规划问题求解（AI Planning）

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Outline

- STRIPS-like plan representation
- Planning with state-space search
- Partial-order planning (POP)
- Planning graphs (GraphPlan)
- Hierarchical task network (HTN) planning
- Probabilistic planning

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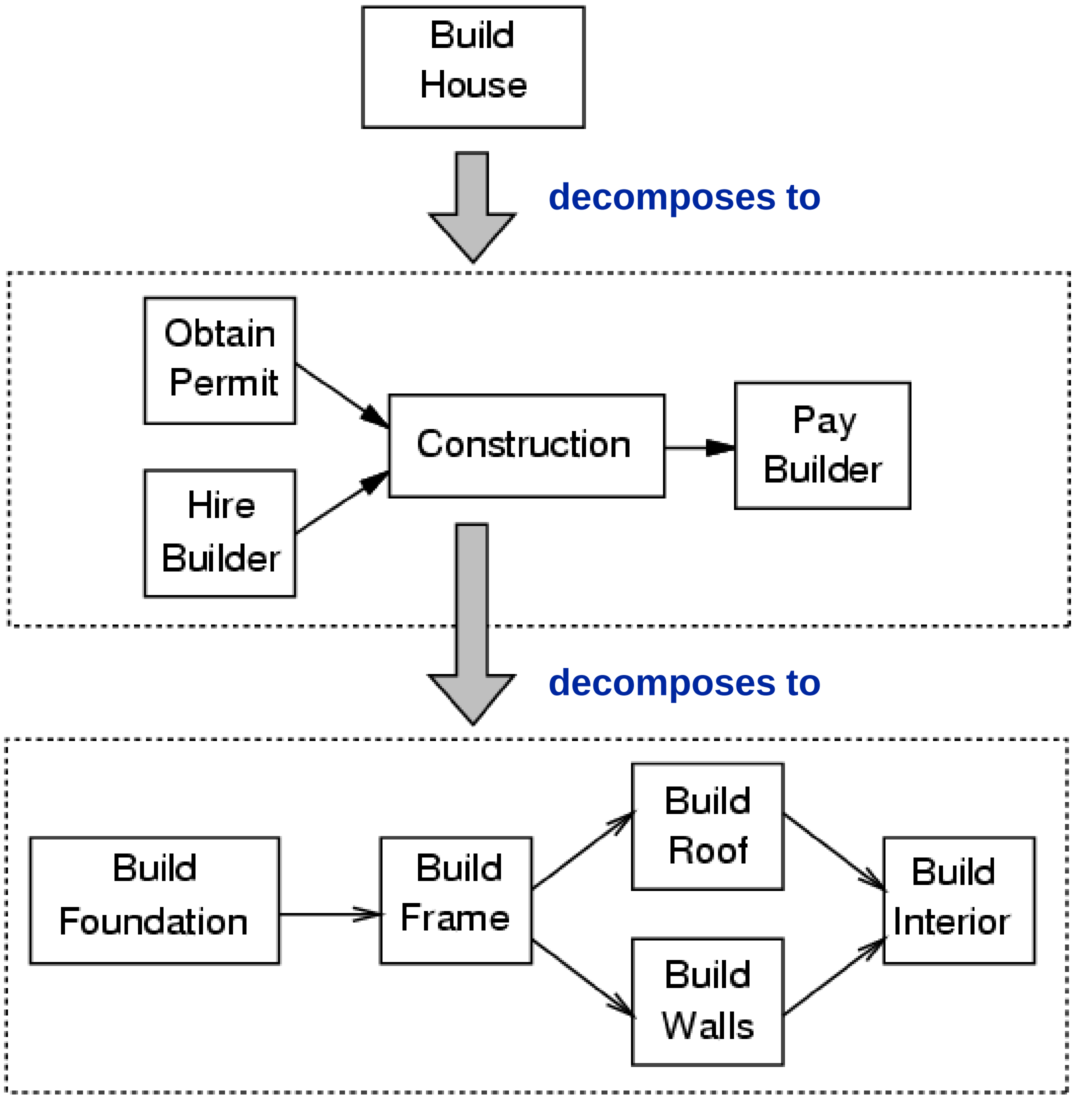
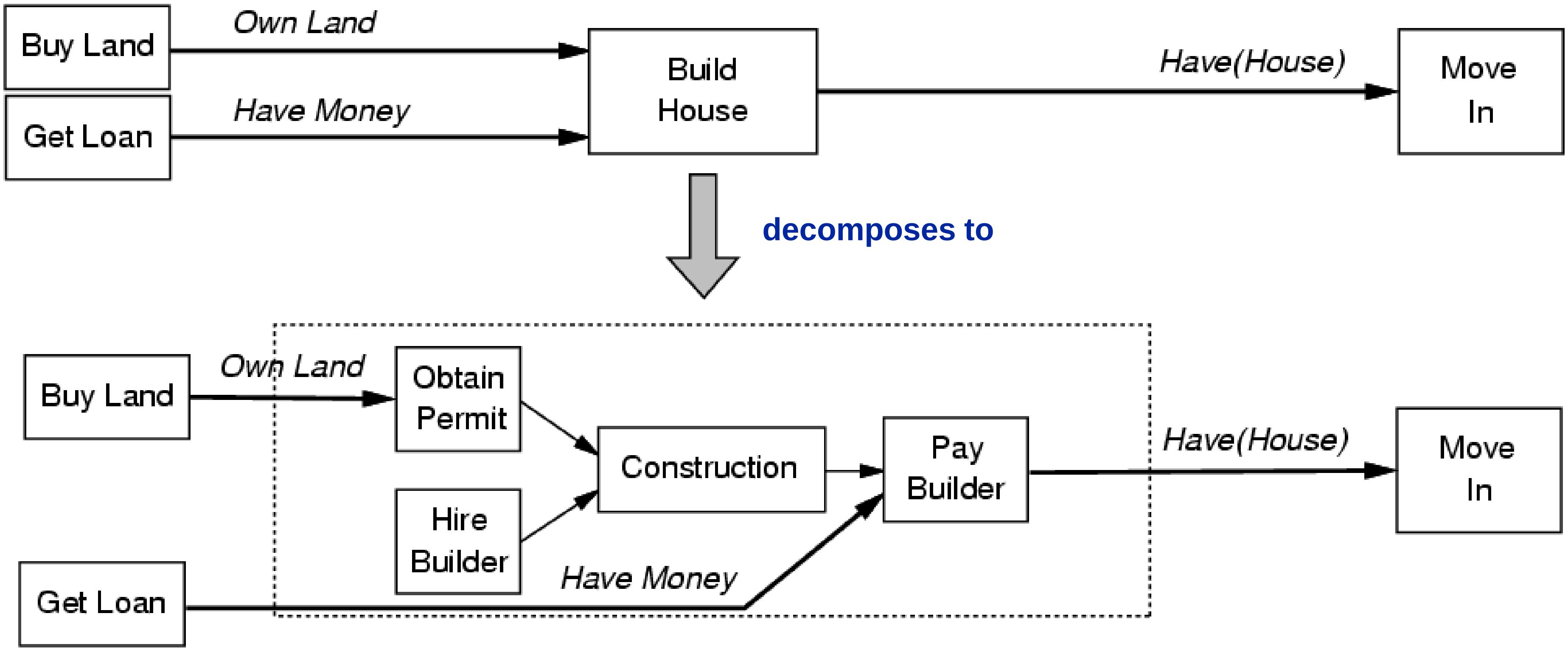
Hierarchical decomposition of actions



