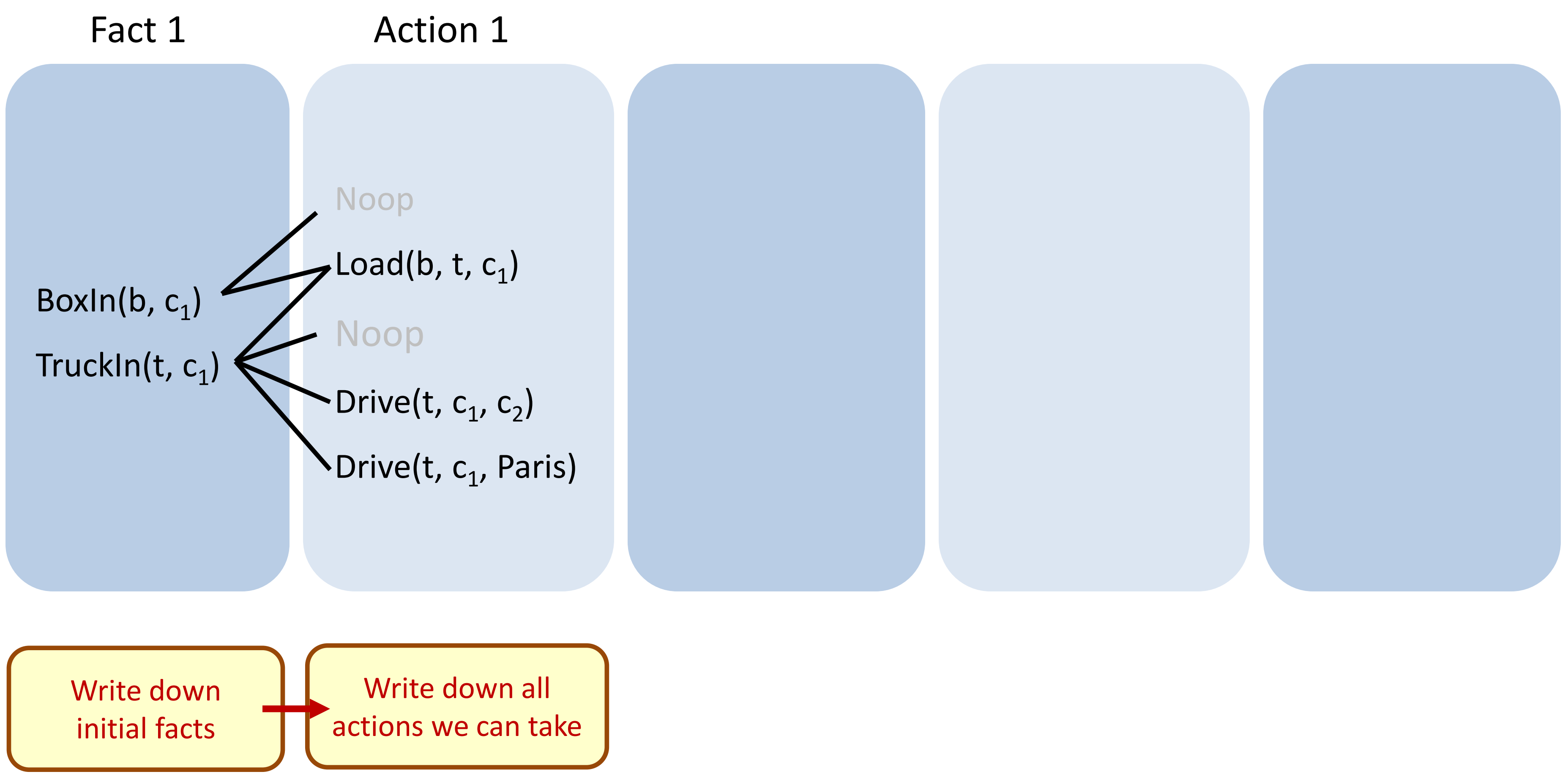
Fact 1

BoxIn(b, c_1)

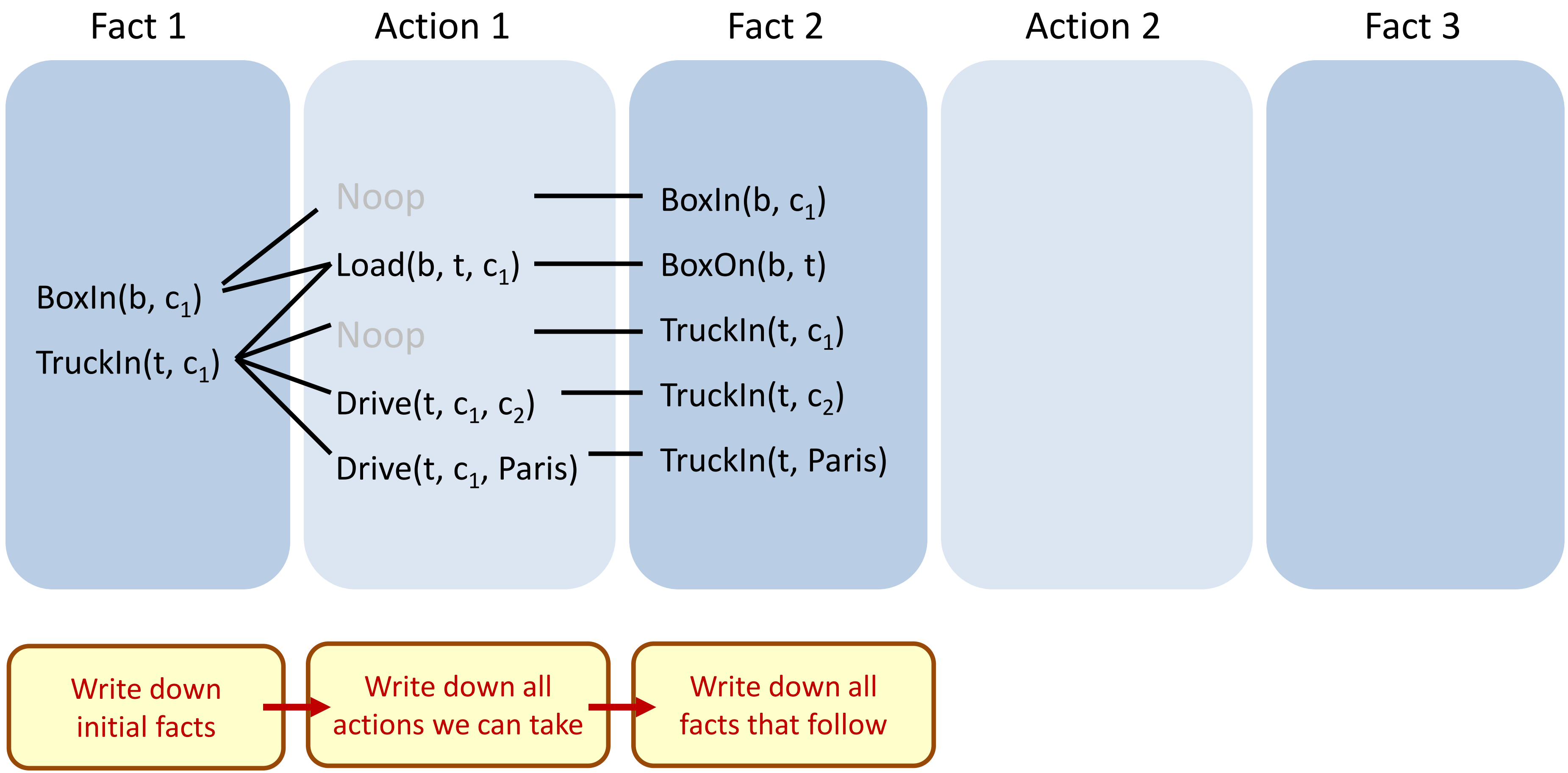
TruckIn(t, c_1)

