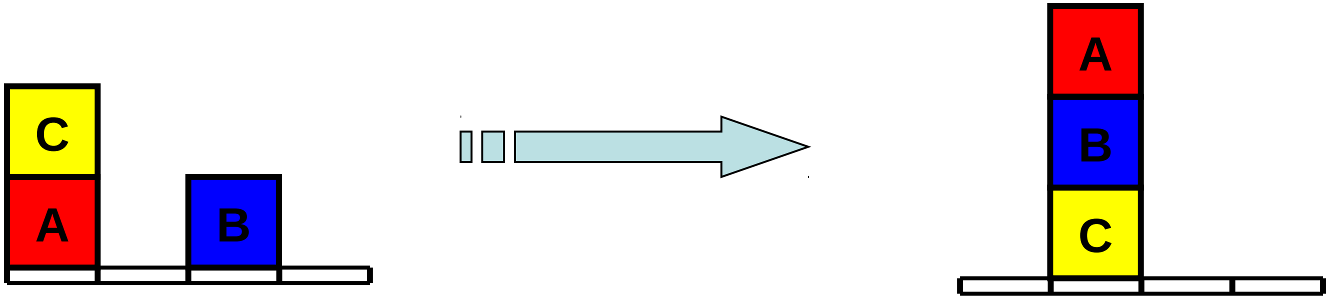
Planning Problems

Want a sequence of actions to turn a start state into a goal state

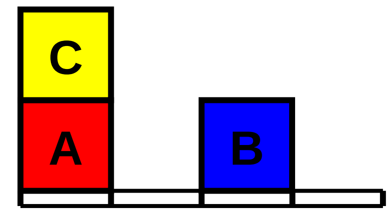


Unlike generic search, states and actions have internal structure, which allows better search methods

This slide deck courtesy of Dan Klein at UC Berkeley

State Space

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

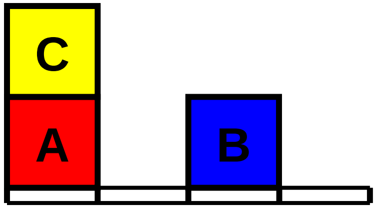


Representation

- States described by propositions or ground predicates
- Sparse encoding (database semantics): all unstated literals are false
- Unique names: each object has its own single symbol

Actions

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

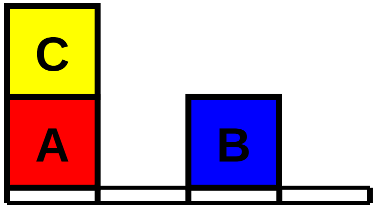


ACTION: Move(b,x,y)
PRECONDITIONS: On(b,x), Clear(b), Clear(y)
POSTCONDITIONS: On(b,y), Clear(x)
¬On(b,x), ¬Clear(y)

ACTION: Move(C,A,Table)
PRECONDITIONS: On(C,A), Clear(C), Clear(Table)
POSTCONDITIONS: On(C,Table), Clear(A)
¬On(C,A), ¬Clear(Table)

Actions

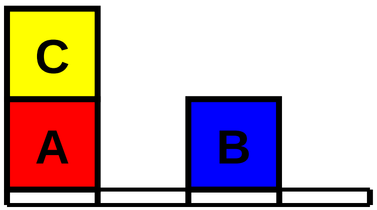
On(C, A)
On(A, Table)
On(B, Table)
Clear(C)
Clear(B)



ACTION: MoveToBlock(b,x,y)
PRECONDITIONS: On(b,x), Clear(b), Clear(y), Block(b), Block(y), $(b \neq x)$, $(b \neq y)$, $(x \neq y)$
POSTCONDITIONS: On(b,y), Clear(x) $\neg$On(b,x), $\neg$Clear(y)

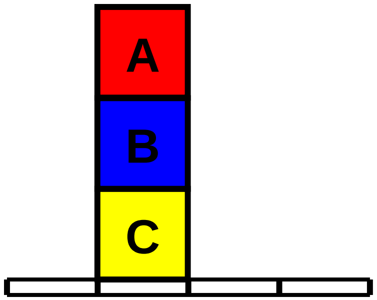
ACTION: MoveToTable(b,x)
PRECONDITIONS: On(b,x), Clear(b), Block(b), Block(x), $(b \neq x)$
POSTCONDITIONS: On(b,Table), Clear(x) $\neg$On(b,x)

Start and Goal States



Start State

On(C, A)
On(A, Table)
On(B, Table)
Clear(C)
Clear(B)
Block(A)
…



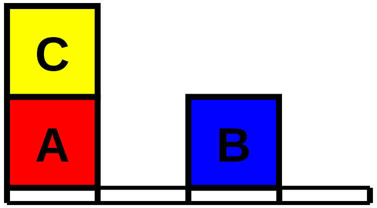
Goal State

On(B, C)
On(A, B)

Important: goal satisfied by any state which entails goal list

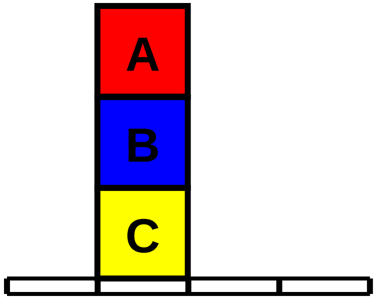
[MoveToTable(C,A), Move(B,Table,C), Move(A,Table,B)]

Planning Problems



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

Sparse encoding, but complete state spec



Goal

Set of goal states, only requirements specified (think unary constraints)

On(B, C)
On(A, B)

Action schema, instantiates to give specific ground actions

Which goal first?

ACTION: MoveToTable(b,x)
PRECONDITIONS: On(b,x), Clear(b), Block(b), Block(x), $(b \neq x)$
POSTCONDITIONS: On(b,Table), Clear(x)
$\neg$On(b,x)

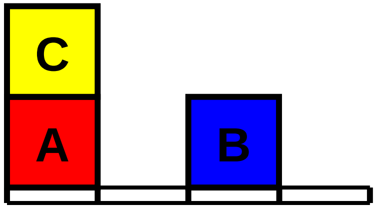
Practice

Problem 10.2: “Applicable”

Problem 10.3a,b: Representation

- Where do they come from?
- Could they be learned?

Kinds of Plans



Start State

On(C, A)
On(A, Table)
On(B, Table)
Clear(C)
Clear(B)
Block(A)
…

Sequential Plan

MoveToTable(C,A) > Move(B,Table,C) > Move(A,Table,B)

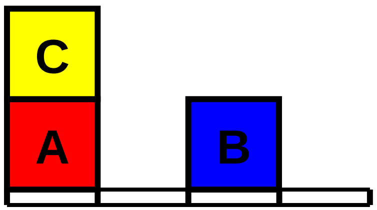
Partial-Order Plan

MoveToTable(C,A)

> Move(A,Table,B)]

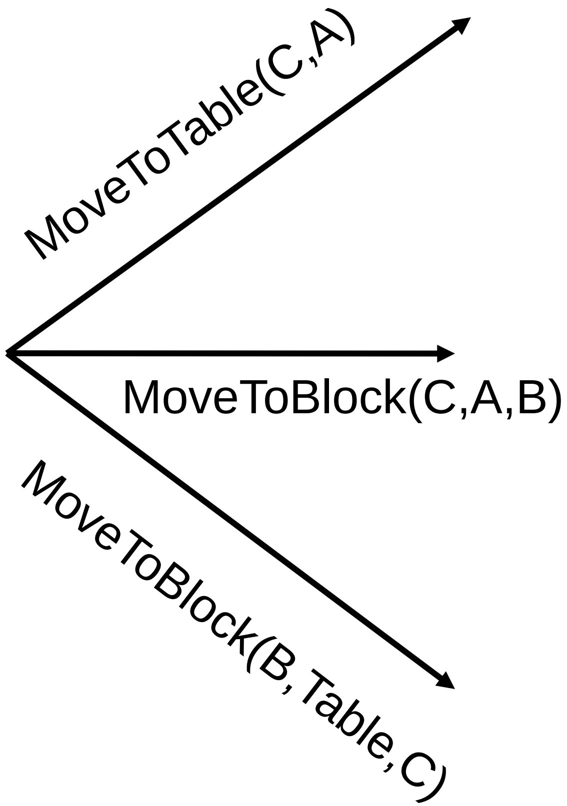
Move(B,Table,C)

Forward Search



Start State

On(C, A)
On(A, Table)
On(B, Table)
Clear(C)
Clear(B)
Block(A)
…



~~On(C, A)~~
On(A, Table)
On(B, Table)
Clear(C)
Clear(B)
Block(A)
…
+Clear(A)
+On(C, Table)

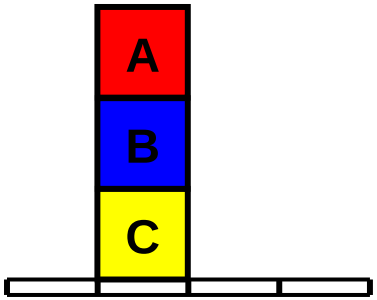
Applicable actions

Backward Search

ACTION: MoveToBlock(b,x,y)
PRECONDITIONS: On(b,x), Clear(b), Clear(y), Block(b), Block(y), $(b \neq x)$, $(b \neq y)$, $(x \neq y)$
POSTCONDITIONS: On(b,y), Clear(x) $\neg$On(b,x), $\neg$Clear(y)

MoveToBlock(A,Table,B)

MoveToBlock(A,x’,B)



Goal State

On(B, C)
On(A, B)

On(B, C)
~~On(A, B)~~
+On(A,Table)
+Clear(A)
+Clear(B)
+…

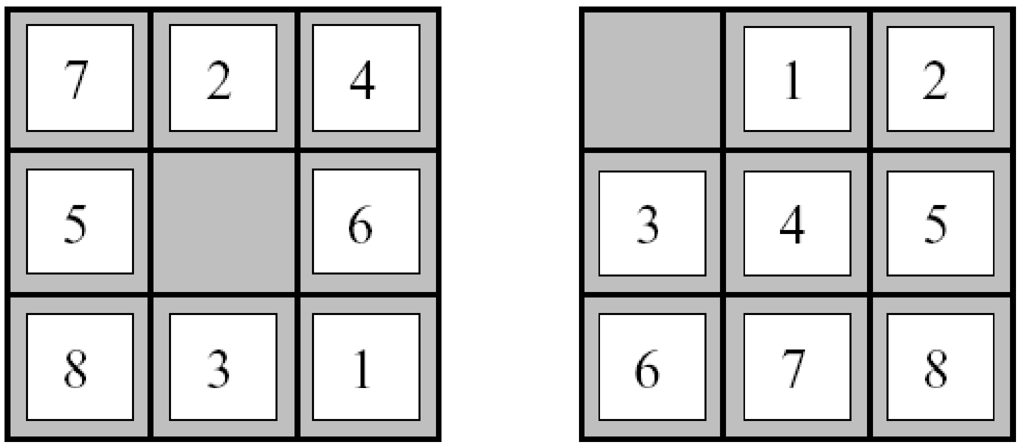
Relevant actions

$$g' = (g - \text{ADD}(a)) \cup Precond(a)$$

Heuristics: Ignore Preconditions

Relax problem by ignoring preconditions

- Can drop all or just some preconditions
- Can solve in closed form or with set-cover methods



