Planning & Knowledge

DV2557

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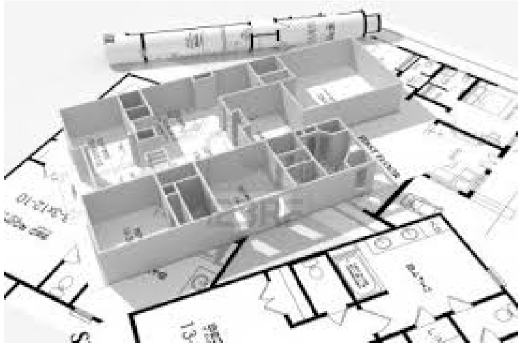


KNOWLEDGE REPRESENTATION

Toy vs. Real World problems

- So far the logic problems we have faced are ”toy” problems.
- It is often quite easy to find a consistent vocabulary and representation for such limited worlds.
- When dealing with real world problems, some more issues arise:
    - Deal with actions
    - How to represent time
    - Physical Objects vs. Mental Objects
    - Beliefs
    - …

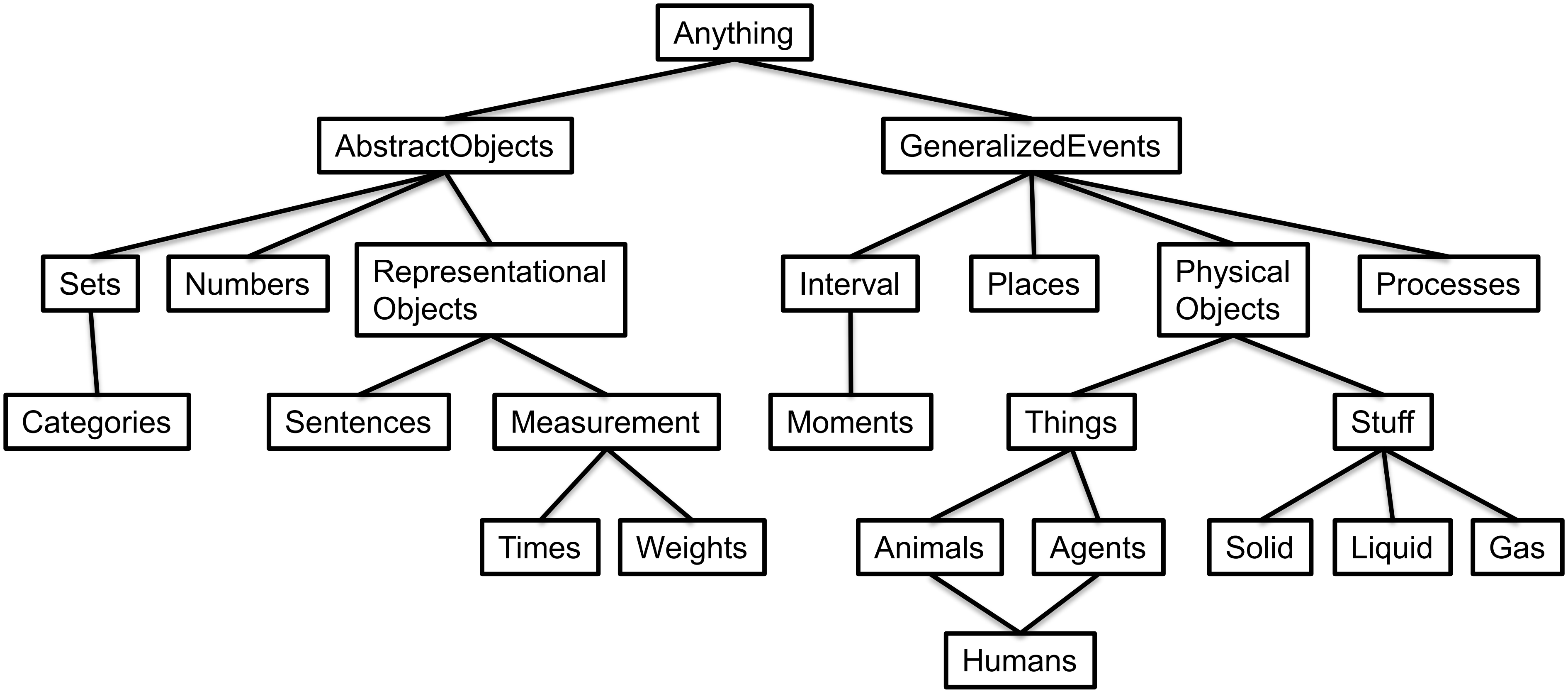
Fortunately…

- … a lot of engineers and philosophers have spent lot of time thinking about this.
- The field is called *ontological engineering*.
- It describes formal, generalized ways of describing the world around us, on different levels of detail.
- It involves describing abstract concepts such as actions, time, physical objects and beliefs.

Upper Ontology

- The *upper ontology* is the general framework for describing a world.
- Very abstract concepts are at the top, and the lower you get in the graph the more specialized the concepts become.
- An ontology for a problem can be seen as an instance of the upper ontology.