Write down initial facts

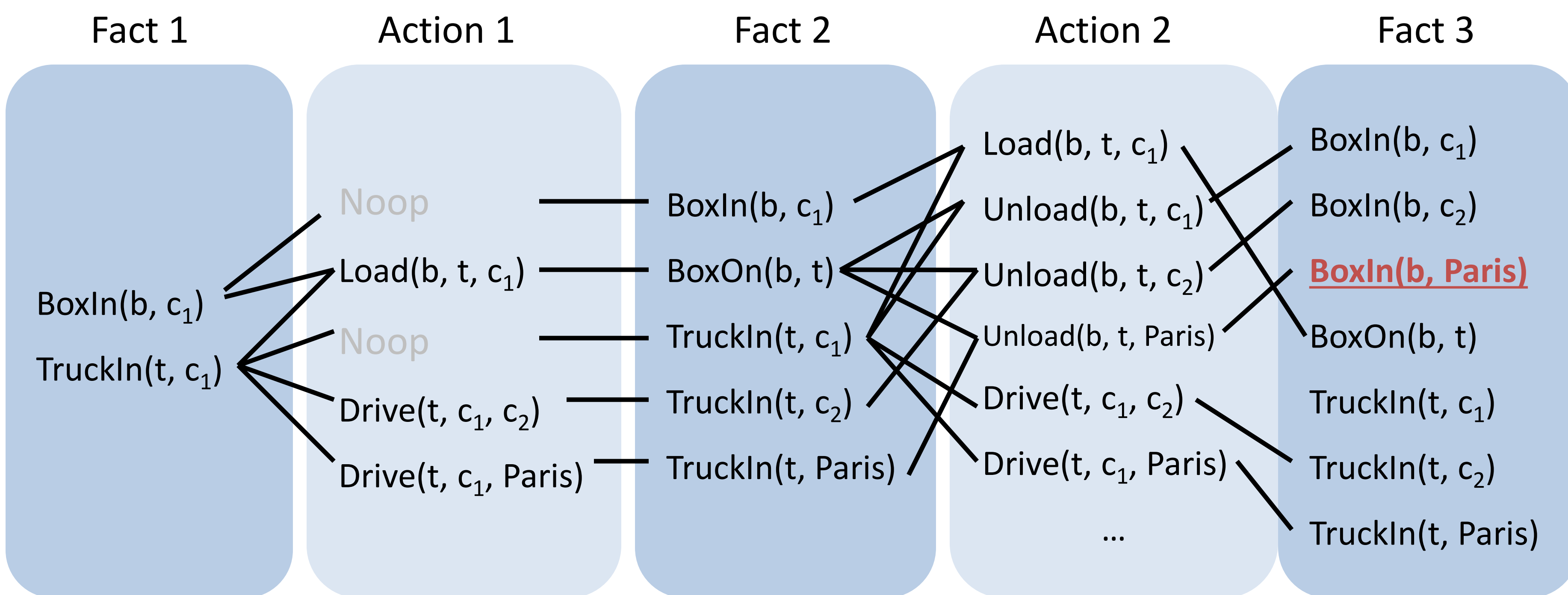
1. Create Relaxed Plan Graph that Encodes All Plans



1. Create Relaxed Plan Graph that Encodes All Plans



1. Create Relaxed Plan Graph that Encodes All Plans

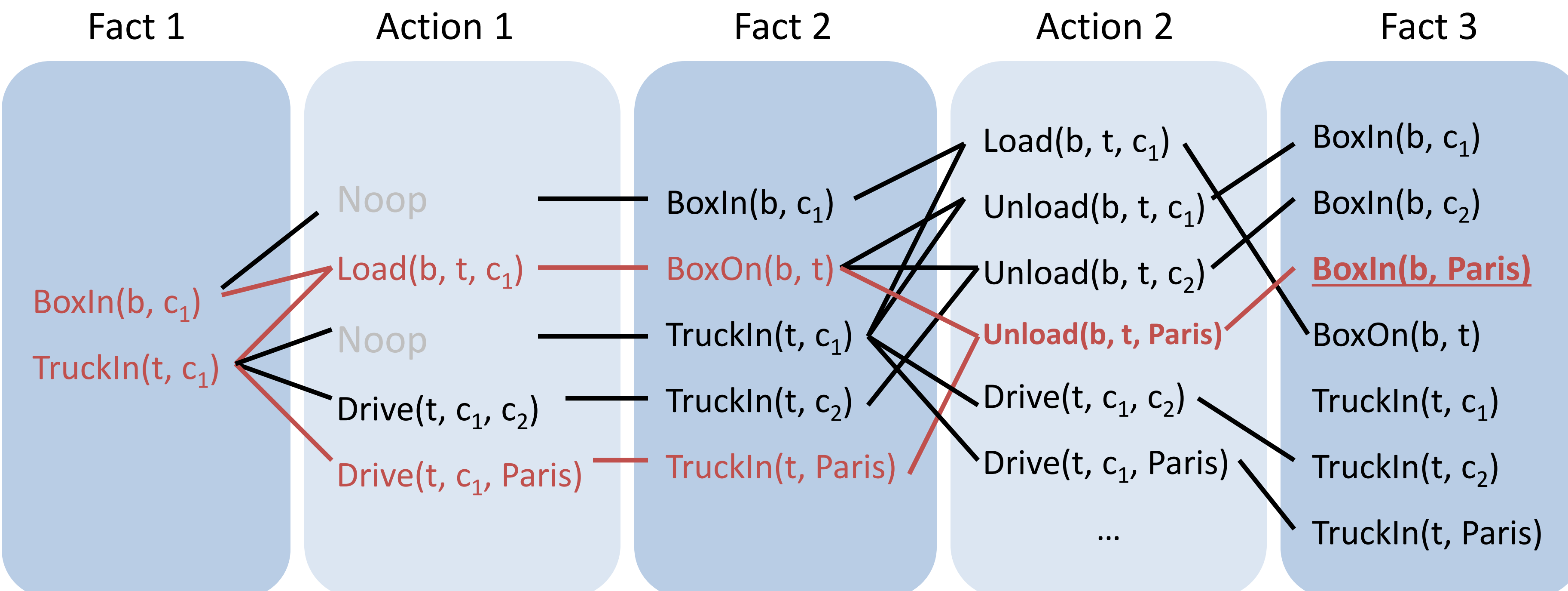


For clarity, no-ops are not explicitly shown in the activity layer, but the facts are carried forward from one layer to the next.

