

The following is an unedited, and unpolished compilation of notes from a planning seminar that I ran at Arizona State University in the spring of 94. The seminar turned out to be mostly about classical planning techniques. In each class meeting, a designated student took notes and mailed them to the class. A compilation of these notes appears below. Notes from spring of 93 are also available in the ftp site at enws318.eas.asu.edu:pub/rao. A couple of times, interesting mails from outside colleagues were cc'd to the list.

Subbarao Kambhampati
[Jun 22, 1994]

Classical Planning:

Compilation of notes from a
Seminar course held at ASU in Spring 93

by

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Working Notes, ASU-CS-TR 94-008

(Please send mail to rao@asuvax.asu.edu, if you
retrieve this document. Thanks.)

From daemon Wed Jan 26 11:44:36 MST 1994
 Return-Path: huson@enuxsa.eas.asu.edu
 Return-Path: <huson@enuxsa.eas.asu.edu>
 Received:
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 From: Mark Huson <huson@enuxsa.eas.asu.edu>
 To: plan-class@parikalpik.eas.asu.edu
 Subject: Notes for 24 Jan 94
 Date: Wed, 26 Jan 1994 11:44:07 -0700 (MST)

Notes for 24 Jan 94 Mark L. Huson (huson@asu.edu)

Agenda
 State Space Planners
 - ProgWS
 - RegWS
 Plan Space (Partial Order) Planners

Article: "An Introduction to Partial Order Planning", Weld

Given the general problem of planning, are there better ways of modeling the problem as a search?

State Space: start with an initial state and produce all possible subsequent states by applying "applicable" actions, and repeat this process for the states generated until a (the) goal state is found.
 Plan Space: start with a null plan, and add those actions which achieve a selected subgoal, repeat until all actions required to achieve the goal state have been identified and, where necessary, ordered.

-----Planning as a Search in the Space of World States

The search space can be represented by a connectivity graph with a distinguished node representing the start state for the search. All states are connected by arcs representing atomic actions. There are two primary methods of performing search, forward search which using the initial world state as the start node for its graph, and backward search which uses the goal state.

*** see Figure 3 for a State Space connectivity graph ***

For the search problem we must have a way to describe the states. For blocks world we may have an initial state such as:

on(A, Tab)	clr(A)	\bar{A}	\bar{B}	\bar{C}
on(B, Tab)	clr(B)	-----	-----	-----
on(C, Tab)	clr(C)			

If our goal state is a conjunction { on(A, Tab) /\ clr(C) } then each time we attempt to create new states by applying actions, we first check to see if we have matched the goal state conditions. Goal states can be defined either as a fully specified state, or as an equivalence class of foal states.

Equivalence Class:	on(A, B) /\ on(B, C)
Fully specified :	on(A, B) /\ on(B, C) /\ on(C, Tab) /\ clr(A)

We also need a set of actions. These actions should contain the following information: an identification; a set of preconditions identifying states where the action is applicable; a set of effects describing the results of applying the action. For example:

identification	-	move (A-Tab-B)
preconditions	-	on(A, Tab) /\ clr(A) /\ clr(B)
effects	-	on(A, B) /\ ~on(A, Tab) /\ ~clr(B)

There are both positive and negative effects for most actions, indicating the conditions in the new state. The new state is described by the conditions of the old state, conjoined with the effects. Contradictions are resolved by setting the new states conditions to the effects.

The STRIPS assumptions is that everything changed by an action is explicitly represented in the effects list of the action.

For the ProgWS (progression world state) Algorithm, we are performing a Forward search in the state space. The forward search proceeds by selecting a state, then applying all applicable actions (those whose preconditions are met) and adding these new states to the set of states to be considered. For non-trivial domains there are many more applicable actions than there are useful actions for achieving the goal state. For this reason, forward (progression) searches usually have a large branching factor. If we know ahead of time which branch leads to the solution, then forward search is as good as any other. Typically this type of control information is not available, and since strategies are ranked according to the worst case, forward search generates a lot of useless states and is therefore seldom the 'best' strategy (though counter examples can be constructed).

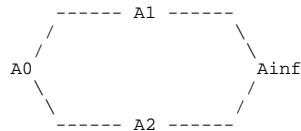
As an alternative, we can start From the goal and work backwards, which is backwards or regression search. In this case we use the "backwards" application of the actions to arrive at the previous state. In this way the plan is generated

Here the order relation $A2 < A1$ indicates action A2 precedes A1.

Two additional dummy actions are added, A0 and Ainfinity. These are used to indicate the first action (*start*) and last action (*end*) of the plan. All other actions are preceded by A0 and followed by Ainfinity. For example

$$A = \{ A1, A2 \} \text{ and } O = \{ A0 < A1 \ A0 < A2 \ A1 < Ainf \ A2 < Ainf \}$$

This represents an unordered plan with actions A1 and A2 (i.e., the actions are independent and can be applied in any order). Graphically,



Here we have a partial order between the actions, where all actions are ordered with respect to A0 and Ainf, but may or may not be ordered wrt other actions. With this representation as an action enters a plan, it is checked to see if we can leave them unordered. By analyzing the results of adding the action, required orderings can be provided. This analysis relies on maintaining a set of "causal links". These links identify actions which provide the preconditions for other actions.

For this processing, planning continues (adding actions and order relations) until all goal conditions have been worked on. Actions are chosen such that they satisfy a goal. The overall goals of the plan are set as preconditions for Ainf

on(A, B) @ Ainf	A
on(B, C) @ Ainf	B
	C

In addition, all initial conditions are considered effects of A0. The set of goals then are added to an "agenda", which is a list of goals which still need to be satisfied (planned for). Actions are added which make a goal on the agenda true. Causal links show which actions provide the preconditions for other actions. When an action is added to the plan, its preconditions are added to the agenda.

The order analysis makes it desirable that nothing comes between an action and the action which has its effects as a precondition.

For example, return to the problem

Initial state:	Goal state:
on(A, Tab) clr(A)	on (A, B) /\ on (B, C)
on(B, Tab) clr(B)	
on(C, Tab) clr(C)	

We have an agenda
{ on(A, B) @ Ainf
 on(B, C) @ Ainf }

Suppose we work on "on (B, C) @ Ainf" first. We choose the A1 as the action "move (B, Tab, C)", and the resulting causal links and agenda are:

Causal Links	Agenda
A0 ----->	{ on (A, B) @ Ainf
A0 ----->	clr (B) @ A1
A0 ----->	on (B, Tab) @ A1
A0 ----->	clr (C) @ A1 }

Three of the goals are satisfied by action A0, so now we look at the goal "on (A, B) @ Ainf". We now choose action A2 to be "move (A, Tab, B)", but we notice one of the effects is ~clr(B). Since A0 provides clr(B) as a precondition to A1, there is an ordering requirement. We can either place A2 as an action before A0 (which is not valid according to our model), or we can place the action between A1 and Ainf. The resulting plan is:

A = { A1 - move (B, Tab, C)	O = { A0 < A1 A0 < A2 A1 < Ainf
A2 - move (A, Tab, B) }	A2 < Ainf A1 < A2 }

where the last order relation is the result of the analysis of the causal links. Except for causal requirements, we leave actions unordered.

*****end of notes for 24 Jan 94*****

From rao Wed Jan 26 22:49:30 1994
Return-Path: <rao>
Received: by parikalpik.eas.asu.edu (4.1/SMI-4.1)
 id AA11396; Wed, 26 Jan 94 22:49:30 MST
Message-Id: <9401270549.AA11396@parikalpik.eas.asu.edu>
From: rao (Subbarao Kambhampati)
To: plan-class
Subject: Teasers
Date: Wed, 26 Jan 94 22:49:30 MST
Reply-To: rao@asuvax.asu.edu

0. Mark set a rather high standard for note-taking, with his first set of notes. I hope those who follow will exceed it ;-)

1. Here are a couple of things to think about before next class:

[A.] When we talked about variables at the end of the class today, I said that variable constraints also have to be maintained, and their consistency checked just as we did for ordering constraints.

A set of binding constraints of the form (x=y, y=z, z=A, y!=B) etc are said to be inconsistent if and only if we can derive a binding as well as its negation
From the constraints (e.g., x=A and x!=A).

It turns out that the cost of checking the consistency of a set of binding constraints depends on whether you the domain of the variables under (i.e., the set of objects which can be the possible values of a variable) consideration is infinite or finite. It is polynomial

($O(n^3)$) for one case and NP-hard (i.e., all known algorithms take exponential time) for the other. Can you guess (a) which case is which? and (b) why does the difference come about?

[B] When we talked about causal links today, we said that a causal link is said to be violated if and only if a step can intervene its producer and consumer and DELETE the condition being supported.

Can you think of any advantages of weakening the definition to say that a causal link is threatened if a step can intervene and either DELETE or ADD the condition?

Can you think of any advantages/disadvantages of strengthening the definition and say that a causal link is violated if a step v intervenes and DELETES the condition, and no step that necessarily comes after v and before the consumer adds the condition back?

[C] Can you think of an example planning problem where you can clearly see that the order in which the goals are worked on drastically changes the search-space size?

Please feel free to email your thoughts to plan-class

Rao

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From rus@seine.eas.asu.edu Mon Jan 31 14:15:12 1994
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To: plan-class@parikalpik.eas.asu.edu
Subject: Seminar notes
Date: Mon, 31 Jan 94 14:24:19 MST
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*****Notes for 26 Jan 1994

Ioana Rus*****

Agenda

- POP
- POP + variables
- POP + Conditions Effects (*)
- POP + Disjunctive Preconditions (*)
- UCPOP (Quantified Effects) (*)

(*) = not covered

Article: "An Introduction to Partial Order Planning", Weld

Last class: why to change search

From plan space to world state space.

One answer: flexibility in plan space planning-keeping partial plans allows to add an action between any other actions.

A possible partial plan:

```
START----- / A1-----A3 \-----END
              \-----A2-----/
```

where START and END are dummy actions

In the final plan

```
START----A5----A1---A6---A3----A2-----END
```

the actions

From the partial plan and their order is preserved.

REFINING planning = adding constraints

```
POP algorithm
-----
```

A plan may be described by a set of actions A and a set of orderings among the actions, O

$\langle A, O \rangle$

such as:

```
A = { A1, A2, A3 }
O = { START < A1 < A3 < END , START < A2 < END }
```

Assume we have the planning problem given by:

the initial state $I = \{I1\}$
 the goal state $G = \{P,Q\}$ where $I1, P, Q$ are predicates

and the following possible actions:

```
A1   precondition: (I1)
      effects: adds P
A2   precondition: ()
      effects: adds Q, deletes I1
A3   precondition: ()
      effects: adds I1
```

Description of initial state:

$\langle \{START, END\}, \{START < END\} \rangle$

agenda (set of goals): $\{ P@END, Q@END \}$

Goal = condition that has to be true at a state
 Top-level-goal = condition that has to true at the end

Pick a goal
 From the agenda and see what action can provide it.
 Action A1 can provide goal P to END.

At each step:- every precondition of the action added to the plan is introduced in the agenda,
 - every goal on which we work is deleted

From the agenda
 the agenda becomes:
 { Q@END, I1@A1 }

the partial plan is:
 START ----->A1-----> END

the causal links between the actions must also be represented,
 so the description of the planner will contain the links, as well:

< A, O, L >

where A = {START, END, A1}
 O = {START < A1 , END}
 L = { A1 -----> END , START -----> A1 }

Another possible partial plan is:

START -----> A3 -----> A1 -----> END

for the moment cannot choose between the two partial plans, so search will have to be performed, in the space of plans.

For the other goal at END, Q there is only action A2 that can provide it.

A2 -----> END

The description of the new partial plan will be:

A = {START, END, A1, A2}
 O = {START < A1 < END, START < A2 , END}
 L = {START -----> A1, A1 -----> END, A2 -----> END}

Links describe commitments in the plan.

When introduce a new step in the plan, must check if the action introduced threatens the links (comes between the producer and consumer of the link and deletes what the producer provides.)

A2 can come between START and A1, but the link between START and A1 is threatened by A2, so A2 must be before START, or after A1. In this case we know that no action can come before START, and A2 must be after A1, but in general some tests must be performed, so the ramification occurs again.

A new order will be add to O : A1 < A2

Now the agende is empty, so the plan is complete. It is:

START -----> A1 -----> A2 -----> END

The termination conditions for the algorithm are :
 - the agenda is empty
 - there are no conflicts (threats).

This final plan can be viewed as the "plan" or a set of possible plans (any plan that respects these constraints is a possible final plan).

IMPLEMENTATION

To verify and avoid conflicts and establish the order among actions, the transitive closure of the partial ordering graph has to be built.

The search performance is $O(b^d)$.

b (the branching factor) is affected by:

- how establish the choice for the source of a precondition
 $b = n + m$, where n is the number of steps in the partial plan
 m is the number of possible actions
- how many possibilities to solve conflict resolutions there can be

d (depth of graph) is affected by:

- number of conditions in the plan

$P * n + n^3$ P= max. number of preconditions for the actions
 ---> conflict resolution, depending on the number of threats

World state space planners have $d \sim P * n$, but b is much greater than for planning in plan space.

COMPLETENESS - is ensured by POP

EFFICIENCY - influenced by the order of working on goals in the agenda.

EXTENTIONS OF POP

POP algorithm with variables

If work with variables (instead of working only with constants), an action could look like:

move x, y, z - move x
 From y to z

x cannot be 'table'

and if the preconditions for this action are : cl(x),cl(z), on (x,y)
 and its effects: on (x,z), not cl(z), not on (x,y), cl(y)

then z cannot be 'table'.

the action move-to-table (x,y) will have
 preconditions: cl(x), on (x,y)
 effects: on (x, table), cl(y), not on (x,y)

When parametrizing for allowing variables to be introduced, must be sure to restrict their domain.

1. Variables

Upto now, all the actions in POP are instantiated actions, like move-A-B-C means move block A From B to C. Then we need a whole bench of actions to represent all the actions of the world.

Now we can use one parameterized action instead of several instantiated actions.

For example, in the blocks world, the action move can be instantiated to several actions, each correspondence to a block. To simplified that, we can introduce a parameterized action move(x,y,z)

```
operator move(x,y,z)
:precondition cl(x)^cl(z)^on(x,y)
:effect !cl(z)^cl(y)^on(x,z)
```

It's fairly clear that the operator move(x,y,z) is a much more economical description than the fully specified move actions it replaces. In addition, the abstract description has enormous software engineering benefits -- needless duplication would likely lead to inconsistent domain definitions if an error in one copy was replaced but other copies were mistakenly left unchanged.

But now each partial plan is a four - tuple:

P=<S,O,B,L>

where S stands for Steps, O for order, B for binding, and L for links.

We should change POP is the following parts of POP:

a. Establishment: introduce an action.

