# Planning

# Techniques seen till now

- Search
  - Most fundamental approach
  - Need to define states, moves, state-transiton rules, etc.
- CSP
  - Search through constraint propagation
- Propositional logic
  - Deduction in a single state, no state change
- Probabilistic reasoning
  - Logic augmented with probabilities
- Temporal logic
  - Logic involving time
- Planning
  - Search involving logic
  - Change of states

# Real world planning problems

- Autonomous vehicle navigation
- Robotics movement
- Travel planning
- Process control
- Assembly line
- Military operations
- Information gathering
- many more . . .

# A simple planning problem

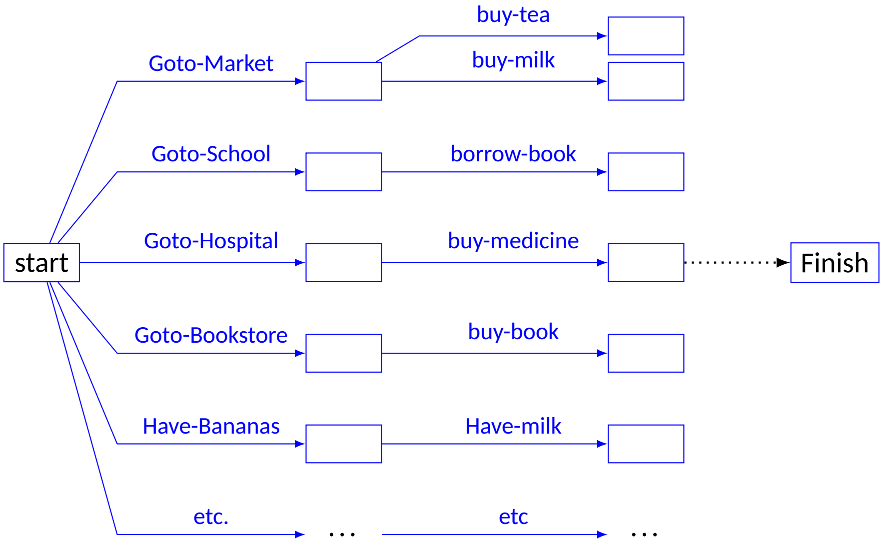
- Get me milk, bananas and a book
- Given
  - Initial state - agent is at *home* without milk, bananas and book
  - Goal state - agent is at *home* with milk, bananas and book
  - Actions / Moves - agent can perform on a given state
    - Buy($X$) - buy item $X$ where $X \in \{milk, bananas, book\}$
    - Steal(X) - steal item $X$ where $X \in \{milk, bananas, book\}$
    - Goto(X) - move to $X$ where $X \in \{market, home\}$
    - ...

# The planning problem

- Generate one possible way to achieve a certain goal given an initial situation and a set of actions

- Similar to search problems
  - Start state
  - List of moves
  - Result of moves
  - Goal state

# Search


buy-tea
Goto-Market
buy-milk
Goto-School
borrow-book
start
Goto-Hospital
buy-medicine
Finish
Goto-Bookstore
buy-book
Have-Bananas
Have-milk
etc.
etc

# Planning vs Search

- Actions have requirements and consequences that should constrain applicability in a given state
  - Stronger interaction between actions and states needed
- Most parts of the world are independent of most other parts
  - Solve subgoals independently
- Human beings plan goal-directed, they construct important intermediate solutions first
  - Flexible sequence for construction of solution
- Planning systems do the following
  - Unify action and goal representation to allow selection (use logical language for both)
  - Divide-and-conquer by subgoaling
  - Relax requirement for sequential construction of solutions

# STRIPS

- **STanford Research Institute Problem Solver**
- **Many planners today use specification languages that are variants of the one used in STRIPS**

# Representation

- States - conjunction of propositions
  - Example: AT(Home)∧¬ Have(tea)∧¬Have(bananas)∧¬Have(book)
- Close world assumption - atoms that are not present are treated as false
- Actions - Serves as names
  - Precondition - conjunction of literals
  - Effect - conjunction of literals
  - Example:
    - Action: Goto(Market)
    - Precondition: AT(home)
    - Effect: AT(Market)
- Plan - Solution for the problem
  - A set of plan steps. Each step is one of the operators for the problem.
  - A set of step ordering constraints. Each ordering constraint is of the form $S_i \prec S_j$, indicating $S_i$ must occur sometime before $S_j$.

# Example - Flight operation

- Flying a plane from one location to another
- Actions - FLY(plane-id, from, to)
  - Preconditions - $AT(plane\text{-}id, from) \wedge Airport(from) \wedge Airport(to)$
  - Effects - $\neg AT(plane\text{-}id, from) \wedge AT(plane\text{-}id, to)$

# Example - Air Cargo

- **Cargo transport involving loading and unloading and flying it from one place to another**

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- **Action - Load(c, p, a)**

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- **Goal state** - $AT(C_1, DEL) \wedge AT(C_2, CCU)$

- **Action - Load(c, p, a)**
  - **Precondition - AT(c, a) ∧ AT(p, a)**
  - **Effect - ¬AT(c, a) ∧ In(c, p)**

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- **Action - Load(c, p, a)**
  - **Precondition - AT(c, a) ∧ AT(p, a)**
  - **Effect - ¬AT(c, a) ∧ In(c, p)**
- **Action - Unload(c, p, a)**

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  - Effect - ¬AT(c, a) ∧ In(c, p)
- Action - Unload(c, p, a)
  - Precondition - In(c, p) ∧ AT(P, a)
  - Effect - AT(c, a) ∧ ¬In(c, p)

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- **Action - Fly(p, from, to)**

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- **Plan**

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  - **Precondition - In(c, p) ∧ AT(P, a)**
  - **Effect - AT(c, a) ∧ ¬In(c, p)**
- **Action - Fly(p, from, to)**
  - **Precondition - AT(p, from)**
  - **Effect - ¬AT(p, from) ∧ AT(p, to)**

- **Plan**
  - **Load($C_1$, $P_1$, CCU)**

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  - **Precondition - AT(p, from)**
  - **Effect - ¬AT(p, from) ∧ AT(p, to)**

- **Plan**
  - **Load($C_1$, $P_1$, CCU)**
  - **Fly($P_1$, CCU, DEL)**

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- **Plan**
  - **Load**($C_1$, $P_1$, **CCU)**
  - **Fly**($P_1$, **CCU, DEL)**
  - **Unload**($C_1$, $P_1$, **DEL)**

# Example - Air Cargo

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- **Action - Fly(p, from, to)**
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  - **Effect - ¬AT(p, from) ∧ AT(p, to)**

- **Plan**
  - **Load($C_1$, $P_1$, CCU)**
  - **Fly($P_1$, CCU, DEL)**
  - **Unload($C_1$, $P_1$, DEL)**
  - **Load($C_2$, $P_2$, DEL)**
  - **Fly($P_2$, DEL, CCU)**
  - **Unload($C_2$, $P_2$, CCU)**

# Example - Flat tire

- **Change a flat tire with a spare one**

# Example - Flat tire

- **Change a flat tire with a spare one**
- **Initial state - Tire(flat) ∧ Tire(Spare) ∧ AT(Flat, Axle) ∧ At(Spare, Trunk)**

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- **Goal state - AT(Spare, Axle)**

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- Change a flat tire with a spare one
- Initial state - Tire(flat) $\wedge$ Tire(Spare) $\wedge$ AT(Flat, Axle) $\wedge$ At(Spare, Trunk)
- Goal state - AT(Spare, Axle)
- Action - Remove(obj, loc)

# Example - Flat tire

- Change a flat tire with a spare one
- Initial state - Tire(flat) $\wedge$ Tire(Spare) $\wedge$ AT(Flat, Axle) $\wedge$ At(Spare, Trunk)
- Goal state - AT(Spare, Axle)
- Action - Remove(obj, loc)
  - Preconditions - AT(obj, loc)
  - Effects - $\neg$AT(obj,loc) $\wedge$ AT(obj, Ground)

# Example - Flat tire

- Change a flat tire with a spare one
- Initial state - Tire(flat) ∧ Tire(Spare) ∧ AT(Flat, Axle) ∧ At(Spare, Trunk)
- Goal state - AT(Spare, Axle)
- Action - Remove(obj, loc)
  - Preconditions - AT(obj, loc)
  - Effects - ¬AT(obj,loc) ∧ AT(obj, Ground)
- Action - PutOn(t, axle)

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- Initial state - Tire(flat) ∧ Tire(Spare) ∧ AT(Flat, Axle) ∧ At(Spare, Trunk)
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- Action - Remove(obj, loc)
  - Preconditions - AT(obj, loc)
  - Effects - ¬AT(obj,loc) ∧ AT(obj, Ground)
- Action - PutOn(t, axle)
  - Preconditions - Tire(t) ∧ AT(t, Ground) ∧ ¬AT(Flat, axle)
  - Effects - ¬AT(t, Ground) ∧ AT(t, axle)

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- Change a flat tire with a spare one
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  - Preconditions - AT(obj, loc)
  - Effects - ¬AT(obj,loc) ∧ AT(obj, Ground)
- Action - PutOn(t, axle)
  - Preconditions - Tire(t) ∧ AT(t, Ground) ∧ ¬AT(Flat, axle)
  - Effects - ¬AT(t, Ground) ∧ AT(t, axle)
- Plan

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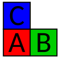
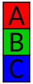
- Action - PutOn(t, axle)
  - Preconditions - Tire(t) $\wedge$ AT(t, Ground) $\wedge$ $\neg$AT(Flat, axle)
  - Effects - $\neg$AT(t, Ground) $\wedge$ AT(t, axle)
- Plan
  - Remove(Flat, Axle)
  - Remove(Spare, Trunk)
  - PutOn(Spare, Axle)

# Example - Blocks world

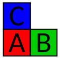
- **Build a 3-block tower**

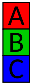


# Example - Blocks world

- **Build a 3-block tower**
- **Initial state - ON(A,Table) ∧ ON(B,Table) ∧ ON(C,A) ∧ Clear(B) ∧ Clear(C)**



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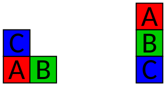

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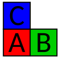
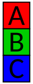
- **Goal state - ON(A,B) ∧ ON(B,C)**
- **Action - move(x, y)**



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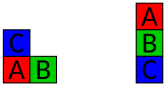
- Goal state - ON(A,B) ∧ ON(B,C)

- Action - move(x, y)
  - Precondition - Clear(x) ∧ Clear(y)
  - Effect - ON(x, y)