Write down initial facts → Write down all actions we can take → Write down all facts that follow → … → Repeat until all goals appear.

2. Extract Relaxed Plan

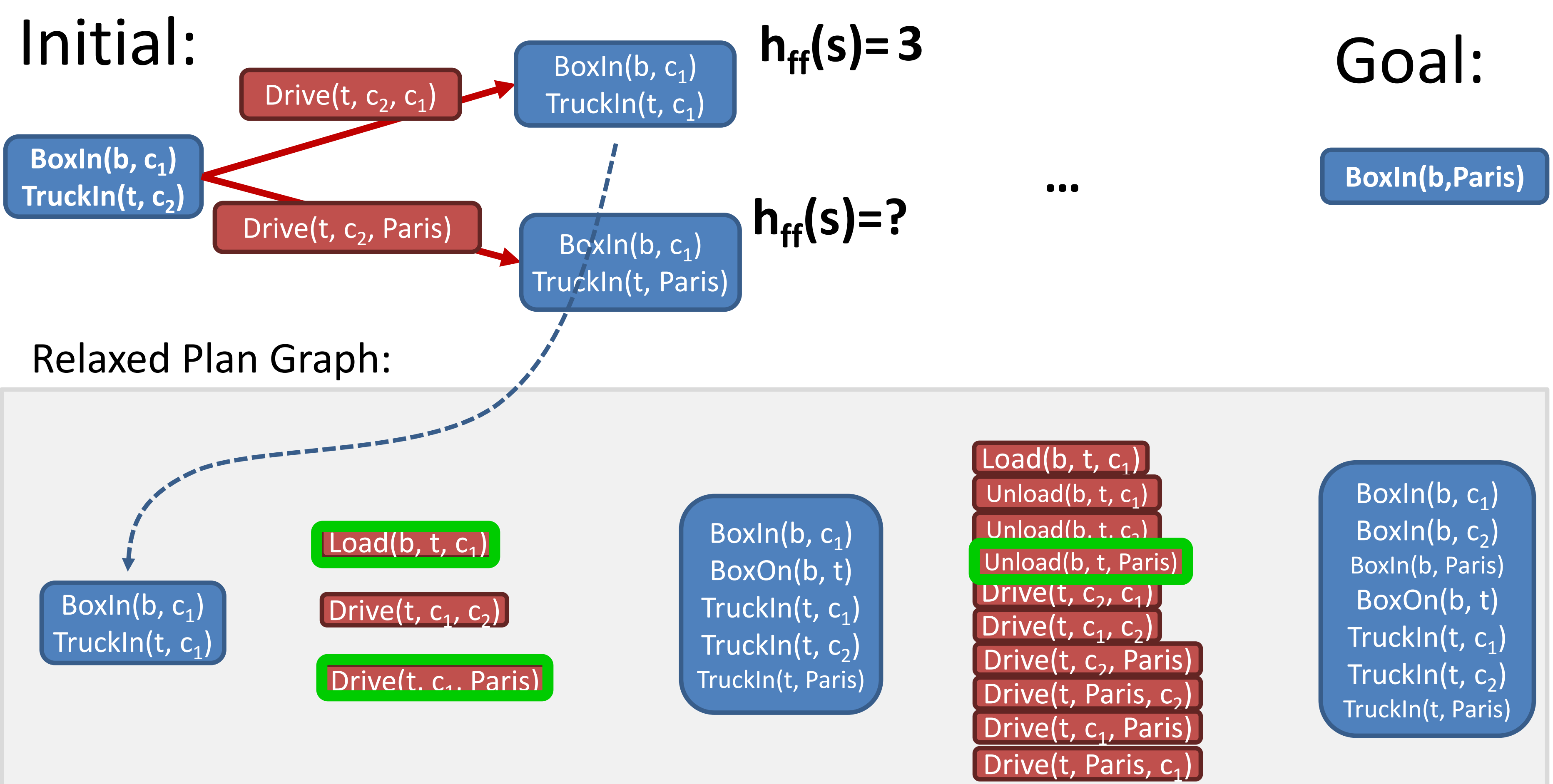
Find the set of actions for the relaxed plan by searching backward in the planning graph.



Recursively select actions that achieve goals

Fast Forward Heuristic

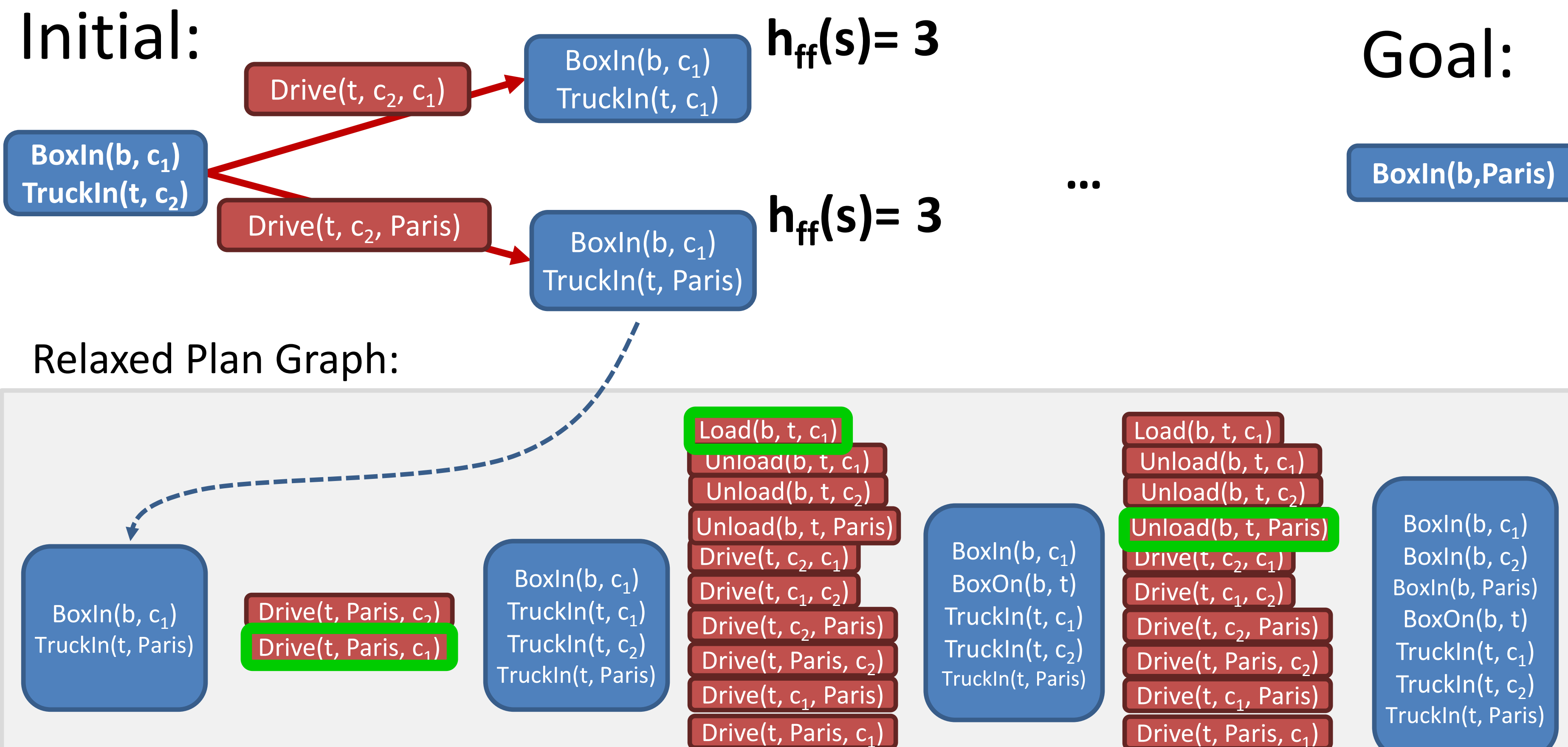
Simple Idea: Search, while maintaining a relaxed plan graph (ignore delete effects),
$h_{ff}(s)$ = the number of actions in the relaxed plan until the goal first appears.