Task reduction



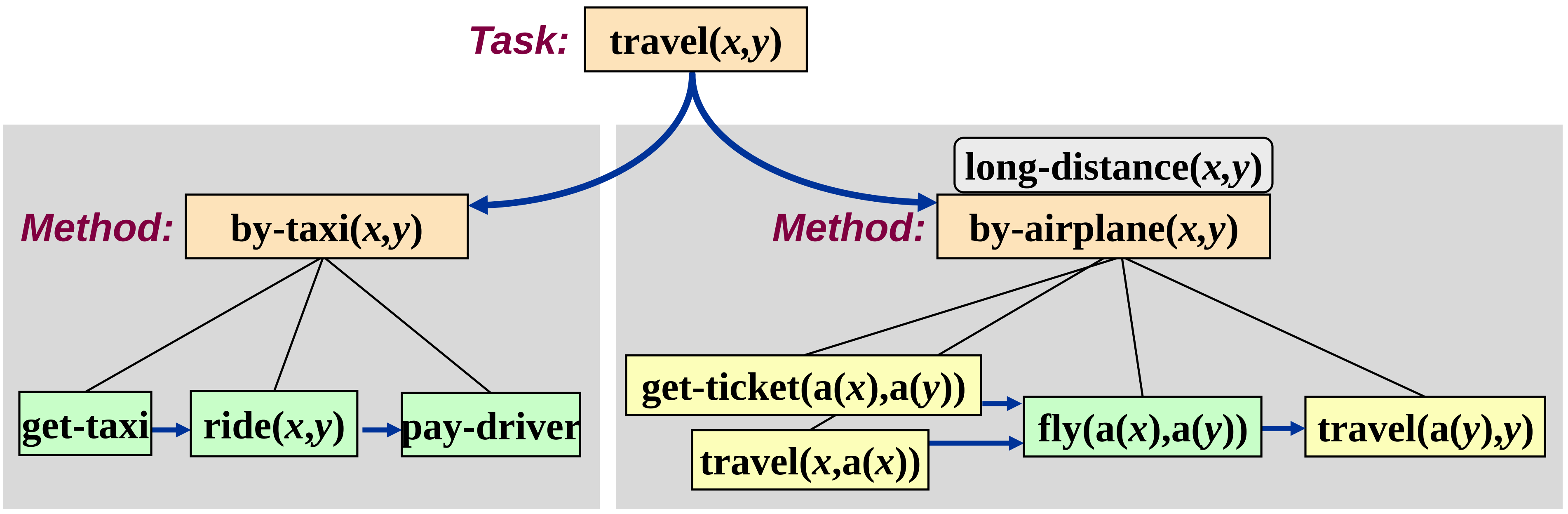
- Naturally encode hierarchical decomposition of actions
- Action hierarchy as domain-specific task knowledge

HTN（层次任务网络）planning

Hierarchical task network (HTN) planning [Erol et al 94]

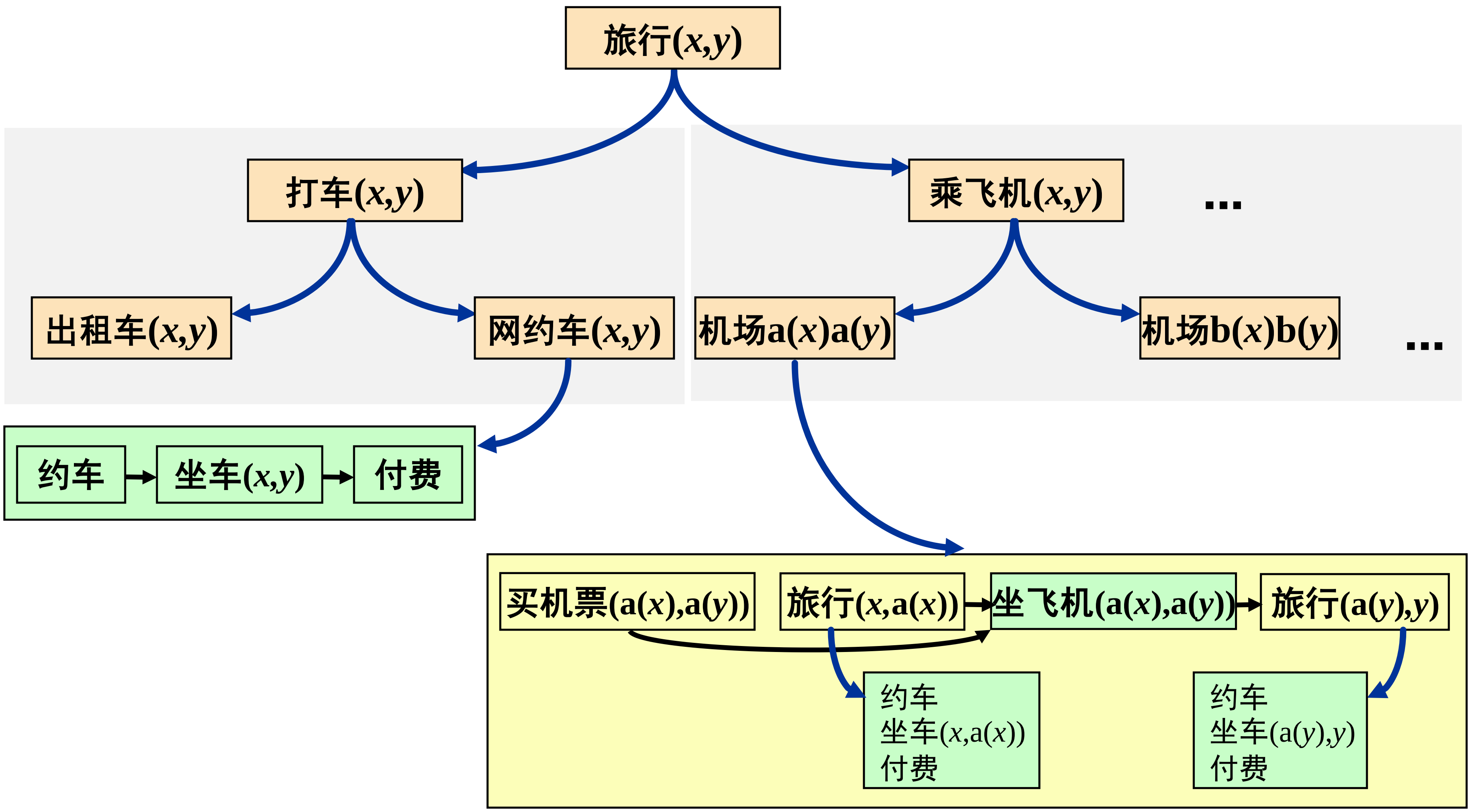
- Capture hierarchical structure of the planning domain
- Planning domain contains non-primitive actions and schemas for reducing them
- Reduction schemas:
  - Given by the designer
  - Describe preferred ways to accomplish a task