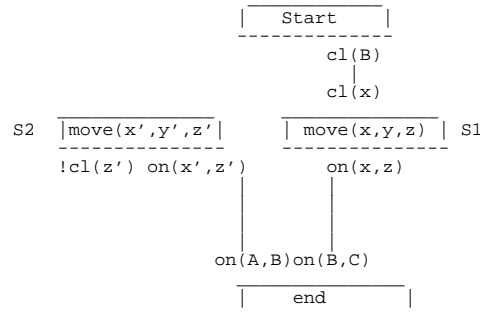
b. Threat detection

ex. in block world , there is one action move(x,y,z)

```
:precondition clear(x)^clear(z)^on(x,y)
:effect !on(x,y)^ on(x,z)
```

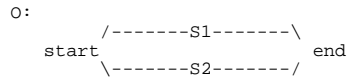
initial state: cl(A) cl(B) cl(C)

goal state : on(A,B) on(B,C)



We use step S1 to resolve on(B,C) and S2 to resolve on(A,B)

Here,
S: start, S1,S2, end



B: {x=B, z=C, x'=A z'=B}

```
cl(B)
L: start----->S1
```

here, S1 is to move B

From someplace to on top of C.

yet in S2 there is a effect of !cl(z'). and, unfortunately, z' is binded to B, so this might be a threat:

```
S2 --> !cl(B)
cl(B) --> S1 : it's a threat.
```

Here, we give the definition of a threat:

Def. A THREAT is any step which intervene the producer and consumer of a action and necessary delete the condition.

If there is a threat, we must resolve it.

If a new action is a threat to an existed casual link, there are two methods to resolve the threat:

- a. Promotion: put the new action in front of the producer, or
- b. Demotion : put the new action after the consumer.

In this example, S2 is a threat to start-->S1 casual link, then we can either put S2 in front of start (promotion), or put S2 after S1 (demotion). In this example, we know that it's impossible to put S2 in front of start, and we can cut out this branch, yet in ordinally case, both two cases should be considered.

Problem: how to detect a confliction among casual links?

Solution: If there is a circle in the constraints, then we should stop this branch and cut it off.

We have assumed that each new steps should be between the dummy steps start and end, so to every step Si, we got start<Si<end

In this example, we have start<S1<end.

in case of promotion, we want to put S2 in front of start, that means we need to add a new constraint S2<start.

Yet it's default that start<S2<end. So there is a circle exist start<S2<start. So we prune this branch.

In UCPOP, new constraints can only be added in, they will never be removed. New steps, add new constraints, are added to resolve the threats existed. so there is one problem: do we need the "white knight", that is, if there is a casual link, for example, +P can we add some steps between S1 and S2

S1---->S2, , Si..Sj, such that P is deleted and than added again, (Si will delete P and Sj will add P)?

Well, the answer is no. Because we don't have to deal with it. UCPOP is sound and completeness, we can find every solution to a problem, if it exists. The situation above will be explored by another plan in UCPOP, without having to use "white knight". We can simplify our planning if we don't deal with white knight, otherwise, the branching factor will be much larger. (To delete a casual link, we need to add in some more steps, and to resolve the new casual links, more and more steps need to be introduced..., the branching factor is much larger.)

Another problem: how can we know that a solution has been found?

In a ground linearization, if there is nothing in the agenda, and there is not threat, then a unique sequence , that is , a solution, has been found.

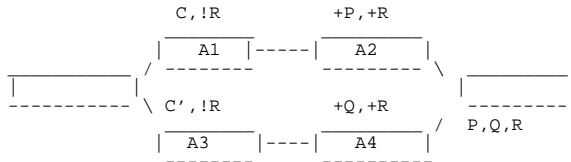
Now the way we make a planning is different From taking a plan and check if it's correct. In some sense, we "make" the current partial correct. All the constraints are kept, and we must make sure that all the link constraints are safe. Nothing will come between with the casual link and delete. When all the ground linearization are correct and nothing left on agenda

nda, then a total is got.

ex1. In the following chart, We want to achieve P,Q,R at goal. At the present partial plan, A2 gives P, A4 gives Q, and no other actions will delete them. so under whatever kind of action sequence, P and Q will always be true.

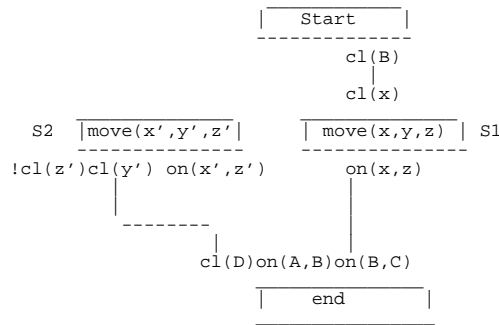
But we can't guarantee that R will be true at this time. Through A2 gives R, A3 will delete R. Similarly, A4 will give R, yet A1 will delete R. So the plan is unsafe.

But if we look deeper into the problem, we'll find that A4 always go after A3, and A2 always after A1. Adder always goes after deleter. So this is a plan.



ex2. In block world.

initial state: on(A,D)^on(d,Tb)^on(C,Tb)^cl(A)^cl(B)^cl(C)
goal state: on(A,B)^on(B,C)^on(C,Tb)^cl(D)



We try to resolve on(B,C) using S1, and add the binding {x=B,y=C}

suppose we want to resolve cl(D) first. It can also be resolved by a move action. We can add a binding here {y'=D}. We needn't make commitment on z' and x' at this time.

Under current binding, there isn't a threat now. Through there MIGHT be a threat in the future binding. In case of variables, the old definition of threat need to be changed. Shall we change threat to a step that possible, instead of unnecessary, intervene the consumer and producer of a link?

If we make this change, there will be a lot of other problem arise. We would like to keep the old definition, consider both codesignation and non-codesignation binding. So we can promote and demote the new step accordingly. This is a better algorithm.

In this example, we should add a non-codesignated binding {z'!=D}

Problem. When variables are introduced, how can we check the conflicts?

1. find all the instantiated codesignation and check if it's conflicted by noncodesignation constraints.

We know that the checking time is n cube. It can be done in polynomial time. If there are variable bindings, we should bind all the variables to real world objects, and check that all the bindings are without confliction.

for example, there is a binding {x=y, y=z, z=B}, then we should bind all the variables to {x=B,y=B,z=B}.

But in this method, we have made a assumption that the domain is a infinite domain. If the domain is a finite domain, there might be some other constraints besides codesignation and noncodesignation constraints. And even through the codesignation check is passed, the plan might still be unsafe.

for example, in a particular domain, y can only be A and B {y=A or y=B}. This constraint won't appear. And if we have the following binding. {x=A y!=x y!=B}

From here, we can't find any confliction, yet in fact, if y!=B, y must be A, and that will conflict with y!=x.

To solve this problem, we should derive new constraints from domain-related constraints and find the transitive closure. But then the checking consistence time won't be polynomial. It become NP hard.

So, we make the infinite domain assumption to make things simpler. yet we should know that in the real world, almost all the domains are finite domains.

One final change is still necessary. We can return a plan only if all variables have been constrained to a unique (constant) value. It's possible to instantiate all the variables in reasonable time when a good search algorithm is used. When a A* or breadth-first search, we can always find a solution, yet we can't guarantee when depth-first search is used.

2. Condition effects

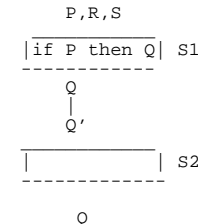
Let's start with blocks world. We have two actions: move-to and move-to-table. The ways it's done like this is that the effect is a little different. We can use only one action instead of two, using condition effects:

```
(operator move(x,y,z)
:precondition cl(x),cl(z),on(x,y)
:effects on(x,z), !on(x,y), cl(y)
  if block(z) then !cl(z))
```

if z is a block, z will not be clear. But if z is a table, clear(z) will still hold.

We need to change two parts of the UCPOP to implement that:

1. Establishment
make sure the P is true at S1 to get Q at a effect.



To make a casual link S1-->S2, we will make a binding {Q=Q'} (this might be a variable binding). And put the preconditions on agenda.

R@S1,S@S1 true already.

To make sure Q is a effect, we must add P@S1 in the agenda.

2. Threat resolution

DISJUNCTIVE PRECONDITIONS

 DISJUNCTIVE PRECONDITIONS are a way of expressing that an action can be done if any one of a number of things are true. For example, the house can be entered if the front door is open or if the side window is open.

DISJUNCTIONS will appear in POPs if any invoked action has a DISJUNCTIVE EFFECT. In the example of tossing a coin, DISJUNCTIVE EFFECTS can express uncertainty (incomplete information). We know that after tossing the coin, we will have either Showing(Heads) or Showing (Tails).

It is **NOT** ok to split a disjunctive precondition into N separate problems and then pursue each problem.

UCPOP **CANNOT** deal with nondeterminism. As in page 3 of Weld, we will limit ourselves in two ways - namely, we will require DETERMINISTIC EFFECTS and OMNISCIENCE.

No actions may have disjunctive effects. From this we get two constraints:
 (1) Complete information -> no disjunctions in the initial state.
 (2) Actions must not have nondeterministic effects.
 Of these two, (2) is more constraining.

Furthermore, all actions must explicitly state their effects - e.g., via the add and delete lists of STRIPS representation.

 HOW TO HANDLE QUANTIFIED EFFECTS

 QUANTIFIED EFFECTS are of two flavors: UNIVERSAL and EXISTENTIAL. Before handling quantifiers, consider why we use them. We use them to avoid many more rules (as a student pointed out) or to avoid rules that mention each item explicitly. Rules that mention each item explicitly are bad because they are sensitive to the number of objects in the world. Such a scheme would require a "rule generation" step according to the world-de-jour.

We could try to handle the UNIVERSALLY QUANTIFIED effects problem by creating another independent rule. Such a rule (in the briefcase example) might state that for each object in the briefcase, that object's location is given by the location of the briefcase. This approach imparts bad modularity
 From a software engineering viewpoint, and the FRAME PROBLEM comes up. In the briefcase example, we would end up having to refer to the new independent rule each time we wanted to know the location of an object. SPHEXISHNESS results.

UNIVERSAL QUANTIFICATION requires two modifications to POP: the ESTABLISHMENT and the THREAT DETECTION schemes must be modified.

The following example shows ESTABLISHMENT with universally quantified effects. Consider the case where putting the dictionary in the briefcase, and taking the briefcase to work gets the dictionary to work:

```
+-----+
| Initial |
+-----+
```

```
+-----+
At(Briefcase,Home) & In(Dictionary,Briefcase) & At(Dictionary,Home)

+-----+
| move ( B, H, O ) |
+-----+

all x * In(X,Briefcase) -> At(X,Office)

At(Dictionary,Office)

+-----+
| goal |
+-----+
```

For all parts of binding with variables that are universally quantified, bring the unified atom(s) to the precondition of the operation. These new preconditions then enter the agenda and links must be formed for them.

```
+-----+
| Initial |
+-----+

In(Dictionary,Briefcase) & At(Dictionary,Home) & At(Briefcase,Home)
    |
    v
    In(X,Briefcase) with binding {Dictionary/X}
+-----+ ( Below, the link for at office bound )
| move ( B, H, O ) | ( X to Dictionary, so we added the )
+-----+ ( precondition In(X,Briefcase) above. )

All x * In(X,Briefcase) -> At(X,Office)
    |
    v
    At(Dictionary,Office)

+-----+
| goal |
+-----+
```

THREAT DETECTION is modified to include unification and confrontation of unified universally quantified variables.

```
+-----+
| Sn |
+-----+

Clear(X)

    |
    v
    Clear(A)

+-----+
| Sn+1 |
+-----+

+-----+
| S |
+-----+

All x * Green(X) -> ~Clear(X)
```

After seeing that ~Clear(X) will give us trouble when X=A, we add the precondition ~Green(A):

```
+-----+
```


features: conditional effects, disjunctive precondition and univereal quantities. UCPOP is sound and complete. That means if there is a solution to a plan problem, UCPOP can always find that. but UCPOP can't guarantee to find the solution in reasonable time: efficiency is always a big problem. And some method are used to improved efficiency.

In Today:

1. Variables

Upto now, all the actions in POP are instantiated actions, like move-A-B-C means move block A From B to C. Then we need a whole bench of actions to represent all the actions of the world.

Now we can use one parameterized action instead of several instantiated actions.

For example, in the blocks world, the action move can be instantiated to several actions, each correspondence to a block. To simplified that, we can introduced a parameterized action move(x,y,z)

```
operator move(x,y,z)
:precondition cl(x)^cl(z)^on(x,y)
:effect !cl(z)^cl(y)^on(x,z)
```

It's fairly clear that the operator move(x,y,z) is a much more economical description than the fully specified move actions it replaces. In addition, the abstract description has enormous software engineering benefits -- needless duplication would likely lead to inconsistent domain definitions if an error in one copy was replaced but other copies were mistakenly left unchanged.

But now each partial plan is a four - tuple:

P=<S,O,B,L>

where S stands for Steps, O for order, B for binding, and L for links.

We should change POP is the following parts of POP:

a. Establishment: introduce an action.

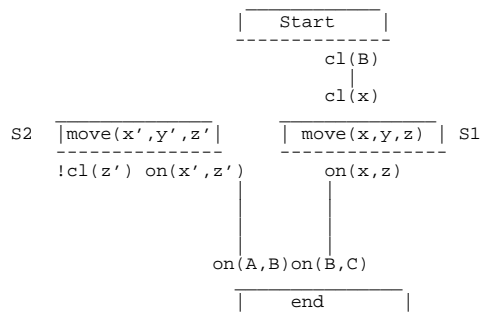
b. Threat detection

ex. in block world , there is one action move(x,y,z)

```
:precondition clear(x)^clear(z)^on(x,y)
:effect !on(x,y)^ on(x,z)
```

initial state: cl(A) cl(B) cl(C)

goal state : on(A,B) on(B,C)



We use step S1 to resolve on(B,C) and S2 to resolve on(A,B) Here,

S: start, S1,S2, end

```
O:
  /-----S1-----\
start                end
  \-----S2-----/
```

B: {x=B, z=C, x'=A z'=B}

cl(B)

L: start----->S1

here, S1 is to move B

From someplace to on top of C.

yet in S2 there is a effect of !cl(z'). and, unfortunately, z' is binded to B, so this might be a threat:

```
S2 --> !cl(B)
cl(B) --> S1 : it's a threat.
```

Here, we give the definition of a threat:

Def. A THREAT is any step which intervene the producer and consumer of a action and necessary delete the condition.

If there is a threat, we must resolve it.

If a new action is a threat to an existed casual link, there are two methods to resolve the threat:

- a. Promotion: put the new action in front of the producer, or
- b. Demotion : put the new action after the consumer.

In this example, S2 is a threat to start-->S1 casual link, then we can either put S2 in front of start (promotion), or put S2 after S1 (demotion). In this example, we know that it's impossible to put S2 in front of start, and we can cut out this branch, yet in ordinally case, both two cases should be considered.