Fast Forward Heuristic

Simple Idea: Search, while maintaining a relaxed plan graph (ignore delete effects),

$h_{ff}(s)$ = the number of actions in the relaxed plan until the goal first appears.



In this simple example, both actions appear equally good.

Fast Forward Heuristic Summary

- Solve a simpler planning problem to aid the harder planning problem.
- # of actions in the *relaxed plan* found in a *relaxed planning graph* is the heuristic.
- Ignoring constraints makes it fast.
- Extendable beyond classical domains
  - Enhance plan graph with more constraint propagation
  - Similar extensions exist for temporal problems

Real-World Planning Problems

Simple (classic) planning is hard!
but, still lacks many real-world features …

- **Classical** – discretized world, finite domains, single agent of change.
- **Numeric** – domain allows continuous values
  - x, y position
- **Temporal** – actions take time, goals can have deadlines
  - walking will take 5-10 minutes, I need to be there in 1 hour.
- **Resources** – a quantity that can be consumed or regulated (type of numeric domain)
  - fuel, battery, CPU usage
- **Optimality** – do we minimize or maximize a particular value
  - number of actions, time spent, fuel used, utility
- **Preferences** – express soft goals, preferred actions, or action ordering.
  - "I would like to visit my friends on the way to grandmothers house."
- **Stochastic** – actions can have uncertain effects, uncertain durations.
  - driving will have a 99% of success of reaching your destination, but a 1% chance of an accident.
- **Multi-agent** – planning for multiple coordinating agents, or against an adversary.
  - multiple UAVs, or planning against cyber-attack.

Outline

- Programming on State with Activity Planning
- Classic Planning Problem
- Planning as Heuristic Forward Search (Fast Forward Planner)
  - Enforced Hill Climbing
  - Fast Forward Heuristic
- Planning with Time (Crikey 3 Planner)
  - Temporal Planning Problem
  - Temporal Relaxed Plan Graph

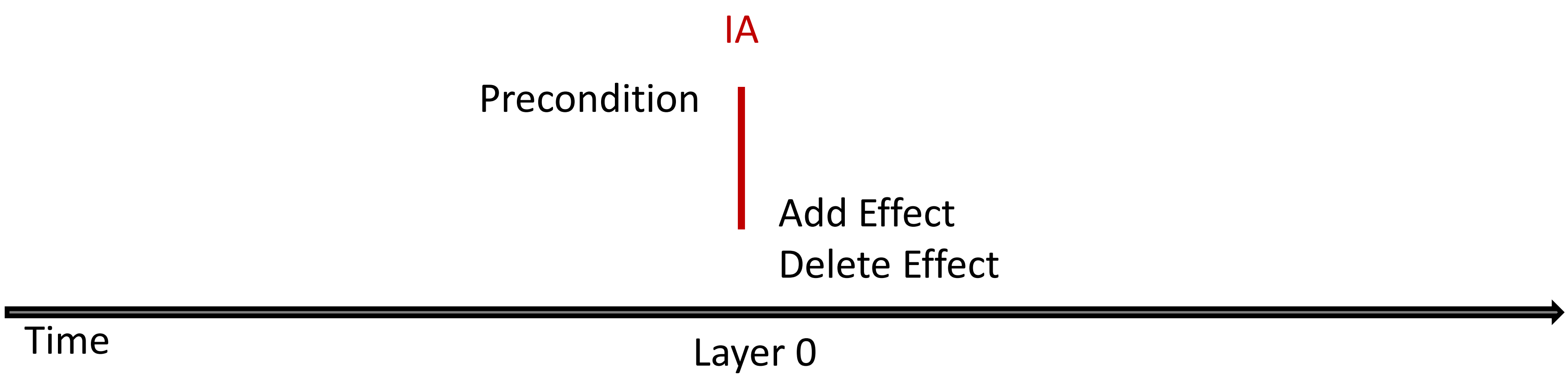
Classical [, Instantaneous] Action

Instantaneous Action, **IA = ⟨C,A,D⟩**

Precondition, C

Effects:

- Add Effect, A
- Delete Effect, D



Time is discretized into "layers", an action applies instantaneously at a particular layer index.