Start State Goal State

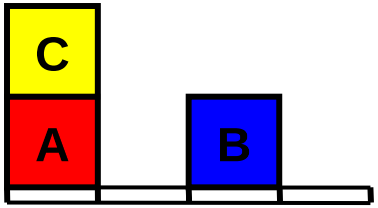
$$
\begin{aligned}
&Action(Slide(t, s_1, s_2),\\
&\quad \text{PRECOND:} \, On(t, s_1) \land Tile(t) \land Blank(s_2) \land Adjacent(s_1, s_2)\\
&\quad \text{EFFECT:} \, On(t, s_2) \land Blank(s_1) \land \neg On(t, s_1) \land \neg Blank(s_2))
\end{aligned}
$$

Heuristics: No-Delete

Relax problem by not deleting falsified literals

Can't undo progress, so solve with hill-climbing (non-admissible)

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



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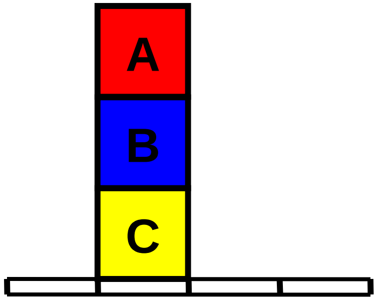
PRECONDITIONS: On(b,x), Clear(b), Clear(y), Block(b), Block(y), $(b \neq x)$, $(b \neq y)$, $(x \neq y)$
POSTCONDITIONS: On(b,y), Clear(x) $\neg$On(b,x), $\neg$Clear(y)

Heuristics: Independent Goals

Independent subgoals?

- Partition goal literals
- Find plans for each subset
- cost(all) < cost(any)?
- cost(all) < sum-cost(each)?



Goal State

On(B, C)
On(A, B)

On(A, B)

On(B, C)

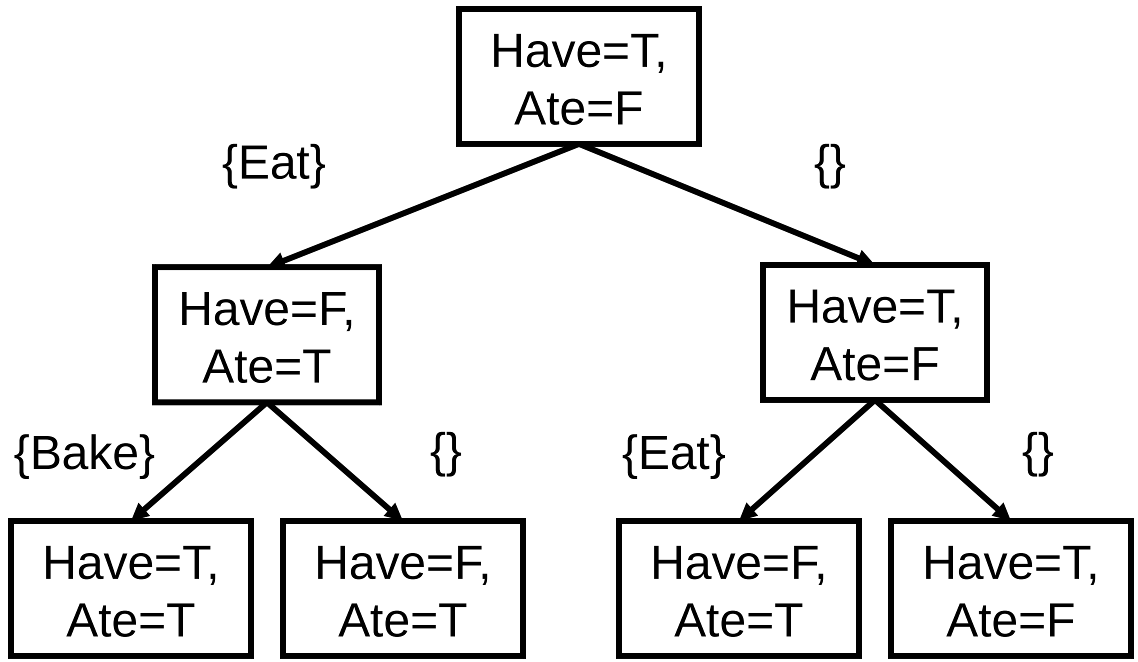
Planning "Tree"

Start: HaveCake

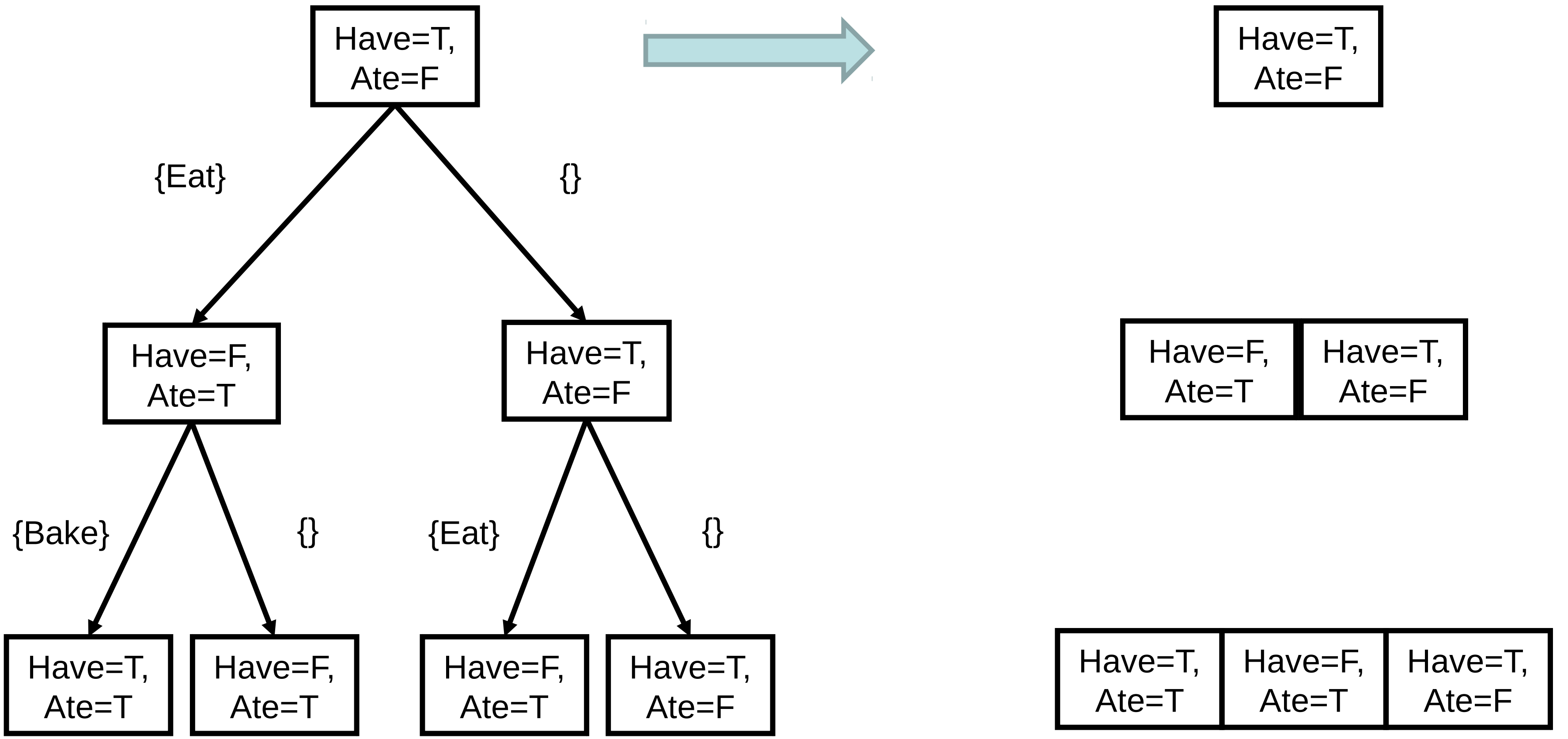
Goal: AteCake, HaveCake

Action: Eat
Pre: HaveCake
Add: AteCake
Del: HaveCake

Action: Bake
Pre: $\neg$HaveCake
Add: HaveCake



Reachable State Sets



Approximate Reachable Sets

Have=T, Ate=F	Have={T}, Ate={F}	
Have=F, Ate=T ; Have=T, Ate=F	Have={T,F}, Ate={T,F}	(Have, Ate) not (T,T) (Have, Ate) not (F,F)
Have=T, Ate=T ; Have=F, Ate=T ; Have=T, Ate=F	Have={T,F}, Ate={T,F}	(Have,Ate) not (F,F)

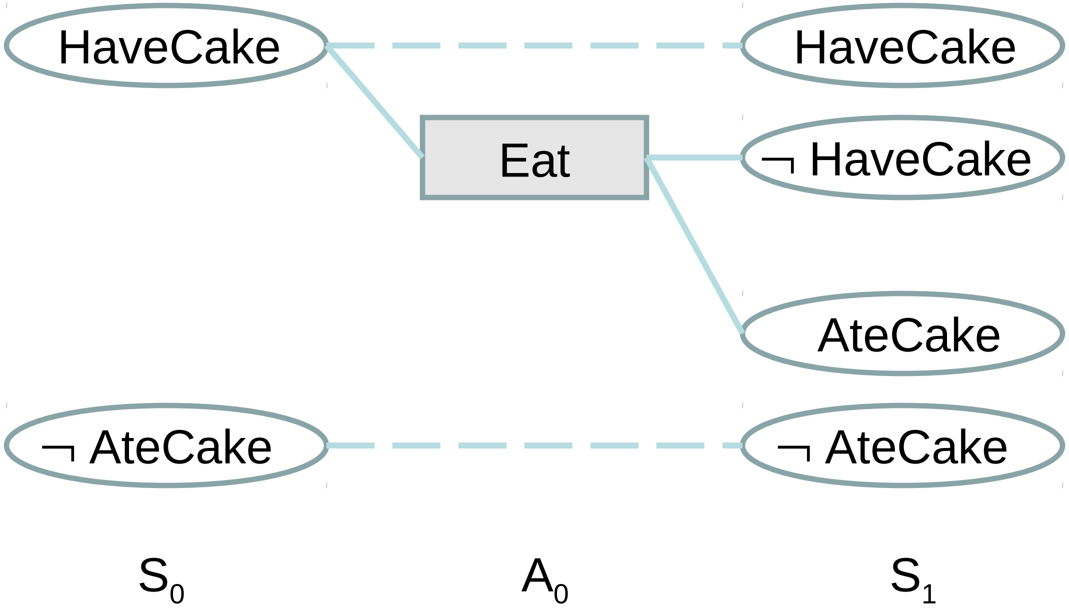
Planning Graphs

Start: HaveCake

Goal: AteCake, HaveCake

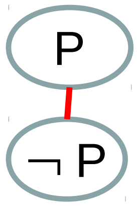
Action: Eat
Pre: HaveCake
Add: AteCake
Del: HaveCake