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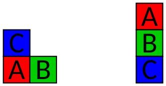
- Build a 3-block tower
- Initial state - ON(A,Table) $\wedge$ ON(B,Table) $\wedge$ ON(C,A) $\wedge$ Clear(B) $\wedge$ Clear(C)
- Goal state - ON(A,B) $\wedge$ ON(B,C)

- Action - move(x, y)
  - Precondition - Clear(x) $\wedge$ Clear(y)
  - Effect - ON(x, y)
- Action - moveToTable(x, Table)



# Example - Blocks world

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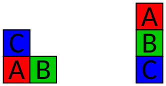
- Goal state - ON(A,B) ∧ ON(B,C)

- Action - move(x, y)
  - Precondition - Clear(x) ∧ Clear(y)
  - Effect - ON(x, y)
- Action - moveToTable(x, Table)
  - Precondition - Clear(x)
  - Effect - ON(x, Table)



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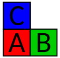
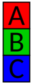
- **Build a 3-block tower**
- **Initial state - ON(A,Table) $\wedge$ ON(B,Table) $\wedge$ ON(C,A) $\wedge$ Clear(B) $\wedge$ Clear(C)**
- **Goal state - ON(A,B) $\wedge$ ON(B,C)**

- **Action - move(x, y)**
  - **Precondition - Clear(x) $\wedge$ Clear(y)**
  - **Effect - ON(x, y)**
- **Action - moveToTable(x, Table)**
  - **Precondition - Clear(x)**
  - **Effect - ON(x, Table)**

- **Plan**



# Example - Blocks world

- Build a 3-block tower
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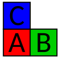
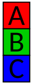
- Goal state - ON(A,B) ∧ ON(B,C)

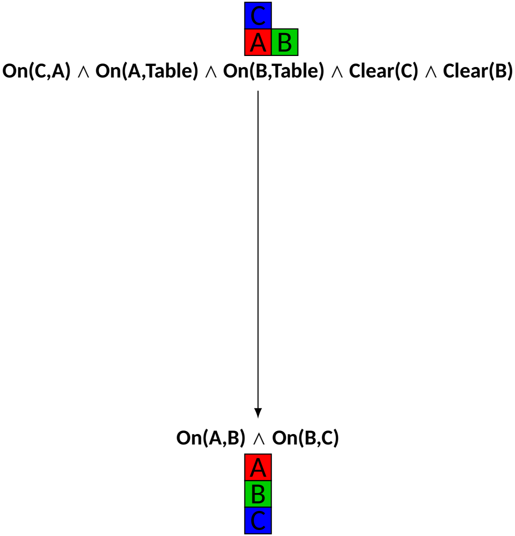
- Action - move(x, y)
  - Precondition - Clear(x) ∧ Clear(y)
  - Effect - ON(x, y)
- Action - moveToTable(x, Table)
  - Precondition - Clear(x)
  - Effect - ON(x, Table)

- Plan
  - moveToTable(C, Table)
  - move(B, C)
  - move(A, B)



# Blocks world - I

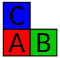



**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

- Move C to the table
  - It achieves none of the goal predicates
- Move C to top of B
  - It achieves none of the goal predicates
- Move B to top of C
  - It achieves On(B,C)

# Blocks world - I




On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)

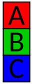
**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

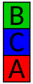
Clear(C) ∧ Clear(B)

Move(B,C)

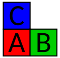
On(A,B) ∧ On(B,C)

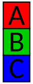



We obtain the following

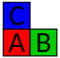


# Blocks world - II



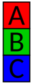



# Blocks world - II

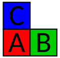



On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)

On(A,B) ∧ On(B,C)



# Blocks world - II

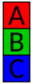



**On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)**

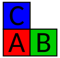
**Action:** **Move(X,Y)**
**Precondition:** **Clear(X) ∧ Clear(Y)**
**Effect:** **On(X,Y)**

**Action:** **MoveTT(X)**
**Precondition:** **Clear(X)**
**Effect:** **On(X,Table)**

**On(A,B) ∧ On(B,C)**



# Blocks world - II




On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)

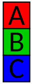
**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

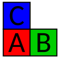
MoveTT(C)

Move(A,B)

On(A,B) ∧ On(B,C)



# Blocks world - II




On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)

**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

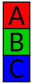
Clear(C)

| MoveTT(C) |
|---|

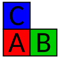
Clear(A) ∧ On(C,Table)

| Move(A,B) |
|---|

On(A,B) ∧ On(B,C)



# Blocks world - II




On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)

**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

Clear(C)

| MoveTT(C) |
|---|

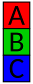
Clear(A) ∧ On(C,Table)

Clear(A) ∧ Clear(B)

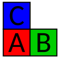
| Move(A,B) |
|---|

¬Clear(B)

On(A,B) ∧ On(B,C)



# Blocks world - II




On(C,A) ∧ On(A,Table) ∧ On(B,Table) ∧ Clear(C) ∧ Clear(B)

Clear(C)

| MoveTT(C) |
|---|

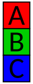
Clear(A) ∧ On(C,Table)

Clear(A) ∧ Clear(B)

| Move(A,B) |
|---|

¬Clear(B)

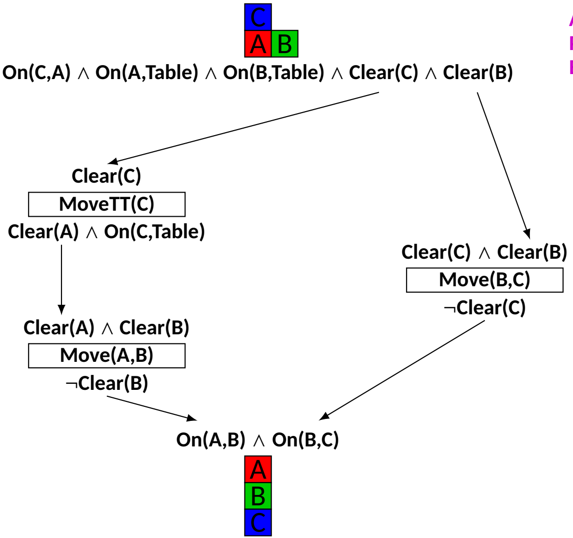
On(A,B) ∧ On(B,C)




**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

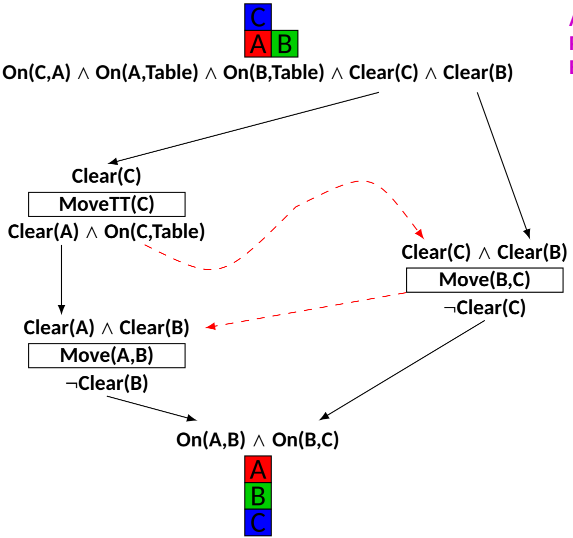
# Blocks world - II




**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

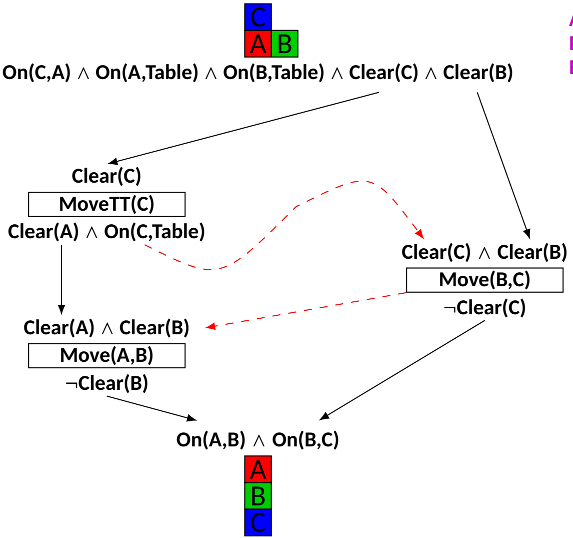
# Blocks world - II




**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

# Blocks world - II




**Action:** Move(X,Y)
**Precondition:** Clear(X) ∧ Clear(Y)
**Effect:** On(X,Y)

**Action:** MoveTT(X)
**Precondition:** Clear(X)
**Effect:** On(X,Table)

- Total ordering is
  - MoveTT(C)
  - Move(B,C)
  - Move(A,B)

# Shocks

- Initial state : ∅
- Goal state: LeftShoeOn ∧ RightShoeOn
- Action - LeftSock
  - Precondition: ∅
  - Effect: LeftSockOn
- Action - RightSock
  - Precondition: ∅
  - Effect: RightSockOn
- Action - LeftShoe
  - Precondition: LeftSockOn
  - Effect: LeftShoeOn
- Action - RightSock
  - Precondition: RightSockOn
  - Effect: RightShoeOn

# Shocks

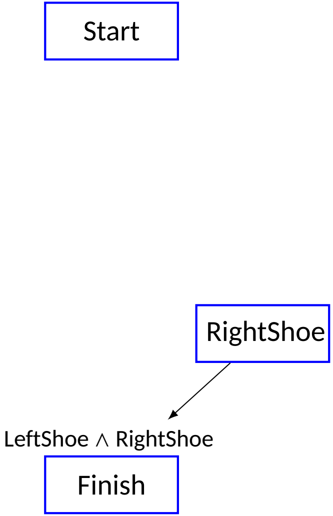
- **Initial state :** ∅
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition:** ∅
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition:** ∅
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**

# Shocks

- **Initial state : ∅**
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition: ∅**
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition: ∅**
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**

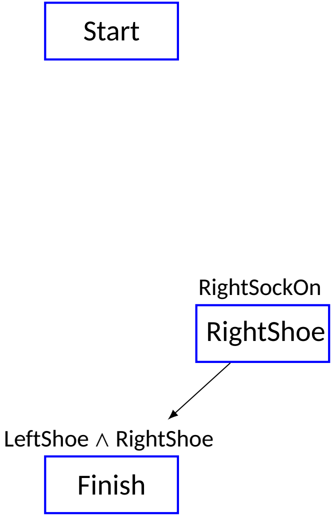
# Shocks

- Initial state : ∅
- Goal state: LeftShoeOn ∧ RightShoeOn
- Action - LeftSock
  - Precondition: ∅
  - Effect: LeftSockOn
- Action - RightSock
  - Precondition: ∅
  - Effect: RightSockOn
- Action - LeftShoe
  - Precondition: LeftSockOn
  - Effect: LeftShoeOn
- Action - RightSock
  - Precondition: RightSockOn
  - Effect: RightShoeOn