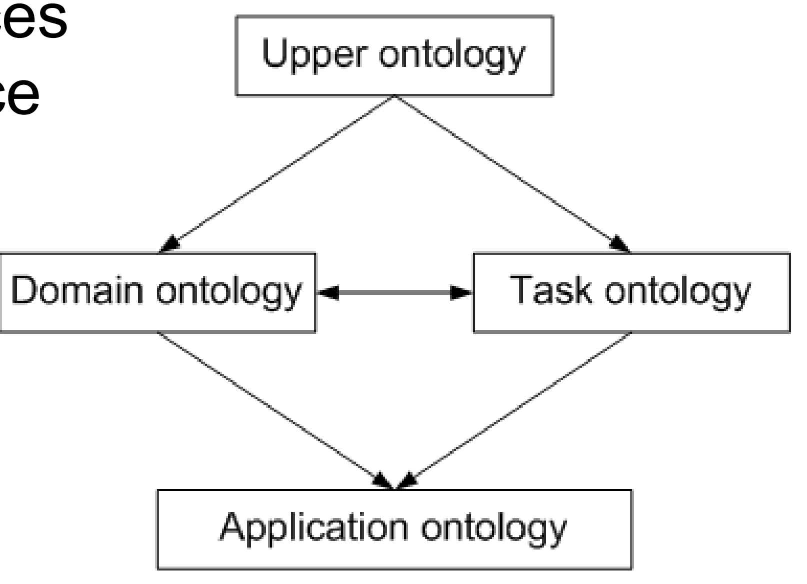
Upper Ontology



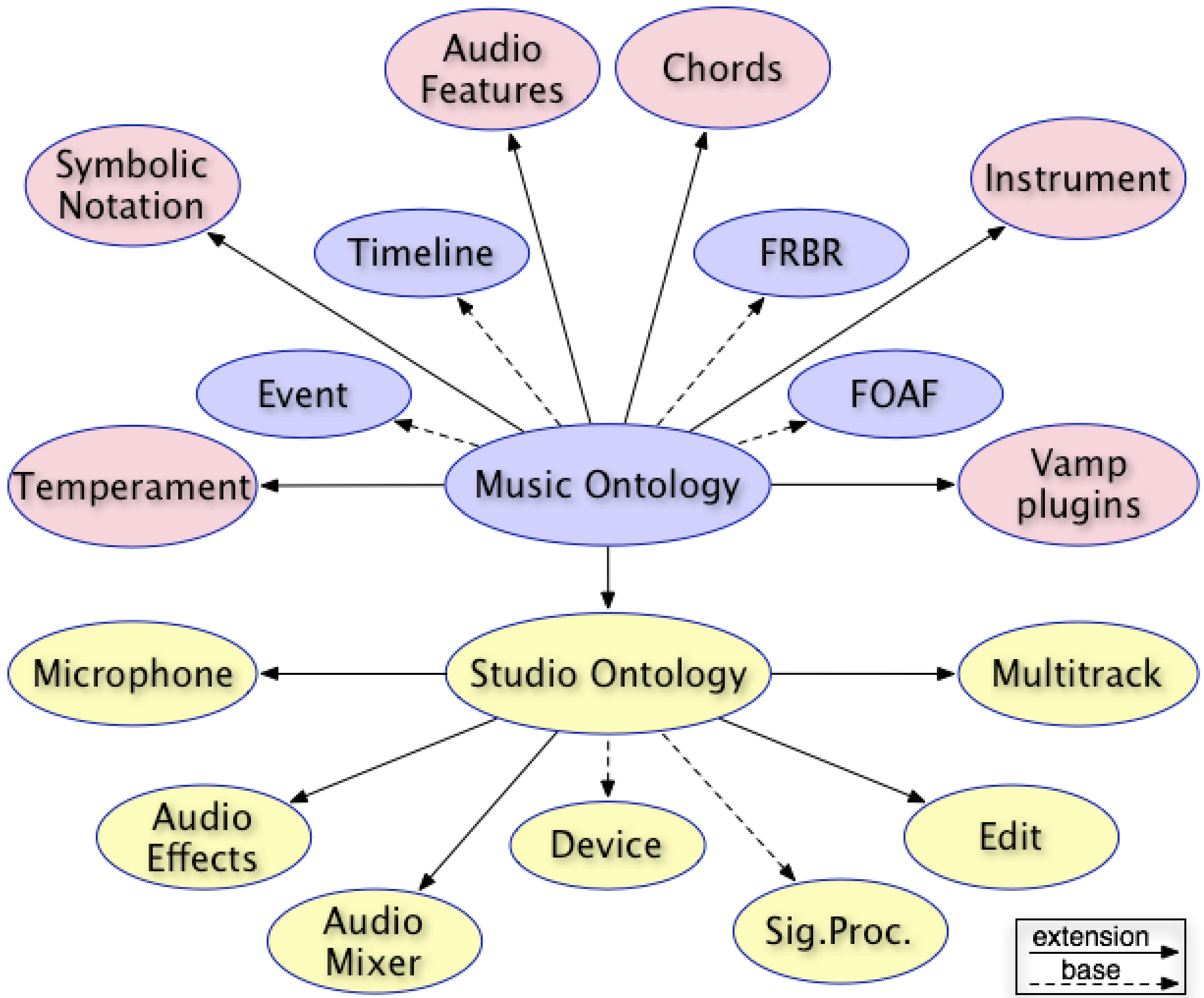
- Each concepts is a more specialized version of the upper one.
- This is one version of upper ontology, there are others…

Upper Ontology

- The two major differences between an upper ontology and a special-purpose ontology are:
  1. A general-purpose ontology shall be applicable in (almost) any special-purpose ontology.
  2. Different areas of knowledge must be unified. Sentences describing time and space must handle seconds, years, meters, mm, …



Application Ontology



Categories and Objects

- The basketball object b_1 is a member of the category *Basketballs*, formally written as:
  - $b_1 \in Basketballs$ ”b_1 is an element of…”
- *Basketballs* are in turn a subcategory of *Balls*:
  - Basketballs $\subset$ Balls ”… is a subset of...”
- This is important, since we can infer that every basketball object is round if *Balls* are round.
- We must however be able to handle exceptions:
  - Most, but not all, tomatoes are red…

Categories and Properties

- All categories can have properties, which are <u>inherited</u> by members and subcategories.
  - $x \in Balls \Rightarrow Round(x)$
  - $x \in Basketballs \Rightarrow Orange(x)$
  - … If:
  - $b_1 \in Basketballs$
  - … then we can infer that:
  - $Round(b_1) \wedge Orange(b_1)$
  - … it can also be used to recognize objects:
  - $Round(x) \wedge Orange(x) \wedge x \in Balls \Rightarrow x \in Basketballs$

Disjoint Categories

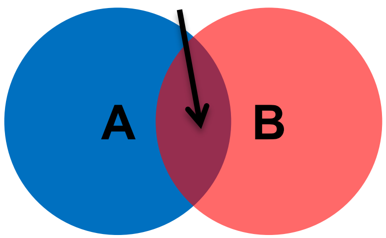
- Sometimes we want to state relations between categories at the same level.
- Example:
  - *Males* ∈ *Humans*
  - *Females* ∈ *Humans*
  - … both are subcategories of the same category, but they have no members in common. We call these *disjoint* categories.
  - *Disjoint*({*Males, Females*})

Disjoint Categories

- Disjoint does not explicitly state that a human must be female if it is not male.
- A category where an object must belong to one of the categories are called an *exhaustive decomposition*:
    - *ExhaustiveDecomposition*({*Americans*, *Canadians*, *Mexicans*}, *NorthAmericans*)
- An *exhaustive decomposition* must not be *disjoint*. Some people have dual citizenship.
- A *disjoint exhaustive decomposition*, like males and females, is called a *partition*:
    - *Partition*({*Males*, *Females*}, *Humans*)