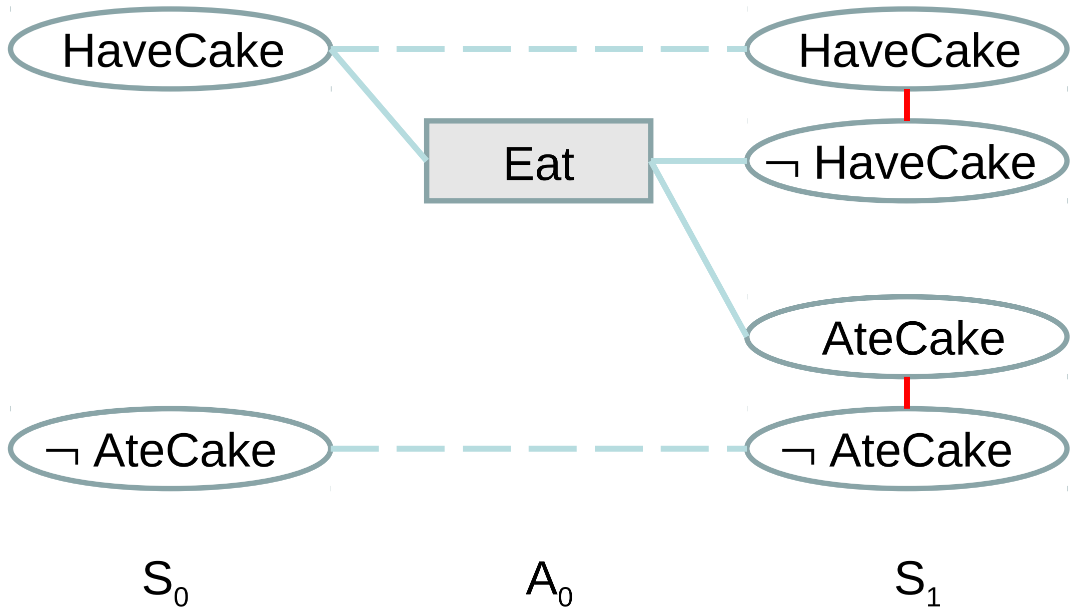
Action: Bake
Pre: ¬HaveCake
Add: HaveCake



Mutual Exclusion (Mutex)

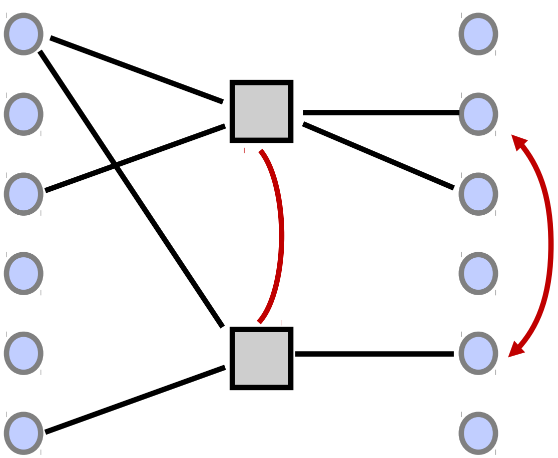
NEGATION
Literals and their negations can't be true at the same time

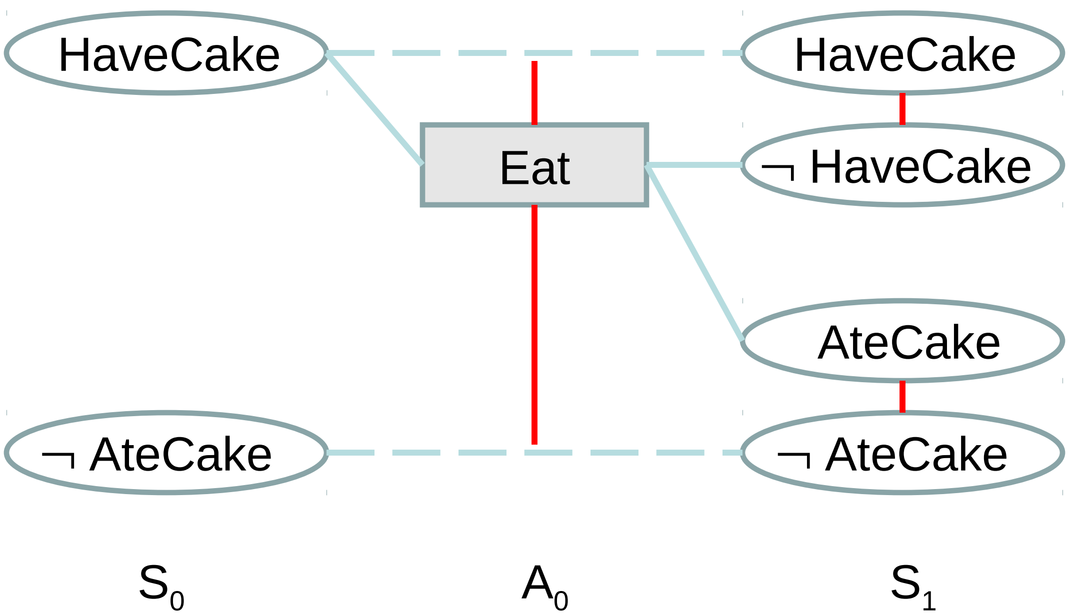




Mutual Exclusion (Mutex)

INCONSISTENT EFFECTS
An effect of one negates the other effect of the other

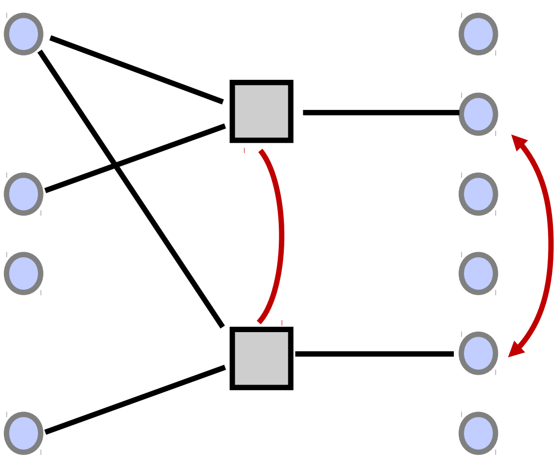


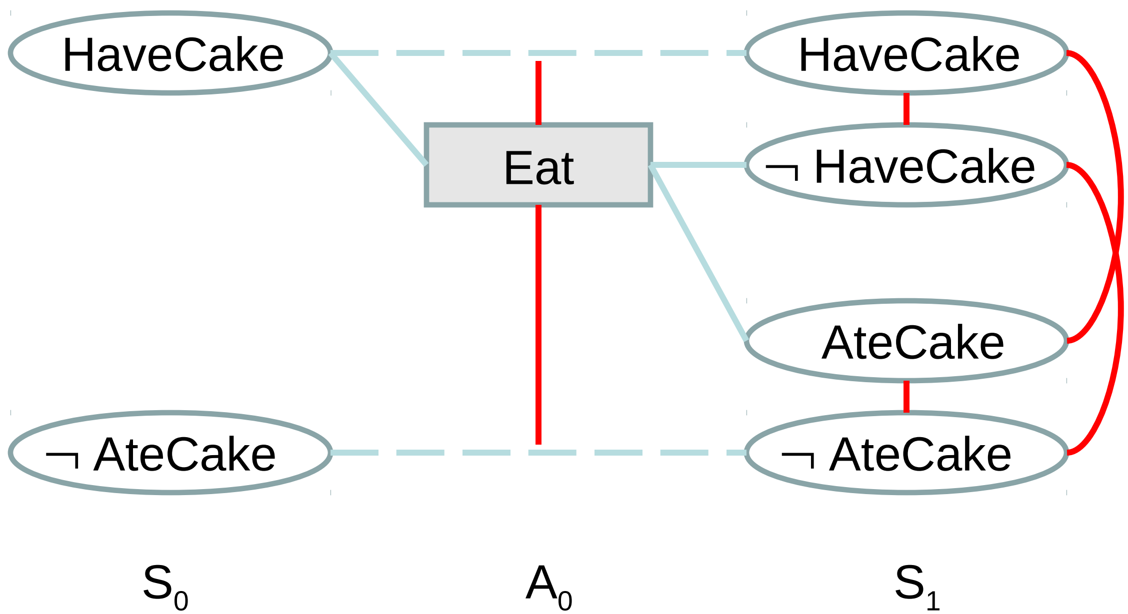


Mutual Exclusion (Mutex)