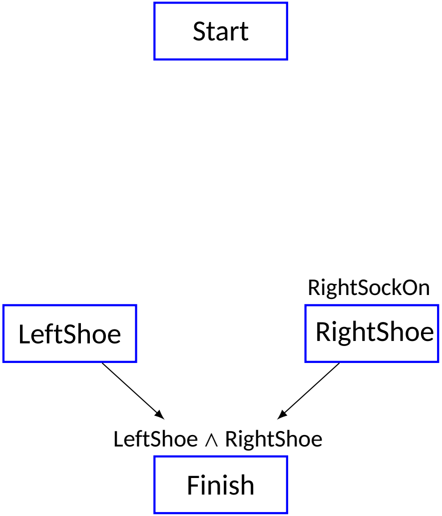
# Shocks

- **Initial state : ∅**
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition: ∅**
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition: ∅**
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**



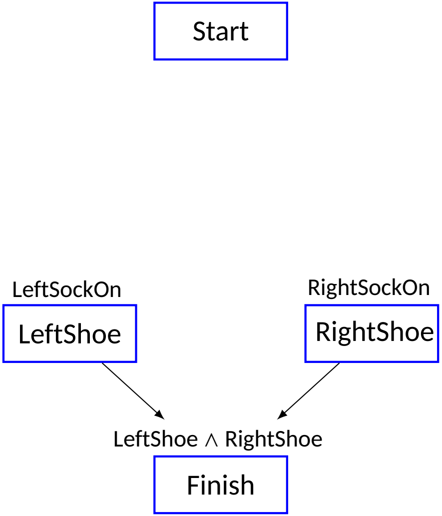
# Shocks

- **Initial state : ∅**
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition: ∅**
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition: ∅**
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**



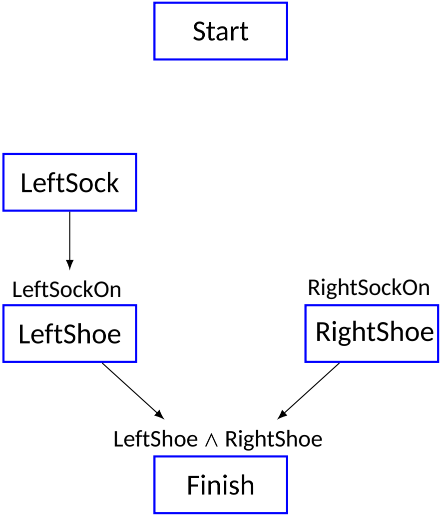
# Shocks

- **Initial state : ∅**
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition: ∅**
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition: ∅**
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**



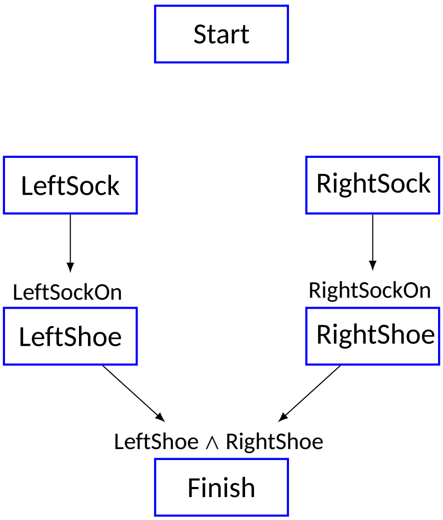
# Shocks

- **Initial state : ∅**
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition: ∅**
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition: ∅**
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**



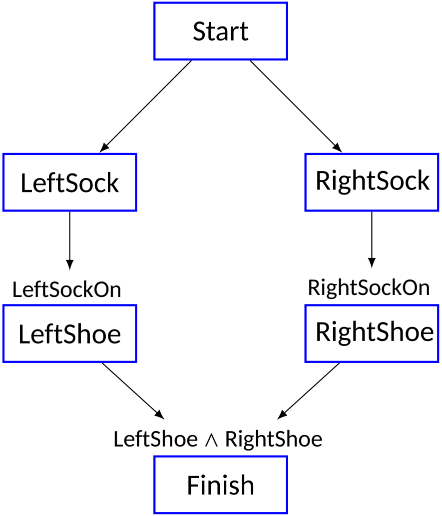
# Shocks

- **Initial state : ∅**
- **Goal state: LeftShoeOn ∧ RightShoeOn**
- **Action - LeftSock**
  - **Precondition: ∅**
  - **Effect: LeftSockOn**
- **Action - RightSock**
  - **Precondition: ∅**
  - **Effect: RightSockOn**
- **Action - LeftShoe**
  - **Precondition: LeftSockOn**
  - **Effect: LeftShoeOn**
- **Action - RightSock**
  - **Precondition: RightSockOn**
  - **Effect: RightShoeOn**



# Shocks

- Initial state : ∅
- Goal state: LeftShoeOn ∧ RightShoeOn
- Action - LeftSock
  - Precondition: ∅
  - Effect: LeftSockOn
- Action - RightSock
  - Precondition: ∅
  - Effect: RightSockOn
- Action - LeftShoe
  - Precondition: LeftSockOn
  - Effect: LeftShoeOn
- Action - RightSock
  - Precondition: RightSockOn
  - Effect: RightShoeOn



# Partial order planning

- Basic idea: Make choices only that are relevant for solving the current part of the problem
- Least commitment choices
  - Ordering - Leave actions unordered, unless they must be sequential
  - Binding - Leave variable unbound, unless needed to unify with conditions being achieved
  - Actions - Usually not subjected to least commitment

# Milk, Bananas, Book

**Initial State:**
**Action: Start**
**Effect: At(Home) $\wedge$ Sells(BS,Book) $\wedge$ Sells(M,Milk) $\wedge$ Sells(M,Bananas)**

**Goal State:**
**Action: Finish**
**Precondition: Have(Book) $\wedge$ Have(Milk) $\wedge$ Have(Bananas) $\wedge$ At(Home)**

**Action: Go(y)**
**Precondition: At(x)**
**Effect: At(y) $\wedge$ $\neg$At(x)**

**Action: Buy(x)**
**Precondition: At(y) $\wedge$ Sells(y,x)**
**Effect: Have(x)**

# Milk, Bananas, Book

Start

$At(Home) \wedge Sells(BS,Book) \wedge Sells(M,Milk) \wedge Sells(M,Bananas)$

# Milk, Bananas, Book

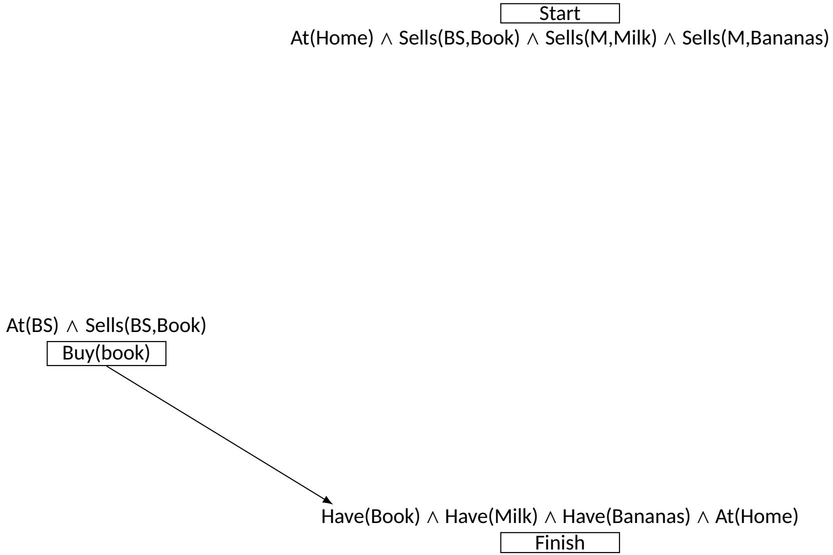
Start

$At(Home) \wedge Sells(BS,Book) \wedge Sells(M,Milk) \wedge Sells(M,Bananas)$

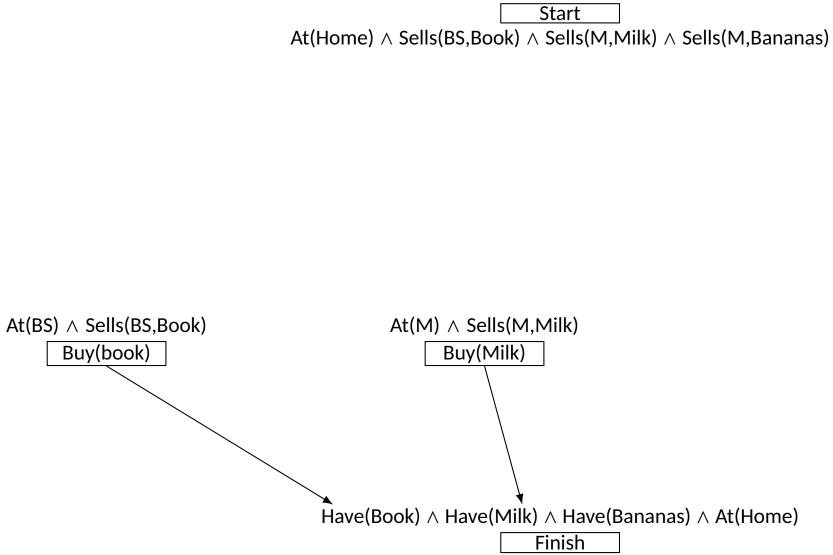
$Have(Book) \wedge Have(Milk) \wedge Have(Bananas) \wedge At(Home)$

