New Approaches

- Since 1995, a number of new algorithmic approaches have been developed, which are much faster than the POP algorithm:
  - Planning based on planning graphs
  - Satisfiability based planning
  - BDD-based approaches (good for multi-state problems – which we ignore here)
  - Heuristic-search based planning

Planning Graphs

- **Parallel** execution of actions possible
- Assumption: Only **positive preconditions** (can be generated by an easy transformation)
- Describe possible developments in a layered graph (fact level/action level)
  - links from (positive) facts to *preconditions*
  - *positive effects* generate (positive) facts
  - *negative effects* are used to mark conflicts
- **Extract plan** by choosing only non-conflicting parts of graph
Generate a Planning Graph

- Add all applicable actions
- In order to propagate unchanged property \( p \), use special action \( \text{noop}_p \)
- Generate all positive effects on next fact level
- Mark conflicts (between actions that cannot be executed in parallel)
- Expand planning graph as long as not all atoms in fact level

Extract a Plan

- Start at last fact level with goal facts
- Select minimal set of non-conflicting actions generating the goals
- Use preconditions of these actions as goals on next lower level
- Backtrack if no non-conflicting choice is possible

Conflict Information

- Two actions interfere (cannot be executed in parallel):
  - one action deletes or asserts the precondition of the other action
  - they have opposite effects on one atomic fact
- They are marked as such
  - and this information is propagated to prune the search early on

Mutex Pairs

- No pair of facts is mutex at fact level 0
- A pair of facts is mutex at fact level \( i > 0 \) if all ways of making them true involve actions that are mutex at the action level \( i-1 \)
- A pair of actions is mutex at action level \( i \) if
  - they interfere or
  - one precondition of one action is mutex to a precondition of the other action at fact level \( i-1 \)
  
- Mutex pairs cannot be true/executed at the same time
- Note that we do not found all pairs that cannot be true/executed at the same time, but only the easy to spot pairs
Example Mutex Propagation

- Mark all interfering actions
- Then start at action level 1 and propagate conflicts
- Expand planning graph as long the goal nodes are not all generated or some are still mutex

Planning Graphs: General Method

- Expand planning graph until all goal atoms are in fact level and they are not mutex
- If not possible, terminate with failure
- Iterate:
  - Try to extract plan and terminate with plan if successful
  - Expand by another action and fact level
- Termination for unsolvable planning problems can be guaranteed – but is complex

Properties of the Planning Graph Approach

- Finds an optimal solution (for parallel plans)
- Terminates on unsolvable planning instances
- Is much faster than POP planning
- Has problems with symmetries:
  - Example: Transport \( n \) objects from room A to room B using one gripper
  - If shortest plan has \( k \) steps, it proves that there is no \( k-1 \) step plans

Planning as Satisfiability

- Based on planning graphs of depth \( k \), one can generated a set of propositional CNF formulae
  - such that each model of these formulae correspond to a \( k \)-step plan
  - basically, one performs a different kind of search in the planning graph (middle out instead of regression search)
  - Can be considerable faster, sometimes …
Heuristic Search Planning

- Forward state-space search is often considered as too inefficient because of the high branching factor
- Why not use a heuristic estimator to guide the search?
- Could that be automatically derived from the representation of the planning instance?
  ➢ Yes, since the actions are not “black boxes” as in search!

Ignoring Negative Effects

- Ignore all negative effects (assuming again we have only positive preconditions)
  ➢ monotone planning
- Example for the buyer’s domain:
  ➢ Only Go and Drop have negative effects (perhaps also Buy)
  ➢ Minimal length plan: <Go(HWS), Buy(Drill), Go(SM), Buy(Bananas), Buy(Milk), Go(Home)>
  ➢ Ignoring negative effects: <Go(HWS), Buy(Drill), Go(SM), Buy(Bananas), Buy(Milk)>
- Usually plans are shorter

Monotone Planning

- Monotone planning is easy, i.e., can be solved in polynomial time:
  ➢ While we have not made all goal atoms true:
    • Pick any action that
      ➢ is applicable and
      ➢ has not been applied yet
    • and apply it
    • If there is no such action, return failure
    • otherwise continue

Monotone Optimal Planning

- Finding the shortest plan is what we need to get an admissible heuristic, though!
- This is NP-hard, even if there are no preconditions!
  ➢ Minimum Set Cover, which is NP-complete, can be reduced to this problem
Minimum Set Cover

- **Given:** A set $S$, a collection of subsets $C = \{C_1, \ldots, C_n\}$, $C_i \subseteq S$, and a natural number $k$.
- **Question:** Does there exist a subset of $C$ of size $k$ covering $S$?
  - Problem is **NP-complete**
  - and obviously a special case of the monotone planning optimization problem

Simplifying it Further ...

- Since the monotone planning heuristic is computationally **too expensive**, simplify it further:
  - compute heuristic distance for each atom (recursively) by assuming independence of sub-goals
  - solve the problem with any planner (i.e. the planning graph approach) and use this as an approximative solution
  - both approaches may over-estimate, i.e., it is not an admissible heuristic any longer

The Fast-Forward (FF) System

- **Heuristic:** Solve the monotone planning problem resulting from the relaxation using a planning graph approach
- **Search:** Hill-climbing extended by breadth-first search on plateaus and with
- **Pruning:** Only those successors are considered that are part of a relaxed solution
- **Fall-back strategy:** complete best-first search

Relative Performance of FF

- **FF** performs very well on the planning benchmarks that are used for the planning competitions
- **Examples:**
  - Blocks world
  - Logistics
  - Freecell
  - Performance data is from the International AI Planning System Competition 2000
Freecell (Performance)

CPU time

Solution size

Search Space Topology

- Why works the FF heuristic so well?
- Look for search space properties such as
  - local minima
  - size of plateaus
  - dead ends (detected & undetected)
- Estimate by
  - exploring small instances
  - sampling large instance
- Try to prove conjectures found this way
  - Goes some way in understanding problem structure

Summary & Outlook

- Recent approaches to planning have boosted the efficiency of planning methods significantly
- Heuristic search planning appears to be one of the fastest (non-optimal) methods
- We are starting to understand the difficulty of a planning domain in terms of its search space topology
- Currently, search technology is transferred into the area of formal verification and synthesis (and vice versa)
- While it may still be long time before we can afford to use these techniques instead of domain-specific methods, the progress looks promising