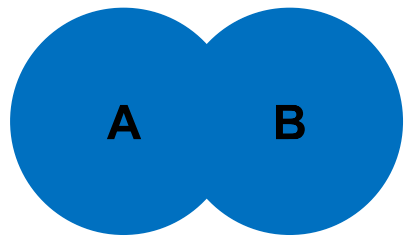
Notes on Set Theory

Intersection



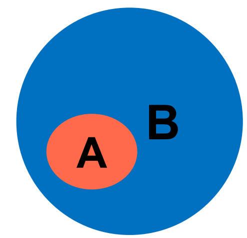
$A \cap B$

Union

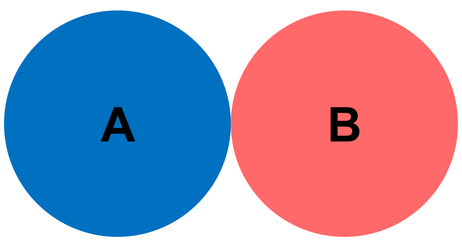


$A \cup B$

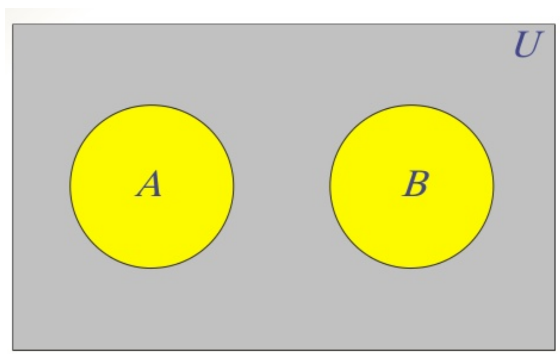
Subset



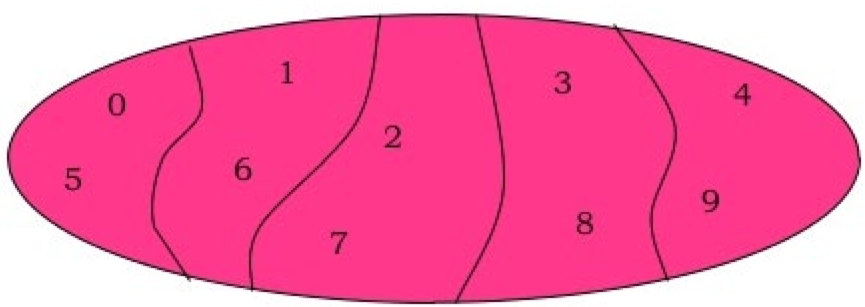
$A \subseteq B$



Intersection(A,B) = { }



Disjoint



Partition

Physical Composition

- We also have to deal with objects being part of other objects:
  - … such as Sweden being part of Europe:
  - *PartOf*(*Sweden*, *Europe*)
  - … Sweden is also part of Scandinavia and Scandinavia is part of Europe. This is called a transitive relationship:
  - *PartOf*(*Sweden*, *Scandinavia*) ∧ *PartOf*(*Scandinavia*, *Europe*) ⇒ *PartOf*(*Sweden*, *Europe*)
- An object consisting of parts is called a *composite object*.

Objects and Stuff

- Most objects are either primitive- or composite objects (objects made up of primitive objects).
- Sometimes we run into a problem where we cannot divide something into distinct objects (*individualization*).
- We call this *stuff*.
- A very good example of *stuff* is butter.

Objects and Stuff

- The distinction is between:
  - Count nouns: holes, theorems, apples
  - Mass nouns: butter, water, energy
- We can divide an apple to get two halves of apple.
- If we divide butter we still have butter.
  - Unless we make a category TwoKilosOfButter, which we can divide into two KiloOfButter. But then it's not stuff any more.

Intrinsic and Extrinsic properties

- We make a distinction between intrinsic and extrinsic properties.
- IP belong to the substance rather than the object:
    - Density, boiling point, flavor, color, …
- EP belong to objects:
    - Weight, length, shape, …
- EP changes if we divide objects, IP does not.
- Things with only IP are substances and belong to the *Stuff* category.
- Things with at least one EP are objects and belong to the *Thing* category.

Measurements

- Quantitative measurements are usually expressed with *unit functions*:
  - *Length*(*a*) = *Centimeters*(3.81)
  - *Length*(*a*) = *Inches*(1.5) = *Centimeters*(3.81)
- Conversions are written as:
  - *Centimeters*(2.54 * *d*) = *Inches*(*d*)
- Measures can describe objects:
  - *Diameter*($basketball_1$) = *Inches*(9.5)
  - $d \in days \Rightarrow Duration(d) = Hours(24)$
  - *Price*($basketball_1$) = $(19)

Actions and Situations

- In many problems the world is not static. Actions happen that change the world, like moving the player in the Wumpus world.
- A world state is called a situation.
    - Initial state is called S_0
    - Executing action a in S_0 is expressed as:
      Result(a, S_0)
    - Returns a result that is a new situation, S_1.

Actions and Situations

- Actions are logical terms that can have parameters:
  - *Forward*, *Turn*(*Right*)
- *Fluents* are functions and predicates that can vary between situations.
  - Location of the player:
    $At([1,1], S_0)$
  - Not holding the gold at the start of a game:
    $\neg Holding(g, S_0)$

Actions and Situations

- Deciding the resulting situation after a sequence of actions is called the *projection* task.

- Finding a sequence of actions that leads to a situation is called the *planning* task.
    - … which we will soon dig further into.

Describing Actions

- To define an action we need:
  - The action to execute
  - Preconditions (called *possibility axiom*)
    $Preconditions \Rightarrow Poss(a,s)$
  - The result (called *effect axiom*)
    $Poss(a,s) \Rightarrow$ changes resulting from a
  - $Poss(a,s)$ means it is possible to do action a in situation s.
- Examples:
  - $At(player,x,s) \wedge Adjacent(x,x1) \Rightarrow Poss(Go(x,x1),s)$
  - $Gold(g) \wedge At(player,x,s) \wedge At(g,x,s) \Rightarrow Poss(Grab(g),s)$
  - … results in:
  - $Poss(Go(x,x1),s) \Rightarrow At(player,x1, Result(Go(x,y),s))$
  - $Poss(Grab(g),s) \Rightarrow Holding(g, Result(Grab(g),s))$

Problem

- The result:
  - $Poss(Go(x,y),s) \Rightarrow At(player,x1, Result(Go(x,y),s))$
- … states that the fluent position is changed so the x coordinate of the player is updated.
- … and that the new situation is the result from the *Go(x,y)* action in situation *s*.
- It says what has changed, but <u>not</u> what stays the same (y coordinate) in the fluent!
  - Frame problem

Frame problem

- One solution to this is to write rules for how things change (and not change).
- This will however lead to a large number of rules.
- The easiest, and most common way, is to assume that if something is not mentioned in the result it stays that same.

Generalized Events

- A *generalized event* occurs over some time, and can include subevents:
  - *SubEvent*(*BattleOfBritain*, *WorldWarII*)
  - *SubEvent*(*WorldWarII*, *TwentiethCentury*)
- We can also state the length of an event:
  - *Duration*(*Period*(*WorldWarII*)) > *Years*(*5*)
  - … *Period(e)* is the smallest interval enclosing the event *e*.

Generalized Events

- We can also use *In* to state where an event took place:
  - *In*(*Sydney*, *Australia*)
- And *Location(e)* for the smallest place enclosing the event *e*:
  - $\exists w\ w \in \mathit{CivilWars} \land \mathit{SubEvent}(w, \mathit{1640s}) \land \mathit{In}(\mathit{Location}(w), \mathit{England})$
  - … a civil war occured in England in the 1640s.