Finish

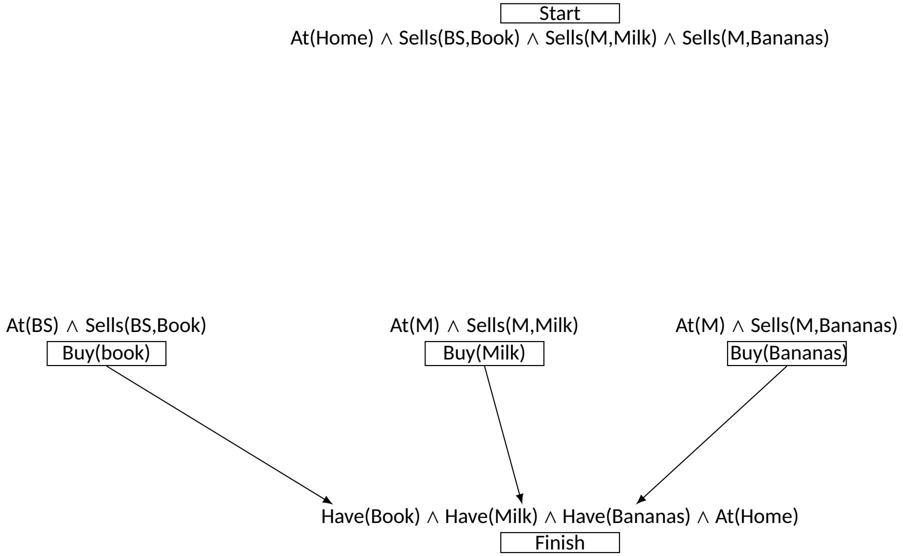
# Milk, Bananas, Book



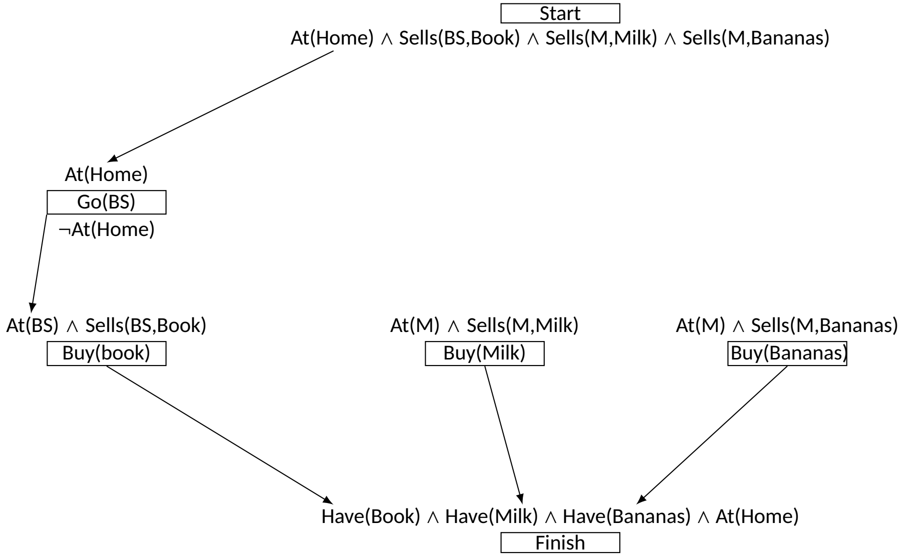
# Milk, Bananas, Book



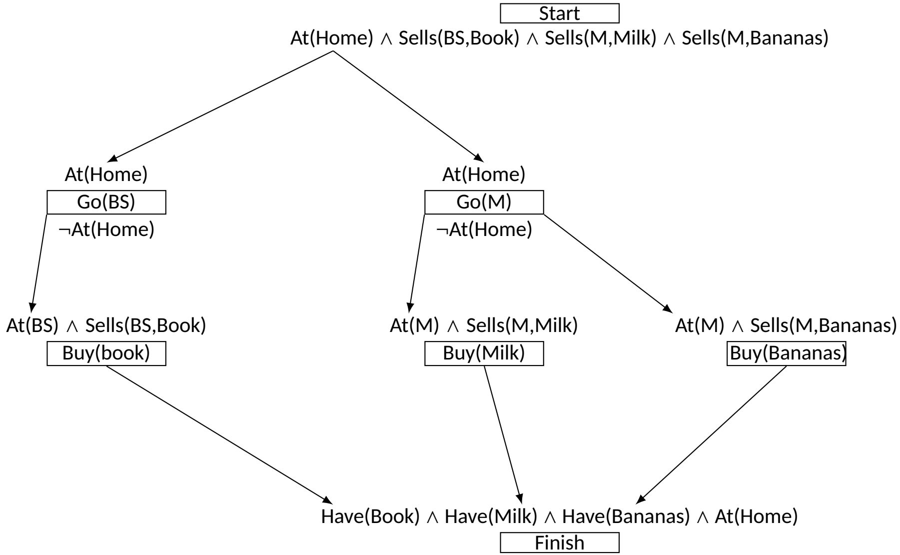
# Milk, Bananas, Book



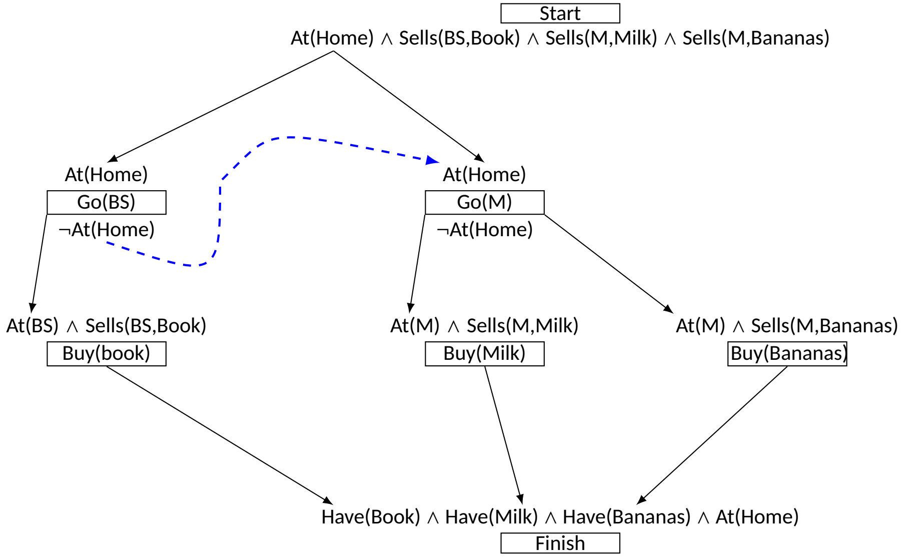
# Milk, Bananas, Book



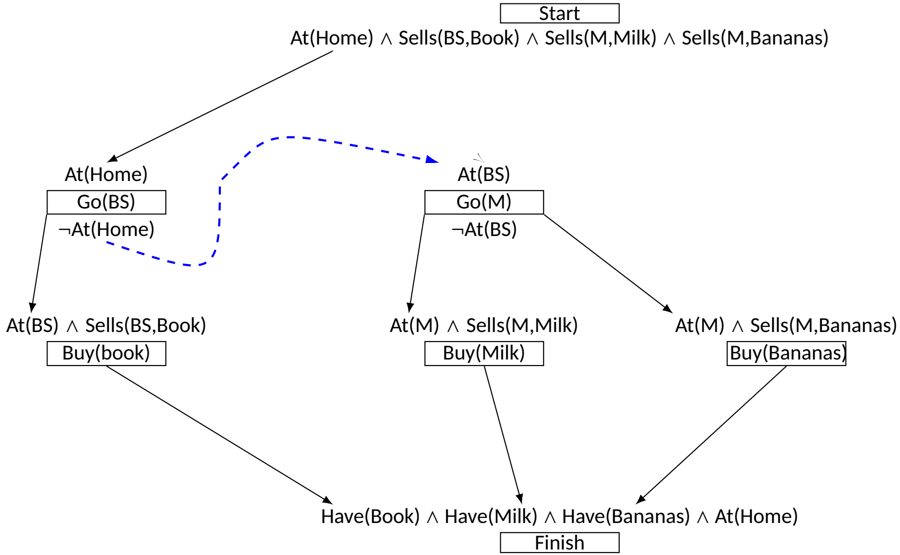
# Milk, Bananas, Book



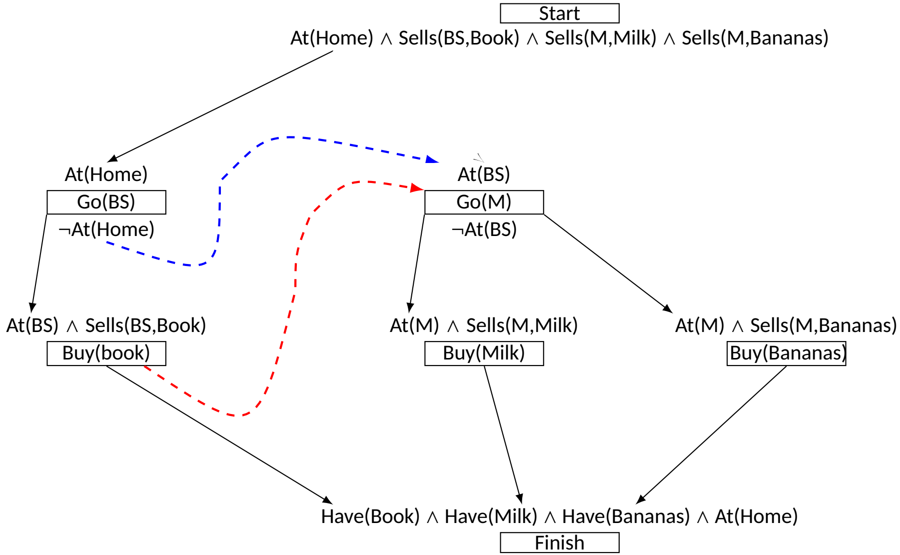
# Milk, Bananas, Book



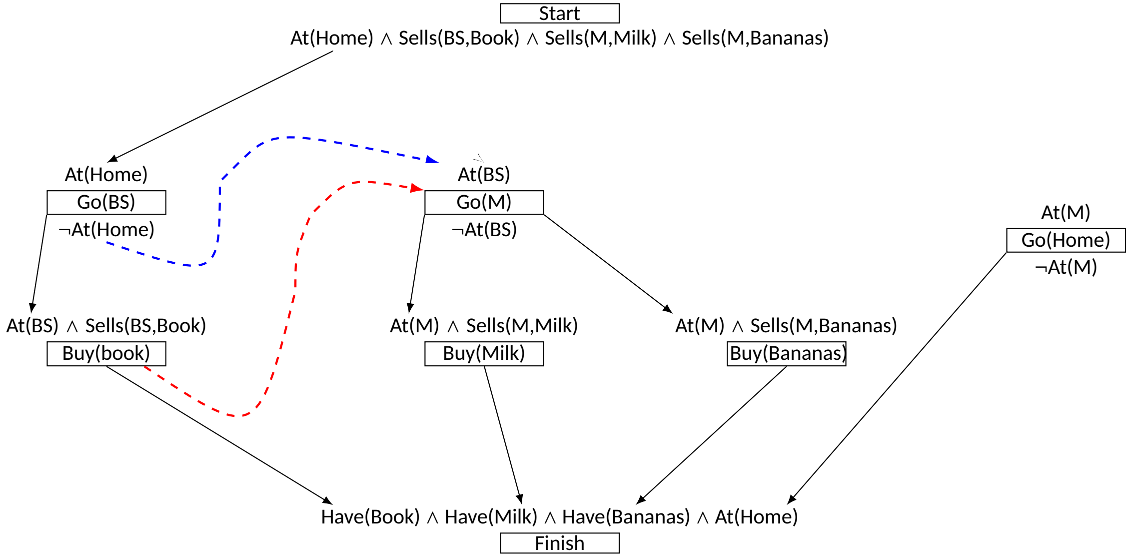
# Milk, Bananas, Book



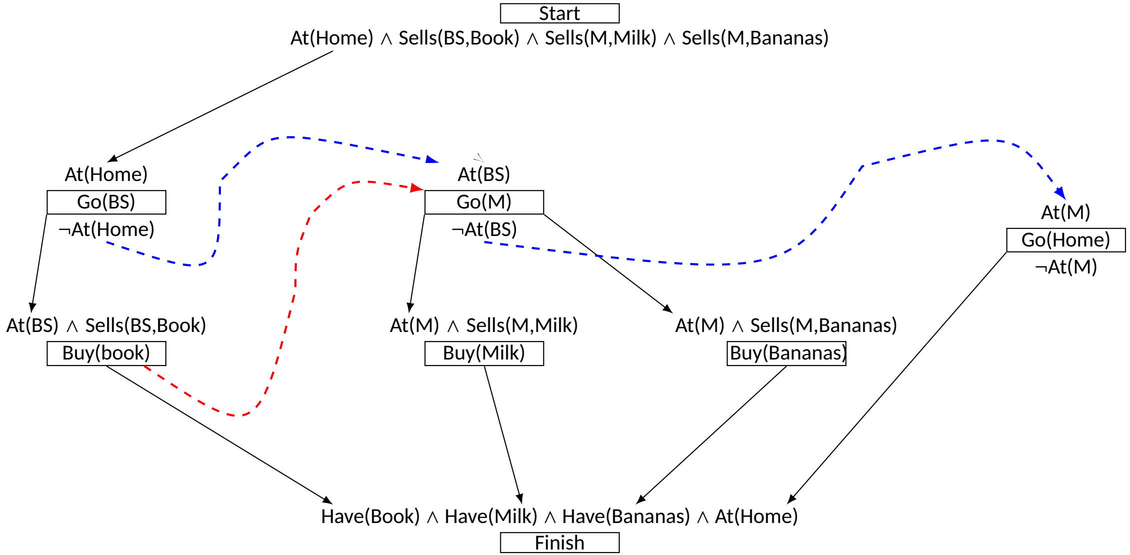
# Milk, Bananas, Book



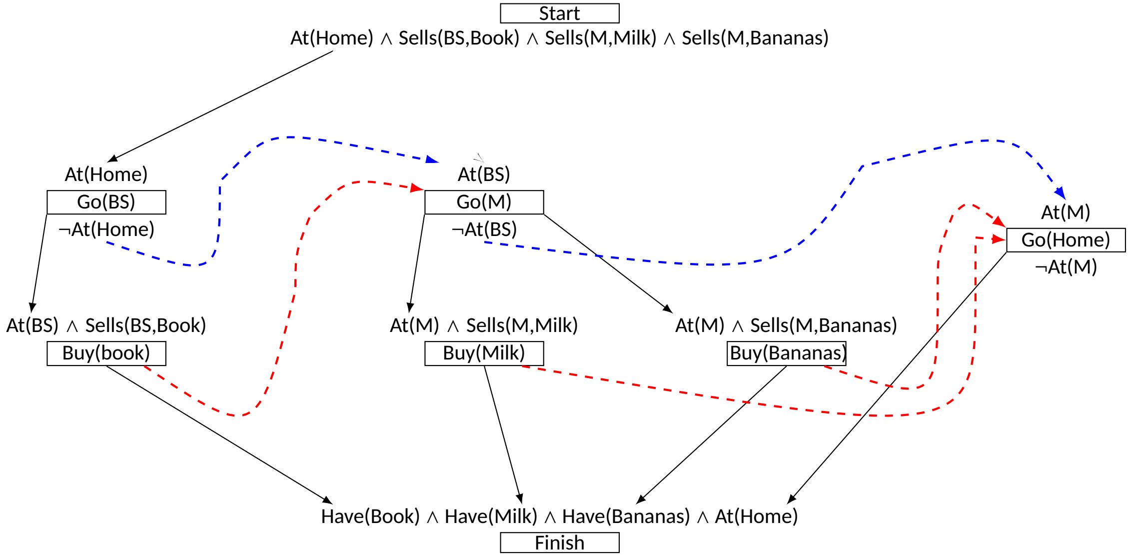
# Milk, Bananas, Book



# Milk, Bananas, Book



# Milk, Bananas, Book



# Planning Graphs

- **Consists of a sequence of levels that correspond to time steps in the plan**
- **Each level contains a set of actions and a set of literals that could be true at that time step depending on the actions taken in previous time steps**
- **For every +ve and -ve literal C, we add a persistence action with precondition C and effect C**

# Planning Graph

**Start:** **Have(Cake)**
**Finish:** **Have(Cake) ∧ Eaten(Cake)**

# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

**Action:** Eat(Cake)
**Precondition:** Have(Cake)
**Effect:** Eaten(Cake) ∧ ¬Have(Cake)

**Action:** Bake(Cake)
**Precondition:** ¬Have(Cake)
**Effect:** Have(Cake)

# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

**Action:** Eat(Cake)
**Precondition:** Have(Cake)
**Effect:** Eaten(Cake) ∧ ¬Have(Cake)

**Action:** Bake(Cake)
**Precondition:** ¬Have(Cake)
**Effect:** Have(Cake)

$S_0$