Problem: how to detect a confliction among casual links?

Solution: If there is a circle in the constraints, then we should stop this branch and cut it off.

We have assumed that each new steps should be between the dummy steps start and end, so to every step Si, we got start<Si<end

In this example, we have start<S1<end.

in case of promotion, we want to put S2 in front of start, that means we need to add a new constraint S2<start.

Yet it's default that start<S2<end. So there is a circle exist start<S2<start. So we prune this branch.

In UCPOP, new constraints can only be added in, they will never be removed. New steps, add new constraints, are added to resolve the threats existed. so there is one problem: do we need the "white knight", that is, if there is a casual link, for example, +P can we add some steps between S1 and S2

S1---->S2, , Si..Sj, such that P is deleted and than added again, (Si will delete P and Sj will add P)?

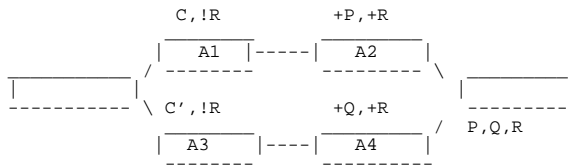
Well, the answer is no. Because we don't have to deal with it. UCPOP is sound and completeness, we can find every solution to a problem, if it exists. the situation above will be explored by another plan in UCPOP, without having to use "white knight". We can simplify our planning if we don't deal with white knight, otherwise, the branching factor will be much larger. (To delete a casual link, we need to add in some more steps, and to resolve the new casual links,

more and more steps need to be introduced..., the branching factor is much

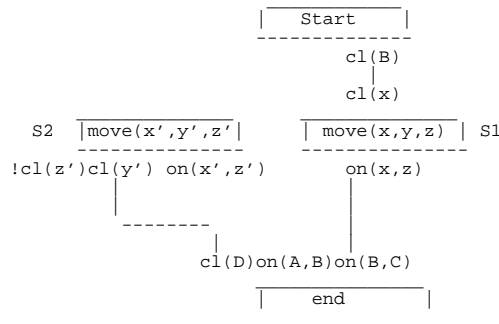
larger.)

Another problem: how can we know that a solution has been found?
 In a ground linearization, if there is nothing in the agenda, and there is no threat, then a unique sequence, that is, a solution, has been found.
 Now the way we make a planning is different
 From taking a plan and check if it's correct. In some sense, we "make" the current partial correct. All the constraints are kept, and we must make sure that all the link constraints are safe. Nothing will come between with the casual link and delete. When all the ground linearization are correct and nothing left on agenda, then a total is got.

ex1. In the following chart, We want to achieve P,Q,R at goal. At the present partial plan, A2 gives P, A4 gives Q, and no other actions will delete them. so under whatever kind of action sequence, P and Q will always be true.
 But we can't guarantee that R will be true at this time. Through A2 gives R, A3 will delete R. Similarly, A4 will give R, yet A1 will delete R. So the plan is unsafe.
 But if we look deeper into the problem, we'll find that A4 always go after A3, and A2 always after A1. Addder always goes after deleter. So this is a plan.



ex2. In block world.
 initial state: on(A,D)^on(d,Tb)^on(C,Tb)^cl(A)^cl(B)^cl(C)
 goal state: on(A,B)^on(B,C)^on(C,Tb)^cl(D)



We try to resolve on(B,C) using S1, and add the binding {x=B,y=C}
 suppose we want to resolve cl(D) first. It can also be resolved by a move action. We can add a binding here {y'=D}. We needn't make commitment on z' and

x' at this time.

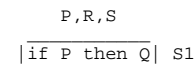
Under current binding, there isn't a threat now. Through there MIGHT be a threat in the future binding. In case of variables, the old definition of threat need to be changed. Shall we change threat to a step that possible, instead of necessary, intervene the consumer and producer of a link?
 If we make this change, there will be a lot of other problem arise. We would like to keep the old definition, consider both codesignation and non-codesignation binding. So we can promote and demote the new step accordingly. This is a better algorithm.
 In this example, we should add a non-codesignated binding {z'!=D}

Problem. When variables are introduced, how can we check the conflicts?
 1. find all the instantiated codesignation and check if it's conflicted by noncodesignation constraints.

We know that the checking time is n cube. It can be done in polynomial time. If there are variable bindings, we should bind all the variables to real world objects, and check that all the bindings are without confliction.
 for example, there is a binding {x=y, y=z, z=B}, then we should bind all the variables to {x=B,y=B,z=B}.
 But in this method, we have made a assumption that the domain is a infinite domain. If the domain is a finite domain, there might be some other constraints besides codesignation and noncodesignation constraints. And even through the codesignation check is passed, the plan might still be unsafe.
 for example, in a particular domain, y can only be A and B {y=A or y=B}. This constraint won't appear. And if we have the following binding.
 {x=A y!=x y!=B}

From here, we can't find any confliction, yet in fact, if y!=B, y must be A, and that will conflict with y!=x.
 To solve this problem, we should derive new constraints
 From domain-related constraints and find the transitive closure. But then the checking consistance time won't be polynomial. It become NP hard.
 So, we make the infinite domain assumption to make things simpler. yet we should know that in the real world, almost all the domains are finite domains.
 One final change is still necessary. We can return a plan only if all variables have been constrained to a unique (constant) value. It's possible to instantiate all the variables in reasonable time when a good search algorithm is used. When a A* or breadth-frith search, we can always find a solution, yet we can't guarantee when depth-first search is used.

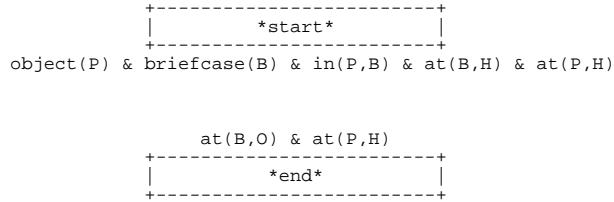
2. Condition effects
 Let's start with blocks world. We have two actions: move-to and move-to-table. The ways it's done like this is that the effect is a little different. We can use only one action instead of two, using condition effects:
 (operator move(x,y,z)
 :precondition cl(x),cl(z),on(x,y)
 :effects on(x,z), !on(x,y), cl(y)
 if block(z) then !cl(z))
 if z is a block, z will not be clear. But if z is a table, clear(z) will still hold.
 We need to change two parts of the UCPOP to imprement that:
 1. Establishment
 makesure the P is true at S1 to get Q at a effect.




```
(forall x such-that object(x))
  when in(x,b)
  then at(x,l2) & ~at(x,l1)
```

1.2. Generating a Plan Using the UCPOP Algorithm

At the beginning we have the following partial plan, based on the initial and the final state, and UCPOP conventions for their representation:



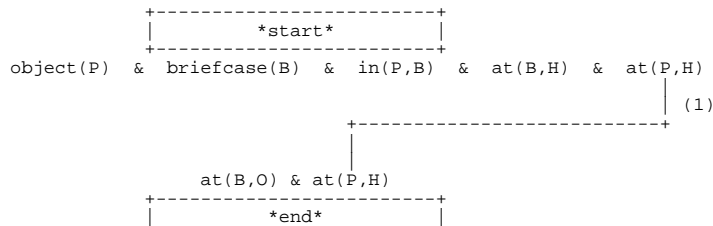
AGENDA: { at(B,O) @ *end*, at(P,H) @ *end* }

UCPOP now picks a conjunct
 From the agenda. Note that it doesn't
 matter (
 From the completeness point of view) which conjunct is chosen
 -- if a solution to the planning problem exists, UCPOP is guaranteed
 to find it regardless of the order of picking the conjuncts

 From the agenda).
 Status: RO
 X-VM-v5-Data: ([nil nil nil nil nil nil nil nil nil
 [nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil
])

Let UCPOP pick the goal conjunct 'at(P,H)
 From the agenda.

UCPOP now needs to establish 'at(P,H)'. One choice is to
 use the 'at(P,H)' effect of the *start* step. The only other
 choice is to instantiate the 'move(b,l1,l2)' action and use
 its effects.
 Let UCPOP nondeterministically decide to use the 'at(P,H)' effect
 of the existing *start* step:



+-----+

AGENDA: { at(B,O) @ *end* }

Note that no new subgoals were introduced in the agenda, and the
 conjunct 'at(P,H)' was deleted
 From the agenda since it is now
 supported ("established") by a causal link. This type of
 establishment, where a goal is supported without introducing
 a new step, is referred to as "simple establishment".

Digression: recall how we "establish" goals in FORWARD PLANNING
 in the space of WORLD STATES.

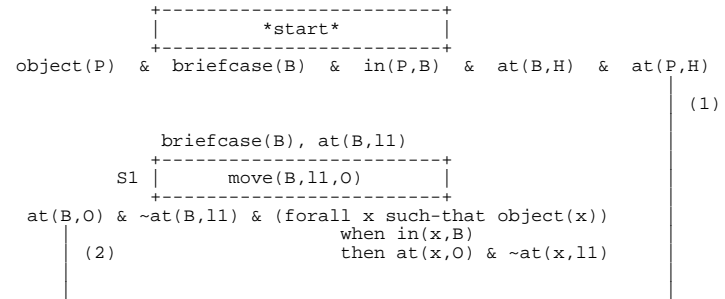
For example, assume we have an initial state
 on(A,Table) & on(B,Table) & on(C,Table),
 and we want to make a plan stacking C on A on B:
 on(C,A), on(A,B), on(B,Table).
 One reasonable step may be 'puton(A,Table,B)',
 which will ESTABLISH on(A,B).

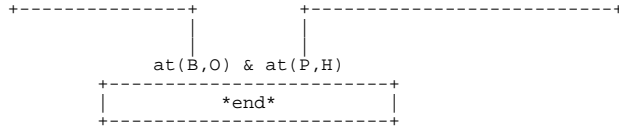
We KNOW that once this step has been included in the
 plan, IT CAN ALWAYS BE EXECUTED in any refinement
 of the plan, since all steps are added AFTER the
 last added step. In other words, once established
 steps can NOT be threatened in planning in the space
 of WORLD STATES.

However, when planning in the space of PARTIAL PLANS,
 we don't have a guarantee that the execution of
 the step will not be threatened by subsequently
 added steps (since steps can be added anywhere
 in the plan). In order to guarantee the execution
 of the step, we must create a causal link that will
 establish the goal conjunct, and make sure that
 the link is never threatened.

UCPOP now takes the only remaining conjunct 'at(B,O)'
 From the agenda.

UCPOP must instantiate a 'move(b,l1,l2)' action, because it is
 the only way to support the 'at(B,O)' goal conjunct.
 We refer to this instantiation of the action as 'S1'.
 We immediately put the bindings b=B, l2=O., in order to be able
 to support the goal conjunct 'at(B,O)'.





```
AGENDA: { briefcase(B) @ S1, at(B,l1) @ S1 }
BINDINGS: { b=B, l2=O, l1 != O }
ORDERINGS: { *start* < S1 < *end* }
```

Note how the conditional effect of the step S1 is specified as an effect of S1.

Also note that at this moment we need NOT bind 'l1' in the step S1. One might be tempted to IMMEDIATELY bind l1 to H (which will later turn out to be the right binding). However, in general it is a mistake to do any bindings prematurely, if they are not necessary to support a link generated at the current iteration.

Let us check against any threatened links at this moment.

(a) The newly introduced link (2) can not be threatened, since no steps can be ordered between S1 and *end* (the only other step is *start*, and it is guaranteed to be before S1).

(b) The new step S1 looks like it can threaten the link (1), which supports 'at(P,H)' and goes

From *start* to *end*..

The step S1 can be ordered between *start* and *end*, and it has a potential of making '~at(P,H)' due to its universally quantified conditional effect ~at(x,l1). Compute MGU(at(P,H), at(x,l1), CURRENT BINDINGS) = { x=P, l1=H }. However, using the definition of a threat in the case of universally quantified effects, we decide that the link is not threatened since in the MGU binding list there is a binding l1=H, and l1 is NOT universally quantified. Intuitively speaking, S1 does not threaten link (1) at this moment since l1 is still not bound. When l1 becomes bound, if l1=H, then S1 will definitely be a threat, and if l1 != H, then S1 will not threaten (1).

Since no threats have been detected, the UCPOP will proceed with the next iteration.

Digression: at this iteration we added goals to the agenda.

Here are all cases when the agenda increases:

1. at the beginning: all goal conjuncts
2. when adding a step: the preconditions of the step
3. when adding a step: (if necessary) the conditional preconditions of the needed effect
4. when protecting a link: (for conditional effects, if necessary) negated conditional preconditions of the threatening effect.

Let UCPOP pick 'briefcase(B)'

From the agenda. It can be established simply by using the effect 'briefcase(B)' of the *start* step.

Then UCPOP picks the only remaining goal conjunct 'at(B,l1)'.

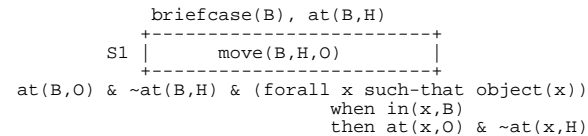
Again, two principal choices are available: one is to simply establish 'at(B,l1)'. From the effect 'at(B,H)' of the *start* step; the other is to generate a new step by instantiating the action 'move' again: 'move(B,l3,l1)' would have an effect 'at(B,l1)' which can be used to establish the current goal 'at(B,l1)'.

UCPOP must consider all possibilities, otherwise it could fail to generate a plan. In other words, UCPOP must keep track of all possible options, in order to backtrack and use them, if necessary. Note, however, that UCPOP is free to use some heuristics to determine the choice which looks most promising to start with.

Let UCPOP nondeterministically decide to support 'at(B,l1)' directly

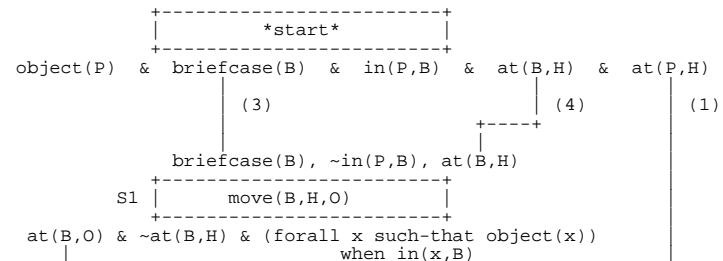
From the effect 'at(B,H)' of the *start* step. This forces the binding l1=H.