Intervals

- An interval is the time between start and end of an event.
  - $Interval(i) \Rightarrow Duration(i) = (Time(End(i)) - Time(Start(i)))$
  - $Duration(Minute) = Seconds(60)$
- We can also describe relative times:
  - $Before(i,j) \Leftrightarrow Time(End(i)) < Time(Start(j))$
  - $After(j,i) \Leftrightarrow Before(i,j)$
  - $During(i,j) \Leftrightarrow Time(Start(j)) \leq Time(Start(i)) \wedge Time(End(i)) \leq Time(End(j))$
  - $Overlap(i,j) \Leftrightarrow \exists k\ During(k,i) \wedge During(k,j)$

Now we know how to describe real world problems, let's move into…

PLANNING

Planning

- Planning is the process of finding a sequence of actions to go from a situation s_1 to a new situation s_2.
- In theory, we can search through all possible combinations of actions and find a solution.
- In practice, most real world planning problems are too large…

Planning

- An efficient planner needs to
  - Be able to work forwards or backwards depending on the problem.
  - Have an efficient heuristic to limit the search space.
  - Be able to do *problem decomposition* – divide a problem into subproblems that can be solved in parallel
  - Be able to compose subplans from decomposition to a full plan.

Language

- A planner for full FOL language will be extremely complex.
- Therefore we need a reduced language that:
  - can describe a wide variety of problems.
  - allow the use of efficient planning algorithms.
- The most widespread language is STRIPS, and variations of it.

STRIPS

- States:
  - A state is represented by a conjunction of positive literals:
  - *Rich* ∧ *Famous* can describe a state.
  - … we can also use first-order literals:
  - $At(Plane_1, Melbourne) \wedge At(Plane_2, Sydney)$
  - … but not functions.
  - Closed-world assumption is used. Any conditions not mentioned are assumed to be *false*.

STRIPS

- Goals:
    - … a goal is a specified state, represented as a conjunction of positive ground literals:
    - *Rich* ∧ *Famous*
    - $At(Plane_1,Tahiti)$
    - … a state *s* satisfies a goal *g* if it contains all literals in *g* (and possible others):
    - *Rich* ∧ *Famous* ∧ *Miserable* satisfies the goal *Rich* ∧ *Famous*.

STRIPS

- Actions:
  - Actions are represented with preconditions and effects, for example:

    $$\begin{aligned}&\mathit{Action}(\mathit{Fly}(p,\mathit{from},\mathit{to}),\\ &\quad \text{PRECOND: } \mathit{At}(p,\mathit{from}) \wedge \mathit{Plane}(p) \wedge \\ &\qquad\qquad\quad \mathit{Airport}(\mathit{from}) \wedge \mathit{Airport}(\mathit{to})\\ &\quad \text{EFFECT: } \neg \mathit{At}(p,\mathit{from}) \wedge \mathit{At}(p,\mathit{to}))\end{aligned}$$

  - This is often called an *action schema*.
  - Effect is sometimes divided into *add list* (positive literals) and *delete list* (negative literals).

STRIPS

- An action is *applicable* in any state that satisfies the precondition.
- The state s_2 is a *result* from executing action *a* in state s_1.
  - = same as s_1, but:
  - All positive effects added. If already in s_1, they are ignored.
  - All negative effects removed. If not in s_1, they are ignored.
  - STRIPS assumption: Every literal not mentioned in effect remains unchanged - avoids the frame problem.
- A *solution* is an action sequence leading from start state to goal state.

Example problem: Change a flat tire

```
Init(At(Flat,Axle) ∧ At(Spare,Trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle))
Action(LeaveOvernight,
  PRECOND:
  EFFECT: ¬At(Spare,Ground) ∧ ¬At(Spare,Axle) ∧ ¬At(Spare,Trunk)
        ∧ ¬At(Flat,Ground) ∧ ¬Flat(Axle))
```

Forward State-Space Search

- Also called *progression planning*.

- Start at the initial state.
- See which actions are applicable.
- Each action generates a new state.
- See which actions are applicable in the new states.
- …

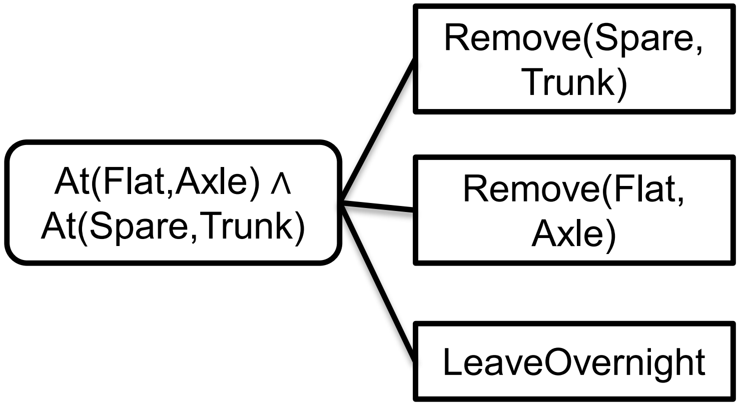
- Literals not mentioned are assumed to be *false*.

Forward State-Space Search

At(Flat,Axle) ∧
At(Spare,Trunk)

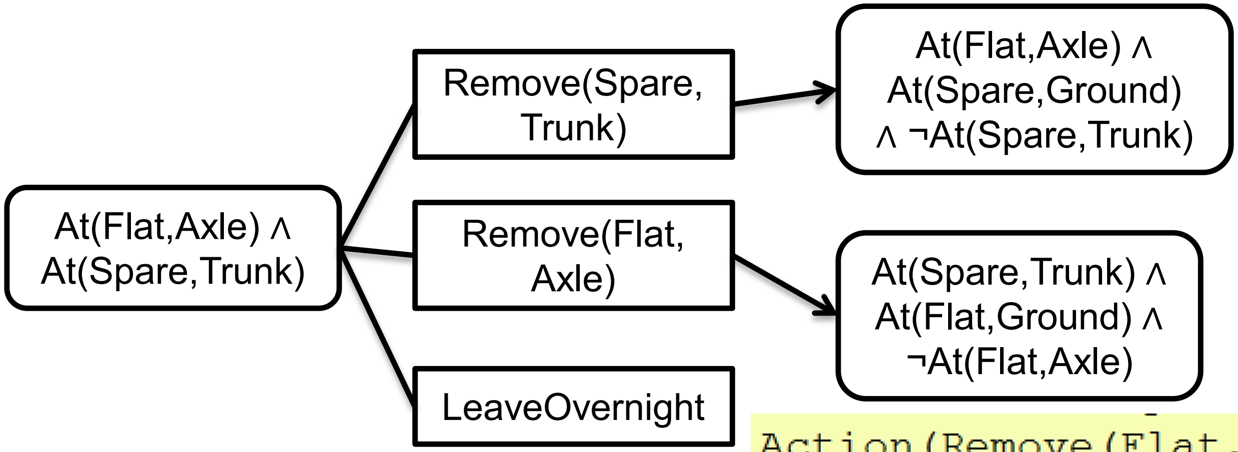
```
Init(At(Flat,Axle) ∧ At(Spare,Trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
Action(LeaveOvernight,
  PRECOND:
  EFFECT: ¬At(Spare,Ground) ∧ ¬At(Spare,Axle) ∧
¬At(Spare,Trunk)
          ∧ ¬At(Flat,Ground) ∧ ¬Flat(Axle))
```