**Have(Cake)**

**¬Eaten(Cake)**

# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

**Action:** Eat(Cake)
**Precondition:** Have(Cake)
**Effect:** Eaten(Cake) ∧ ¬Have(Cake)

**Action:** Bake(Cake)
**Precondition:** ¬Have(Cake)
**Effect:** Have(Cake)

$S_0$ $A_0$

**Have(Cake)**

**¬Eaten(Cake)**

# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

**Action:** Eat(Cake)
**Precondition:** Have(Cake)
**Effect:** Eaten(Cake) ∧ ¬Have(Cake)

**Action:** Bake(Cake)
**Precondition:** ¬Have(Cake)
**Effect:** Have(Cake)

$S_0$ $A_0$

**Have(Cake)**

**Eat(Cake)**

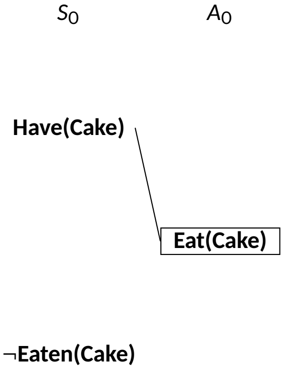
**¬Eaten(Cake)**

# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

**Action:** Eat(Cake)
**Precondition:** Have(Cake)
**Effect:** Eaten(Cake) ∧ ¬Have(Cake)

**Action:** Bake(Cake)
**Precondition:** ¬Have(Cake)
**Effect:** Have(Cake)

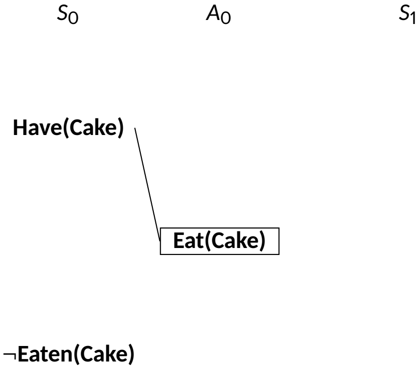


# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

**Action:** Eat(Cake)
**Precondition:** Have(Cake)
**Effect:** Eaten(Cake) ∧ ¬Have(Cake)

**Action:** Bake(Cake)
**Precondition:** ¬Have(Cake)
**Effect:** Have(Cake)



# Planning Graph

**Start:** Have(Cake)
**Finish:** Have(Cake) ∧ Eaten(Cake)

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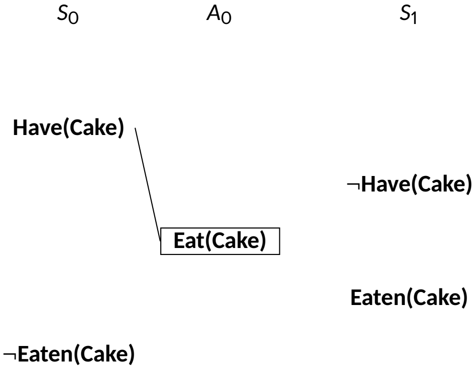

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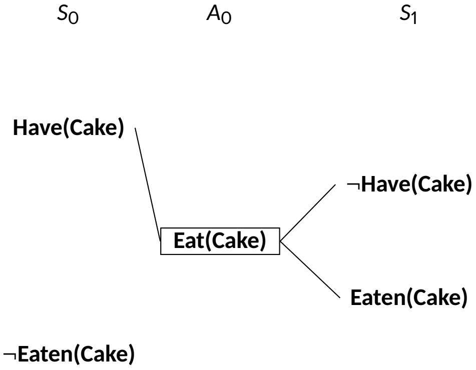

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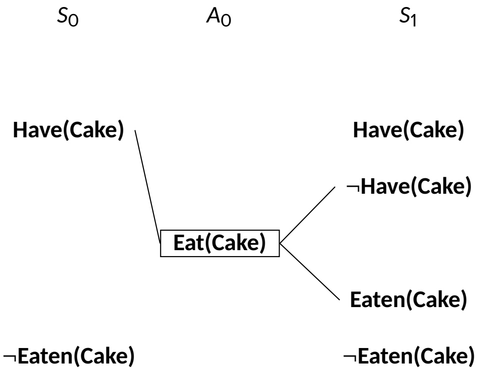

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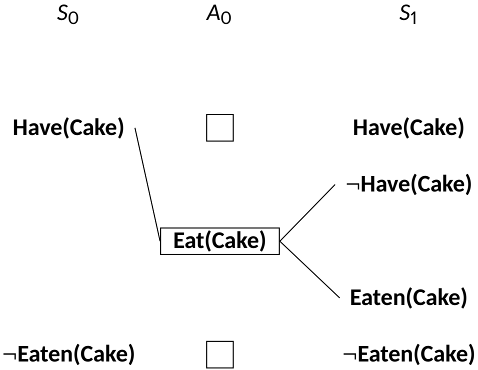