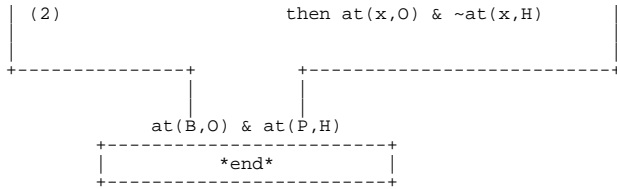
The step S1 now is as following:



However, the conditional effect '~at(x,H)' now threatens the link (1), which establishes 'at(P,H)' (see the last partial plan). UCPOP must protect the link (1). However, neither promotion nor demotion can be used, since the step S1 can not be ordered before *start* or after *end*. The only choice is to use CONFRONTATION in order to disallow the conditional effect '~at(P,H)'. For the confrontation purposes, it is sufficient to add '~in(P,B)' as a precondition of S1.

Note that it is NOT necessary to confront the conditional effect for ALL objects x, since we are only concerned to disallow '~at(P,H)', and we are NOT disallowing the effect '~at(x,H)' for any x != P.

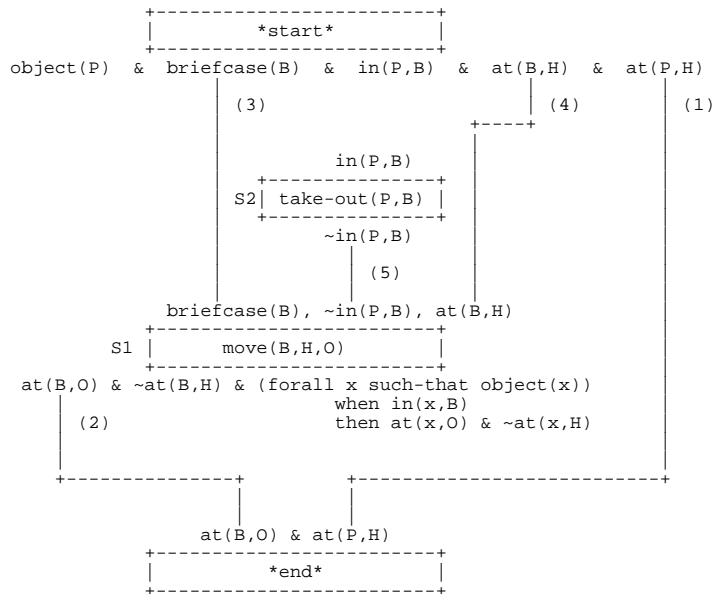




```
AGENDA: { ~in(P,B) @ S1 }
BINDINGS: { b=B, l2=O, l1 != O, l1=H }
ORDERINGS: { *start* < S1 < *end* }
```

No other links are threatened, so we can go on with the establishment step.

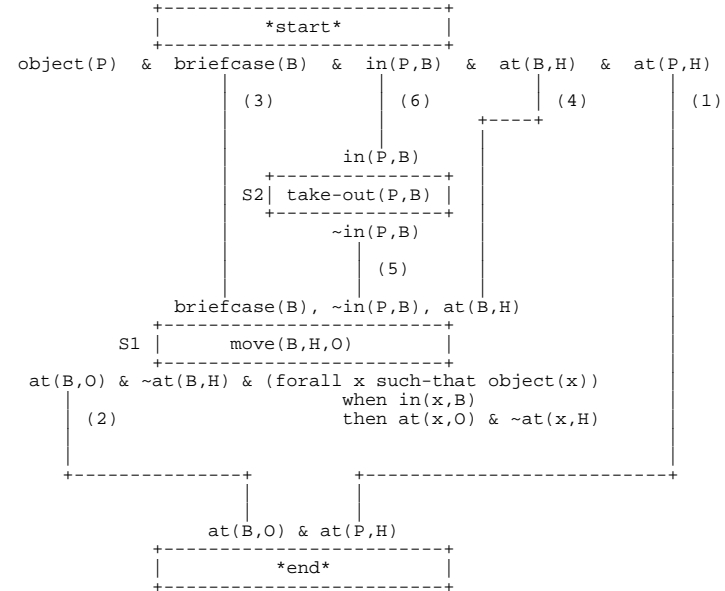
The only way to establish '~in(P,B)' is to instantiate the 'take-out' action. We refer to this instantiation of the action as 'S2'. We immediately put the bindings x11=P, b11=B, in order to be able to support the goal conjunct '~in(P,B)'. Note that we are using new variable names, different from the variable names used in previous instantiations of any actions.



```
AGENDA: { in(P,B) @ S2 }
BINDINGS: { b=B, l2=O, l1 != O, l1=H, b11=B, x11=P }
ORDERINGS: { *start* < S1 < *end*, *start* < S2 < *end*, S2 < S1 }
```

The new step S2 does not threaten any links; the new link (5) is not threatened by any other steps.

The last step establishes the link (6) supporting the 'in(P,B)' goal:



```
AGENDA: { }
BINDINGS: { b=B, l2=O, l1 != O, l1=H, b11=B, x11=P }
ORDERINGS: { *start* < S1 < *end*, *start* < S2 < *end*, S2 < S1 }
```

The new link (6) is not threatened.

The agenda is empty, the binding constraints are consistent, there are no threatened links, and there is a ground linearization of the ordering constraints: *start* --> S2 --> S1 --> *end*.

Therefore, the planning process successfully terminates, giving the plan: take-out(P,B) --> move(B,H,O).

 2. OTHER COMMENTS ABOUT SPECIFIC FEATURES AND DETAILS OF UCPOP
 2.1. Note how unification has to be done for the purposes of

the UCPOP algorithm:

MGU (P1, P2, CURRENT BINDINGS)

The unification of P1 and P2 is done in the usual way, with the following two additions:

- (a) The list of CURRENT BINDINGS must be respected ;
- (b) The CURRENT BINDINGS may contain NON-CODESIGNATION constraints, such as $l1 \neq 0$, which also must be respected in the process of finding the most general unifier.

2.2. In the example we presented above, we illustrated the handling of the possible threatening effects of UNIVERSAL QUANTIFICATION. However, the UNIVERSALLY QUANTIFIED EFFECTS can be used to support goals as well.

For example, let us slightly extend the above example, requiring that the object D (originally in the briefcase) be moved to the office.

We need not add any extra steps in the plan. We can support the new goal 'at(D,O)' by the conditional effect of step S1:

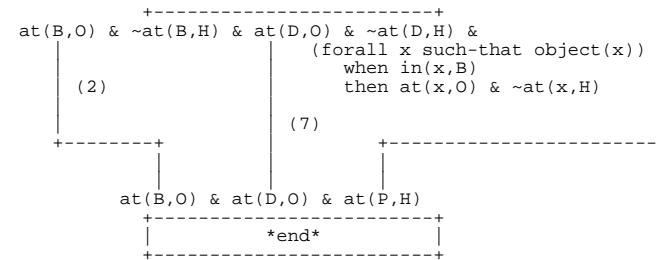
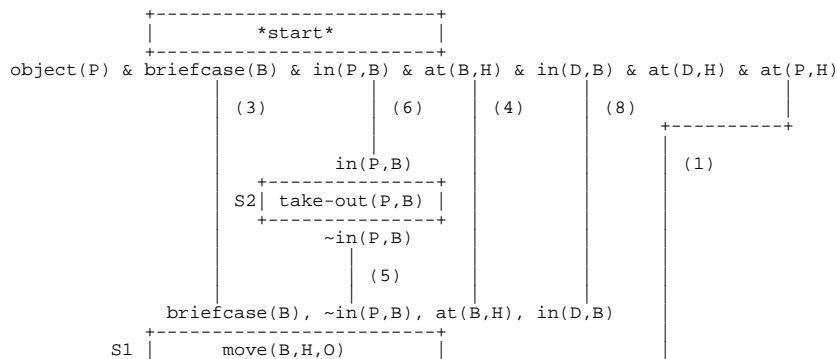
```

forall x such-that object(x)
  when in(x,B)
  then at(x,O) & ~at(x,H)
    
```

We only need to use the effect instance for $x=D$. We then need to add the condition 'in(D,B)' of the utilized effect to the agenda. This condition, in turn, is directly supportable by the initial state, which contains 'in(D,B)'.

Note how WITHIN A SINGLE UNIVERSALLY QUANTIFIED CONDITIONAL EFFECT, one instance of the effect threatened a link and had to be confronted, and still in the same plan, another instance of the same effect was used to support another link.

The complete plan is as follows:



2.3. Let us consider planning problems where the GOAL is universally quantified. Referring again to our original example, we may require that ALL objects be moved to the office:

```

(forall x such-that object(x)) at(x,O)
    
```

Assuming a finite domain of objects, we can "expand" the universal quantifier, and try to generate a plan that will achieve: $at(obj1,O) \& at(obj2,O) \& \dots \& at(obj-n,O)$. Since this is a finite ground conjunction, which is no different

From the UCPOP examples we have considered so far, UCPOP will be able to generate the plan.

2.4. The handling of negated goals in UCPOP is not different from the handling of non-negated goals. We have already illustrated the handling of negated subgoals that were introduced in the agenda by the confrontation. The treatment of real negated goals is no different in any way.

2.5. Consider the following planning problem:

All files in the directory of a UNIX machine should be deleted. Two UNIX commands (ACTIONS) are at disposal:

```

rm *      (deletes all files in the directory)
          (** PLEASE BE CAREFUL WHEN USING THIS COMMAND **)
rm file   (deletes a given file)
    
```

Obviously, there are two basic approaches (plans): the first is to use 'rm *' and have a one-step plan; the other is to delete the files one-by-one, using the 'rm single-file' action (other plans are also feasible, such as using 'rm single-file' several times, and then using 'rm *', but they are not as interesting).

The question is: given a good formal specification of the actions, is UCPOP going to generate the two interesting plans? The answer is positive :

Formal specification (D=directory, f-i = i-th file in D):

```

initial state: in(f1,D), in(f2,D), ..., in(f-n,D)
final state:  ~in(f1,D), ~in(f2,D), ..., ~in(f-n,D)
action1:     rm f-i
    
```

```

        precondition: in(f-i,D)
        effect:       ~in(f-i,D)
action2:  rm *
        precondition: none
        effect:       (forall f-i such-that file(f-i))
                       when in(f-i,D)
                       then ~in(f-i,D)

```

Plan1: UCPOP will instantiate a separate 'action1' for each goal !in(f-i,D). Each of those steps will have the precondition in(f-i,D) which will be supported directly from the initial state. Therefore, the planning will successfully terminate.

Plan2: UCPOP will instantiate 'action2' once (it will have a clue to look at 'action2' since individual instances of its (conditional) effect unify with the goals in the agenda). For each file f-i it will use the corresponding instance of the universally quantified effect '~in(f-i,D)', which unifies with the corresponding goal '~in(f-i,D)'. In order to satisfy the precondition of each used instance of the universally quantified effect, UCPOP will add goals of the form in(f-i,D) to the agenda. But these goals are directly supported by the initial state, and the planning will successfully terminate.

2.6. Let us look again at the example presented in 2.5

From a different perspective. The crucial assumption that allowed for successful planning was that we KNEW IN ADVANCE all files in the directory. However, what if the planner was given the ability to use the full command set of UNIX? In particular, there are commands that can CREATE new files. Nothing in UCPOP can then prevent the algorithm from trying to use such commands (actions) to support intermediate goals of the form in(f-i,D).

Let us consider the following scenario: UCPOP expanded the universally quantified goal in the very first step. In the process of planning, it may use an action that generates a new file. Since the non-existence of that NEW file is nowhere required as a goal that must be achieved, the planning may successfully terminate (according to UCPOP), but there may still be files in the directory. Although none of these files was among the original files in the directory, the outcome is still unsatisfactory, since we wanted to get rid of ALL files and end up with an empty directory.

The example shows that the the assumption of having STATIC UNIVERSE of objects is not realistic for some domains.

An open research question is how to deal with such non-static universes WITHIN the basic framework if UCPOP, in a CLEAN way.

Note that the ONLY change in UCPOP which is sufficient to handle non-static universes is TO CHANGE THE DEFINITION OF A THREATENED LINK, and appropriately handle such threats while generating the plan. Referring to the above example, the definition of a threat must somehow recognize the

creation of a new file as a threat to the goal "all files in the directory must be deleted".

3. CHALLENGING VARIOUS ASPECTS OF UCPOP

We now take a look at UCPOP algorithm from another perspective.

We want to understand the rationale behind its individual steps, and we try to consider alternative ways of dealing with some particular problems of partial order planning.

Here we will raise some doubts that will serve as a motivation for the discussion on the topics scheduled for the next session.

3.1. Why do we need causal links ?

Why do we utilize the links in this particular way ?

- why wouldn't we deal with MAINTENANCE GOALS ?
- why wouldn't we allow deletion of a subgoal, and then its addition, as opposed to disallowing the plan (as UCPOP does) ? It seems that allowing such steps may help, and (as long as such steps don't violate a maintenance goal) we don't mind such deletions.

3.2. Why wait until all preconditions are worked on ?

- why work on each goal separately ?
- it seems that very often many subgoals would come as side effects of establishment of other goals. Then why should we work on such subgoals, when anyway they would be achieved, without special steps devoted to them ?

3.3. Why wait until ALL ground linearizations are solutions ?

- recall that all the time we have a PARTIALLY ORDERED PLAN, which in general has many ground linearizations. However, we are perfectly happy with ONLY ONE plan (totally ordered sequence of steps). Then why wait until ALL ground linearizations become solutions ? Why wouldn't we stop as soon we have a single ground linearization ?

3.4. Why do we need to treat the threats as we do in UCPOP ?

- as soon as an establishment is done, why do we need to resolve all threats AT THAT MOMENT ?
- why wouldn't we wait, hoping that some of the threats would be resolved as side-effects of other steps ?
- why wouldn't we wait until any threat becomes a REAL THREAT, not just a temporary threat ?

We know that it is always better to defer the branching of the search to the very end. By resolving non-essential threats, we are effectively prematurely introducing branching in the search space, thus decreasing the performance of the planning in general.

- VI. Suppose we know that a set of variables have finite domains, but suppose our planning algorithm ignores this fact and checks the consistency by acting as if they have infinite domains. What effect does this have on the soundness and completeness of the planning algorithm?
- VII. Why exactly is it that you do not need to backtrack on the order in which the planning goals on the agenda are addressed in the case of plan-space planning?
- VIII. Explain in what sense UCPOP/POP algorithms use closed-world assumption? In what sense does it use static-universe assumption?
- Give an example of a problem domain where these assumptions don't hold. Explain what sorts of failures will UCPOP have in such domains.
- IX. UCPOP attempts to implement a planner for ADL. Pednault's theory of ADL planning allows for incomplete initial states. Explain the parts of UCPOP algorithm that are less general than is required
- X. What will be the effect of not using conditional effects in modeling a domain (does it effect completeness? soundness? efficiency? domain-size? operator size?)
- What about universal quantification?
- XI. Consider the following types of effects: (a) Forall (x) (not(P x))
(b) (not (Forall (x) (P x)))
- Can an operator in UCPOP/ADL representation have effects of type "a"? How about effects of type "b"? Explain.
- XII. Explain when the ucpop's treatment of disjunctive preconditions will not be enough.
- PART B: Thinking questions:
(The answers to the following have not been directly discussed in the class, but can be provided with a little thinking. They thus test whether you are able to apply what you heard in the class).
- I. Suppose you are told that three events E1, E2 and E3 are going to occur during the execution of your plan (i.e. between *start* and *end*). All these events are beyond your control and cannot be prevented. You are also told that E1 is going to occur either before E2 or before E3. Can this precedence relation between the three events be represented in our usual partial ordering representation? If so how? If not, why not? Explain.
- II. Here is a blocksworld planning problem with a twist which shows how UCPOP can be creatively extended to deal with unplanned for actions. Suppose in addition to your move(x,y,z) action, you have an event of type Blow-up. This event occurs whenever block A is not on top of block B. Its effect is to shake the table such that all

the block stacks are destroyed (and all the blocks fall down to the table).