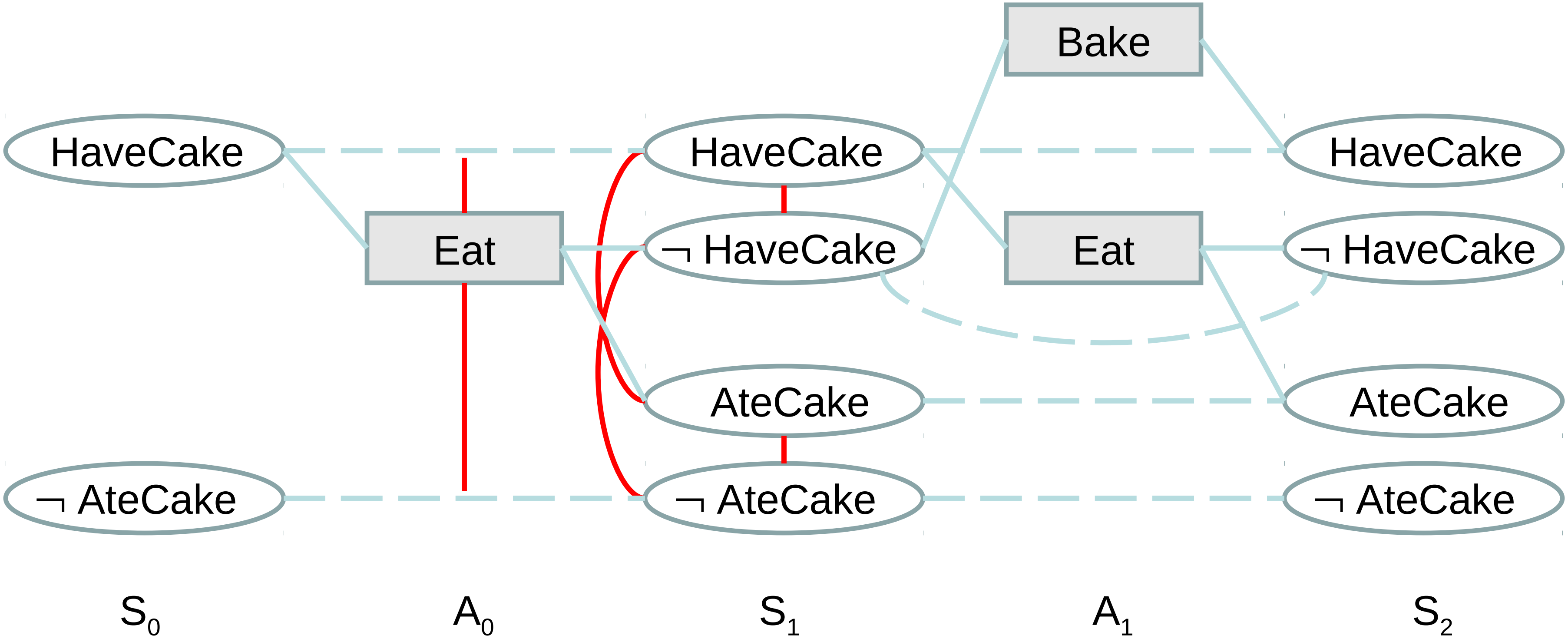
INCONSISTENT SUPPORT

All pairs of actions that achieve two literals are mutex



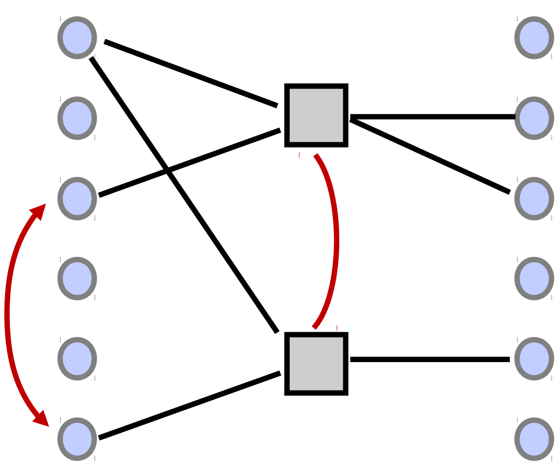


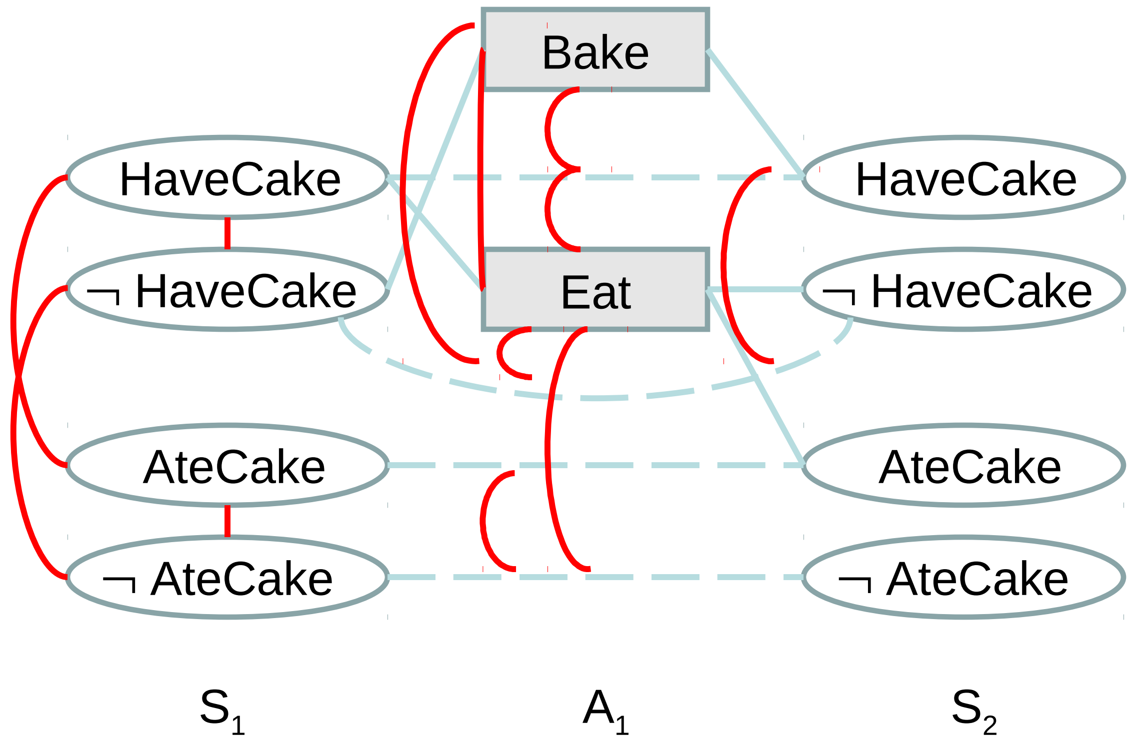
Planning Graph



Mutual Exclusion (Mutex)

COMPETITION
Preconditions are mutex; cannot both hold

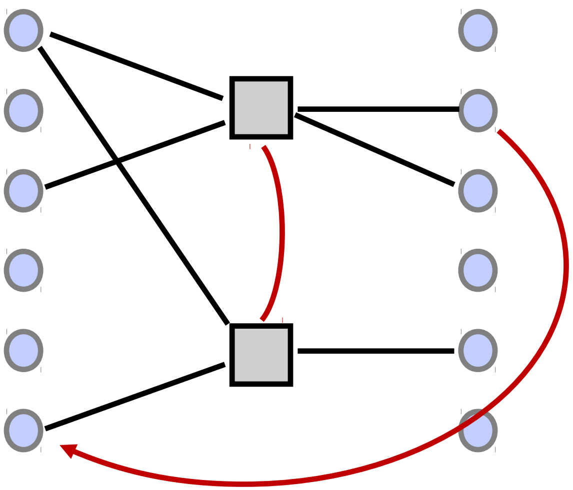


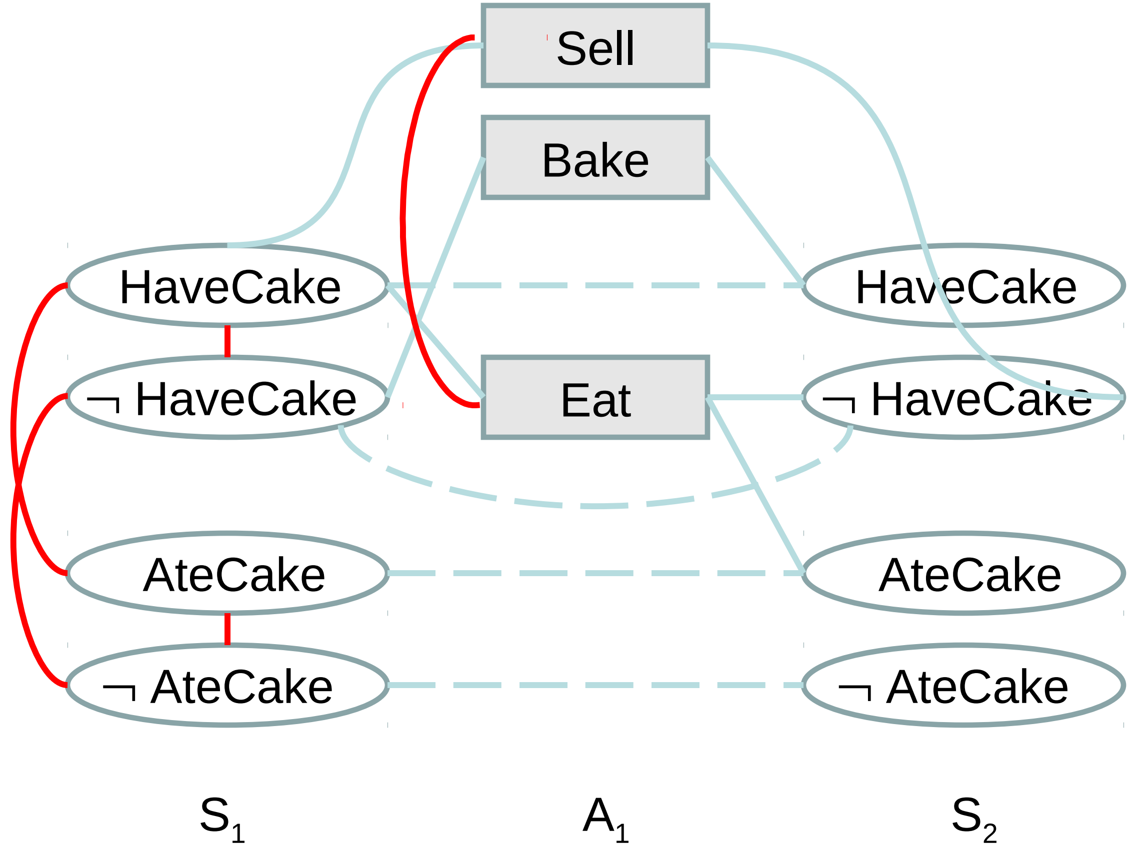


INCONSISTENT EFFECTS
An effect of one negates the effect of the other

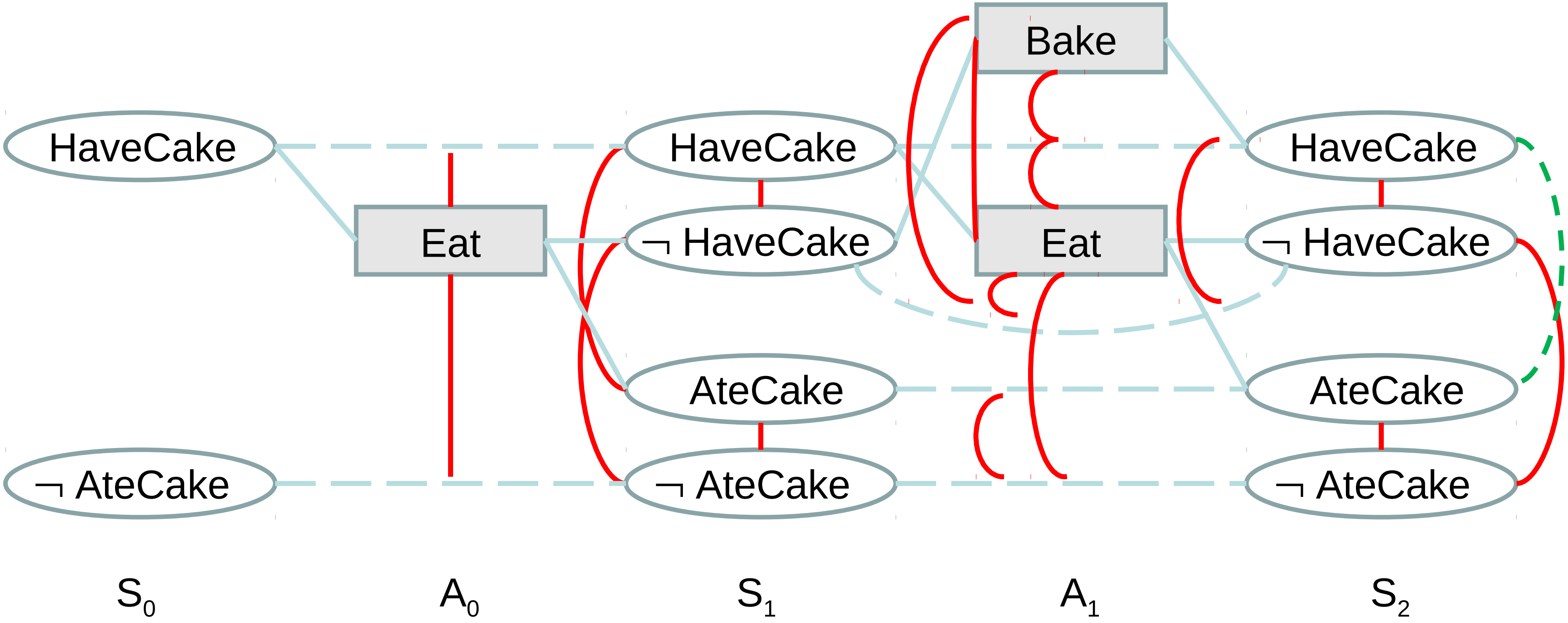
Mutual Exclusion (Mutex)