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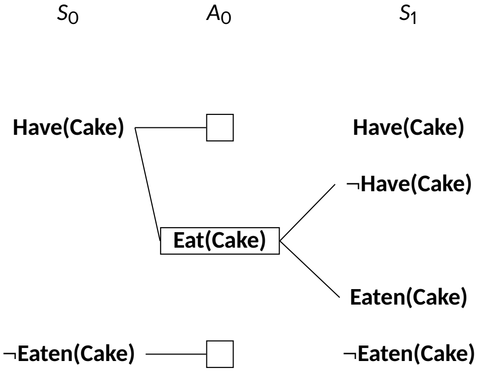

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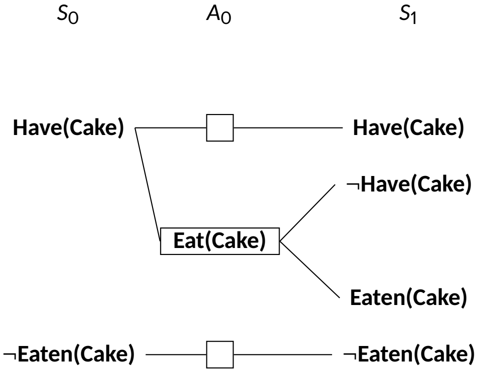

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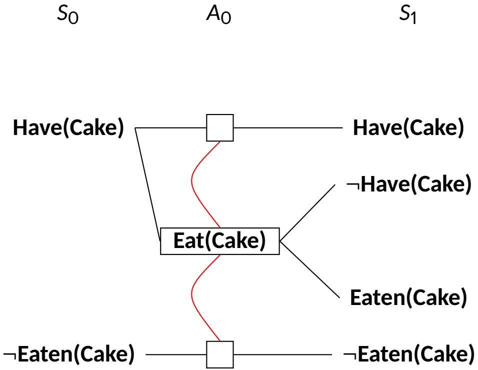

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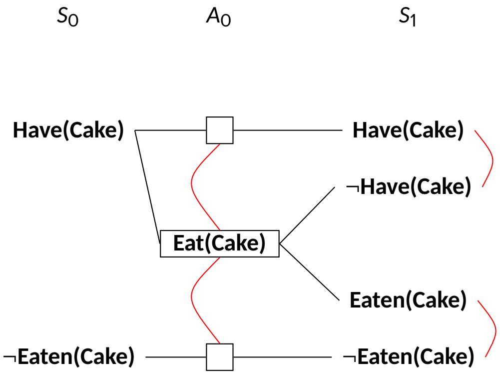

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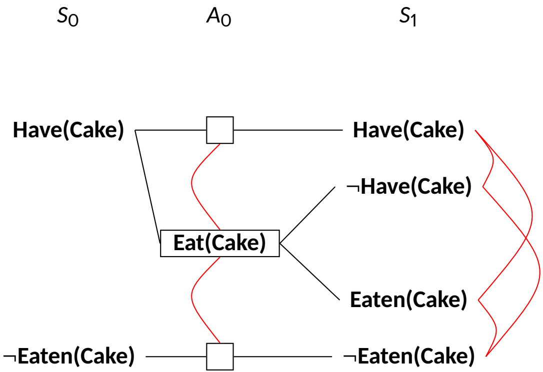

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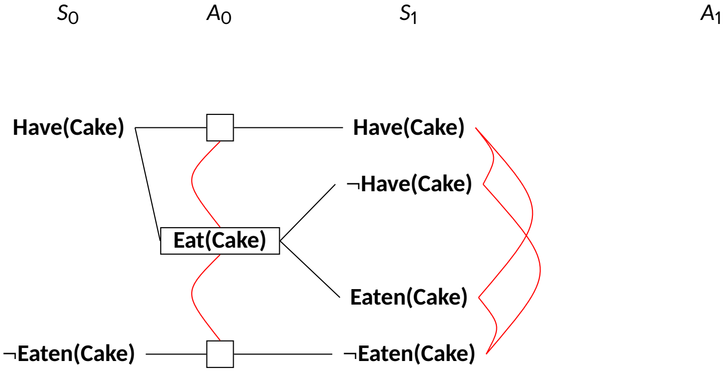

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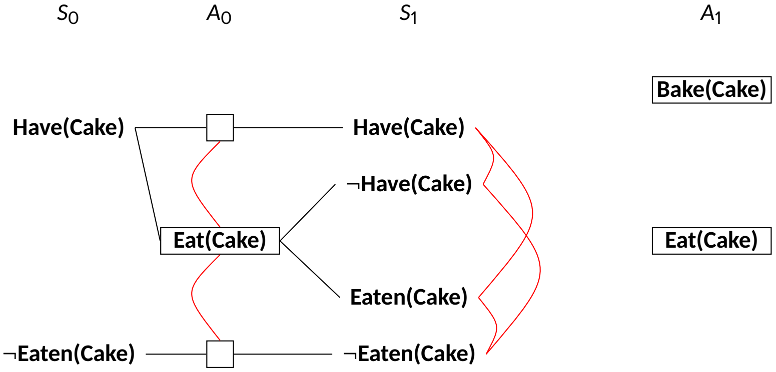

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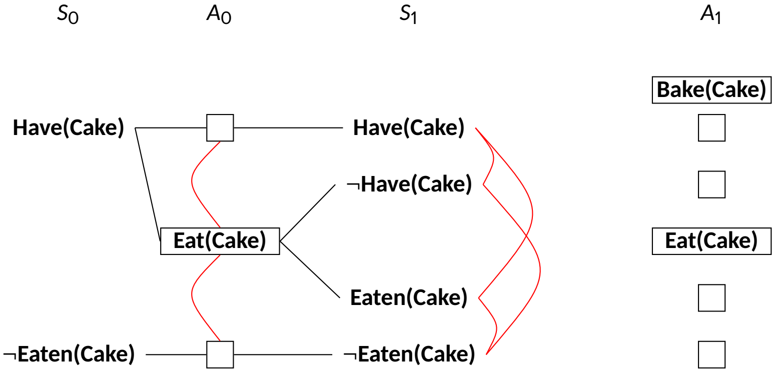

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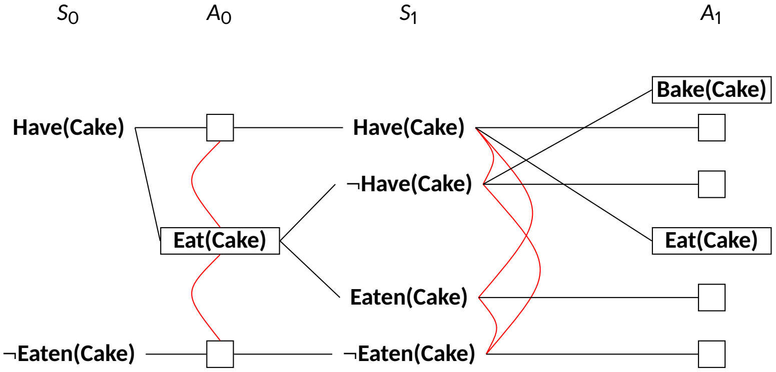

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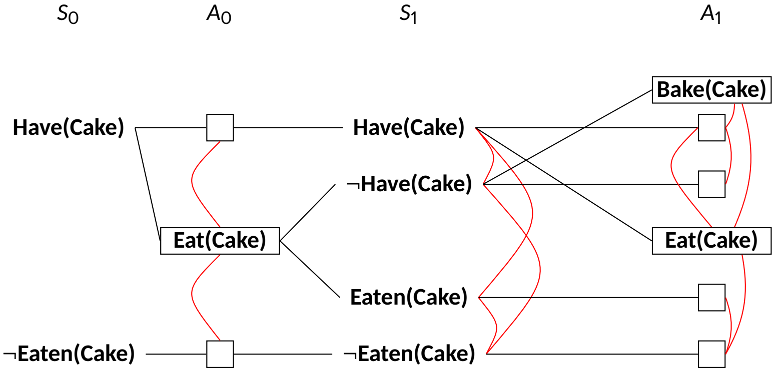

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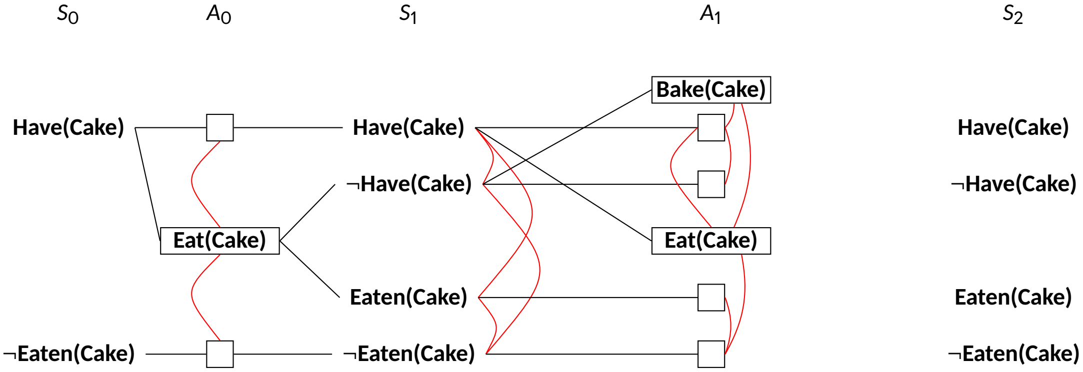

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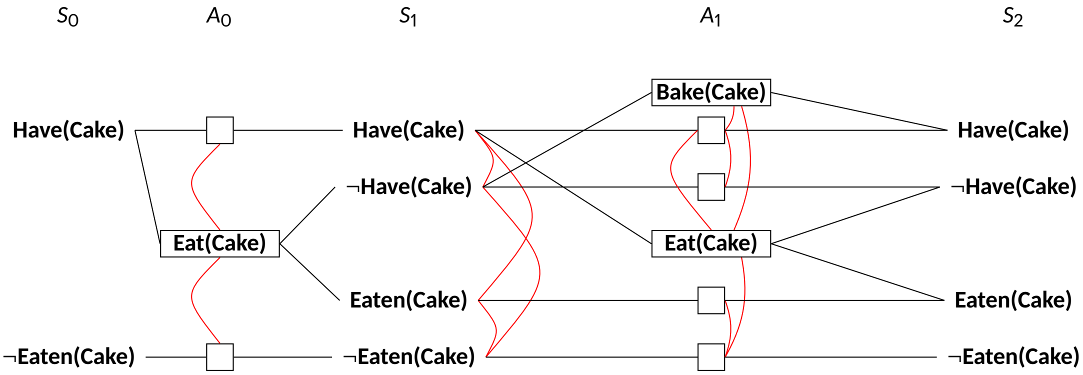