Model this event using (not(On A B)) as the trigger condition, and the stack-destroying as its effect (you will need to use universally quantified effects).

Suppose your initial state contains A on top of B, and C and D on table. Your goal state is to get (On C D). Explain how you will solve this problem with UCPOP (extending UCPOP in minimal ways).

III. We have talked about the fact that we can start UCPOP/POP with partially specified dummy plans (which contain actions other than *start* and *end*, as well as constraints other than the top level goals).

Can we start state-space planners also (consider both the forward search or the backward search version) with partially specified plans?

In particular, consider (1) the possibility of solving the round-trip problem using state-space planners. (2) the blocks world blow-up problem described in the previous question.

Compare and contrast the plan-space and state-space planners in this regard.

IV. Ability to start with partially filled plans provides for a rudimentary ability to reuse previous plans, and extend them to solve new problems. Suppose you have just found a plan for putting On(A,B) and On(C,D), starting with an initial situation where everything is on table. Suppose your plan is move(A,T,B) -> move(C,T,B), where T is the Table.)

Suppose you have the new problem where the initial state remains same, but the goal state is On(A,B) & On(B,C) & On(C,D). Suppose further that you want to start your planner off with the plan for the old problem.

Compare and contrast the way state space planners and plan-space planners will reuse the old plan.

V. We observed in the class that UCPOP/ADL representation shortcuts the frame (ramification) problem by ensuring that each action specifies all the predicates which will be made true, either directly or indirectly, by the action. We also said that this is not allow for good software engineering/modularity (since sometimes we would like to keep the invariant laws of the domain, such as the fact that any block which has another block on top of it, is not clear, separate

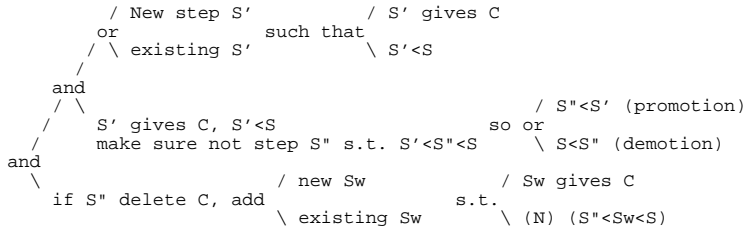
From the actions).

Explain why it is bad software engineering to not keep such laws separate. How exactly does UCPOP deal with them?

Suppose you are forced to use domain axioms separate from the action representation. Speculate on the type of extensions that will be

Criteria 2. (a necessary and sufficient one).
 for every step S" in current plan which can come between S' and S,
 (S' < S and S' gives C), and S" delete C, there is another step Sw necessary before S and necessary after S' such that it make C true.

We can invert criteria 2 to get an algorithm to make something necessary true: that's what we do in establishment:
 If a step S" needs to come before S,



Note: (N) means necessary. I'll use this notation further on. (I can't draw the little block using ascii character.)

This criteria is sound and complete. That is, all the ground linearization can be achieved in this partial plan if it's already a solution. But some solution can't be returned by UCPOP (ucpop can't deal with the white knight, its goal establishment is sufficient but not necessary).

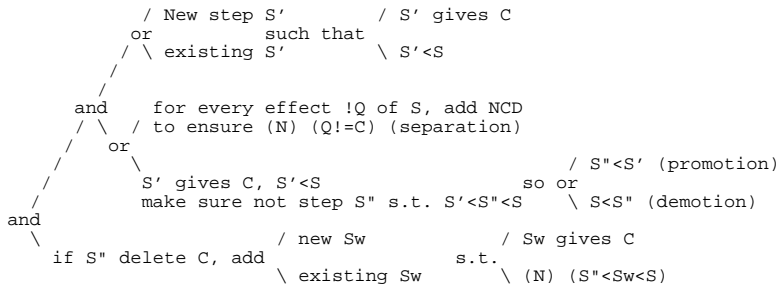
We should notice that the goal of planning is to make something true but not checking if something is true. So, sufficient is enough.

By the way, we might don't need to check true before picking a goal.

What we were talking was planning with variables. It's Chapman who first give the necessary and sufficient condition for establishment of variable version. On the base of the instantiated criteria, we add some more constraints in case of variables:

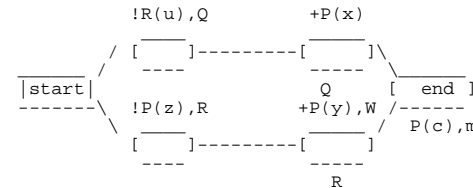
criteria 1. ...
 if there exist S, (N) (S' < S) and S' have an effect P, s.t. (N) (P ~ C)
 (P necessary binds to C).

criteria 2 can be represented as the following chart:



Note: NCD means "noncodesignation"

Here is an example:



For example, in the plan, for P(c) to be necessary true at end, we should:
 (x ~ C or if z ~ C, we set y ~ C), or
 (y ~ C or if u ~ C, we set x ~ C)
 here we use the inverse of criteria 2, change
 From "give" to "make", make
 it not happen by add the negative of the precondition. So in the case of
 variables, we add one more branch: separation.

For example, !Q : !on(x,y)
 C : on(A,B)
 To separate: x != A or y != B
 To be sufficient and necessary, we need to add explicitly noncodesignation to add one more branch. But also we can ignore this branch totally, make the planning not necessary but sufficient. That's because the goal of planning is to guarantee the completeness of result. And a sufficient goal establishment is enough, as long as all the goals can be found. Similarly, we don't introduce white knight in UCPOP to add the branching factor and add in redundancy. We don't need to be sure that a particular goal must be true at a particular time phase. (We do need necessary and sufficient at some time, which we will discuss later.) At this time, sufficient is enough. The reason for search is just to find a ground operation sequence. To do that, we have better keep it as a partial plan.
 Also, we should remember that when in search, we just want to find a goal, (exist), we are not searching for the optimal goal.

Now let's discuss the complexity of these algorithms.
 It's clear that ground linearization checking is NP complete (suppose n steps, we should totally order these steps, and the sequence is n!).

Using criteria 2. (necessary & sufficient)
 a. No variable
 That's polynomial time, to be more precisely, n cube. Stick to the assumption of transitive closure, to check a goal, we can find the last action that add this condition, then check if all the deleter of this condition don't fall between them. It require n cube time.
 b. with variables
 Compare with the case without variable, we need one more work: checking the bindings of the variables.
 Now the problem goes back to the finite and infinite domain. If the domain is infinite, then the complexity is polynomial, yet according to transitive closure assumption, the variable of the polynomial is the number of variables instead of number of steps.
 If it's a finite domain, the problem become NP hard. That's because

if variables have finite domain, the noncodesignation might imply some new codesignation, which doesn't appear explicitly. To check that the problem become NP hard.

Yet what we discuss up to know are actions without conditional effects. If there exists actions with conditional effect, the establishment become NP hard. We can image that (some kinds of informal proof):

Suppose we want to check if a particular goal C is true at a point, we check all the actions that add this goal. Suppose there is one step S with conditional effect that add this goal C. To check if this goal C after S, we must make sure first that if the precondition Q of S is true or not when S is executed. Here again the checking of goal Q will repeat the checking procedure of goal C. Through this kind of recursion doesn't necessarily means the problem is NP complete, we can find some method to prove it.

So, checking the true criteria will be NP hard, make the problem intractable, and the planning become very hard. This is why Chapman give up partial planning.

But, it isn't a must that we should use a necessary and sufficient goal establishment algorithm to pick up a not necessary true goal. Also, we can expand searching space to reduce the searching time.

Those problem will be discuss in next class.

```
-----
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X-Sun-Data-Description: default
X-Sun-Data-Name: note2
X-Sun-Content-Lines: 230

*****
                Class note for Feb 14 94
CSE 591: PLANNING & LEARNING METHODS IN ARTIFICIAL INTELLIGENCE
                Taken by: Yong Qu
*****
```

Agenda : Goal Establishment
 -TWEAK
 -ADL

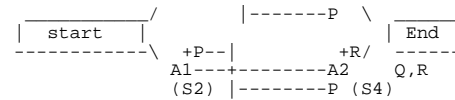
Now we have extend the representation of a partial to a five-tuple:

P : <T,O,B,ST,L> where:
 T: Steps
 O: Ordering
 B: Binding
 ST: Symbol Table
 L: auxillary constraints

Here the auxillary constraints can be comprehended as the casual link. We introduce the ST (Symbol table) to deal with the case that two instances of one same action appear in the partial plan. That is, more than one steps correspond to one same action, we need a mapping from steps to actual actions.

For example, the current partial plan is <T,O,B,ST,L> , where

```
(S1)+P--|          +Q
Al----+----->A2 (S3)
```



```
T: {S1,S2,S3,S4,Start, End}
ST: {S1-->A1, S2-->A1, S3-->A2, S4-->A2}
L: {
    P          P          Q          R
    S1-->S3,  S2-->S4 , S3-->End , S4-->End
}
```

A ground linearization is a fully instantiated total ordering of the steps of a partial plan that satisfy all the Ordering and Bindings (Constraints).

On top of that, a ground linearization is a safe ground linearization if and only if it also satisfies all the auxiliary constraints.

As we have defined, a ground operator sequence is a solution to a planning problem, we say that each safe ground linearization correspond to a ground linearization .

If a safe ground linearization is got, we can add some more steps to the plan without violating the existing constraints and auxiliary constraints, we can still get more solutions to the planning problem. (Through they aren't minimal solution)

Here we define an algorithm of refinement plan:

Algorithm Refinement Plan-1

- 0. Termination: If a solution can be picked up from P, return it.
- 1. Goal Selection: select an open goal G of some steps S of P
- 2. Goal Establishment: (split partial plan into candidate set, make the goal true refinementsly)
 - refine P into different subplans, each corresponding to a different way of establishment G@S.
- 3. Consistency check: if the partial plan is inconsistent, prune it.

Refinement Plan-1 is complete if step 2 is complete.

The problem comes to: how to select a goal from the open goals?

Here we present the Theory of Establishment Refinement: approach A. Modal True Criteria (MTC) given by Chapman. This is a necessary and sufficient modal truth criterion.

For example, we want to make L true at A2.

- 0) First, we check if L is already true at A2?
 - if yes, we are done.
 - 1) if not, find out the action that can satisfy it (make it true).
- But , how can we check that L is already true at A2?
 Tool1. necessary & sufficient condition to check if a goal is true.
 Tool2. use a set of sufficient condition to ensure that goal is true.

There is a straight forward method to check if P is necessary true : just find all the ground linearization and check if they are true. We can check if it's necessary true, necessary false, or possible true (possible false).

But it's clear that this method isn't very useful. We want ways to check if P is necessary true without exhausting list all the ground linearization.

Criteria 1. C is true at S, if there exist a step S' , it's necessary that S'<S (appear before S), S' gives C, and there is no step S" go between S' and S and delete C.

This is a sufficient criteria. There exist some cases that doesn't satisfy criteria. (the problem of white knight).

If it's a finite domain, the problem become NP hard. That's because if variables have finite domain, the noncodesignation might imply some new codesignation, which doesn't appear explicitly. To check that the problem become NP hard.

Yet what we discuss up to know are actions without conditional effects. If there exists actions with conditional effect, the establishment become NP hard. We can image that (some kinds of informal proof):

Suppose we want to check if a particular goal C is true at a point, we check all the actions that add this goal. Suppose there is one step S with conditional effect that add this goal C. To check if this goal C after S, we must make sure first that if the precondition Q of S is true or not when S is executed. Here again the checking of goal Q will repeat the checking procedure of goal C. Through this kind of recursion doesn't necessarily means the problem is NP complete, we can find some method to prove it.

So, checking the true criteria will be NP hard, make the problem intractable, and the planning become very hard. This is why Chapman give up partial planning.

But, it isn't a must that we should use a necessary and sufficient goal establishment algorithm to pick up a not necessary true goal. Also, we can expand searching space to reduce the searching time.

Those problem will be discuss in next class.

```
From ihrig@enws318.eas.asu.edu Wed Feb 23 14:15:35 1994
X-VM-v5-Data: ([nil nil nil nil nil nil nil nil nil nil
  [nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil
])
Status: RO
Return-Path: <ihrig@enws318.eas.asu.edu>
Received:
From enws318.eas.asu.edu by parikalpik.eas.asu.edu (4.1/SMI-4.1)
id AAL5660; Wed, 23 Feb 94 14:15:35 MST
Received:
From enws322.eas.asu.edu by enws318.eas.asu.edu (4.1/SMI-4.1)
id AA08080; Wed, 23 Feb 94 14:13:10 MST
Date: Wed, 23 Feb 94 14:13:10 MST
From: ihrig@enws318.eas.asu.edu (Laurie Ihrig)
Message-Id: <9402232113.AA08080@enws318.eas.asu.edu>
To: plan-class@enws228
```

```
*****
Class note for Feb 16 94
CSE 591: PLANNING & LEARNING METHODS IN ARTIFICIAL INTELLIGENCE
Taken by: Laurie H. Ihrig
(notetakers comments in brackets)
*****
```

Agenda : Goal Establishment
-TWEAK
-ADL

As discussed previously:
Algorithm Refinement Plan-1
0. Termination: If a solution can be found in P, return it.
1. Goal Selection: select an open goal G of some step S of P

2. Goal Establishment:
generate refinements of P, each corresponding to a different way of establishing G@S.
3. Consistency check: if the partial plan is inconsistent, prune it.

