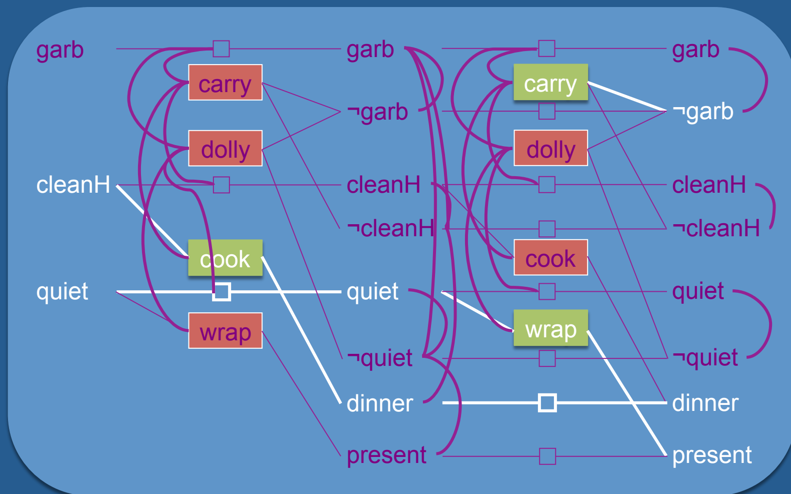


GRAPH PLANNING

EECS 492 Lecture 15
February 24th, 2011

State-Space Planning (Recap)

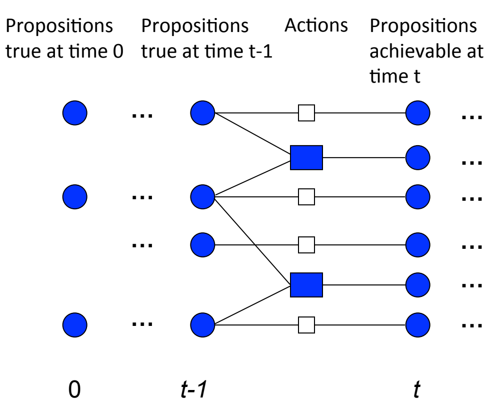
- Planning as state-space search
  - Forward (progression) from initial state
  - Backward (regression) from goal
- Action is *fully specified* at time of introduction to plan
  - All variables bound to specific objects
  - Ordering in sequence with existing actions

GraphPlan

- Blum & Furst, 1995.
- Radical reformulation of plan search space
  - Applies to propositional encodings
    - Must propositionalize knowledge
  - Compacted state space with plan graph rep'n
  - Demonstrated dramatic performance improvements

Planning Graphs

- Interleave *levels* of literals and actions, related by support, precondition, and mutex



GraphPlan Algorithm

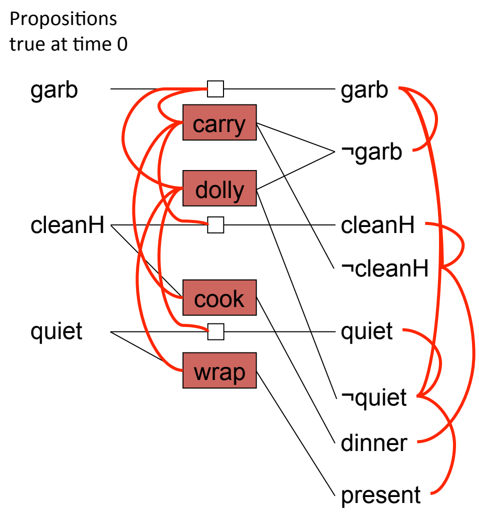
- zeroth level ← initial state
- Repeat until solution or "level off":
  - Extend planning graph by considering application of actions
  - *Attempt* to extract solution

Example: "Dinner Date"

- Object: Take out garbage, fix dinner, wrap present.
- Goal: ¬garb ∧ dinner ∧ present
- Actions: (*act* [*preconds*] [*effects*])
  - cook [cleanH] [dinner]
  - wrap [quiet] [present]
  - carry [] [¬garb ¬cleanH]
  - dolly [] [¬garb ¬quiet]
- Initial: garb ∧ cleanH ∧ quiet

from Weld, "Recent advances in AI planning", *AI Magazine*, 1999.