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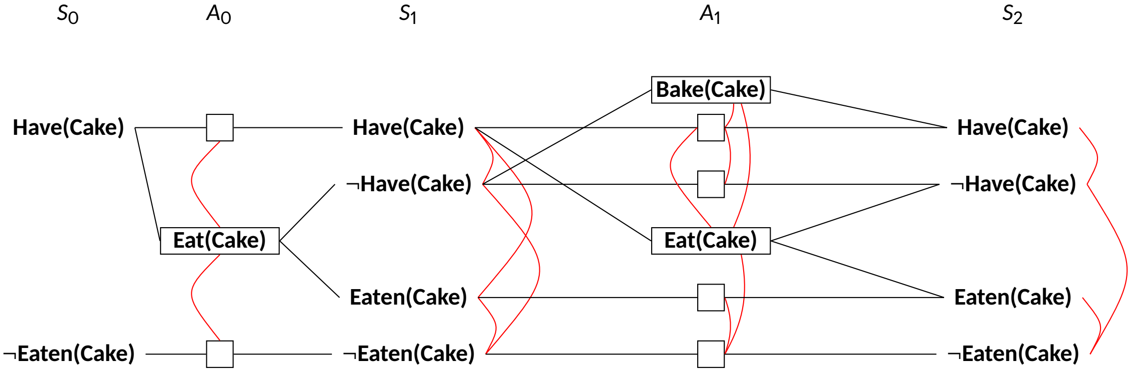
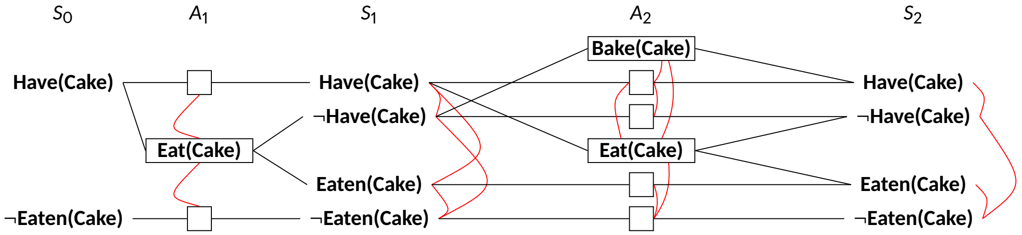


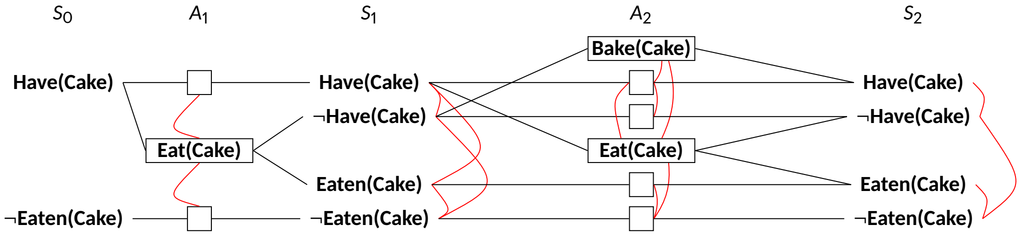
# Mutex actions

- Mutual exclusion relation exists between two actions if
  - Inconsistent effects - once action negates an effect of the other
    - Eat(Cake) causes ¬Have(Cake) and Bake(Cake) causes Have(Cake)
  - Interference - one of the effects of one action is the negation of a precondition of the other
    - Eat(Cake) causes ¬Have(Cake) and the persistence of Have(Cake) needs Have(Cake)
  - Competing needs - one of the preconditions of one action is mutually exclusive with a pre-condition of the other
    - Bake(Cake) needs ¬Have(Cake) and Eat(Cake) needs Have(Cake)



# Mutex literals

- **Mutual exclusion relation exists between two literals if**
  - **One is the negation of the other, OR**
  - **Each possible pair of actions that could achieve the two literals is mutually exclusive (inconsistent support)**



# GraphPLAN algorithm

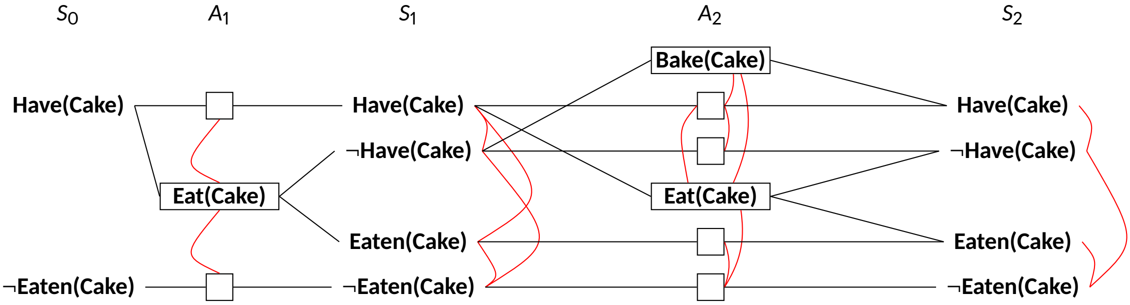
```
Function GraphPlan
graph ← Initial-Planning-Graph( problem )
goals ← Goals[ problem ]
do
    if goals are all non-mutex in last level of graph then do
       solution ← Extract-Solution( graph )
       if solution ← failure then return solution
       else if No-Solution-Possible (graph )
          then return failure
    graph ← Expand-Graph( graph, problem )
```

# Termination

- Termination when no plan exists
  - Literals increase monotonically
  - Actions increase monotonically
  - Mutexes decrease monotonically

# Finding the plan

- Once a world is found having all goal predicates without mutexes, the plan can be extracted by solving a constraint satisfaction problem (CSP) for resolving the mutexes
- Creating the planning graph can be done in polynomial time, but planning is known to be a PSPACE-complete problem. The hardness is in the CSP.



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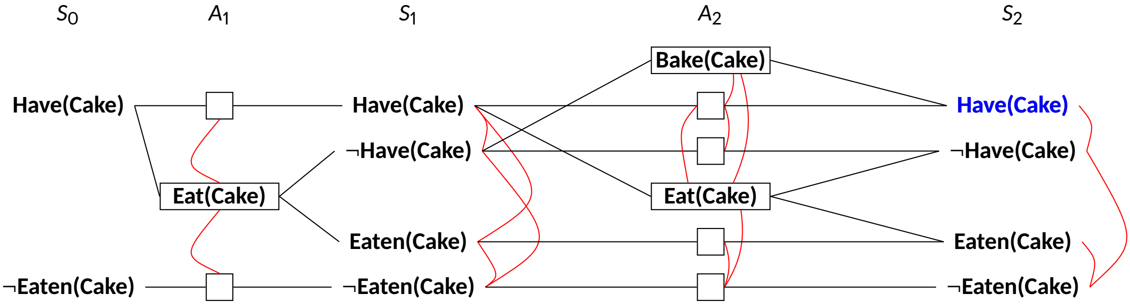

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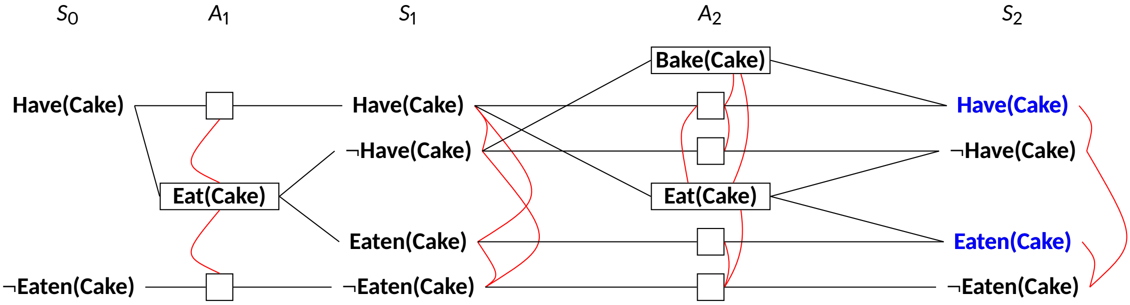

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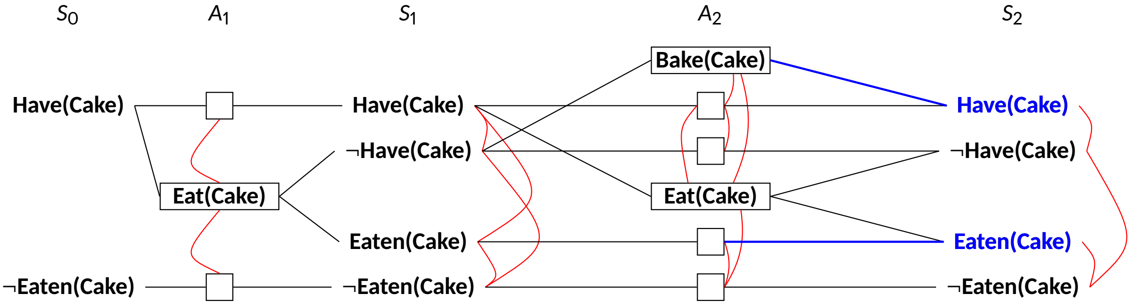

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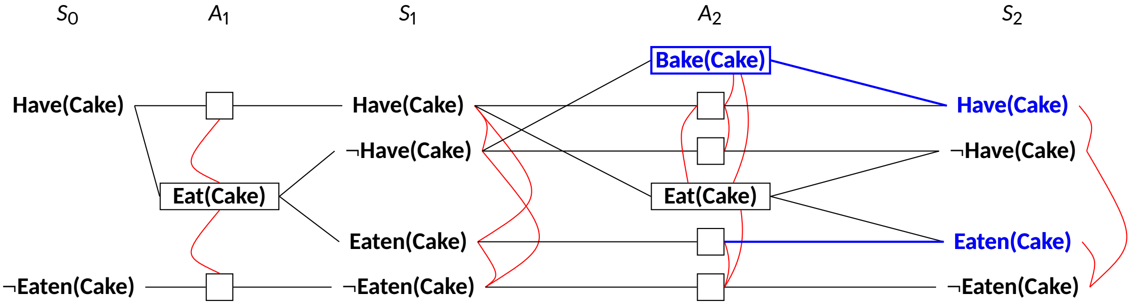