PDDL Durative Action

Durative Action, **DA=** $\langle C_S, C_O, CE, A_S, A_E, DS, D_E, lb, ub \rangle$

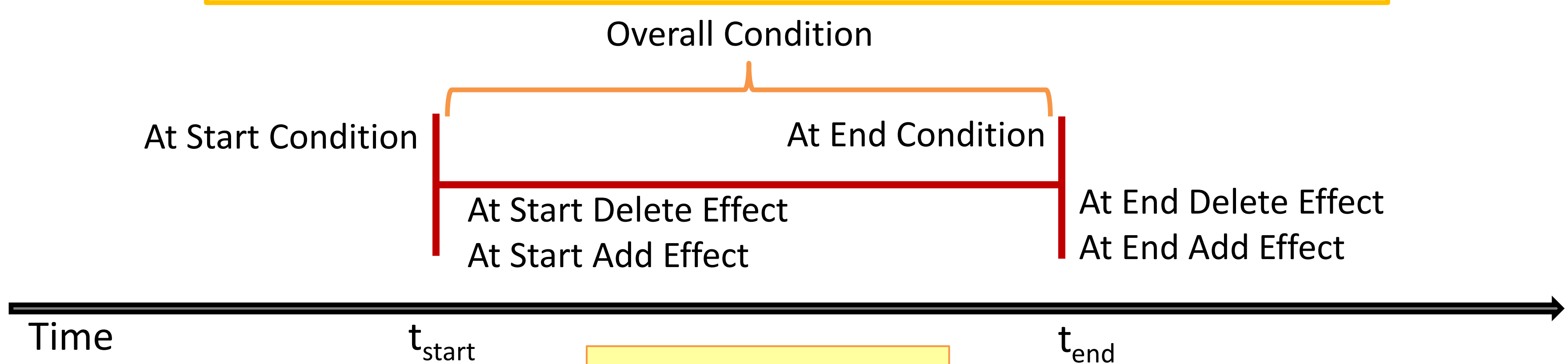
Duration: [lb, ub]

Conditions:
- At Start Condition, C_S
- Overall Condition, C_O
- At End Condition, C_E

Effects:
- At Start Add Effect, A_S
- At Start Delete Effect, D_S
- At End Add Effect, A_E
- At End Delete Effect, D_E

A Durative Action consists of:
- two instantaneous (aka "snap") actions, and
- a condition that must hold during its execution,

but must be applied atomically (all or nothing).



$lb \leq t_{end} - t_{start} \leq ub$

Temporal Planning

Combination of Planning & Scheduling

- Planning – Deciding **what** to do.
- Scheduling – Deciding **when** to do it.

Strategies for Planning with Durative Actions

- **Compression**
  - Convert the Durative Action to Instantaneous Actions
    - $C = C_S \cup \left((C_E \cup C_O) \backslash A_S\right)$ - union of conditions
    - $A = (A_S \backslash D_E) \cup A_E$ - union of add effects
    - $D = (D_S \backslash A_E) \cup D_E$ - union of delete effects
  - Plan using classical planner, expand and schedule at the end.
  - *Pro: Allows the use of classical planners*
  - *Cons: Not as expressive*

Crikey3 [Coles et al.]

- **Snap Actions**
  - Convert the Durative Action to two Instantaneous Actions
  - Modify the Search the Enforce the Duration and Overall Condition
  - Pro: Builds on planning strategies developed for classical planners.
  - Cons: doubled number of actions
- **Automata**
  - We'll talk about this next week.

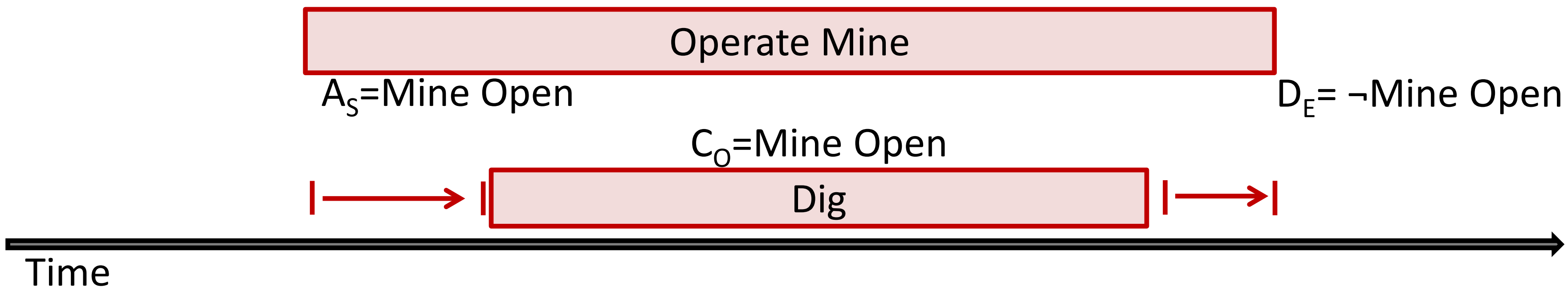
Note: There are many approaches and variations on those listed.

Complications in Temporal Planning: Required Concurrency

Required Concurrency – a property of the temporal planning problem, when two actions ***must*** temporally overlap in any working plan.

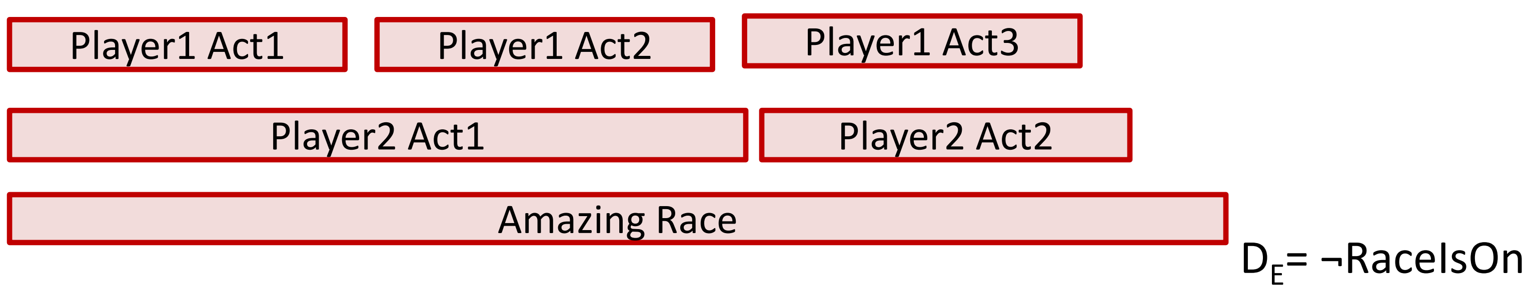
Therefore: Conditions/Effects must be considered at the same time as Duration.

Case 1. Action[s] Must Contain Another:



Case 2. "Deadlines" force Actions to co-occur:

Initial State:
RaceIsOn



State Space of Crikey 3

Classical Planner State = Set of Facts

Crikey3 State = $\langle F, E, T \rangle$

- F – Set of Facts
- E – Set of Start Events in the form $\langle StartAct, i, min, max \rangle$
  - the action that has started
  - index indicating the ordering of events, and
  - the duration of the original durative action.
- T – Set of Temporal Constraints (A Simple Temporal Network)

A Coles, M Fox, D Long, A Smith. Planning with Problems Requiring Temporal Coordination.

Recall: Enforced Hill-Climbing Search

Crikey 3 uses the same basic Enforced Hill-Climbing algorithm,
but with a more complex "successor" function than what we've seen so far.