Forward State-Space Search



Forward State-Space Search

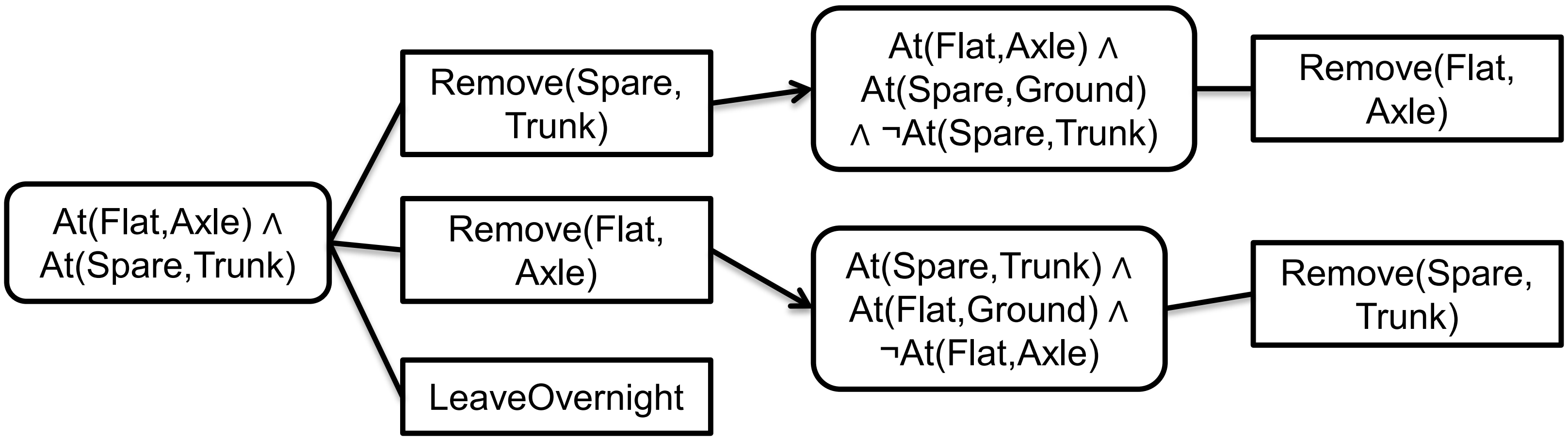
```
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
```



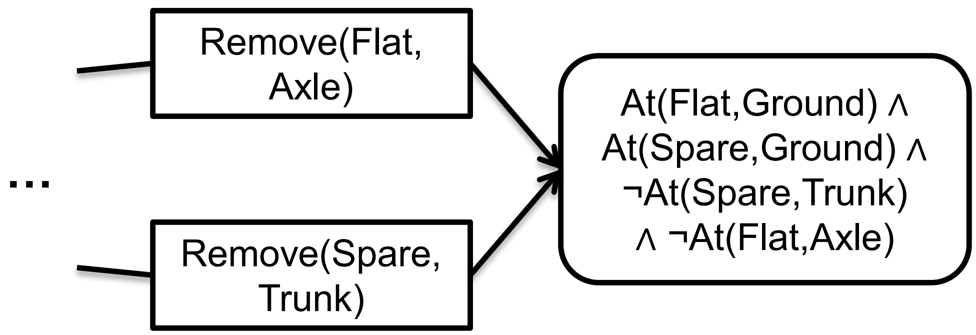

```
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
```

LeaveOvernight is a dead end, since we cannot do any actions after it. All literals are false.

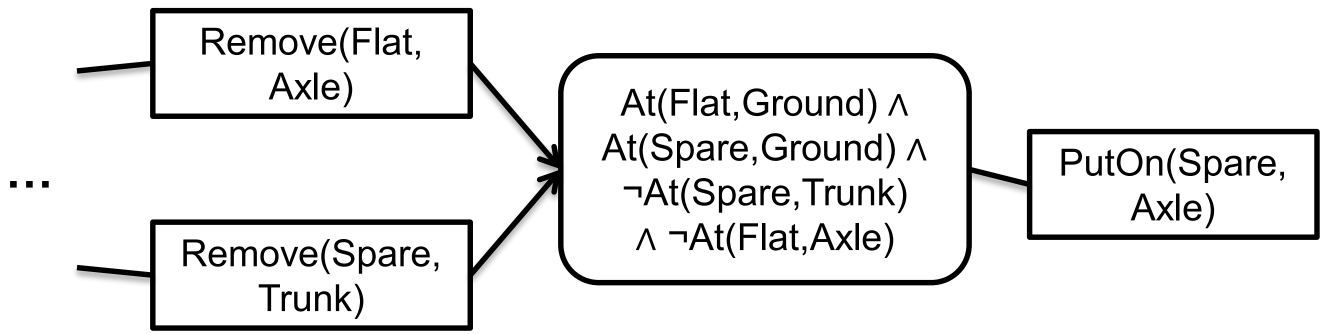
Forward State-Space Search



Forward State-Space Search



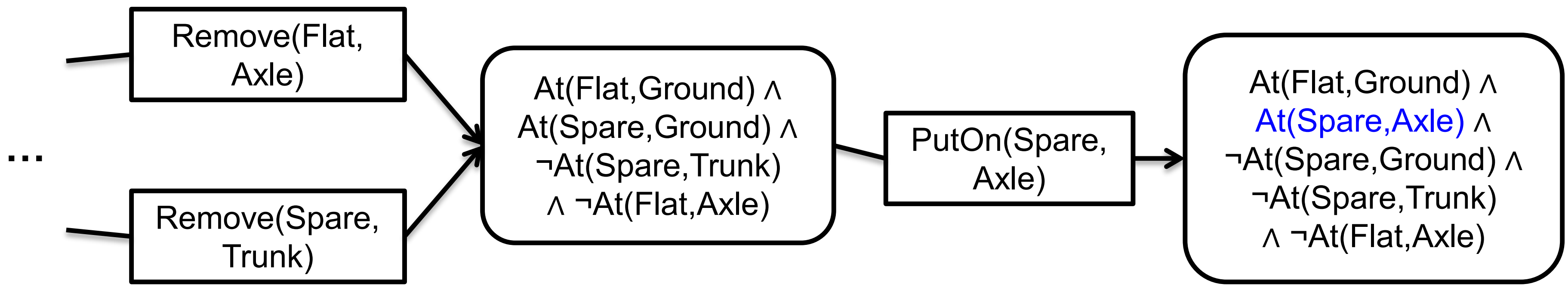
Forward State-Space Search




```
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
```

Forward State-Space Search

`Goal(At(Spare,Axle))`



Satisfies goal
At(Spare,Axle).