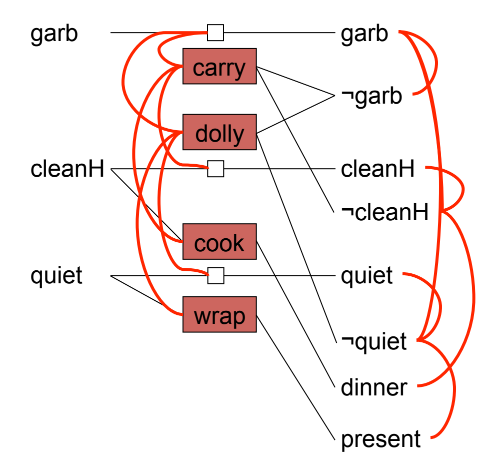
Constructing the Plan Graph



Mutex

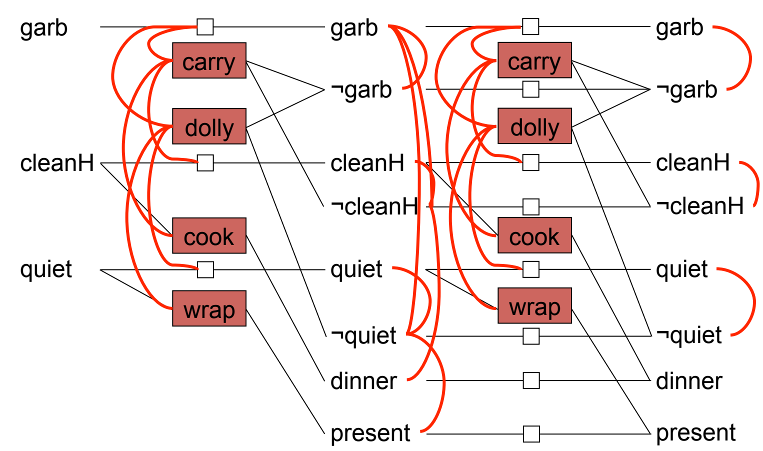
- Actions
  - Inconsistent effects
    - Effects conflict
  - Interference
    - Effects conflict w Preconditions
  - Competing needs
    - Preconditions conflict
- Propositions
  - Complements
  - Inconsistent support
    - Actions that generate propositions are mutex

Solution?

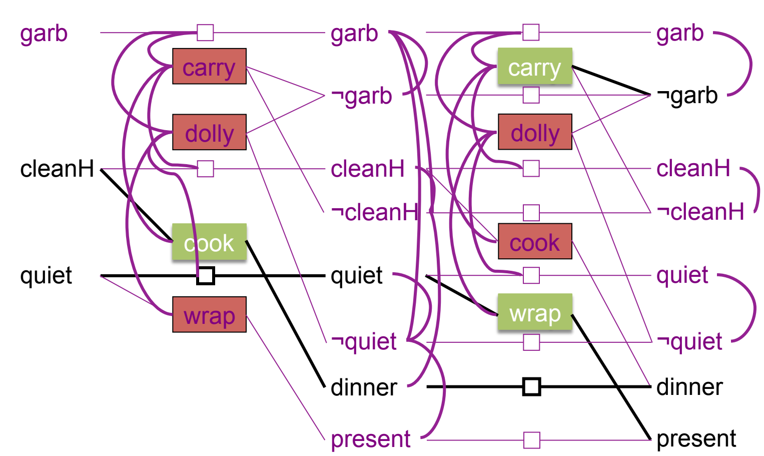


- Can achieve ¬garb, dinner, present separately
- Two "solns":
  {carry, cook, wrap}
  {dolly, cook, wrap}
- But:
  mutex(carry, cook)
  mutex(dolly, wrap)

Extend the Plan Graph



Solution!



Graph Plan: Summary

- We still have to do a TreeSearch to extract a solution from the graph.
  - So why did we build the graph in the first place?