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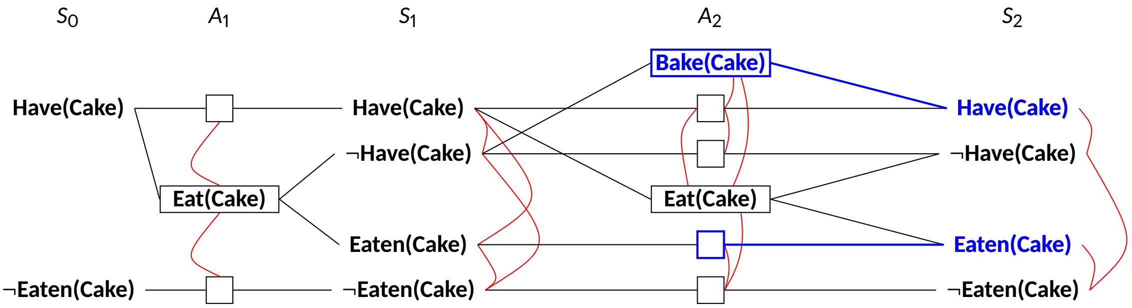

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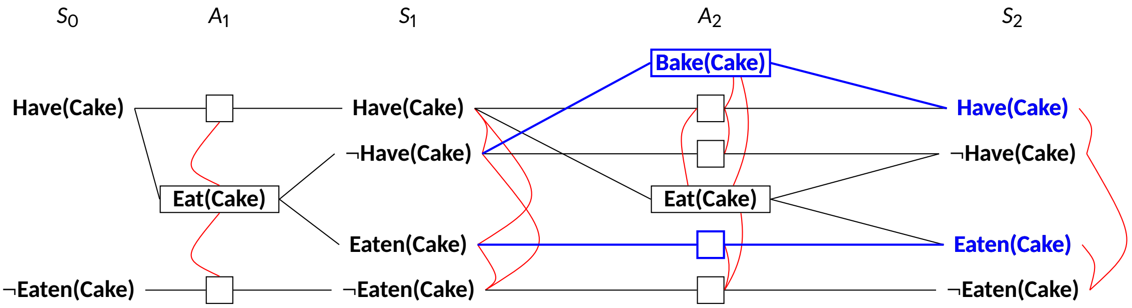

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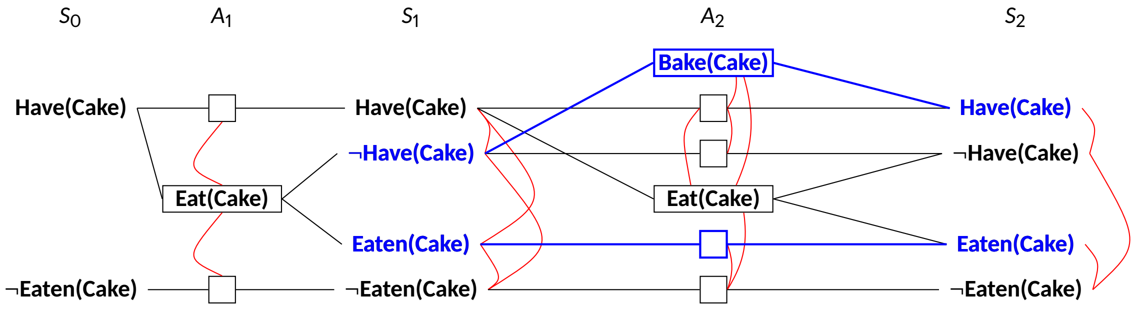

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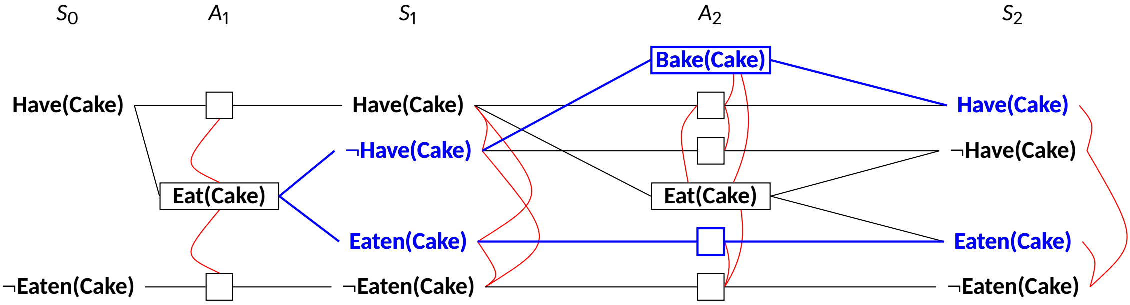

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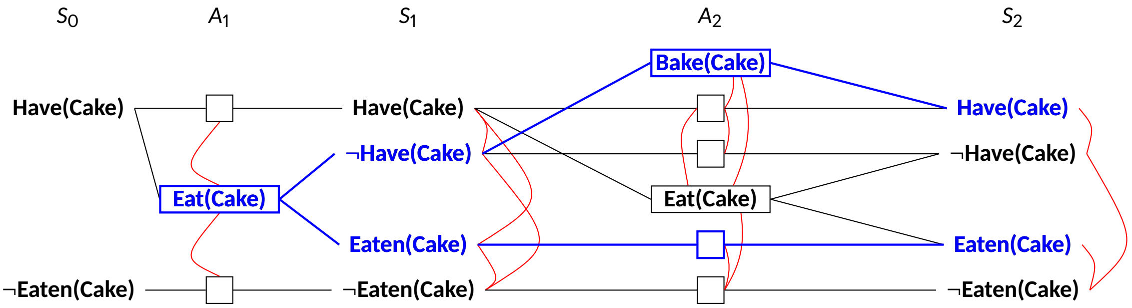

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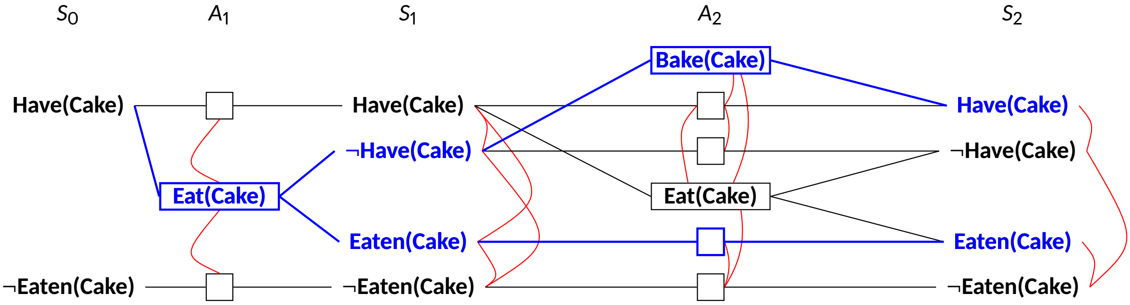

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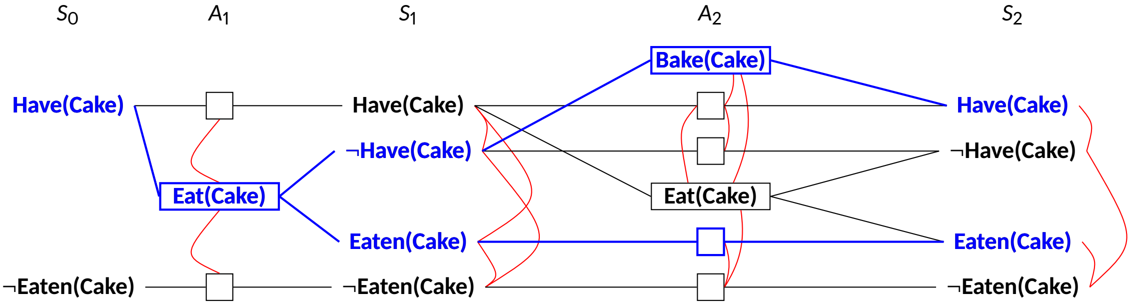

# Planning with Propositional Logic

- The planning problem is translated into a CNF satisfiability problem
- The goal is asserted to hold at a time step T, and clauses are included for each time step up to T.
- If the clauses are satisfiable, then a plan is extracted by examining the actions that are true.
- Otherwise, we increment T and repeat

- Constructing formulas to encode bounded planning problems into satisfiability problems
  - If $f$ is a fluent $At(M)$, we write $At(M, i)$ as $f_i$, $i$ denotes time stamp
  - If $a$ is an action $Move(A, B)$, we write $Move(A, B, i)$ as $a_i$.
  - Notations: PC - precondition, E - effects, $E^+$ - effects in the +ve form, $E^-$ - effect in the -ve form, $s_0$ - start state, $g$ - goal state, $g^+$ - literals in +ve form in goal state, $g^-$ - literals in -ve form in goal state, A - set of actions

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  - $C_4 : \left(\neg f_i \wedge f_{i+1} \implies \left(\bigvee_{\{a \in A \mid f_i \in E^+(a_i)\}} a_i\right)\right) \wedge$
    $\left(f_i \wedge \neg f_{i+1} \implies \left(\bigvee_{\{a \in A \mid f_i \in E^-(a_i)\}} a_i\right)\right)$
  - **Explanatory frame axioms - set of propositions that enumerate the set of actions that could have occurred in order to account for a state change.**

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  - $C_4 : \left(\neg f_i \wedge f_{i+1} \implies \left(\bigvee_{\{a \in A \mid f_i \in E^+(a_i)\}} a_i\right)\right) \wedge$
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  - **Explanatory frame axioms - set of propositions that enumerate the set of actions that could have occurred in order to account for a state change.**
- **Complete exclusion axiom - only one action occurs at each step.**

# SAT encoding

- **Formula is built with these five kinds of sets of formulas:**

- **Initial state:**
  - $C_1 : \left(\bigwedge_{f \in s_0} f_0\right) \wedge \left(\bigwedge_{f \notin s_0} \neg f_0\right)$
- **Goal state:**
  - $C_2 : \left(\bigwedge_{f \in g^+} f_T\right) \wedge \left(\bigwedge_{f \in g^-} f_T\right)$
- **Action**
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- Need to check satisfiability of $C_1 \wedge C_2 \wedge C_3 \wedge C_4 \wedge C_5$

# Excercise

- **Consider a simple example where we have one robot $r$ and two locations $l_1$ and $l_2$. Let us suppose that the robot can move between the two locations. In the initial state, the robot is at $l_1$; in the goal state, it is at $l_2$. The operator that moves the robot is: Action:** $move(r, l, l')$**, Precond:** $At(r, l)$**, Effects:** $At(r, l'), \neg At(r, l)$**. In this planning problem, a plan of length 1 is enough to reach the goal state. Write the constraints.**

# Summary

- **Search involving logic along with change of state**
- **We looked into planning problem where the environment is fully observable, deterministic and static**
- **We looked into planning graph and SAT based planning**
- **Application domains - robotics, autonomous systems, etc.**

*Thank you!*