Done!

Backward State-Space Search

- Also called *regression planning*.

- Start at the goal state.
- See which actions that lead to the preconditions of the goal state.
- Generate new states from the actions.
- …

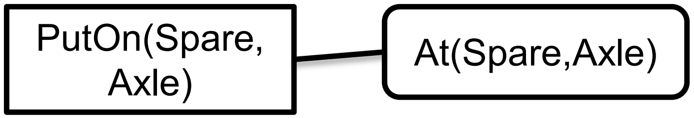
- Literals not mentioned are assumed to be *false*.

Backward State-Space Search

```
Init(At(Flat,Axle) ∧ At(Spare,Trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
Action(LeaveOvernight,
  PRECOND:
  EFFECT: ¬At(Spare,Ground) ∧ ¬At(Spare,Axle) ∧
¬At(Spare,Trunk)
          ∧ ¬At(Flat,Ground) ∧ ¬Flat(Axle))
```

At(Spare,Axle)

Backward State-Space Search

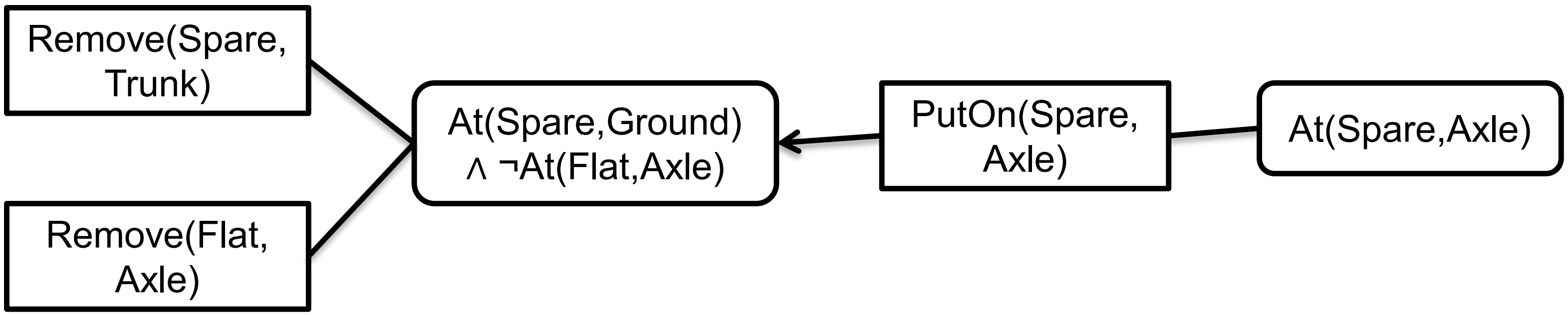



```
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
```

Backward State-Space Search

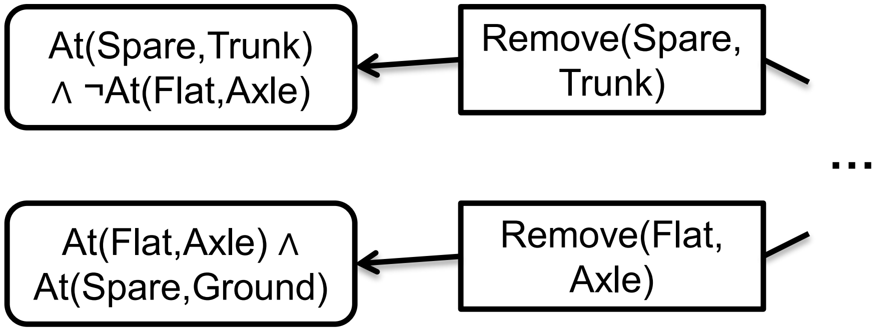

```
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
```

Backward State-Space Search



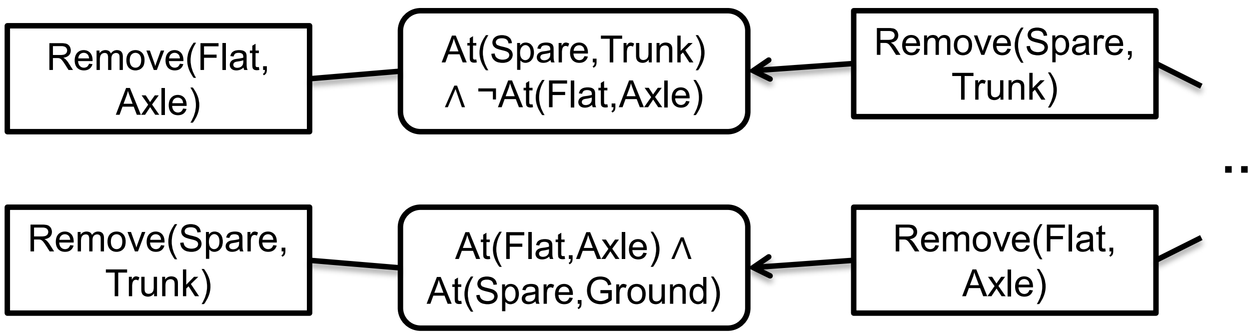

```
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
```

Backward State-Space Search




```
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
```

Backward State-Space Search




```
Action(Remove(Spare,Trunk),
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  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
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  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
```
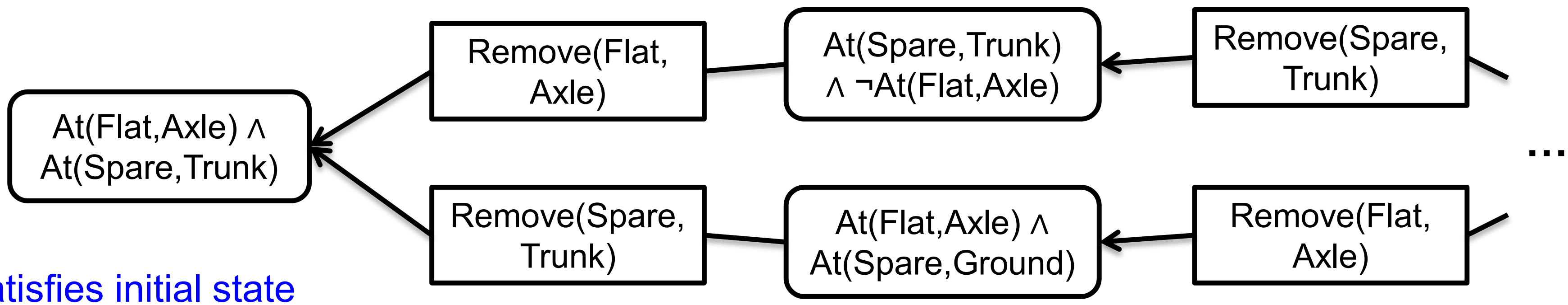

Backward State-Space Search



Satisfies initial state
At(Flat,Axle) ∧ At(Spare,Trunk).