Planning in the real world

- Major challenges:
  - Major parts of the world are unknown
    - How do we generate plans when we don't know what's around the corner?
  - Very large search spaces
    - Continuous-valued actions
    - Interactions of multiple agents

Conditional Planning

- Uncertainty at plan construction time may be resolved by execution time
  - Example: shopping plan, don't know how much milk costs
  - Problem: cannot specify complete guaranteed plan without specifying amount of money for *Pay* action
  - Solution: find out the price when we get to Busch's

Conditional Planning

- Identify conditions that will be observable at execution time
- Include construct in plan that selects course of action based on condition:

```
If (OnSale(Milk))
    Pay($0.99)
  else
    Pay($1.49)
```

- What if we don't know (yet) whether the milk is on sale?
  - The conditional is undefined!
  - Is there an action that would resolve the uncertainty?

Information-Gathering Action

CheckOnSale (x, y)
  Precond: InStore(x)
  Effect: KnowsWhether("OnSale(y)")

- KnowsWhether: eligible for conditioning
- A legal (conditional) plan:

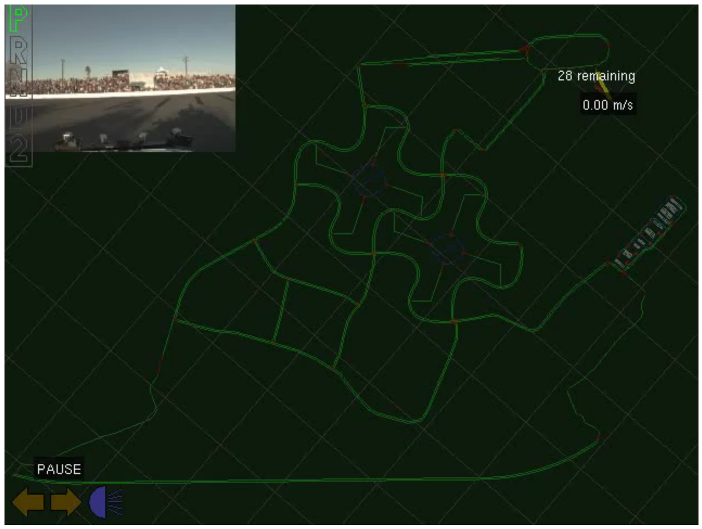
```
Move(John, Store)
CheckOnSale(John, Milk)

 If ( OnSale(Milk) )
         Pay(John, Store, $0.99)
 else
         Pay(John, Store, $1.49)
```

Continuous replanning

- Alternative:
  - Construct plan for expected case
    - "There are no obstacles"…
    - "The milk is on sale"…
  - Update plan as information is revised
    - There's a log in the road!
    - The milk *isn't* on sale
  - Creates *real-time* issues

Online replanning



Very large search spaces

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- How many actions for path planning with a car?
  - Infinite number of possible actions!
  - Finding "perfect" solutions (e.g., a perfect parallel parking maneuver) is:
    - Very difficult
    - Generally unnecessary
  - How do we efficiently search the space?
    - Make good use of our computational resources to find the best possible plan

Deterministic Motion Planning

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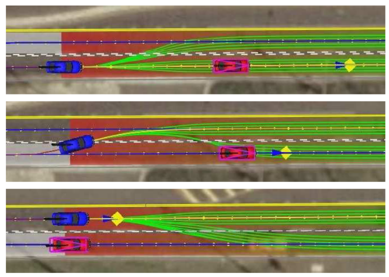
- We can sometimes consider only a few discrete (say 5) actions



- Shortcomings
  - Algorithm is no longer complete (or optimal).
  - If we had more CPU time, could we compute a better plan?