Historically, there have been two methods of establishment:

Theories of Establishment Refinement:

1. Invert a necessary and sufficient Modal Truth Criterion (MTC)

From Chapman
-includes white knights
-includes separation

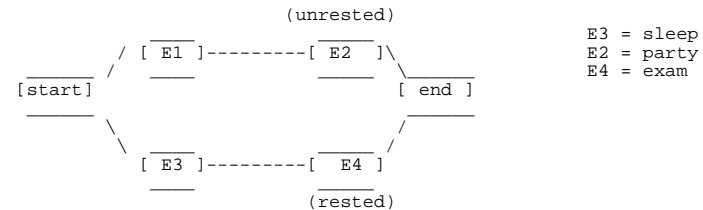
-this method provides completeness in terms of partially ordered plans
-but we don't need completeness in terms of PO plans, only in terms of ground operator sequences
-therefore we can used second method below:

2. Add sufficient constraints to make a given condition true

From Pednault

There are some instances where you would require 1, for example if we want to deal with events as well as actions. Consider that events are actions over which the planning agent has no control (for example, actions performed by the agent's spouse)

Suppose that part of the problem specification includes a set of such events and that these events are partially ordered. Establishing a goal requires knowing if a certain condition will be true at a certain point in time. Suppose we have the following ordering for events E1 to E4:



Suppose that E4 is an exam, and you want to know if you will be rested before the exam. But E2 is a party which will cause you to become unrested.

The problem then is that you only have a partial order for events. Moreover, there is no way you can establish an ordering since these events are out of your control.
ie. If you could order events, you could always demote the party, but since you can't demote the party (since this is under the control of the spouse) planning will only be complete if you know the necessary and sufficient conditions, ie use method 1, MTC.

In UCPOP cannot do that, because:

- it is to conservative:

PVQ----A1----A2----R
 Q

If A2 gives R to the final state, Q has to be true before A2.

UCPOP can be changed, such that causation precondition=regression, but it still

- splits a disjunctive precondition,

so, THE REAL DIFFERENCE between ADL and UCPOP is that UCPOP assumes completely specified initial states.

When have completely specified initial state, can:

- differentiate causation

From regression (and can make it a formula simpler then regression);

- work on a disjunction by working on the disjunct parts separately.

For any action A, A (F) - where F is a formula-can be distributed over the components of the formula.

For actions with nondeterministic effects (like action A1=tossing a coin: the effects will be H(ead) V T(ail). We want to know what are the weakest conditions before A1, such that T will be true after A1.

We can look regression as Weakest SUFFICIENT conditions (no necessary)

-1
A1 (T)=T
-1
A1 (H)=H
-1
A1 (TVH)=True which is different

From TVH

Adopting this definition of regression, all its distributive properties will be no longer valid.

If the initial state is completely specified, then causation and preservation are subformula of the regression.

Establishment in UCPOP is adding:

- ordering
- bindings
- preconditions
- links.

As a solution constructor, can take the following:

1. take a ground linearization of the plan;
2. check if satisfies ADL correctness principles forward execution, and if there is a plan, the termination will be successful.

There may be branches in the search space in which establishment is do and undo, but in the whole search space there is at least one branch which will lead to a solution. So, having a complete search algorithm, will have completeness (for plans).

Case Study - TWEAK (Chapman)

-
- Theory of establishment is different
 - From ADL.
 - It cares for efficiency.
 - TWEAK can work on the same open condition arbitrary many times, within the same branch.
 - TWEAK is not systematic.

For seeing TWEAK 's redundancy and doing and undoing establishments, see figure 4, in 'Planning as Refinement Search...', by S. Kambhampati.

Completeness: - if there is a plan, it will be found. If no plan exists, the algorithm may loop forever.

BOOKKEEPING strategies - 3 ideas:

- Idea 1 - GOAL PROTECTION - to work only once on each condition, and take it out
From the agenda. When agenda is empty and the solution is not a candidate one, then can abandon that branch.

Goal protection / whenever a goal already established becomes necessarily untrue, quit that part! or
 \ when work on a goal, remove it
From the agenda (doing this, the efficiency can be smaller)

Idea 2 - PROTECT THE INTERVAL
 g
A1-----A2 (A1 gives g to A2)

if an action A3 (A1<A3<A2) deletes g, that path can be quit and backtrack. Protection of intervals can be seen like goals maintenance (protect causal links)

Idea 3 - CONTRIBUTOR PROTECTION -for having systematicity

 g
A1-----A2
|--A3--|
 g
|--A4--|
 because
 the contributor that gives goal g is protect!

an action A1 gives g to A2
- if A3 comes between A1 and A2 and deletes g, it is not allowed
- if A4 can come between A1 and A2 and also adds g, that path will be quit

That leads to systematicity: if P1 and P2 are plans in different branches, then no ground operator sequence S will be consistent with both P1 and P2.

Algorithm Refine-Plan-2

```

0. Termination
1. Goal selection
2. Goal establishment
   2.1. Bookkeeping - add auxiliary constraints (causal links)
                        to remember establishment decisions
   This is a new step!
3. Consistency checking
-----
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X-Sun-Data-Name: r.pla
X-Sun-Content-Lines: 242
    
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NOTES FOR 20 FEBRUARY CLASS

Ioana Rus

Agenda:

1. ADL vs. UCPOP
2. Case study: TWEAK
3. Algorithm Refine-Plan-2

1. ADL vs UCPOP

Here is a simplified version of the bomb-in-the-toilet problem that ADL based planning theory can solve but UCPOP cannot.

Problem

Initial state: P V Q
 Final state: R
 Actions: (two actions are available)

```

A1
precond: nil
effects: If P then R
    
```

```

A2
precond: nil
effects: If Q then R
    
```

We know that the following plan

A1 --> A2

will solve this problem (i.e., if you execute A1 and then A2, you are guaranteed to have R true in the resulting situation).

Qn 1. Explain how the secondary preconditions based theory of planning can be used to (a) check that this plan is correct and (b) make this plan.

Qn 2. What are the reasons UCPOP algorithm is not able to deal with this problem?

Answers:

```

           if P       if Q
           then R     then R
P V Q -----A1-----A2-----End
                                   R
    
```

```

-1
A2 (R)=QVR

-1      -1      -1
A1 (QVR)=A1 (Q) V A1 (R)= QVPVR
    
```

if I \models A1 (A2 (phi)), then phi is true after the execution of the plan.
 (that means initial state entails...)

Let us see what are conditions for a plan A1, A2, ..., An to make phi true, after it is executed.

EXECUTABILITY:

```

I  $\models$  PI
      A1

-1
I  $\models$  A1 (PI )
      A2

.....

-1 -1 -1      -1
I  $\models$  A1 (A2 (A3 (...(An-1 (PI )))).. )
      An
    
```

The regression of phi over action A = the weakest condition required before A, such that phi is true after A.

```

-1      -1 -1
I  $\models$  A1 (...(An-1 (An (phi))).. )
    
```

Can convert proof of correctness of a plan into a theorem proving.

The second precondition theory - for phi to be true at an action A, there must be some action A', A' < A that causes phi and every action A' < A'' < A must preserve phi.

Unless you know what action makes phi true, cannot distinguish differences between causation precondition and preservation. Regression can be used to prove that this plan is correct, and also to generate it.

```

           A2-----A1-----End
PVQVR           PVR           R
    
```

```

---A1
\      -1
/      A1 (R)= PVR
---R
    
```


the contributor that gives goal g is protect!

That leads to systematicity: if P1 and P2 are plans in different branches, then no ground operator sequence S will be consistent with both P1 and P2.

Algorithm Refine-Plan-2

- ```

0. Termination
1. Goal selection
2. Goal establishment
 2.1. Bookkeeping - add auxiliary constraints (causal links)
 to remember establishment decisions
 This is a new step!
3. Consistency checking

```

```

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 [nil nil nil nil nil nil nil nil nil nil nil nil nil nil nil
])
Status: RO
Return-Path: <AZEWS@ACVAX.INRE.ASU.EDU>
Received:
From ACVAX.INRE.ASU.EDU by parikalpik.eas.asu.edu (4.1/SMI-4.1)
 id AA05309; Mon, 28 Feb 94 20:37:13 MST
Received:
From ACVAX.INRE.ASU.EDU by ACVAX.INRE.ASU.EDU (PMDF V4.2-13 #2382) id
 <01H9FKDSRUY800J887@ACVAX.INRE.ASU.EDU>; Mon, 28 Feb 1994 20:34:03 MST
Date: Mon, 28 Feb 1994 20:34:02 -0700 (MST)
From: AZEWS@ACVAX.INRE.ASU.EDU
Subject: class notes of monday, feb 28 --- in a jiffy !
To: plan-class@parikalpik.eas.asu.edu
Message-Id: <01H9FKDSXR4Y00J887@ACVAX.INRE.ASU.EDU>
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Content-Transfer-Encoding: 7BIT

```

```

***** Notes for 28 Feb 1994 Ed Smith *****

Administrative Notes:
* Have questions about the sanity check for next time (Wed).
* Make-up class period: Friday, 4 Mar ERC 393 15:00 to 16:40.
* For Wednesday: Read: NONLIN, FORBIN, NOAH, SIPE papers

```

```

LAST TIME:

We talked about bookkeeping. Bookkeeping supports the objective of
REFINEMENT SEARCH, wherein search is defined as the process of
splitting a node into a number of nonempty nodes in such a way that
the child nodes are mutually uncommon; i.e., they share no children.

```

- Book keeping methods we saw last time are:
- 1 Agenda (weak ;-don't backtrack till agenda empty)
  - 2 Protection

3 Contributor Protection (strongest protection)

Last time we also saw the equation:

$$Fd = K * Rd / kd$$

where:  
 Fd == # of fringe nodes @ level d of search tree  
 K == total # of ground operator sequences  
 Rd == average redundancy of the dth level of the search tree  
 kd == average size of the nodes (candidate sets)

Bookkeeping strategies reduce Rd; attacking Rd sooner rather than later is better, all other things being equal.

For Contributor Protection, Rd == 1 ( :- )

Doing a consistency check ---> no empty nodes will get added to the search tree.

```

IF WE ASSUME THE COST OF CONTRIBUTOR PROTECTION IS SMALL:

Impact on unsolvable problems:
 With Protection:
 * overall search space WE EXPLORE will be smaller since Rd = 1.
 Without Protection:
 * the search space explored will be larger.

```

Impact on solvable problems:  
 \* if density of solutions in search space is high, no difference.  
 \* if density of solutions in search space is low, we approach the unsolvable problem situation.

```

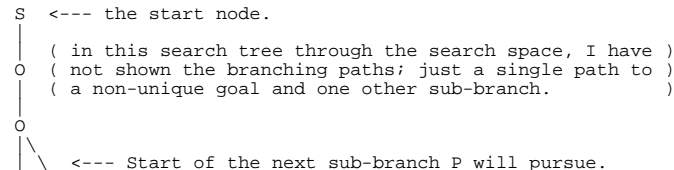
so, PROTECTION STRATEGIES ARE LIKE INSURANCE:
(log-linear performance plots of time vs. complexity bore this out)