Done!

Heuristics

- The change tire problem is very simple compared to most real world problems.
- For more complex problems, a heuristic is needed to guide the search.
- One such heuristic is the *relaxed problem* approach.
- It means that we should select the state with least number of positive literals.
- Because it is assumed that the more positive literals a state has, the farther it is from the goal.

Partial-Order Planning

- Forward and Backward State-Space Search are *totally ordered* plan searchers.
- It means that they work in a linear fashion, and cannot take advantage of problem decomposition.
- Partial-Order Planning can do this, by working independently on subgoals to create subplans which can be combined to a full plan.

Partial-Order Planning

- POP requires some more information about a problem.
- Ordering constraints:
  - $A \prec B$ Action A must be executed before B
  - $B \succ A$ Action B must be executed after A
- Causal links:
  - $A \xrightarrow{p} B$ A *achieves* p for B, meaning that A satisfies the precondition p for B. This also means that we are not allowed to add a new action between A and B that is in conflict with the link, i.e. has the effect ¬p.

Partial-Order Planning

- Open preconditions:
  - A precondition is open if it is not solved by some action in the plan. POP works by reducing the number of open preconditions, until all are solved.
- Consistent plan:
  - The goal of the planner is to create a *consistent plan*, which means a plan with no causal link conflicts, no cycles in ordering constraints and no open preconditions in the set.
- Start and Finish state:
  - The planner starts with a *Start* state with the initial state as effect, and a *Finish* state with the goal as precondition.

Let's go back to our example

```
Init(At(Flat,Axle) ∧ At(Spare,Trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
Action(LeaveOvernight,
  PRECOND:
  EFFECT: ¬At(Spare,Ground) ∧ ¬At(Spare,Axle) ∧ ¬At(Spare,Trunk)
          ∧ ¬At(Flat,Ground) ∧ ¬Flat(Axle))
```

Partial-Order Planning

Partial-Order Planning

Pick one open precondition
to solve.

At(Spare,Trunk)

Start

At(Flat,Axle)

At(Spare,Axle) Finish

Partial-Order Planning

At(Spare,Trunk) Remove(Spare,Trunk)

Remove(Spare,Trunk) has the open precondition as its pre-condition.

Start

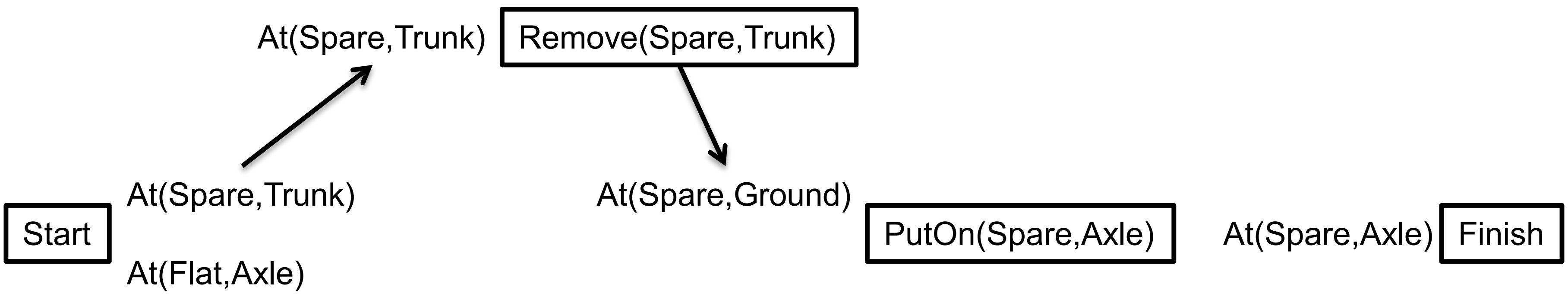
At(Spare,Trunk)

At(Flat,Axle)

At(Spare,Axle) Finish

```
Action(Remove(Spare,Trunk),
  PRECOND: At(Spare,Trunk)
  EFFECT: ¬At(Spare,Trunk) ∧ At(Spare,Ground))
```

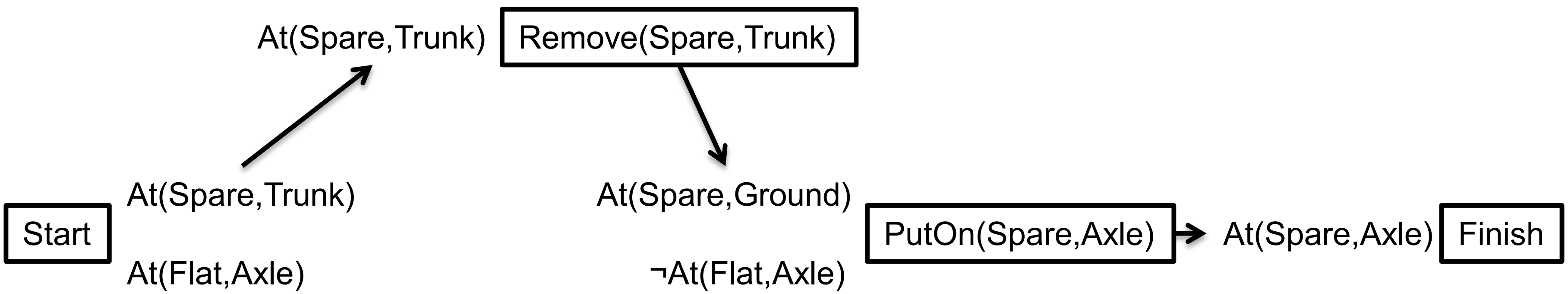
Partial-Order Planning



Remove(Spare,Trunk) has the effect At(Spare,Ground). The only matching action is PutOn(Spare, Axle).

```
Action(PutOn(Spare,Axle),
  PRECOND: At(Spare,Ground) ∧ ¬At(Flat,Axle)
  EFFECT: ¬At(Spare,Ground) ∧ At(Spare,Axle)
```