INTERFERENCE
One deletes a precondition of the other

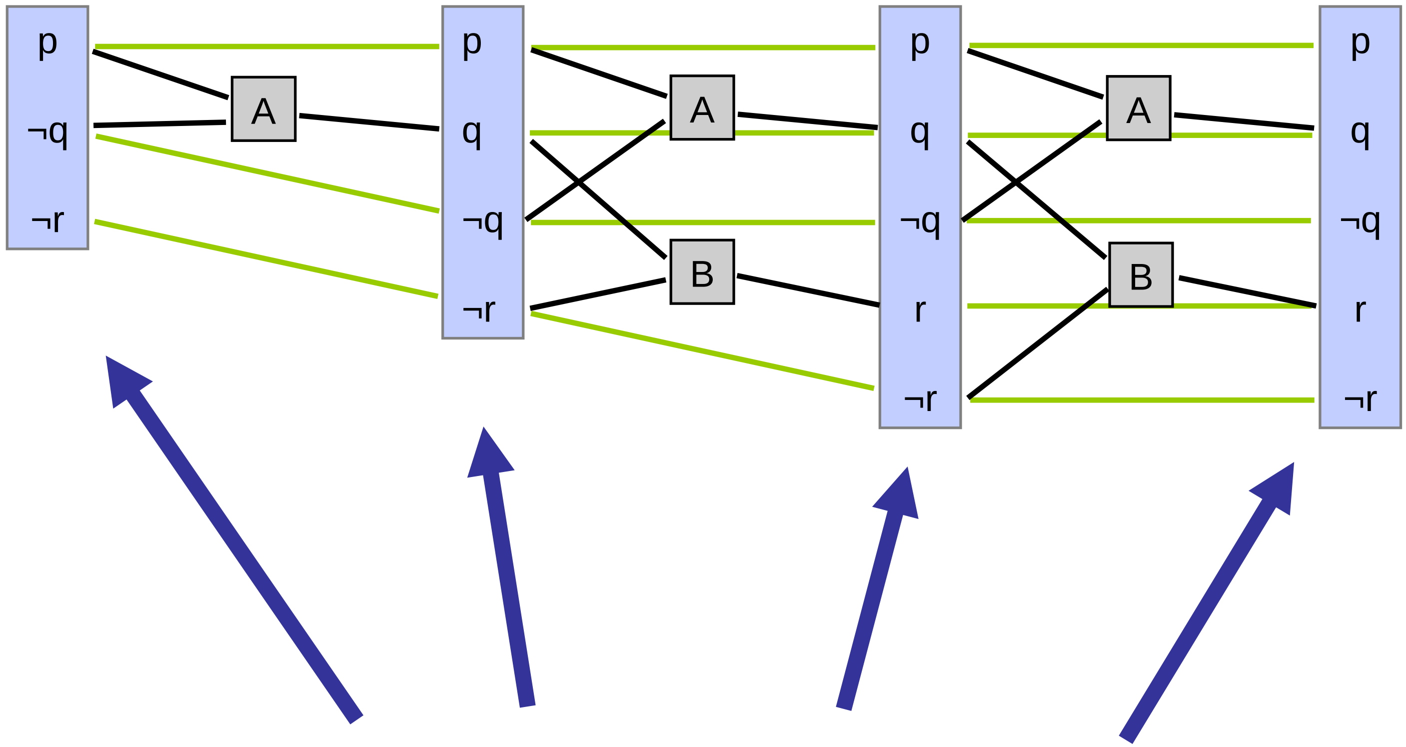




Planning Graph

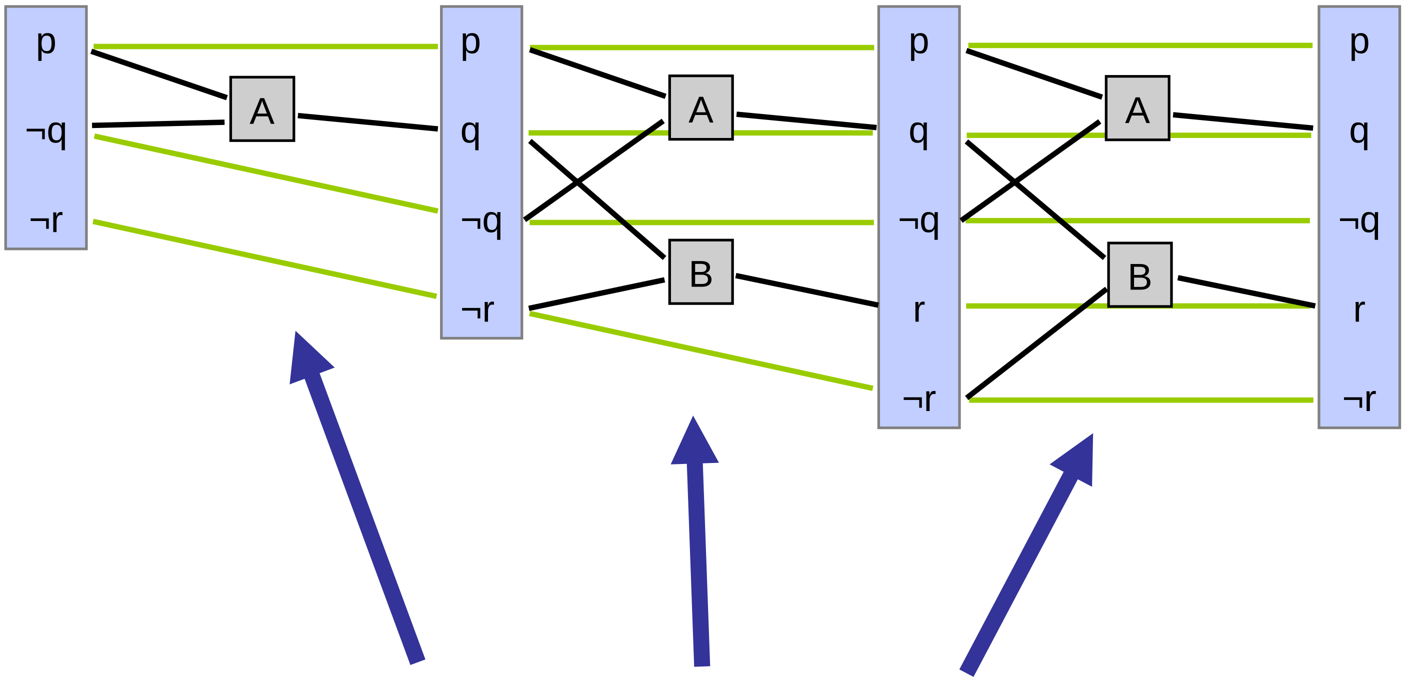


Observation 1



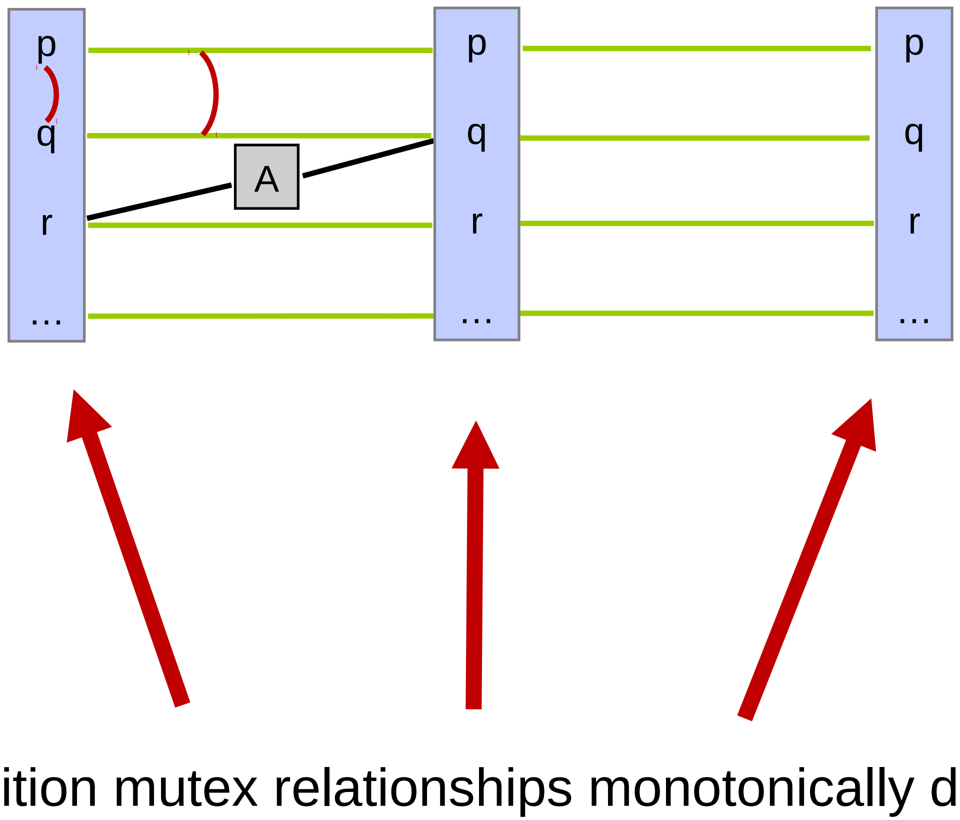
Propositions monotonically increase
(always carried forward by no-ops)