Task network example

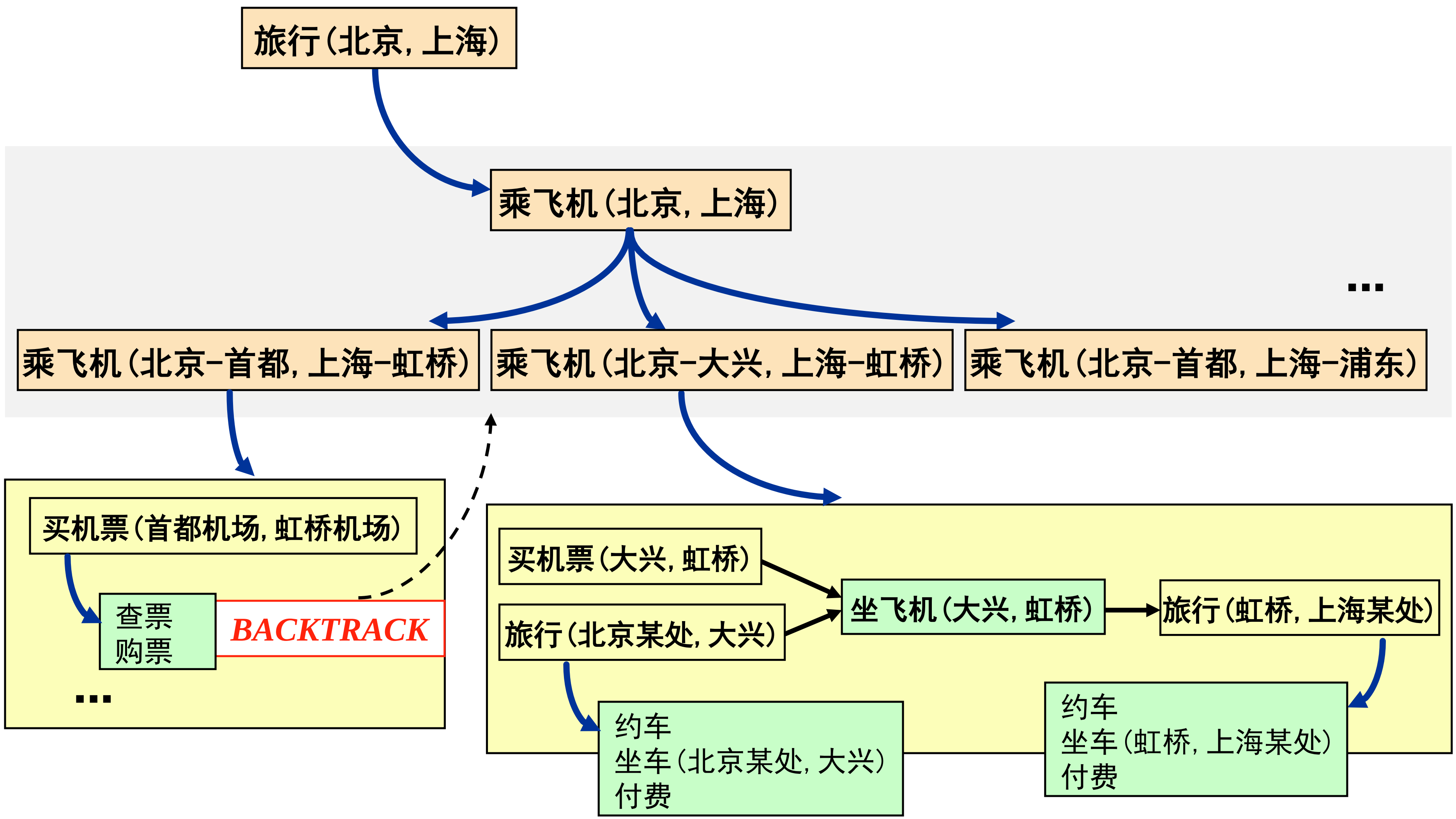


- *Tasks* rather than goals
  - *Primitive*（原始的）vs *nonprimitive*（抽象的）actions
- *Methods* describe task reduction
  - Ways to decompose tasks into subtasks

Task network example



