Planning, Execution & Learning
1. Transformational Planning

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Transformational Planning

- Basic Idea
  - ***Create new plan by* modifying *existing plan***
    - Reordering steps
    - Removing/replacing steps
    - Changing parameter bindings
    - …

- When Useful?
  - Tweaking or merging existing plans (***case-based planning***)
  - "Planning as Debugging"
    - Can be viewed as "***intelligent backtracking***"

Partial Plans

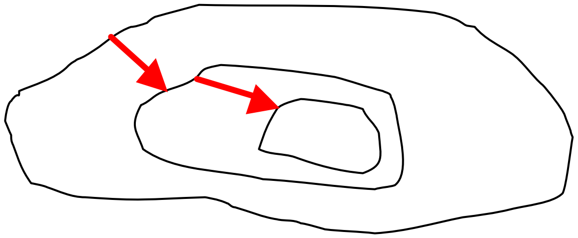
- ***Complete Plan***
  - Total order, all parameters bound

- ***Plan Completion Set***
  - Set of complete plans

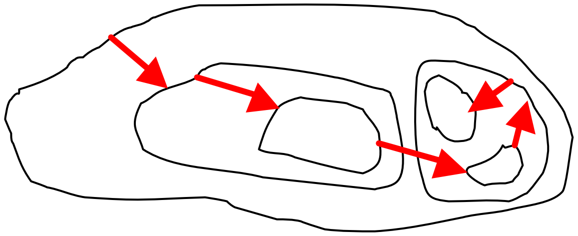
- ***Partial Plan***
  - Plan consistent with one plan completion set

Transformational Search Space

- Search Space of ***Refinement*** Planners (UCPOP, Prodigy)
  - Can move from one node in search space to another only if completion set of second plan is ***subset*** of first



- Search Space of ***Transformational*** Planners
  - No relationship necessary between completion sets of connected nodes in search space
  - Can “jump” between partial plans without backtracking



Advantages and Disadvantages

+ New Search Opportunities

+ Can Avoid Unnecessary Backtracking

+ Can Use Total-Order Planner and Get Many of the Advantages of Partial-Order Planner

+ Can Use for Modifying Existing Plans (plan libraries, case bases)

- Much Larger Branching Factor

- More Complex Algorithms

- Need to Detect Cycles in Search Space

- Hard to Guarantee Completeness

Hacker (Sussman, 1975)

- “A Theory of Skill Acquisition”
  - Either use an existing plan (“subroutine”) from a “library”, or create a new one (either from scratch, or by conjoining and debugging existing plans)
- **“The Virtuous Nature of Bugs”**
  - ***Critics*** look for failures or “un-aesthetic” plans (e.g., moving same object twice in a row)
  - Bugs are ***patched***, then ***generalized***
  - But, patching never leads to wholesale rearrangement
- Cannot Optimally Solve “Sussman’s Anomaly”
  - Linear Planner (no interleaving of learned subroutines)

CHEF (Hammond, 1987)

- Plan Repair for ***Case-Based Planning***
  - Build new plans from “memories” (instances) of old ones
  - Tweak plans to fit new situations
- Use ***Causal Explanations*** to Access Different Repair Strategies
  - Produced by simulation / forward propagation
- Repair Failure Without Interfering with Other Goals
  - Each repair strategy breaks a link in the causal chain
  - Seventeen general repair rules (mostly domain-independent)
    - Reorder events
    - Remove precondition
    - Split step into two and run concurrently
    - Replace existing tool
    - Increase “down” side of a balance relationship
  - Question-answering approach

Making the Perfect Soufflé

- **Strategy**: Trying to make strawberry soufflé by adapting regular soufflé recipe
- **Observe**: Soufflé is ***flat***

  Failure: Side-Effect:Disabled-Condition:Balance

  ***Evaluate Strategy*: Alter-Plan:Precondition**

  Question: Is there an alternative to "bake batter for 25 minutes" that will satisfy "batter now risen" and does not require "thin liquid in bowl from strawberries"?

  Response: *None*

  ***Evaluate Strategy*: Alter-Plan:Side-Effect**

  Question: Is there an alternative to "pulp strawberries" that will enable "dish tastes like berries" and does not cause "thin liquid in bowl from strawberries"?