Observation 2



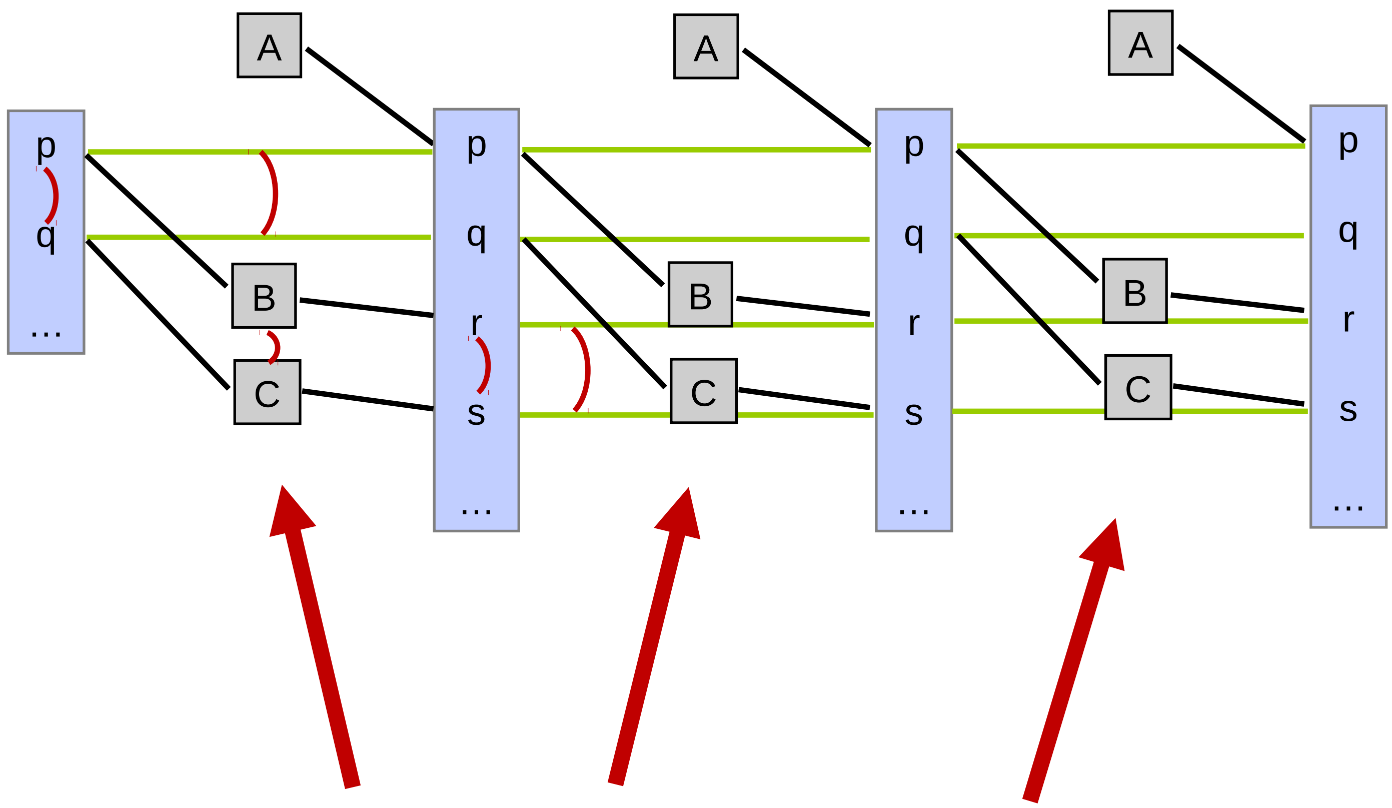
Actions monotonically increase
(if they applied before, they still do)

Observation 3



Proposition mutex relationships monotonically decrease

Observation 4



Action mutex relationships monotonically decrease

Observation 5

Claim: planning graph “levels off”

- After some time k all levels are identical
- Because it’s a finite space, the set of literals cannot increase indefinitely, nor can the mutexes decrease indefinitely

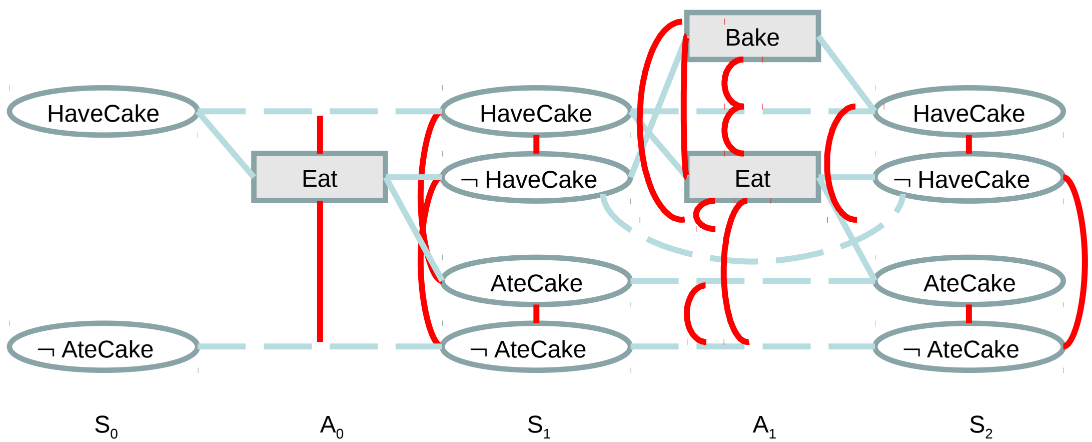
Claim: if goal literal never appears, or goal literals never become non-mutex, no plan exists

- If a plan existed, it would eventually achieve all goal literals (and remove goal mutexes – less obvious)
- Converse not true: goal literals all appearing non-mutex does not imply a plan exists

Heuristics: Level Costs

Planning graphs enable powerful heuristics

- Level cost of a literal is the smallest S in which it appears
- Max-level: goal cannot be realized before largest goal conjunct level cost (admissible)
- Sum-level: if subgoals are independent, goal cannot be realized faster than the sum of goal conjunct level costs (not admissible)
- Set-level: goal cannot be realized before all conjuncts are non-mutex (admissible)



Graphplan

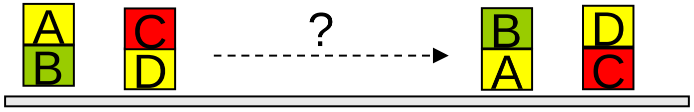
Graphplan directly extracts plans from a planning graph

Graphplan searches for **layered plans** (often called parallel plans)

- More general than totally-ordered plans, less general than partially-ordered plans

A layered plan is a sequence of **sets** of actions

- actions in the same set must be compatible
- all sequential orderings of compatible actions gives same result

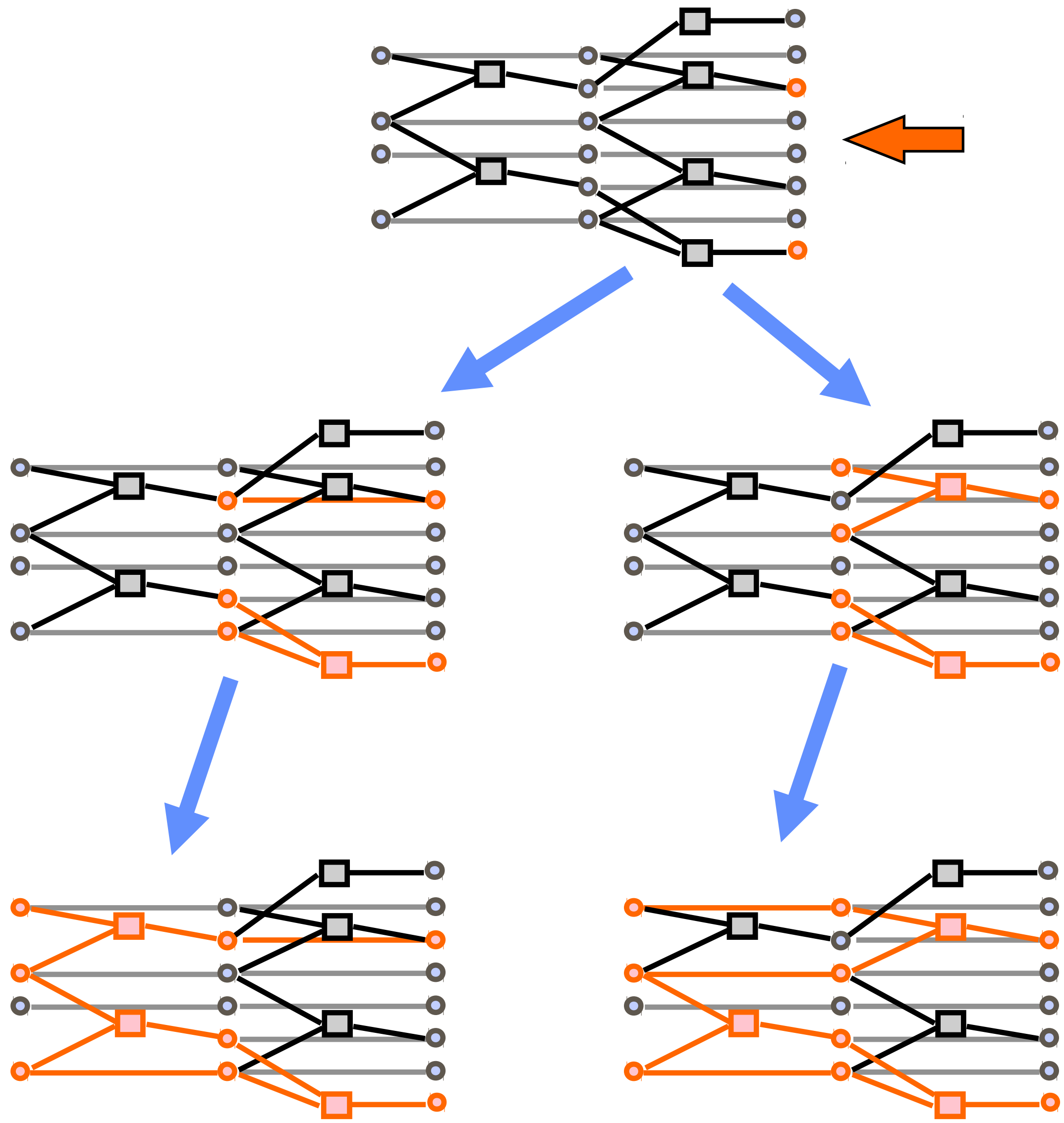


Layered Plan: (a two layer plan)

$$\left\{ \begin{array}{l} \text{move(A,B,TABLE)} \\ \text{move(C,D,TABLE)} \end{array} \right\} ; \left\{ \begin{array}{l} \text{move(B,TABLE,A)} \\ \text{move(D,TABLE,C)} \end{array} \right\}$$

Solution Extraction: Backward Search

Search problem:
- **Start state: goal set at last level**
- **Actions: conflict-free ways of achieving the current goal set**
- **Terminal test: at S_0 with goal set entailed by initial planning state**



Note: may need to start much deeper than the leveling-off point!

Caching, good ordering is important

Scheduling

In real planning problems, actions take time, resources

- Actions have a duration (time to completion, e.g. building)
- Actions can consume (or produce) resources (or both)
- Resources generally limited (e.g. minerals, SCVs)

Simple case: known (partial) plan, just need to schedule

Even simpler: no resources, just ordering and duration

JOBS

[AddEngine1 < AddWheels1 < Inspect1]
[AddEngine2 < AddWheels2 < Inspect2]

RESOURCES

EngineHoists (1)
WheelStations (1)
Inspectors (2)

ACTIONS

AddEngine1: DUR=30, USE=EngHoist(1)
AddEngine2: DUR=60, USE=EngHoist(1)
AddWheels1: DUR=30, USE=WStation(1)
AddWheels2: DUR=15, USE=WStation(1)
Inspect1: DUR=10, USE=Inspectors(1)
Inspect2: DUR=10, USE=Inspectors(1)

Resource-Free Scheduling

JOBS
[AddEngine1 < AddWheels1 < Inspect1]
[AddEngine2 < AddWheels2 < Inspect2]

RESOURCES
EngineHoists (1)
WheelStations (1)
Inspectors (2)

ACTIONS
AddEngine1: DUR=30, USE=EngHoist(1)
AddEngine2: DUR=60, USE=EngHoist(1)
AddWheels1: DUR=30, USE=WStation(1)
AddWheels2: DUR=15, USE=WStation(1)
Inspect1: DUR=10, USE=Inspectors(1)
Inspect2: DUR=10, USE=Inspectors(1)

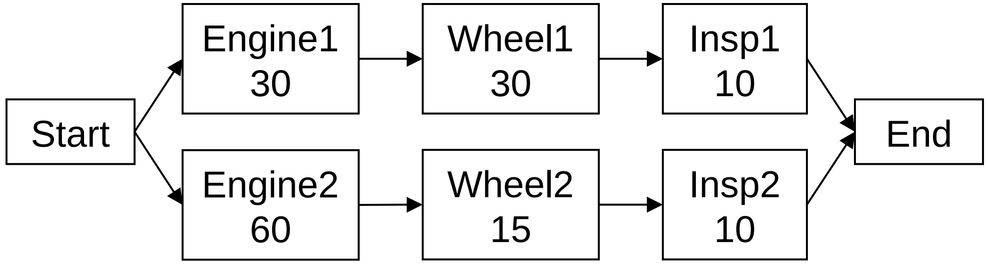
How to minimize total time?