They will help us in situations without solutions, and in situations
with low solution densities. Protection strategies cost something
to implement, and may even steer the search AWAY
From SOME
solutions. Consider a protection scheme P:

```

At each node, we have:  
 P = { Pe , Pp }

where:  
 Pe are the establishments  
 Pp are the (imposed) protection requirements









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       id AA00600; Sat, 5 Mar 94 15:05:18 MST  
 Message-Id: <9403052205.AA00600@parikalpik.eas.asu.edu>  
 From: rao (Subbarao Kambhampati)  
 To: plan-class  
 Subject: Pre-ordering strategies (an EVEN clearer story)  
 Date: Sat, 5 Mar 94 15:05:18 MST  
 Reply-To: rao@asuvox.asu.edu

The mail I sent earlier on pre-ordering strategies is erroneous. This modified version is correct (or so I believe right now)...

Here is a more complete story on the pre-ordering strategies.

Pre-ordering strategies use a localized interaction test to check if a pair of (unordered) steps should be ordered with respect to each other. They will refine the plan until no pair of interacting steps are left unordered.

The "interacts" routine uses the local properties of the steps to decide whether they interact

Here are a variety of ways of defining this routine, in increasing order of eagerness to order steps.

#### 1. UA (unambiguous truth ordering)

c1. s1 interacts with s2 if s1 has a precondition C and s2 has an effects that either negates C or adds C

OR

c2. s1 has an effect C and s2 has an effect that negates C

Using UA will not only ensure that the partial plans in the search queue will be necessarily safe or necessarily unsafe with respect to protection intervals, but will also ensure that the partial plans are unambiguous.

When a plan is unambiguous, every condition is either necessarily true or necessarily untrue (irrespective of whether or not there is a causal link supporting it already).

Thus if the plans are unambiguous, we can check necessary truth of a condition in polynomial time and only work on those conditions that are not necessarily true (i.e., are necessarily FALSE).

In the literature, unambiguity was first introduced to show a systematicity like property. But, it turns out that unambiguity has nothing to do with systematicity. Systematicity depends only on whether or not the planner uses causal links based on contributor protection.

[ As Yong Qu pointed out in the class, if we are only interested in the necessary safety/unsafety with respect to protection intervals, and will only be interested in truth and falsity of the preconditions of the steps of the plan, than c2 above can be changed as follows:

c2': s1 has an effect C, such that C is the precondition of some action in the domain, or one of the top level goals of the problem and s2 has an effect that negates C ]

#### 2. UCA (unambiguous contributor ordering)

c1. s1 interacts with s2 if s1 has a precondition C and s2 has an effect that either negates or adds C

c2. s1 has an effect C and s2 has an effect that either negates or ADDS C

Note that the difference between UA and UCA is in the clause c2 --UCA orders two steps not only when the condition added by one is deleted by another, but also when the condition added by one is also added by another.

It is easy to see that UCA is strictly stronger than UA in that it orders every pair of steps that UA orders, and more.

With UCA, the plan will have the property of unambiguous contributors-- that is every true condition will have a unique contributor step in all linearizations of the plan. Because of this, in a plan that is interaction free with respect to UCA, every contributor protection constraint is either necessarily safe or necessarily unsafe.

#### 4. TO:

s1 always interacts with s2

This is the most conservative of interaction definitions, and it will wind up ordering every pair of unordered steps, thus making each partial plan in the search queue a totally ordered one.

Thus, it not only gives all the properties of PI, CPI and UA, but also makes the planning totally ordered plan-space planning.

It should be easy to see that the branching factor introduced by PI will be less than that introduced by CP, which will be less than that introduced by UA, which in turn will be less than that introduced by TO. As the branching factor increases, so does the search space size (and the impact of the chemistry between b\_t and b\_e factors on performance).

Suppose we want to compare the pre-ordering strategies with conflict resolution strategies.

The corresponding "interacts" routine checks the interactions between a step and an auxiliary constraint (which is typically made up of a range and a condition protected in that range). Then we can also cover conflict resolution using the same notion. Specifically, conflict resolution strategies consider a pair of steps to interact only when they are together taking part in the violation of an auxiliary constraint (causal link).

[And







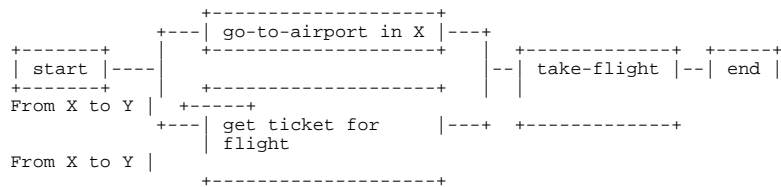


"you will be at the destination of the flight 1234".  
Note that the action is totally instantiated.

The same HTN planner in the same domain may have the action "fly From X to Y". Its preconditions are "be at X" and "have ticket for flight From X to Y". The effect is "you will be at Y". This action is an action template, since it contains variables. Action templates are perfectly legal in HTN planners, as they are in UCPOP planners, too.

Even more general action may exist in the same HTN planner in the same domain, such as "go From X to Y". It has similar preconditions and effects as the above action. However, it does not specify the means of travel. It can be viewed as the general action "go From X to Y by M", where M is the means of travel.

The action "go From X to Y", may be reduced to the following plan:



Note that the means of travel is already set to "flight". The existence of the action "go-to-airport in X" ensures that there is an airport in city X (such condition will probably be directly supported by the initial state).

Note how the action "go-to-airport in X" provides the precondition "be-at-airport in X" for the action "take-flight From X to Y".

This plan may be further reduced, depending on whether the actions (such as "get ticket...") are primitive or not.

During the refinement of the plan, it may turn out that no further refinements are possible, and the plan is not valid (for example, it may still contain non-primitive actions, or some preconditions of the actions may not be supported). In the above example, it may be that the action "get ticket for flight From X to Y" has a precondition "have 300 \$ in the pocket", which is not satisfied in the start state, and there are no actions that can increase the amount of money in the pocket.

The above reduction of the action "go From X to Y" illustrates a typical "recipe" for task reduction used in HTN planning. There

may be several recipes known to the planner for reduction of each task. For example, another possible reduction of the action "go From X to Y" may involve traveling by bus. In such reduction, actions such as "go-to-bus-station in X" and "take-bus from X to Y" may appear.

The planner may backtrack when a given reduction does not lead to a valid plan. The planner is guaranteed to find a valid plan (if one exists) if it considers all alternatives, using some complete search strategy. However, backtracking should be avoided as much as possible, since it reduces the efficiency. Moreover, one of the big motivations for HTN planning is improved efficiency, since there is a reason to hope that efficiency is inherent to the hierarchical approach. Therefore, relying heavily on backtracking will affect one of the key advantages of HTN planning: efficiency.

By choosing to do HTN planning, one hopes that the refinement of two different tasks in the higher-level plan usually will not ADD new constraints between the two groups of subtasks generated by refining these two "parent" tasks.

Note that when doing HTN planning, we are still doing binding, have constraints, auxiliary constraints, etc., similarly to the familiar UCPOP planning.

Another simple example of action refinement in HTN planning may be the refinement of the single action "make-hole-by-drilling" to the lower-level actions: (1) "position the hole", (2) "make primary hole", and (3) "fine-drill the hole".

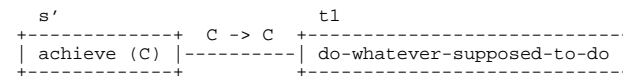
### 3. SELECTED DETAILS OF TASK REDUCTION

Any HTN algorithm performs the planning in refinements cycles. Each cycle includes two basic steps: (1) reducing the steps (tasks), and (2) taking care of the constraints.

In order to support an open precondition C of a step in the plan, HTN has two options: (1) to use the effect C of an existing step, or (2) to instantiate a new step providing the effect C. The latter option creates the so-called "precondition achievement tasks". There may be several candidate tasks that can provide the effect C.

During the task reduction process, usually there are more different ways to reduce a given task. Some of the reductions may include NO-OPERATION (NOOP) subtasks. NOOP tasks are useful when one of the choices for task reduction is to reduce to no subtasks. The NOOP tasks are also sometimes needed to keep track (to enforce) the auxiliary constraints (causal links) that are can not be assigned to the other subtasks generated by the reduction.

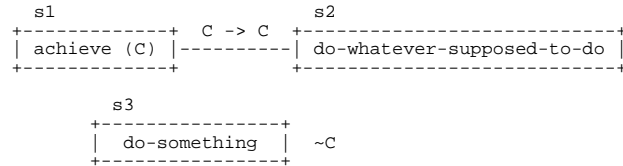
When introducing tasks to support preconditions of existing tasks, causal links are added to the plan structure. For example, if the existing task t1 needed the precondition C, a new task s' may be instantiated having an effect C:





Once causal links are allowed in the plan, then they can be threatened, so there should be some form of conflict resolution, similarly to UCPOP.

Consider the following example:



The task s3 threatens the causal link s1 --> s2. It doesn't matter whether s3 is a primitive task or not. So some threats may be spotted and dealt with on a higher level, with non-primitive tasks. Actually, it is desirable to detect the threats on a higher level, where they can be dealt with more efficiently.

Note that after each task reduction it is necessary to check the interdependencies of all generated subtasks to all other tasks currently in the plan.

The consistency check should be applied after each reduction (refinement) cycle, and if the plan does not satisfy the constraints, it should be abandoned.

Digression: Learning is one of the attractive aspects of HTN planners. HTN planners seem to be better suited to include learning capabilities.

4. DIFFICULTIES IN TASK REDUCTIONS

Task reduction is the basic refinement step in HTN planning. There are some technical problems associated to the reduction and checking of constraints and threats. Some natural questions immediately arise: (1) how to do reductions, and (2) how to merge the reductions into the existing plan. The necessity to address these questions is what makes HTN planners different from UCPOP-like planners.

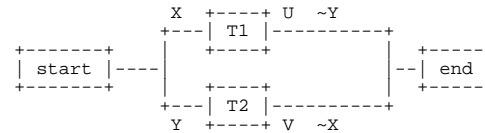
Note that task reductions may ADD new dependencies between two non-primitive tasks, that on a higher level were not visible. This possibility adds to the complexity of doing HTN planning, and generally reduces the efficiency of the planning process. While doing conflict resolution, one may apply exactly the same algorithms as used in UCPOP. However, it will usually be less efficient, since no advantage will be taken of the hierarchical structure of tasks in HTN, where it is usually the case that no new interactions will be introduced by task reductions.

Another design question for HTN planners is whether to keep reducing the selected task until only non-primitive subtasks are left, or

to take one task and reduce it once, then go to some other task, reduce it once, etc., and then recursively reducing the subtasks in the same manner. The former approach is similar to the LIFO data structure, while the latter corresponds to FIFO data structure. Both strategies are complete, although it seems that FIFO approach would be more efficient, since it is more likely to take advantage of the hierarchical nature of HTN planners.

Let us return to the MERGING-OF-REDUCTIONS problem that HTN planners must address. Two questions arise: (1) what happens to causal links between higher-level actions when they are reduced to subtasks, and (2) what happens to the partial orderings. Both questions address the same type of problem: how to split the obligations of the parents among their children.

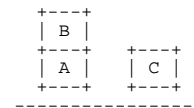
In order to further illustrate the problems that HTN planners face, consider a simple single-task plan, where the task requires the preconditions X and Y, and generates U & V (the goal). One possible reduction of the task may lead to the following plan:



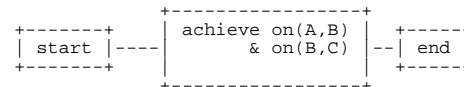
It is clear that the refined plan can NOT be executed. So, starting with an executable high-level plan, the HTN planner may end up with an illegal plan, after performing some reductions. In such a case, the HTN planner will have to backtrack.

The opposite case is also possible, although less likely to appear in realistic planning problems. Namely, a given plan may be illegal (not executable) on a higher level, but after performing some reductions it may turn out to be a viable plan! We are to come (for homework) with an example illustrating this case. The example should be very simple, assuming a plan with a single start and single end points, and only two steps.

Let us consider an HTN planning problem in the blocks world. Let the initial state be:



Let the initial plan contain a single non-primitive action:









5) BLOCK-SERIALIZABLE subgoals

Definition: serializable sequences of multiple subgoals

Serializability can be considered function of the sets of subgoals.  
Can abstract, grouping subgoals into serializable sets.  
The abstraction can be at one level, or at multiple levels.

MACRO-OPERATORS are sequences of primitive operators.

Defining macro-operators involves learning. It's usefull when

- the same problem must be solved many times
- many similar problems to solve-> the cost of learning will be amortized over all the problems instances to be solved.

For non-serializable subgoals, can define macros that leave previously achieved goals intact, even though they may violate them temporary.

The goals become serializable w.r.t. the set of macros.  
An exponential number of problem instances can be solved without any search, using only a linear amount of knowldege expressed as macros.

In [3], the hierarchy of subgoal interaction is extended:

6) TRIVIALY SERIALIZABLE subgoals

Definition: each subgoal can be solved sequentially in any order, without ever violating past progress

7) LABORIOUSLY SERIALIZABLE subgoals

Definition: there exists 1/n orders in which the subgoals cannot be solved without possibly violating past progress

In [3], they claim that the partial order planners have the advantage that if all planners perform well only when confronted with trivially serializable subgoals, more domain are serializable for partial order planners than for the total order planners.

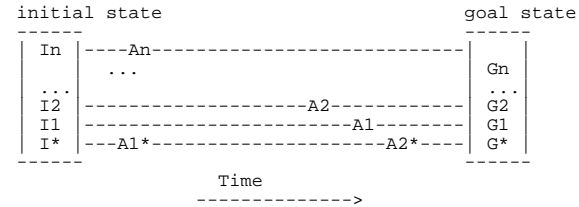
To support this, they analyze the performance of three different planners for an artificial domain, created for the analysis.

- The three planners are:
- TOPI - plan-space algorithm, isomorphic to a regression search in the state space
  - TOCL - total order planner
  - POCL - partial order planner

The domain is called D1S1\*, and it uses a STRIPS representation:

```
(def-step: action Ai
 precondition {Ii}
 add {Gi}
 delete {Ii+1,I*})
```

```
(def-step: action A2*
 precondition {P*}
 add {G*}
 delete {I1})
(def-step: action A1*
 precondition {I*}
 add {P*}
 delete {})
```



- The subgoals specified by this domain are:
- non-serializable for TOPI,
  - trivially serializable for POCL
  - laboriously serializable for TOCL

Their empirical results shown that both total order planners should find problems in this domain intractable, while the partial order planner should have no difficulty.

CONCLUSIONS

- The serializability of a problem depends on:
- the subgoals
  - the initial state
  - the operators
  - the problem solver

Protection and serializability are defined differently for the two planning approaches : state space and plan space, but still attempted to be compared.

References:

1. David Joslin and John Roach, "A Theoretical Analysis of Conjunctive\_Goal Problems", AI 41 (1989/90) 97-106
2. Richard E. Korf, "Planning as Search: A Quantitative Approach", AI 33 (1987) 65-88
3. Anthony Barrett and Daniel Weld, "Characterizing Subgoal Interaction for Planning", IJCAI 1993

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CSE 591                      SPRING 1994  
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notes for the class on April 22, taken by Ioana Rus  
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Planning as Search Involving Quasi-Independent Subgoals  
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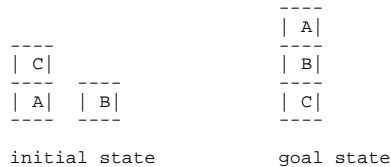
1. Overview

- A theoretical analysis of conjunctive goals problem
- Planning as search using subgoals, macro-operators and abstraction as knowledge sources
- Characterizing subgoals interaction for planning
- Conclusions

2. A theoretical analysis of conjunctive goals problem

When final goal is a conjunction of subgoals, the plan depends on the goals interaction. Goal protection means to protect a goal already achieved. But this is not always possible.

For example, the Sussman anomaly:



or a robot planning problem: the robot (X) is in a room, in position 1; it has to go in the other room, near a sink ([] position 4), thru a door (positions 2-3). In the final state, the door must be closed.

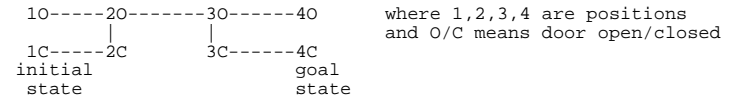


For these problems, goal protection cannot be satisfied. In [1], they provide a method for analyzing the linearity of a problem,

using graphs.

A nonlinear problem is one for which the subgoals cannot be solved in some linear order without having to take into account the way the subgoals interfere with each other.

If planning is done as a search in the world state space, and this space is finite, then it can be represented as a graph:



State space

The goal is composed by two subgoals: position 4 and door closed (C). The graph can be decomposed into subgraphs, corresponding to the subgoals:



If assume that the operators can be reversed, then these subgraphs are undirected. They have connected components for the subgoals. To achieve a goal means entering in any of these connected components. To protect a goal, is to confine to that connected component; if it doesn't contain the final goal state, then protecting the subgoals prevents solving the problem.

Using this method, by analysing the graphs, one can say whether the problem is or is not nonlinear: having a connected component that doesn't contain a final goal state is a necessary condition for nonlinearity .

(That doesn't mean that there cannot be any algorithm able to avoid entering that component)

3. Planning as search using subgoals, macro-operators and abstraction as knowledge sources

Planning as search can be done either by brute-force search, or using some knowledge sources, such as heuristics, subgoals interaction, macro-operators, and abstraction. All of these are used in order to reduce the complexity.

For brute-force search, the space is  $O(b^d)$  for breadth first search,

or  $O(d)$  for depth first search, and the time is  $O(b^d)$ , where b=branching factor, and d=depth of the tree.

Heuristics reduce the branching factor.

If the problem can be decomposed, this tends to devide the exponent.

In [2], they develop a subgoals interaction hierarchy, as follows:

1) INDEPENDENT subgoals

Definition: each operator can change the distance to a single subgoal  
 Property: by concatenating the optimal solutions for the subgoals, can get the optimal solution for the global goal.  
 Complexity reduction: both the base and the exponent, by the number of subgoals.

2) SERIALIZABLE subgoals

Definition: there is an ordering among the subgoals, such that the subgoals can be always solved sequentially without ever violating a previously solved subgoal in the order.

Advantages: reduces the branching factor (knowing that the goals are serializable, and that a subgoal was achieved, the paths with the subgoal not yet reached will be pruned)

Disadvantages:- proving serializability is as difficult as proving that a problem is solvable  
 From the initial state.  
 - protecting goals may increase the length of the solution

3) NON-SERIALIZABLE subgoals

Definition: previously achieved goals must be violated for making further progress towards the main goal, regardless of the solution order.

Complexity: - is not reduced

Advantages: - in general, solving subgoals, even non-serializable, reduces the distance to the goal.

4) PATHOLOGICAL subgoals

Definition: solving the subgoals doesn't decrease the distance to the main goal.

Example: sets of subgoals for Rubik's cube

5) BLOCK-SERIALIZABLE subgoals

Definition: serializable sequences of multiple subgoals

Serializability can be considered function of the sets of subgoals.  
 Can abstract, grouping subgoals into serializable sets.  
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Defining macro-operators involves learning. It's useful when  
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In [3], the hierarchy of subgoal interaction is extended:

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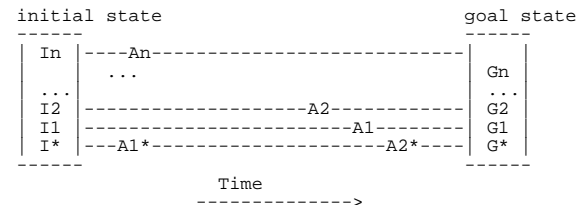
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(def-step: action A2*
 precondition {P*}
 add {G*}
 delete {I1})
(def-step: action A1*
 precondition {I*}
 add {P*}
 delete {})
```







The general planning problem is UNDECIDABLE. It means that given a PLANNING PROBLEM and a PLANNING ALGORITHM, in general one can NOT tell in advance whether the planning algorithm will HALT.