Basic Enforced Hill-Climbing Algorithm

```
Start with the initial state.
If the state is not the goal:
1.  Identify applicable actions.
2.  Obtain heuristic estimate of the value of
    the next state for each action considered.
3.  Select action that transitions to a state with
    better heuristic value than the current state.
4.  Move to the better state.
5.  Append action to plan head and repeat.
(Never backtrack over any choice.)
```

Formally, we call this a "successor" function.

Crikey 3's Successor Function
Big Ideas

Input: Current State, S = $\langle F, E, T \rangle$
Output: Set of Successor States, S' = $\langle F', E', T' \rangle$

Recall: Crikey splits a durative action into two "snap" [instantaneous] actions: a start action and an end action.

The successor states can be found by applying all applicable start actions and end actions to the current state. (As in the classical case, this involves checking whether the preconditions of the snap action exist in F, and then applying its effects to create the successor F', but there is also some bookkeeping for E and T)

- Applying the start action is trivial.
- Applying an end action is more complicated. We must make sure the corresponding start action has already been executed, the durative action from which the end action was created has an overall condition that is consistent with all other actions being executed, and the temporal constraints are consistent.

Crikey 3's Successor Function

Input: Current State, S = $\langle F, E, T \rangle$

Output: Set of Successor States, S' = $\langle F', E', T' \rangle$

- For each start action that could be applied to S, create S' s.t.
  - F' = add/delete effects of start action from F.
  - E' = E ∪ $\langle StartAct, i, min, max \rangle$.
- For each end action that could be applied to S
  - For each start action event, e ∈ E, that the end action closes, create S' s.t.
    - F' = add/delete effects of end action from F.
    - E' = E \ e
    - T' = T ∪ (e.min ≤ time(EndAct) – time(e.i) ≤ e.max)
  - Include S' in the successor states if:
    - the overall condition of action is consistent with the started actions in E,
    - T' is temporally consistent

Temporal Relaxed Planning Graph (TRPG) Big Ideas

Input: Current State, S = $\langle F, E, T \rangle$

Output: R = a relaxed planning graph

In the Classical Plan Graph:	fact and action layers are indexed by integers.
In the TRPG:	layers are indexed by “real” time, starting with the current state S at t=0.

We still build the plan graph in a “forward” in time, but how do we know **when** we should add a new pair of fact and action layers?

- Look at the lower-bound times of all started actions. Add a layer when the earliest action could end.
- If the earliest end time is 0, advance time by some small amount of time, ε, just to make sure layers don’t overlap.

Temporal Relaxed Planning Graph (TRPG)

Note: We will keep track of:

- A fact "layer", indexed by continuous time, start with facts F.
- current time index, starts at 0
- The earliest time an action can end for each start action event in E.

Build the TRPG

Input: Current State, S = $\langle F, E, T \rangle$

Output: R = a relaxed planning graph

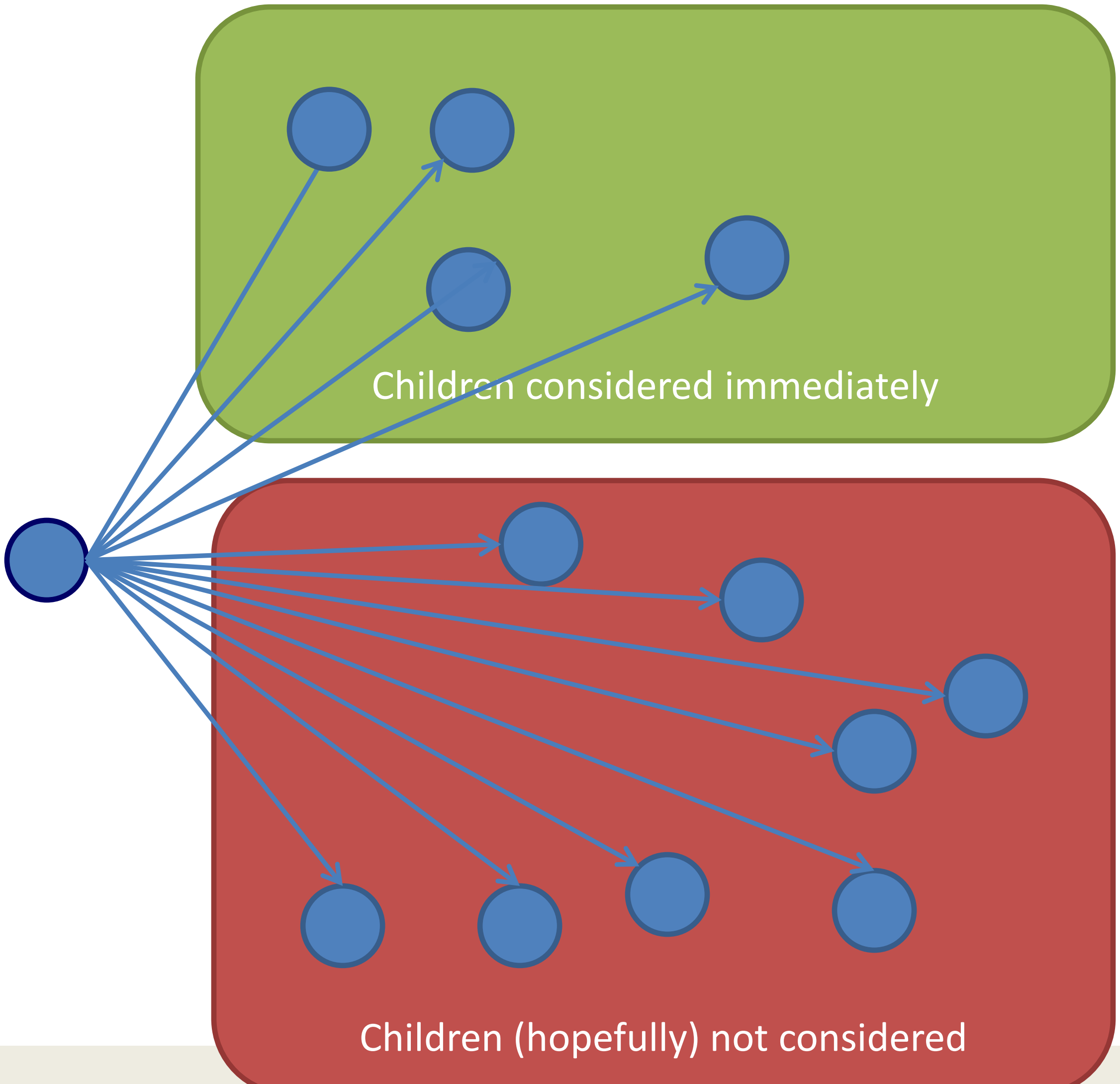
- For each possible action.
  - If the action has started in E, set its earliest end to 0.
  - Else set it to infinity.
- While t < inf
  - Create a new fact layer indexed at t + ε, with all the facts of the previous layer.
  - Add effects of all end actions whose preconditions are met to the fact layer.
  - Add effects of all start actions whose preconditions are met to the fact layer, and update the earliest end time of any new actions.
  - If the fact layer has more facts, increment by t by ε
    - Otherwise, if all start actions have ended by now, return all fact layers.
    - If there are still start actions running, t = earliest of the end times.