Task network example

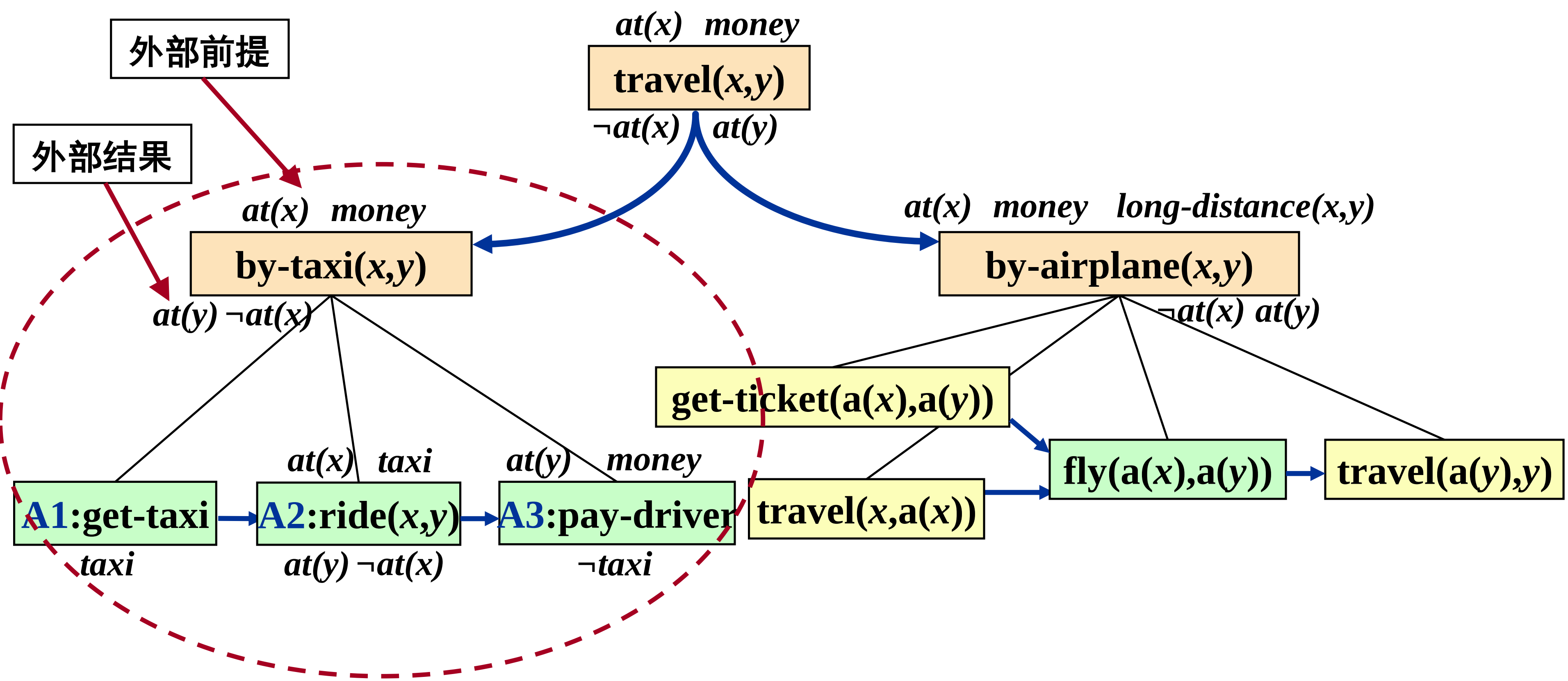


HTN planning intuition

Problem reduction:

- Decompose tasks into subtasks
- Handle constraints
- Resolve interactions
- If necessary, backtrack and try other decompositions