  Response: Use "strawberry preserves" instead

  ***Evaluate Strategy*: Recover**

  Question: Is there a plan to recover from "thin liquid in bowl from strawberries"

  Response: After "pulp strawberries" do "drain strawberries"

- Heuristic (domain-specific) knowledge used to choose which repair to actually use for a given failure

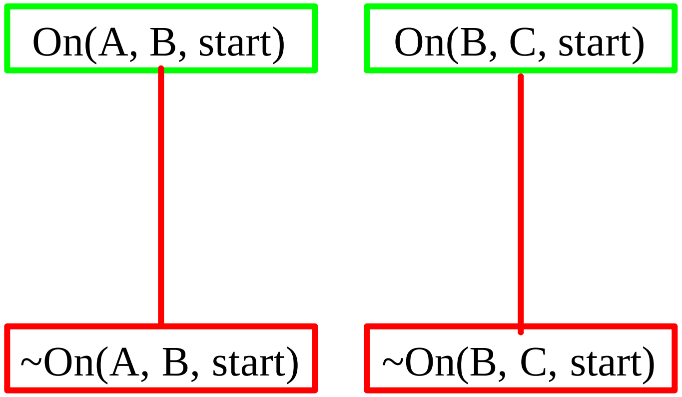
Gordius (Simmons, 1987)

- Debug Plans Produced by “Case-Based” Systems
  - Debugging “**almost right**” plans
  - Also “**planning as debugging**”: Debug initially null plan
- Analyze Causal Explanations for Bugs
  - ***Bug*** is an inconsistency between desired and predicted (observed) state of the world
  - Bug ***manifestation*** indicates underlying error in problem solving
  - Can change predicted to match desired, or *vice versa*
- ***Assumption-Oriented*** Repair Strategy
  - Trace causal explanation to assumptions underlying bugs
  - Replace potentially faulty assumptions
  - Regress desired state to determine how to change plan

Debugging Sussman's Anomaly

Initial State

Goal



On(A, B, start)

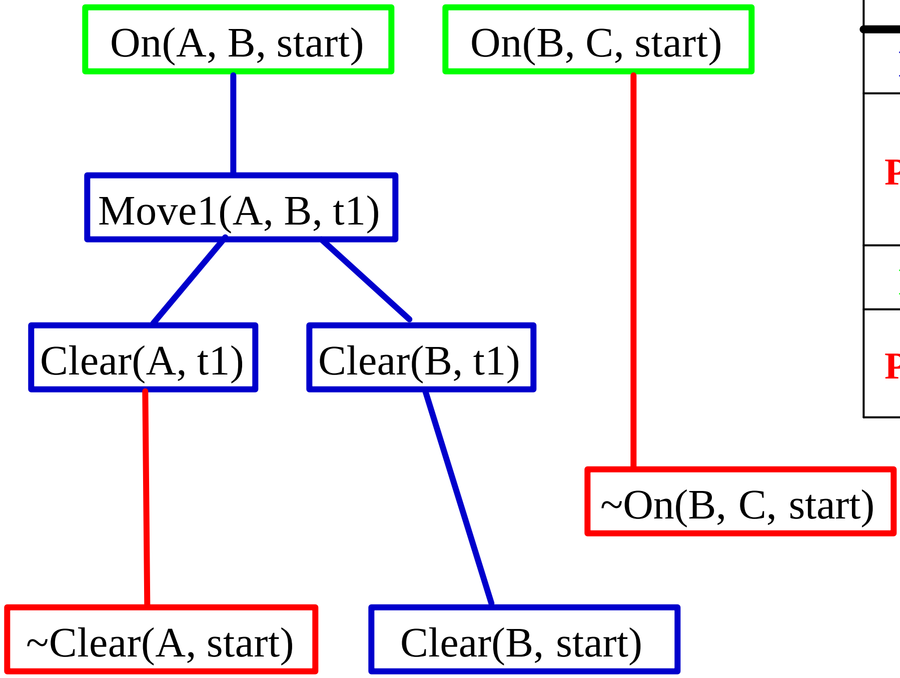
On(B, C, start)

~On(A, B, start)

~On(B, C, start)

	Bug	**Reasons**
Desired	**On(A, B, end)**	**{Goal}**
Predicted	**~On(A, B, end)**	**{start < end, *persistence*}**
Desired	**On(B, C, end)**	**{Goal}**
Predicted	**~On(B, C, end)**	**{start < end, *persistence*}**

Debugging Sussman's Anomaly



On(A, B, start)

On(B, C, start)

Move1(A, B, t1)

Clear(A, t1)

Clear(B, t1)