Questions?

Appendix

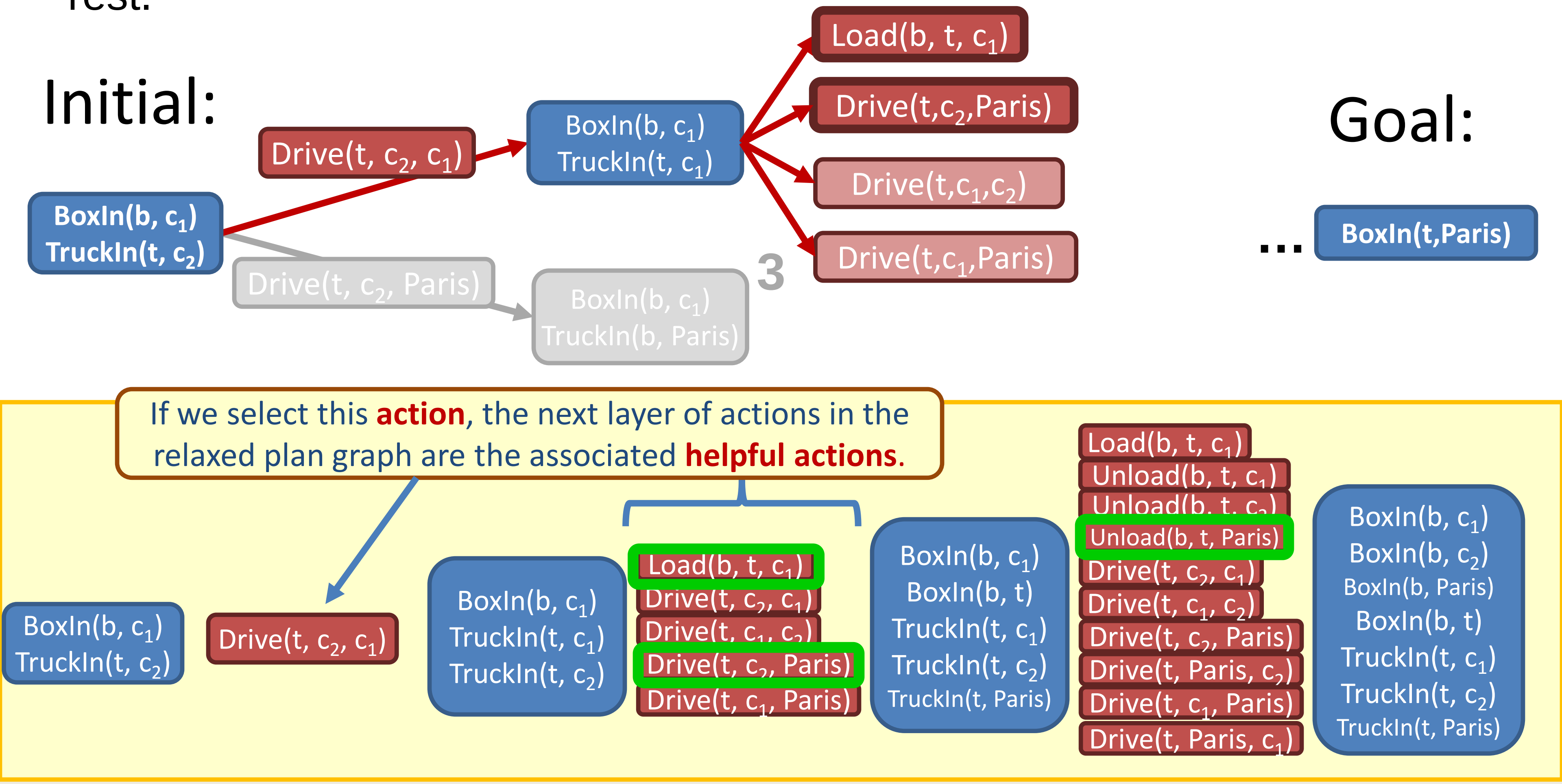
Fast Forward Heuristic – Details
Limiting Children Evaluation

- Nodes typically have many children
- h(s) might be slow to compute
- h(s) may suggest "helpful" children to try first



Fast Forward Heuristic – Details
Helpful Actions

Problem: Evaluating the heuristic for all possible actions takes time!
Solution: Start with actions on the helpful actions list, before evaluating the rest.



Building the Helpful Action List

Another Perspective....

Action layer 1

Possible Action	State	h(s)	Relaxed Plan
A_1	s_1	$h(s_1) = 4$	$\{A'_1\}, \{A'_2, A'_3\}, \{A'_4\}$
A_2	s_2	$\boxed{h(s_2) = 3}$	$\boxed{\{A'_5, A'_6\}}, \{A'_7\}$
A_3	s_3	$h(s_3) = 4$	$\{A'_8, A'_9\}, \{A'_{10}\}, \{A'_{11}\}$

A_2 Minimizes h(s)

Helpful Actions List

Action layer 2

Possible Action	State	h(s)	Relaxed Plan
A'_5	s'_1	$\boxed{h(s'_1) = 2}$	$\boxed{\{A''_1, A''_2\}}$
A'_6	s'_2	$h(s'_2) = 3$	$\{A''_3\}, \{A''_4\}, \{A''_5\}$

A'_5 Minimizes h(s)

Helpful Actions List

Fast Forward Heuristic – Details
How to assert a negative goal?

- What if goal state requires no truck in Paris?
  – Generate negative versions of each atom

Action	Preconditions	Add Effect	Delete Effect
Drive(t, c, c')	TruckIn(t, c)	TruckIn(t, c'), NoTruckIn(t, c)	TruckIn(t, c), NoTruckIn(t, c')
Drive'(t, c, c')	TruckIn(t, c)	TruckIn(t, c'), NoTruckIn(t, c)	--

State S'_0	
Atom	**Value**
TruckIn(t, c_1)	False
TruckIn(t, c_2)	True
TruckIn(t, Paris)	False
NoTruckIn(t, c_1)	True
NoTruckIn(t, c_2)	False
NoTruckIn(t, Paris)	True