Non-Deterministic Planning

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- How do we explore a large search tree, finding a *good enough* answer while making use of what CPU time we have available?
- Consider sequences of random actions
  - Build a *tree* of actions
    - Node = state
    - Edge = action
  - A plan is a sequence of actions, i.e., a path from the root (initial state) to a leaf near the goal
- Skeleton algorithm:
  - while time remains
    - Select a node (call it **parent**) in the tree
    - Generate a new action **a**
    - Create new node: child = propagate(parent, **a**)
    - If action is safe
      - Add node to tree
  - return best plan found so far

Implementation here is critical…

Analogous to fringe.get()

Non-Deterministic Planning Variants

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- We'll consider three basic variants
  - **Random**: Pick a parent node at random. Pick an action at random.
  - **RRT**: Pick a destination at random. Find parent node that is closest to destination. Compute action that goes towards destination
  - **RRT-Biased**: Pick the destination randomly, but in a biased way (i.e., prefer directions that are heuristically likely to work out)

Random Policy

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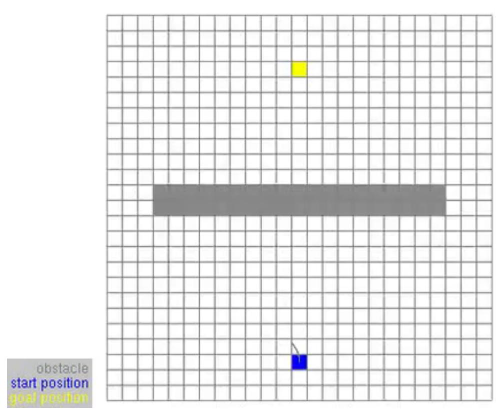
- **Random**: Pick a parent node at random. Pick an action at random.



Random Policy: Analysis

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- Complete?
- Optimal?
- Practical?

RRT Policy

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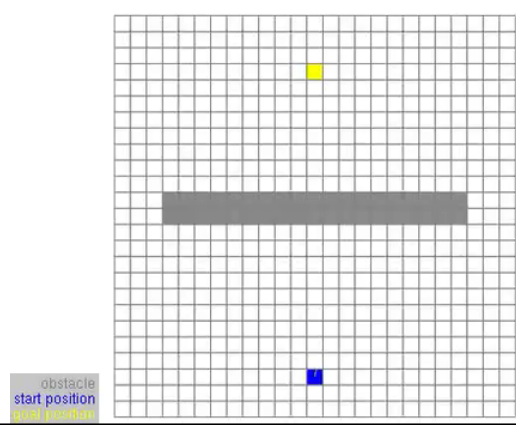
- **RRT**: Pick a destination at random. Find parent node that is closest to destination. Compute action that goes towards destination



RRT Policy (Biased Sampling)

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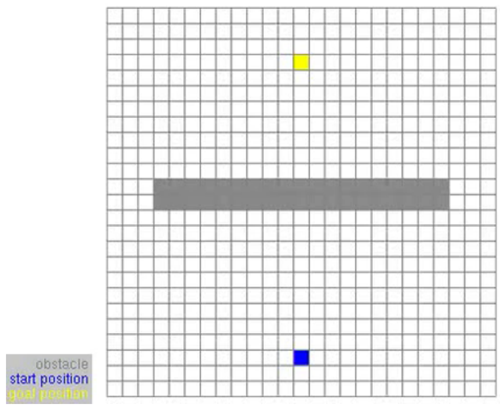
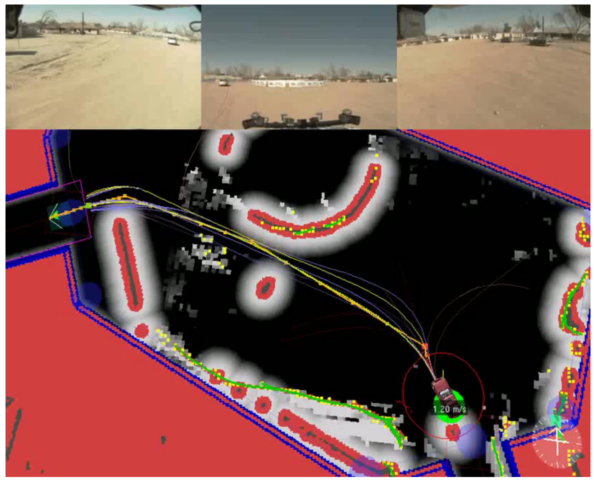
- **RRT-Biased**: Pick the destination randomly, but in a biased way (i.e., prefer directions that are heuristically likely to work out)