Easy: schedule an action as soon as its parents are completed

$$ES(START) = 0$$

$$ES(a) = \max_{b:b \prec a} ES(b) + DUR(b)$$

Result:



Resource-Free Scheduling

JOBS
[AddEngine1 < AddWheels1 < Inspect1]
[AddEngine2 < AddWheels2 < Inspect2]

RESOURCES
EngineHoists (1)
WheelStations (1)
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AddWheels1: DUR=30, USE=WStation(1)
AddWheels2: DUR=15, USE=WStation(1)
Inspect1: DUR=10, USE=Inspectors(1)
Inspect2 DUR=10, USE=Inspectors(1)

Note there is always a critical path

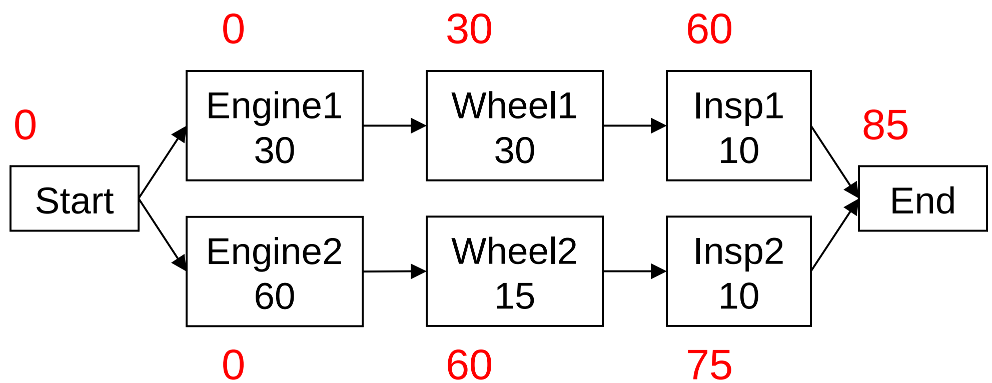
All other actions have slack

Can compute slack by computing latest start times

$$LS(END) = ES(END)$$

$$LS(a) = \min_{b:a \prec b} LS(b) - DUR(a)$$

Result:



Adding Resources

For now: consider only released (non-consumed) resources

View start times as variables in a CSP

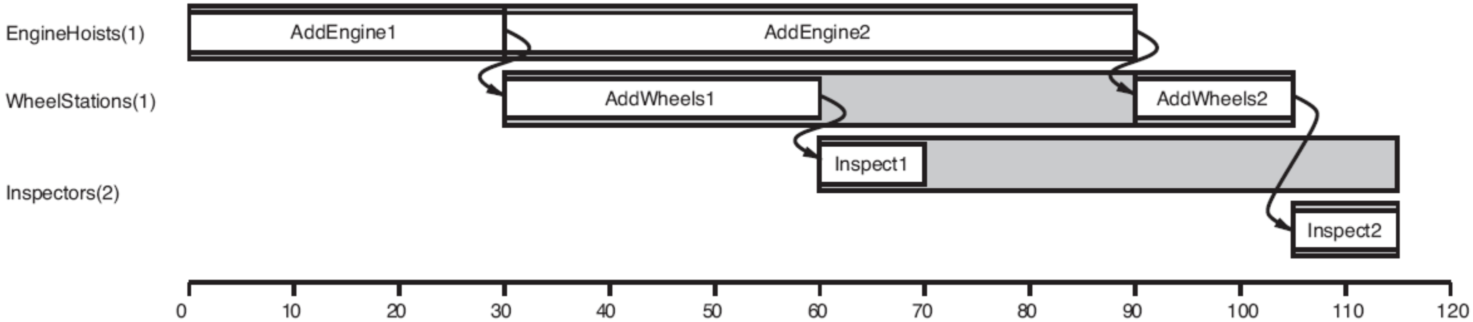
Before: conjunctive linear constraints

$$\forall b : b \prec a \quad ES(a) \geq ES(b) + DUR(b)$$

Now: disjunctive constraints (competition)

$$\begin{aligned}&\text{if competing}(a, b)\\ &\quad ES(a) \geq ES(b) + DUR(b) \vee\\ &\quad ES(b) \geq ES(a) + DUR(a)\end{aligned}$$

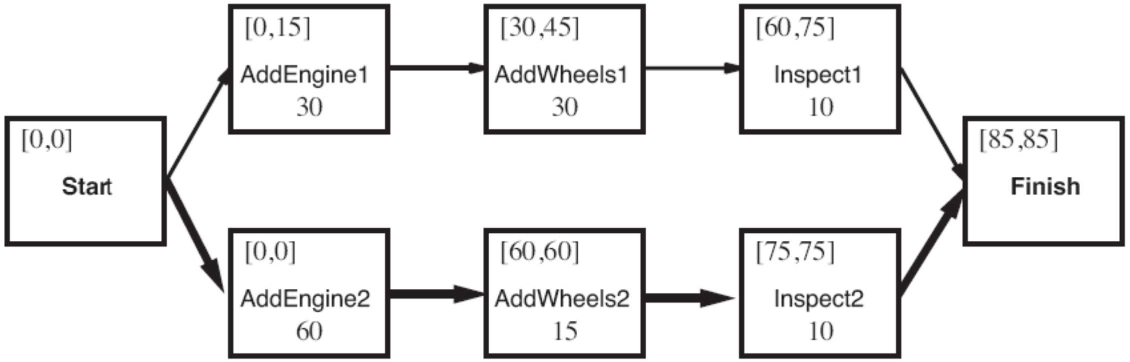
In general, no efficient method for solving optimally



Adding Resources

One greedy approach: min slack algorithm

- Compute ES, LS windows for all actions
- Consider actions which have all preconditions scheduled
- Pick the one with least slack
- Schedule it as early as possible
- Update ES, LS windows (recurrences now must avoid reservations)



Resource Management

Complications:

- Some actions need to happen at certain times
- Consumption and production of resources
- Planning and scheduling generally interact

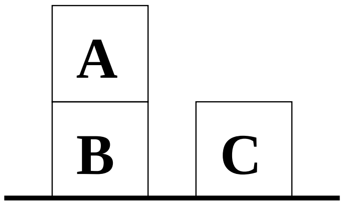
Prodigy

- A classical STRIPS-style planner
  - Domain Representation: objects, operators
  - Problem Representation: initial state, goal state
- Operators have preconditions and effects

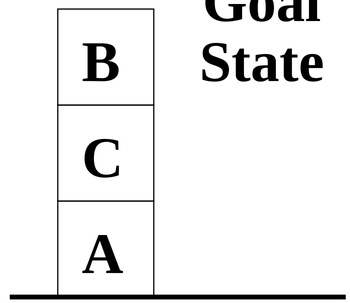
Example – Blocksworld

(On A B)
(On B Table)
(On C Table)
(Clear A)
(Clear C)
(Clear Table)
(Arm−empty)

Initial State



Goal State



(On C A)
(On B C)

[+ whatever]

Operators:

(Pickup x)

preconds: (Clear x)
(Arm−empty)

adds: (Holding x)
if (On x y), (Clear y)

dels: (Arm−empty)
if (On x y), (On x y)

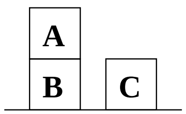
(Putdown x y)

preconds: (Holding x)
(Clear y)

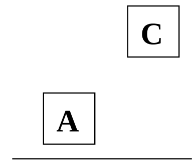
adds: (On x y)
(Arm−empty)

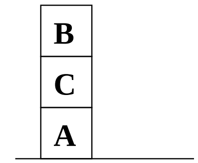
dels: (Holding x)
if (y != Table), (Clear y)

Prodigy/Blocksworld (cont.)



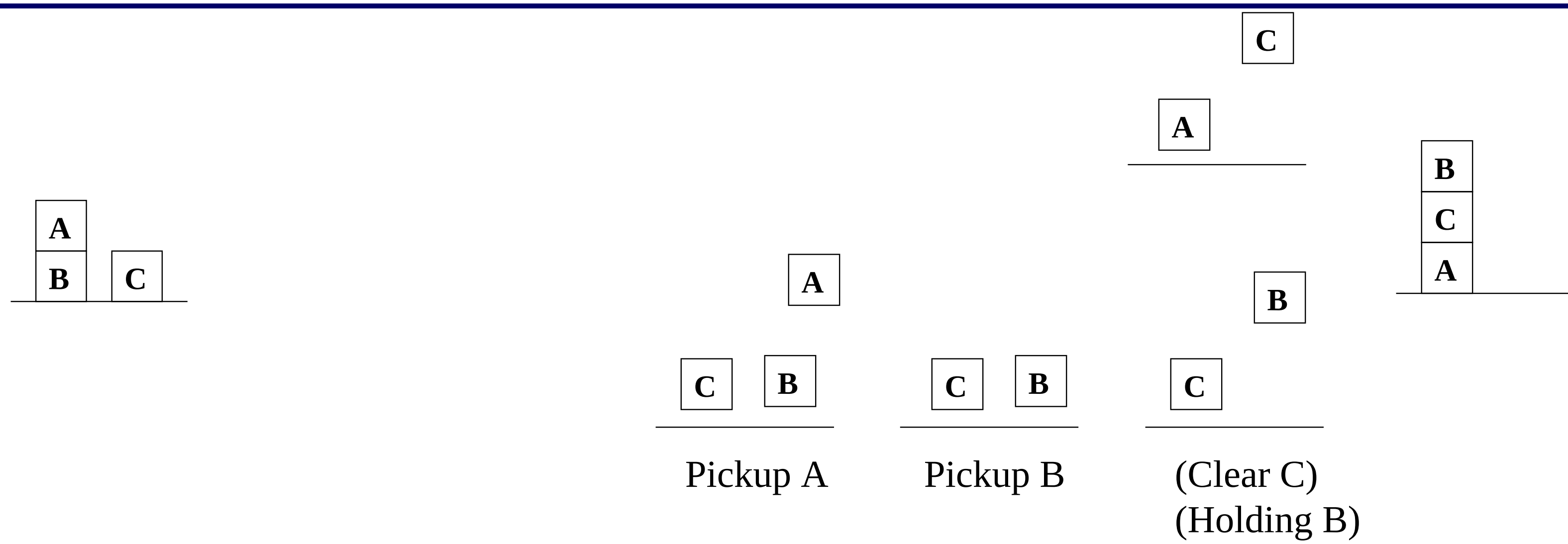
Putdown C A
(Holding C)
(Clear A)