Relaxed Drive'(t, c_2, Paris) →

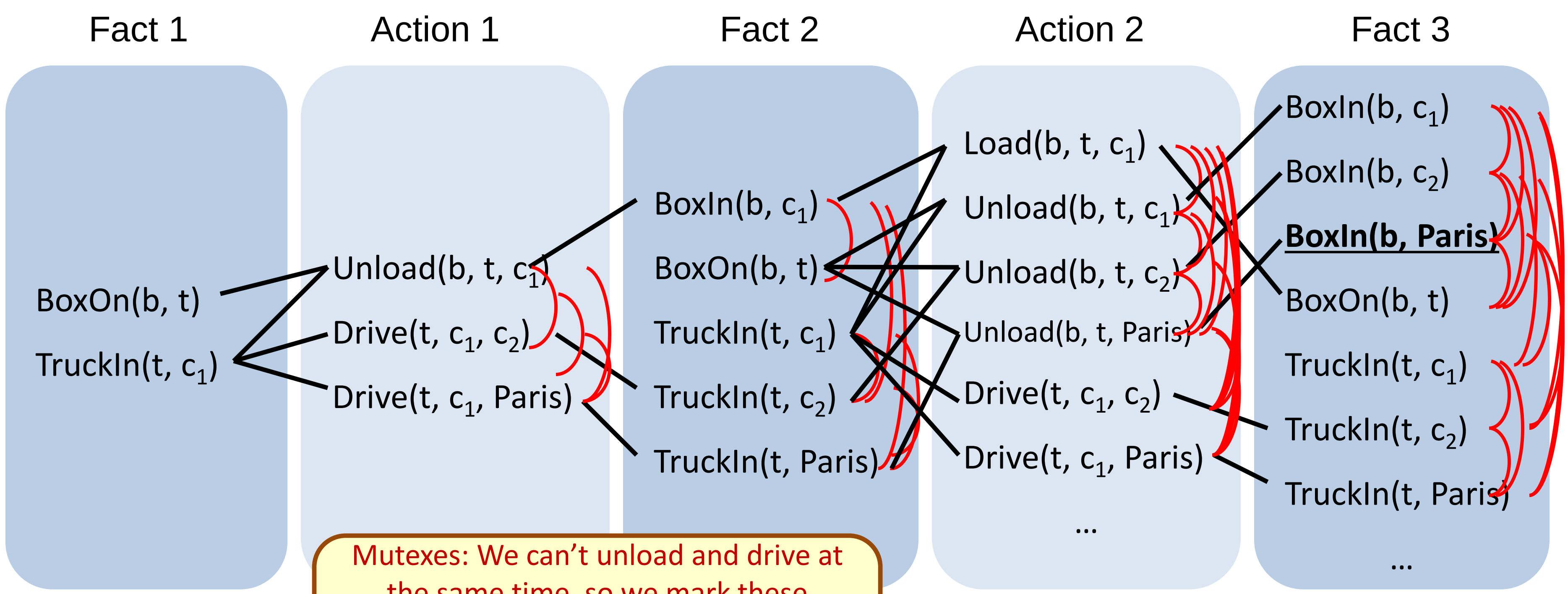
State S'_1	
Atom	**Value**
TruckIn(t, c_1)	False
TruckIn(t, c_2)	True
TruckIn(t, Paris)	True
NoTruckIn(t, c_1)	True
NoTruckIn(t, c_2)	True
NoTruckIn(t, Paris)	True

Planning Graph Intution

- A plan graph is a compact way of representing the state-space.
- It collapses:
  - all the states 1 operation (action) away from the initial state into Fact Layer 2.
  - all the states 2 operations away from the initial state into Fact Layer 3.
  - etc…

Plan Extraction

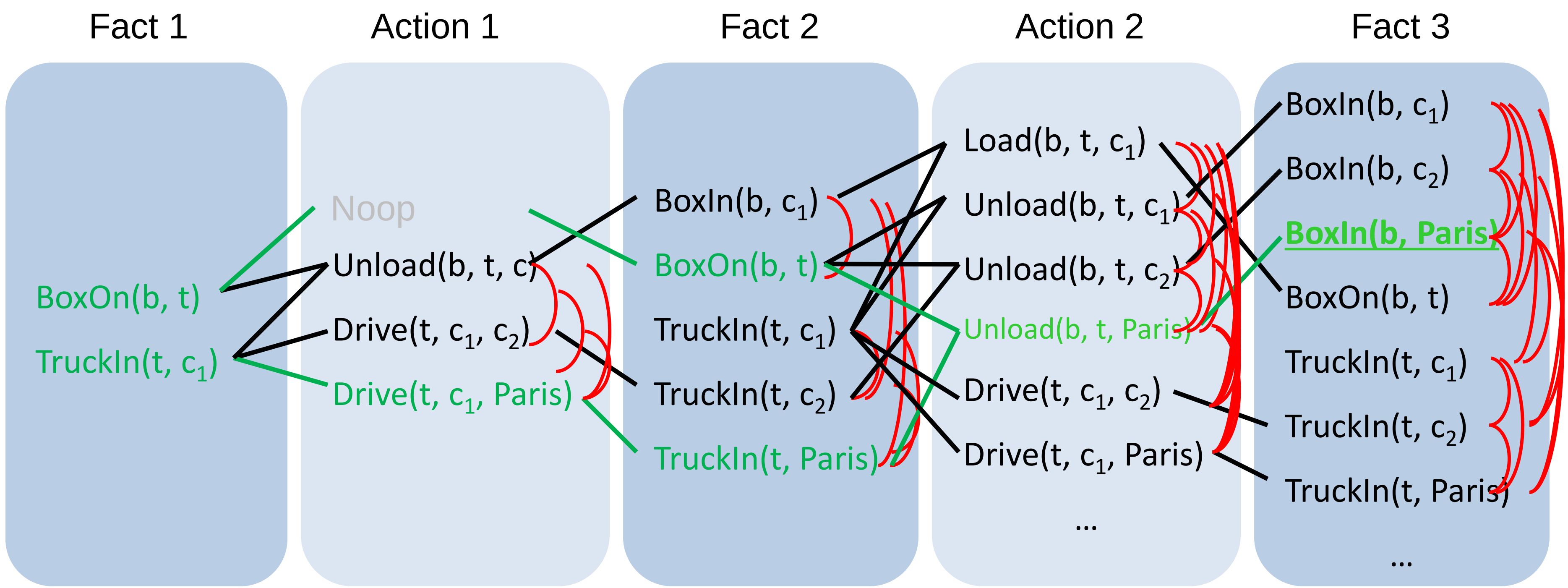
- Step 5: Adding "Mutexes" – We add some realism back by marking facts and actions that could not possibly occur at the same time (**mut**ual **ex**clusions)
  - There are rules for how to compute mutexes, but they are not important for this lecture.



Mutexes: We can't unload and drive at the same time, so we mark these actions as mutex. If some actions can't happen at the same time, some effects also can't appear at the same time.

Plan Extraction

- Step 6: Search – Find a path from each goal to the initial state that is free of mutexes in each layer
  - i.e. two facts in the same "layer" can only be included in the plan if there is not a mutex between them. The same goes for actions.
  - Search can be done via DFS, by following back-pointers.



Relaxed Planning Graph

Problem: Mutexes make plan extraction & generating action layers hard
What if…

- Remove the mutexes!
- Settle for suboptimal plan, instead of the optimal (shortest one).