To clarify the implications of undecidability, consider a run of a planning algorithm on a planning problem, where the algorithm is allowed to take ANY finite time and resources (provided that the limits are set prior to the running of the algorithm). If the planning algorithm fails to generate a plan (or fails to determine that no plan exists) within the predetermined limits, one can NOT tell whether a plan that solves the planning problem exists or not.

Clearly, undecidability is a very undesirable property for the practical use of planning. The expressiveness of the general planning problem needs to be sacrificed in order to avoid undecidability.

### 1.2. Restricted Planning Problems

Several planning formalisms have been proposed that restrict the expressiveness of the general (unrestricted first-order) planning formalism, trying to deal only with "easier" planning problems. The expressiveness of the domain, the operators, and the initial and goal states (and any combination of these) can be restricted.

The best-known restricted planning formalisms include the following:

#### a. STRIPS formalism

- Restricts the expressiveness of the operators. Each operator is defined by three lists: precondition, add, and delete list. The operator is applicable in a given state if that state entails all sentences of the PRECONDITION list. If the operator is executed, the sentences of the ADD list are added to the world state, and the sentences of the DELETE list are removed from the world state.

- In its most general form, STRIPS does not impose any restrictions on the domain.
- Very often, only the PROPOSITIONAL restriction of STRIPS is considered. Under this restriction, neither the domain nor the operators can contain quantified sentences or functions. The states and the operator lists are restricted to sets of propositional atoms. Negated preconditions and goals are allowed.

Problems that can be cast in the PROPOSITIONAL STRIPS formalism are DECIDABLE.

#### b. TWEAK formalism

- Uses the STRIPS restriction of operators (precondition, add, delete lists) .
- Limits the state and operator descriptions to conjunctions of literals (atoms and negated atoms) .
- Allows partially specified (incomplete) initial states .

Although there has been much controversy about the decidability of problems cast in the TWEAK formalism, it is now known that the planning in TWEAK is DECIDABLE, provided that both (1) functions are not allowed, and (2) there are finitely many constants in the domain.

Later in this presentation we cover the SAS+ planning formalism, which is basically a variant of propositional STRIPS, but uses multi-valued state variables (see 4.). Planning in SAS+ is decidable, and many interesting complexity results have been proven for this formalism (see 5.).

### 1.3. Inherently Hard Problems

Many problems are inherently hard. Regardless of the formalism in which such problems are formulated, they have the potential of requiring enormous resources (time) for their solution. A simple and somewhat striking example of such problems is the problem of finding an OPTIMAL plan for the BLOCKS WORLD domain. It has been proven [4] that this problem is NP-complete (see 1.4. for overview of NP and other basic complexity classes). (Note that the problem of finding a non-optimal plan in the blocks world is polynomial).

When a PROBLEM is known to be hard, no ALGORITHM can be devised to solve that problem in time less than the inherent complexity of the problem. So, in the worst case, any algorithm solving the problem will take enormous amount of resources (time).

The planning process for inherently hard problems can be improved (on the average case) by using domain-specific heuristics. However, the domain-specific heuristics have the disadvantages of (usually) being very hard to find, and being different for different domains.

### 1.4. (Digression) Basic Complexity Classes

Computational problems can be classified in the following major classes according to their complexity:

- a. Polynomial (tractable) - for each problem of this class an algorithm is known that solves the problem in time that is upper-bounded by a polynomial function of the problem size.
- b. NP-complete (almost certainly intractable) - no algorithm is known that solves these problems in polynomial time. On the other hand, none of them is being proven to require exponential time. It is BELIEVED that NP-complete problems are intractable. If any NP-complete problem can be solved in polynomial time, then ALL NP-complete problems are provably solvable in polynomial time. A lot of NP-complete problems are well-known, important practical problems, all of which have resisted the attacks of researchers and practitioners trying to solve them in polynomial time. This provides further evidence that NP-complete problems are intractable.
- c. P-SPACE complete (almost certainly intractable) - similar to the NP-complete problems, this (larger) class of problems

in addition requires polynomial SPACE for their solution.

- d. Provably Intractable Problems - for any problem of this class it has been PROVEN that they will take time that is lower- and upper-bounded by exponential function of the problem size.

Of all these classes of problems, only the tractable (polynomial) problems can be solved (in principle) in the worst case for any reasonably big problem size. Due to the astonishing growth rate of exponentials, the intractable (including the NP-complete) problems can not be solved in reasonable time. Usually, intractable problems with problem size of more than 30 elements are considered too hard for the current technology.

2. DEALING WITH COMPLEXITY

Many practical planning problems are intractable, meaning that they can not be solved satisfactorily in the general case. Several approaches have been proposed and used to address the solution of such problems:

- a. Reactive Planning (Chapman) - instead of generating plans in ADVANCE, the agent has a prepared set of useful rules of behavior and starts acting in the world. At any given point, he decides on the following step based on the current state of the world and the set of rules of behavior.

This approach certainly has its merits; however, it is difficult to guarantee any formal properties of the process, such as whether the agent will reach the goal (if adequate sequence of actions does exist), etc.

- b. Restrict the Generality - instead of attacking the most general problem, try to solve a restricted version of the problem. Two basic approaches can be followed when trying to identify the most general TRACTABLE subproblem:

- start with the most general problem, and add restrictions until a tractable approximation of the problem can be modelled.
- start with a provably tractable problem, and relax restrictions as long as the problem is still tractable.

One of the advantages of the SAS+ formalism (see 4.) is that it seems to support well the modelling of problems according to this approach.

The challenge with this approach is to have expressive enough formalism to capture general planning problems, and at the same time to support easy-enough formulation of constraints that can be used to restrict planning problems to tractable, yet practically interesting ones.

Since any given formalism will be overexpressive for some planning problems, any yet limited for others, it is natural to try to identify subclasses of problems that have mutually similar properties, and utilize such properties to (1) devise tailored algorithms for the corresponding problems, (2) prove the basic characteristics of the subclasses, and then (3) analyze how to reduce each subclass to a tractable subclass

of problems. Note that no domain-specific heuristics is used, although the PROVABLE properties of the problems ARE being used to identify the subclasses.

- c. Relax the Completeness Criterion - if the failure to find a plan (that otherwise exists) can be tolerated, then algorithms can be devised that can generate the plans (the ones they are capable of generating) in polynomial time.
- d. Use Domain-Specific Heuristics - the performance of the planning algorithm can be improved in the average case using the domain-dependent heuristics. However, the domain-specific heuristics have the disadvantages of usually being very hard to find, and being different for different domains.

To satisfactorily solve a practical planning problem, often a combination of the above techniques will be employed.

3. COMPLEXITY OF STRIPS PROPOSITIONAL PLANNING - SUMMARY

We briefly summarize some known results on the complexity of STRIPS propositional planning, as presented in [2]:

- Note:
- '\*' stands for 'any number of'
  - '+' stands for 'positive (non-negated)'
  - each number specifies the maximum number of corresponding entities.

For example, '2 + precondition' stands for "each operator has AT MOST two positive preconditions".

The restrictions are on the maximum number and type of allowed preconditions and postconditions of the operators.

| Complexity Class | Examples of problems (each line defines a separate problem class) |              |                                       |
|------------------|-------------------------------------------------------------------|--------------|---------------------------------------|
| PSPACE COMPLETE: | * precondition,                                                   | * postcond   |                                       |
|                  | * precondition,                                                   | 1 postcond   |                                       |
|                  | 2 + precondition,                                                 | 2 postcond   |                                       |
| NP-HARD:         | 1 precondition,                                                   | * postcond   |                                       |
|                  | 1 + precondition,                                                 | 2 postcond   |                                       |
| NP-COMPLETE:     | * precondition,                                                   | * + postcond |                                       |
|                  | 1 precondition,                                                   | 1 + postcond |                                       |
| POLYNOMIAL:      | * + precondition,                                                 | 1 postcond,  | number of goals limited by a constant |
|                  | 1 precondition,                                                   | * postcond,  |                                       |
|                  | 0 precondition,                                                   | * postcond   |                                       |

The results clearly illustrate that even in PROPOSITIONAL STRIPS, which itself is a very restricted formalism, most of the problems are

very hard, even with additional restrictions on the number of preconditions and postconditions of each operator.

The results can be restated as follows [2]:

- (1) Propositional planning is PSPACE - complete even if each operator is limited to one postcondition (with any number of preconditions)
- (2) It is PSPACE-complete even if each operator is limited to two positive preconditions and two postconditions
- (3) It is NP-hard even if each operator is restricted to one positive precondition and two postconditions
- (4) It is NP-complete if operators are restricted to positive postconditions, even if operators are restricted to one precondition and one positive postcondition
- (5) It is polynomial if each operator is restricted to positive preconditions and one postcondition
- (6) It is polynomial if each operator has one precondition and if the number of goals is bounded by a constant
- (7) It is polynomial if each operator is restricted to no preconditions

#### 4. THE SAS+ FORMALISM

##### 4.1. Background

The SAS+ planning formalism [1] is based on planning experiences in sequential control applications in industry, where the PROVABLE correctness and tractability (efficiency) are strongly required.

The SAS+ formalism is similar to the STRIPS formalism in that it relies on precondition/add/delete lists for operator representation. The major difference is that the domain (and therefore operators, too) is modelled by a multi-valued (as opposed to boolean TRUE/FALSE) variables.

Another slight difference is in the definition of the operators: in SAS+ each operator has three conditions:

- (1) preconditions that must be satisfied before the operation (and are CHANGED by the operation)
- (2) post-conditions that are asserted (or deleted) by the operators
- (3) prevail-conditions that are required to be satisfied before the operation, and are NOT changed by the operation.

One might ask why a new planning formalism would be useful, especially knowing the result [1] that it is strictly equivalent in its expressiveness to the traditional propositional STRIPS. The reasons may include: (1) SAS+ seems to be better suited for sequential control applications, (2) it seems to be easier to identify restrictions in SAS+ that seem relevant to practical applications, (3) it provides a different, alternative, fresh look

at the planning problems.

##### 4.2. An Example of a Planning Problem in SAS+

The traditional BLOCKS WORLD can be modelled in SAS+ using two state variables for EACH block:

- Position of the block (on another block or on the table)
- Is the block clear (true/false)

Each state can be conveniently represented by a tuple of the state variables. For example, given a domain with three blocks (A, B, C), where in the initial state A is on B, and B and C are on the table, and the goal state is A on B, B on C, and C on table, can be represented as follows:

```

State Tuple
(template) (PosA, ClrA, PosB, ClrB, PosC, ClrC)

Initial State (B, true, Table, false, Table, true)
Goal State (B, true, C, false, Table, false)

Move A-from-B-to-C
Preconditions (B, u, u, u, u, u)
Postconditions (C, u, u, true, u, false)
Prevail-conditions (u, true, u, u, u, u)

```

(note: 'u' stands for "doesn't matter")

It is clear that there would be a lot of ground operators defined in the above fashion. However, nothing prevents us to use operator templates, using variables. The above ground representation is more convenient when complexity issues and expressiveness are analyzed.

##### 4.3. SAS+ Planning Subproblems

Several standard problems can be stated for problems expressible in SAS+:

- (1) SAS+ plan existence problems:
  - unbounded plans ("is there a plan of any length ?")
  - bounded plans ("is there a plan with no more than 'k' steps ?")
- (2) SAS+ plan search problems:
  - unbounded plans ("find a plan, doesn't matter how long")
  - bounded plans ("find a plan with no more than 'k' steps")
- (3) SAS+ minimal plan search:
  - find a plan with minimal number of steps.

Of course, the same problems can be stated for any other planning formalism. However, SAS+ formalism seems to allow easier analysis of the complexity of such problems, especially for restricted problems (see 4.5.).



```

U PSPACE PSPACE intractable intractable
S PSPACE PSPACE intractable intractable
unrestricted PSPACE PSPACE PSPACE PSPACE

```

It is interesting to note that it has been proven that the minimal plans in all but PUBS, PUS, UBS, and US restrictions can have exponential length with respect to the problem size. Therefore, the PLAN SEARCH PROBLEM can NOT be tractable anyway for such problems (generating an exponentially long plan can not be done in polynomially bounded time).

5.3. SAS+ Theoretical Importance

The analysis of SAS+ planning made by Backstrom [1] significantly extends our understanding of the complexity of planning. SAS+ provides a well-founded framework for future research on the complexity of planning.

SAS+ provides the first truly interesting fully tractable planning class (SAS+ PUS). In addition, SAS+ shows that releasing any of the restrictions of this class leads to intractability.

Another very important contribution of SAS+ is the proof of the strong mutual equivalence of the expressiveness of the 'standard' propositional planning formalisms, and (in addition) their equivalence to SAS+ planning formalism.

Finally, SAS+ demonstrates one feasible approach for handling the tractability of planning problems. By defining other restrictions (other than P, U, B, S), one may model various subclasses of planning problems and try to identify tractable, yet practically interesting subsets of planning problems.

6. CONCLUSION

Planning problems are in general computationally very hard. Therefore, various restrictions must be applied in order to allow solving realistic, practical problems.

Provably complete and provably polynomially upper-bounded algorithms are always a nice thing to have, and for some critical applications (such as industrial control applications) they are a basic requirement.

One feasible approach to handle the complexity of planning is to identify tractable subclasses of planning problems. It can be done by starting with a reasonably general class of problems, and then removing the not-so-badly needed expressiveness 'features' until a tractable subclass tailored to the specific need is identified.

It seems that many of the available options for reducing the complexity may have to be applied in CONJUNCTION in order to satisfactorily solve all but the most trivial realistic planning problems.

7. REFERENCES:

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- [4] Naresh Gupta and Dana S Nau, "On the complexity of blocks-world planning", Artificial Intelligence, 56:223-254, 1992.

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 END OF NOTES  
 From THE SESSION ON APRIL 25th  
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