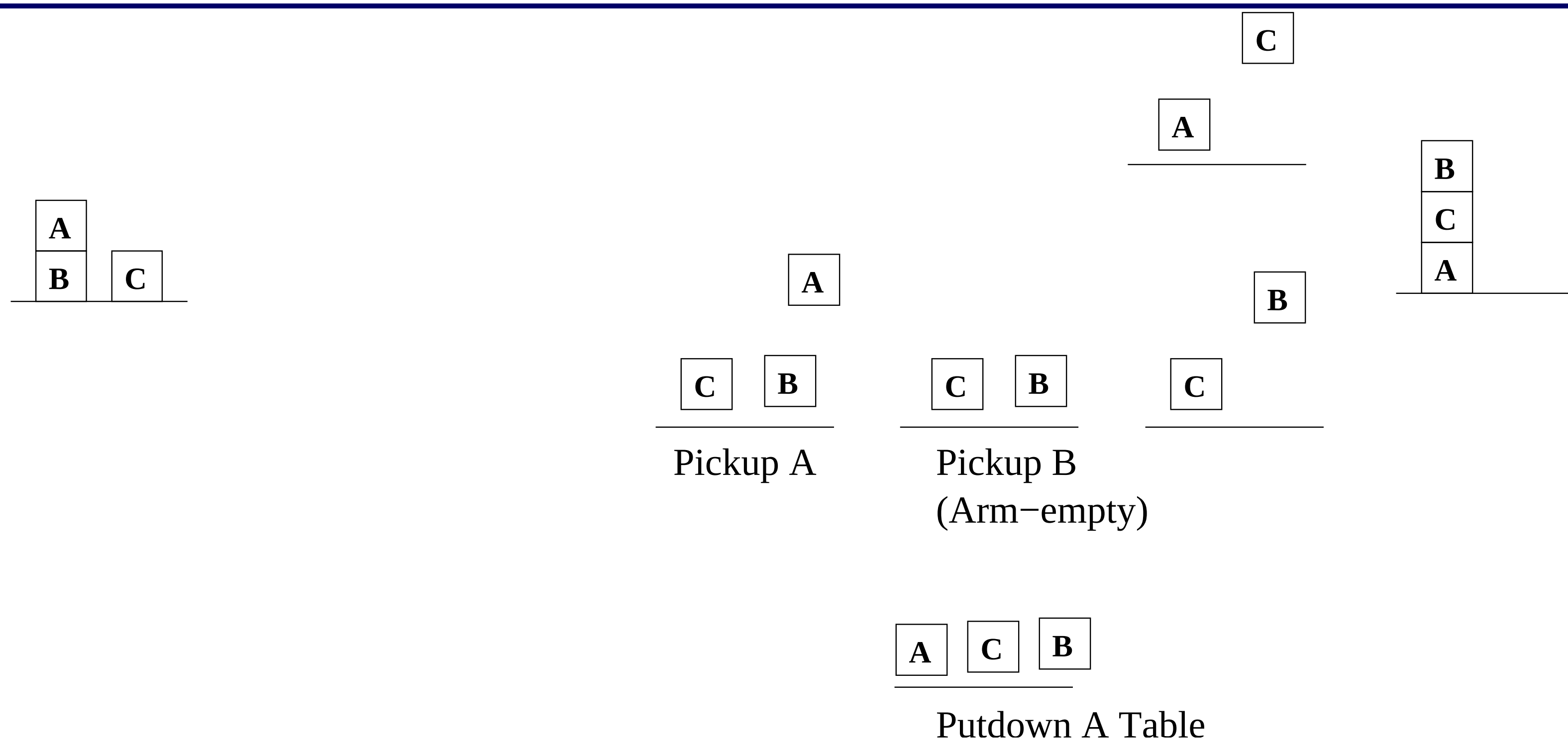


(On C A)
(On B C)

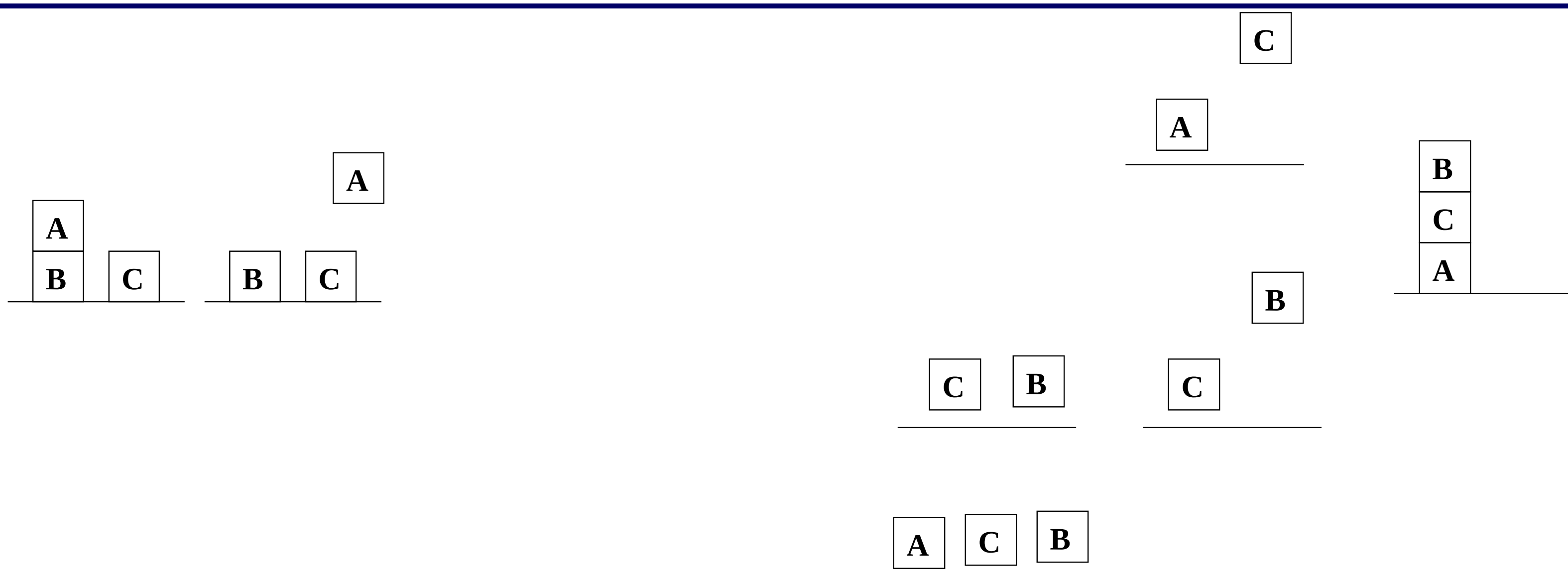
Prodigy/Blocksworld (cont.)



Prodigy/Blocksworld (cont.)

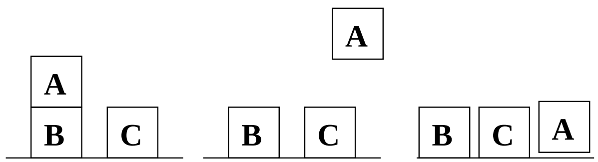


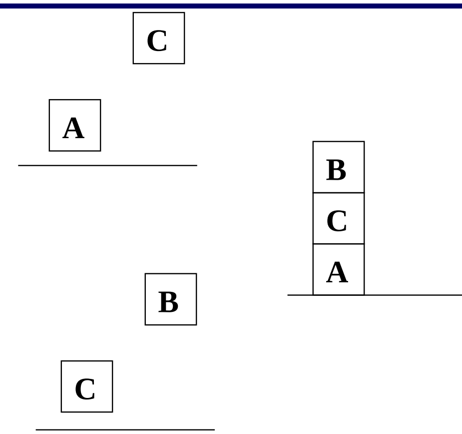
Prodigy/Blocksworld (cont.)



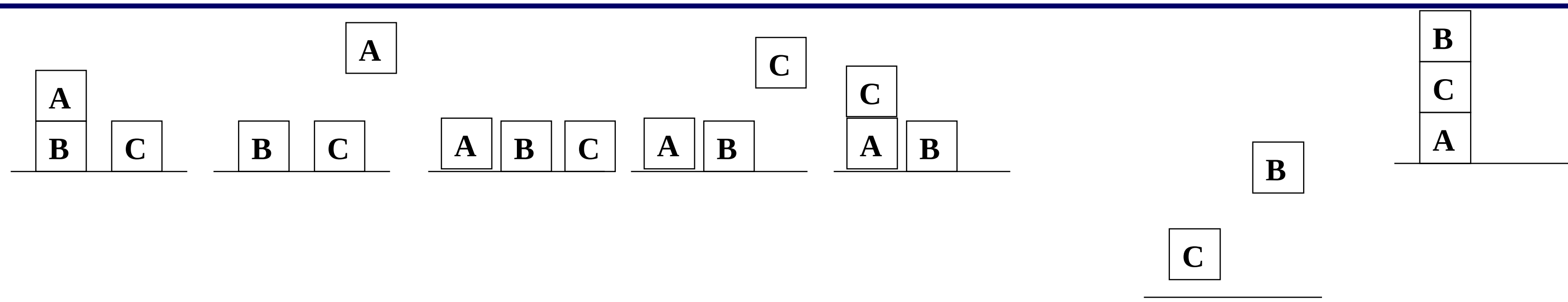
Putdown A Table

Prodigy/Blocksworld (cont.)





Prodigy/Blocksworld (cont.)



Issues in Planning

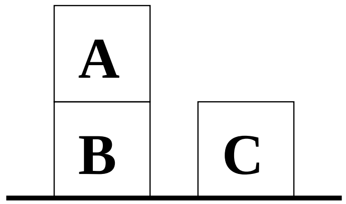
- Representations
- Algorithms
- Conditional effects
- Dynamic worlds
- Mixing planning and execution
- Learning
- Large-scale applications

Fairly mature field

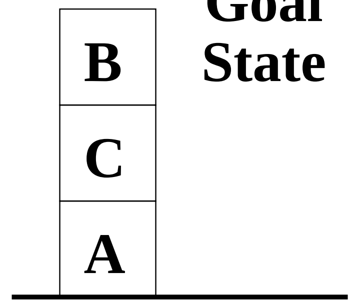
Example – Blocksworld

(On A B)
(On B Table)
(On C Table)
(Clear A)
(Clear C)
(Clear Table)
(Arm−empty)

Initial State



Goal State



(On C A)
(On B C)

[+ whatever]

Operators:

(Pickup x)

preconds: (Clear x)
(Arm−empty)

adds: (Holding x)
if (On x y), (Clear y)

dels: (Arm−empty)
if (On x y), (On x y)

(Putdown x y)

preconds: (Holding x)
(Clear y)

adds: (On x y)
(Arm−empty)

dels: (Holding x)
if (y != Table), (Clear y)