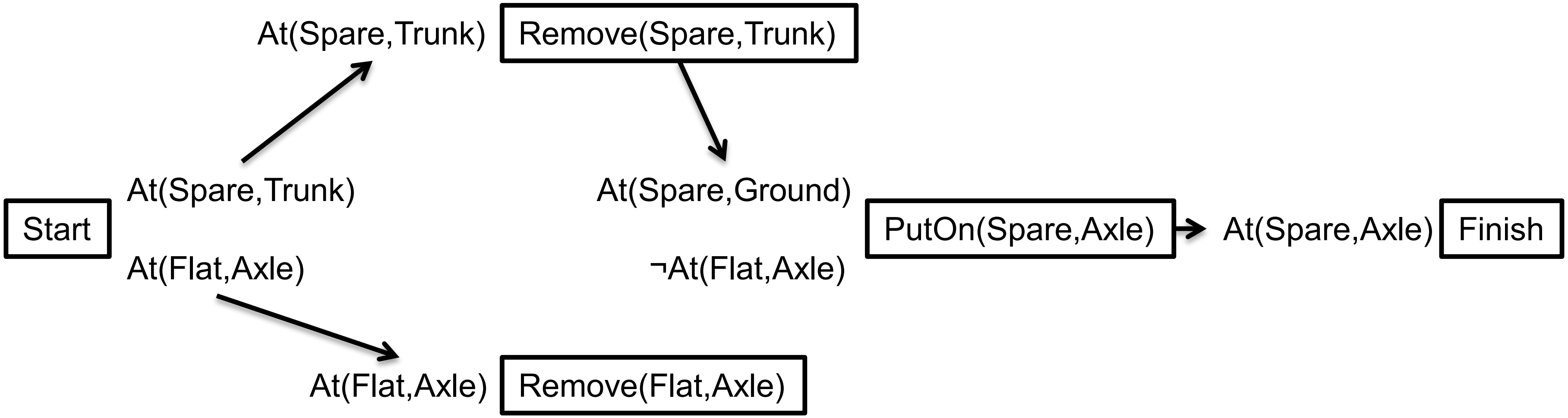
Partial-Order Planning



We have two more open preconditions to deal with.

PutOn(Spare,Axle) also matches the precondition at Finish.

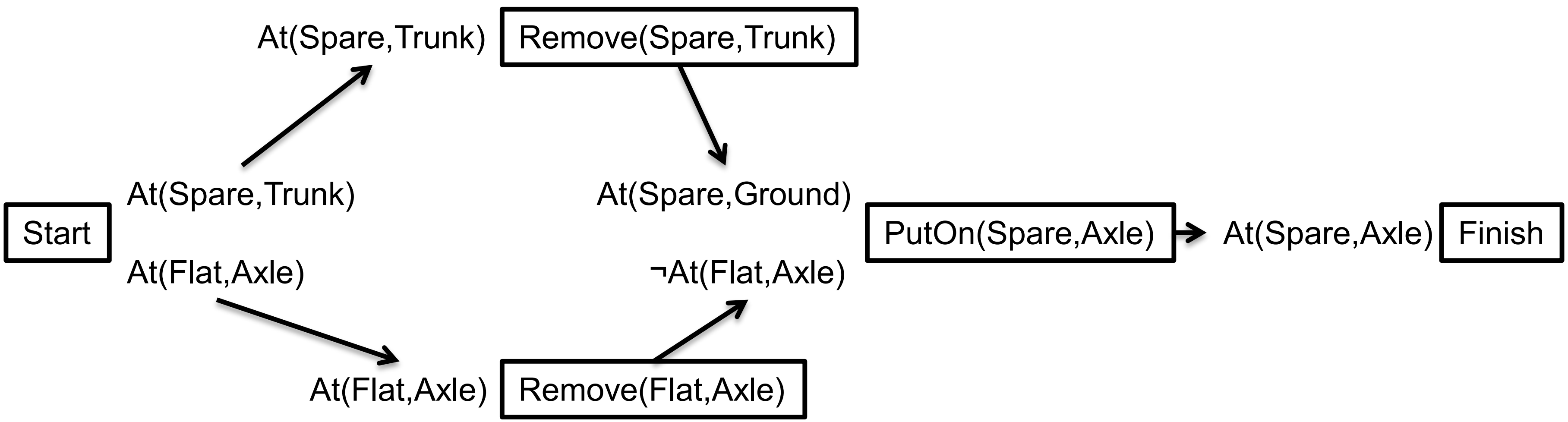
Partial-Order Planning



Remove(Flat,Axle) solves the open precondition at start.

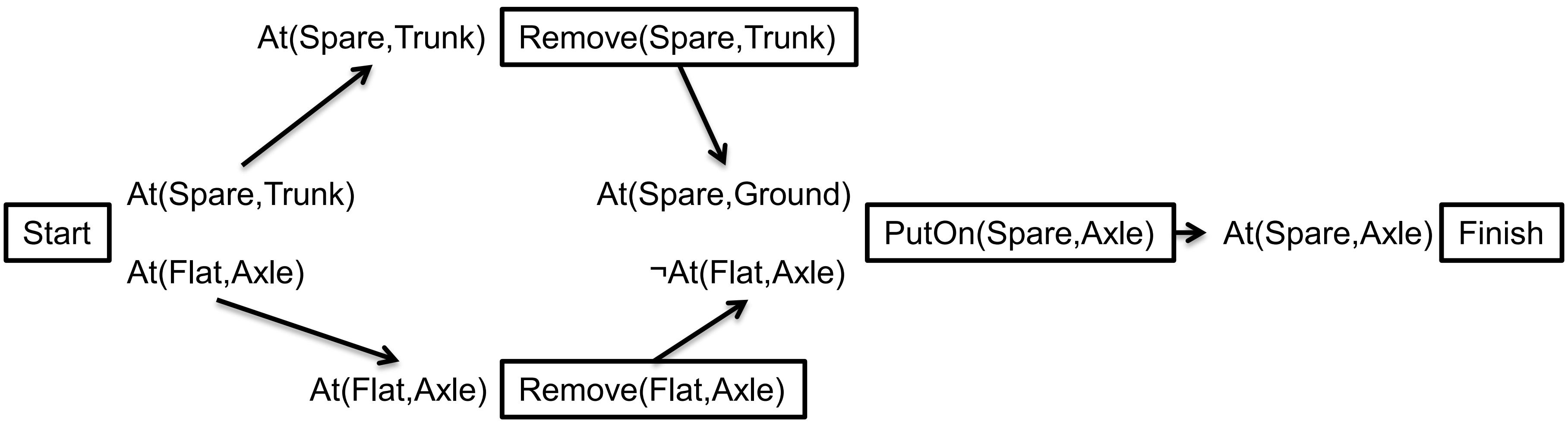
```
Action(Remove(Flat,Axle),
  PRECOND: At(Flat,Axle)
  EFFECT: ¬At(Flat,Axle) ∧ At(Flat,Ground))
```

Partial-Order Planning



… and also satisfies the open precondition at PutOn(Spare, Axle).

Partial-Order Planning



Now we have a consistent plan.

Done!

Summary

- There are lots of other planning algorithms:
    - Planning Graphs
    - Graphplan
    - Planning with propositional logic
    - Conditional Planning
    - …
- The ones we have learned about are very common, and should give us an idea about how planners work.

That was all for this lecture

Acknowledgements

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