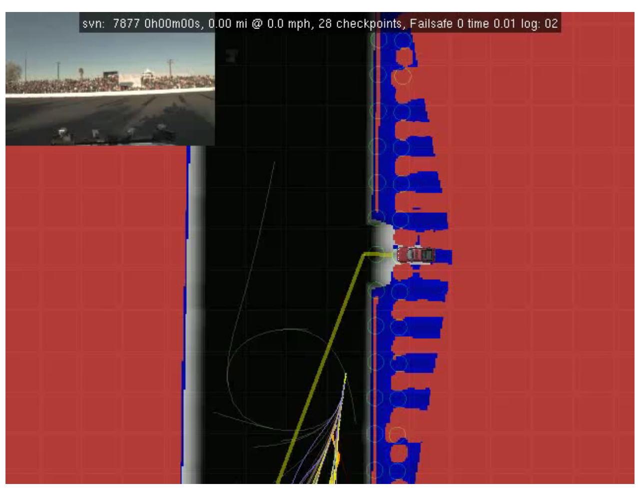
RRT Discussion

- Results in trees with specific structure:
  - In 2D path planning, results in *planar* trees
    - Paths don't overlap each other
- This means, even in limit of t -> infinity, that not all paths will be computed any more
  - No longer complete!
- However, very useful in practice
  - Explores search space very rapidly
  - Good diversity of solutions
  - Random restarts "fixes" completeness problem

Continuous Replanning



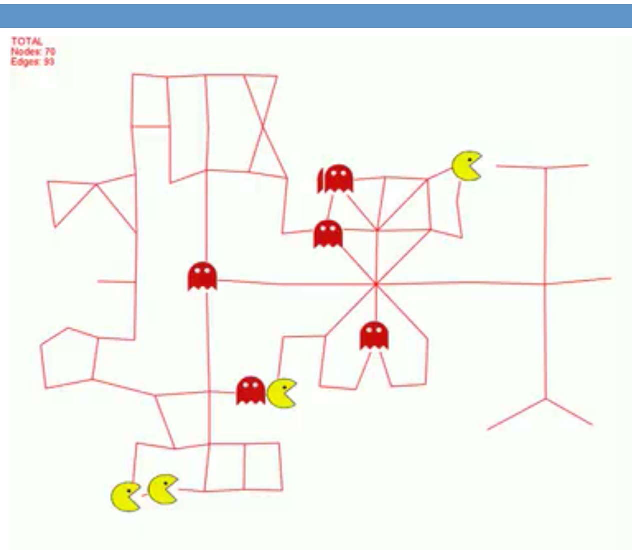
Continuous Replanning



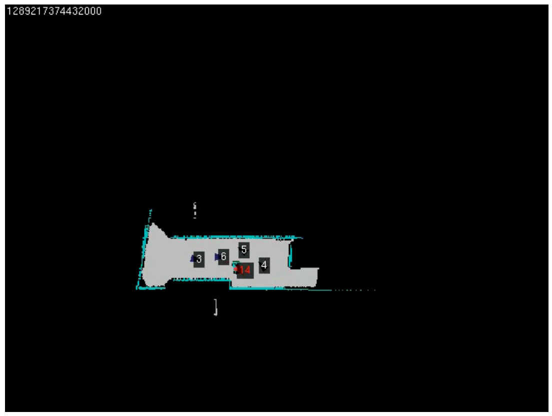
Multi-Agent Planning

- Adversarial
  - Mini-max style searches (we saw this before)
- Cooperative
  - Just a bigger search space
  - Suppose depth-limited search of depth d, with one robot that can move N, S, E, or W. Complexity?
  - What if we have N robots?
- Coexist
  - Model other agents' actions as uncertain

Pursuit/Evasion



Multi-agent exploration



Next time: Probability

- Suppose the P(heads) of a coin is p.
- What is the probability of N heads in a row?
- What's the probability of at least 1 tails in N trials?
- Suppose a coin comes up heads, heads, heads. What is the probability that the fourth toss is also heads?
- Suppose x and y are two random variables. Define conditional, marginal, joint probability.

Review Questions