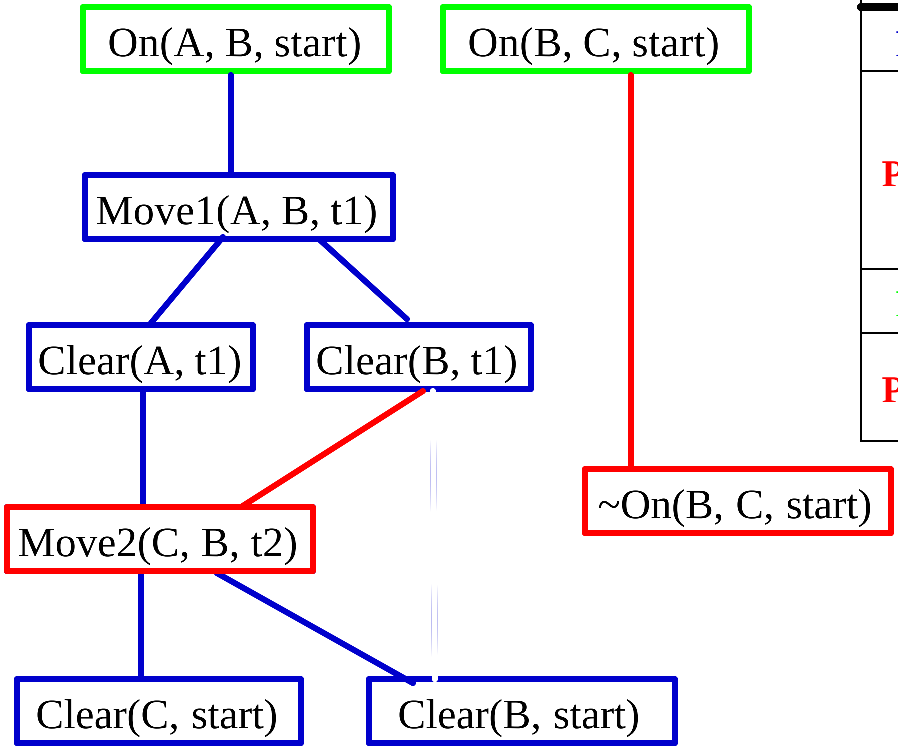
~On(B, C, start)

~Clear(A, start)

Clear(B, start)

	Bug	**Reasons**
Desired	**Clear(A, t1)**	**{Move1}**
Predicted	**~Clear(A, t1)**	**{start < t1, *persistence*, move1.arg1 = A}**
Desired	**On(B, C, end)**	**{Goal}**
Predicted	**~On(B, C, end)**	**{start < end, *persistence*}**

Debugging Sussman's Anomaly



	Bug	**Reasons**
Desired	**Clear(B, t1)**	**{Move1}**
Predicted	**~Clear(B, t1)**	**{t2 < t1, Move2, *persistence*, move2.arg2 = B}**
Desired	**On(B, C, end)**	**{Goal}**
Predicted	**~On(B, C, end)**	**{start < end, *persistence*}**

TPOP (Younes)

- Transformational Partial Order Planner
  - Built on top of UCPOP
  - Record ***reasons*** for adding constraints to plan (links, bindings, orderings, actions, …)
  - Add transformational operators as threat resolution mechanisms
    - Relink
    - Reorder *(may be exponential # of changes that can undo constraint)*
    - Alter bindings
  - Need to propagate changes if reasons no longer valid
  - Need to avoid cycles in search space
  - Very much dependent on good search heuristics

•Work in Progress

Structured Reactive Controllers (Beetz)

- Create Reactive Controllers that are "Transparent"
  - RPL: Expressive, high-level programming language specialized for reasoning about plan execution

```
(with-policy (check-signposts-when-necessary)
     (partial-order
        (top-level
            (:tag command-2
                (seq (go 2 2)
                    (let ((obs (look-for '((category ball) 0)))
                        (if (not (null obs))
                            (start-tracking (first obs) 0)
                            (fail))))))))
```

- Planner Detects Failures (Real or Simulated) and Debugs
  - Library of plan revisions (XFRML)
  - Uses Monte-Carlo simulation of plans to deal with ***uncertainty*** (execution, sensing, environment)
  - Analyzes execution trace to understand bug

Repairing Reactive Procedures

- Plan-Transformation Rules
  - "**If** a goal might be clobbered by a robot action, **then** execute the clobbering subplan before achieving the goal"
  - "**If** a goal might be left unachieved because the robot overlooked an object, **then** use a different sensing routine for perceiving the object"
  - "**If** a goal might be left unachieved because the robot had an ambiguous object description, **then** achieve the goal for all objects satisfying that description"
  - "**If** a goal might be clobbered by an exogenous event, **then** stabilize the goal immediately after achieving it"
    - **If** GOAL(OB) is clobbered by an exogenous event and DESIG is the data structure returned by the sensing routine that saw OB and the robot tried to achieve GOAL(DESIG) with plan P
    - **Then** replace P with SEQ(P, STABILIZE(GOAL(DESIG)))

Open Questions

- Can we create simple transformational planning algorithms?
- Can we create provably sound and complete transformational planning algorithms
- Under what circumstances do transformational planners perform better than pure refinement planners?
- Can we improve efficiency by combining assumption-oriented approach (GORDIUS, TPOP) with fault-type approach (HACKER, CHEF)?