Task network example

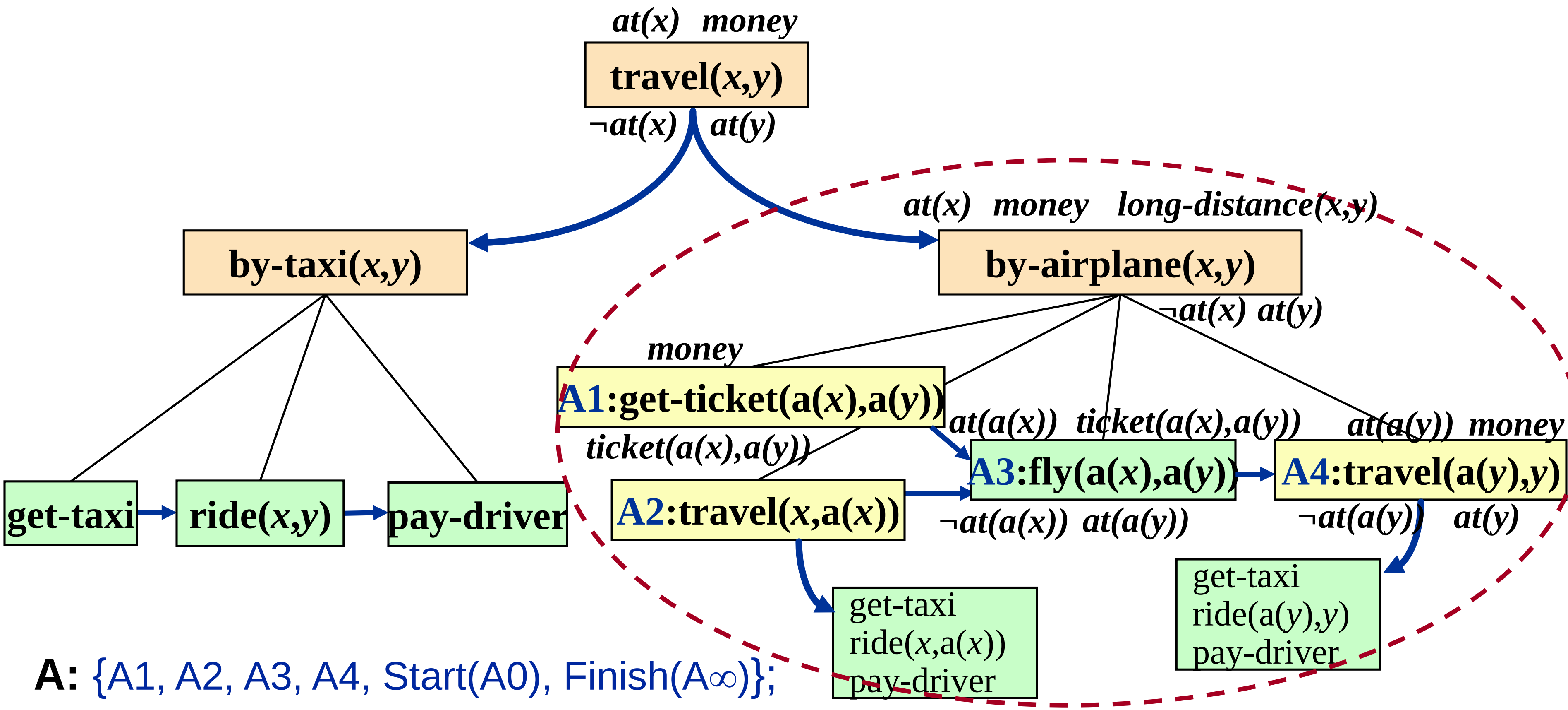


Primitive actions: {A1, A2, A3, Start(A0), Finish(A∞)};

Orderings: {A1<A2, A2<A3}

Causal links: {(A0 $\xrightarrow{at(x)}$ A2), (A0 $\xrightarrow{money}$ A3), (A1 $\xrightarrow{taxi}$ A2), (A2 $\xrightarrow{at(y)}$ A3), (A2 $\xrightarrow{at(y)}$ A∞)}

Task network example



A: {A1, A2, A3, A4, Start(A0), Finish(A∞)};

O: {A1<A3, A2<A3, A3<A4}

L: {(A0 $\xrightarrow{\text{money}}$ A1), (A0 $\xrightarrow{\text{at(x)}}$ A2), (A0 $\xrightarrow{\text{money}}$ A2), (A0 $\xrightarrow{\text{money}}$ A4), (A1 $\xrightarrow{\text{tkt(a(x),a(y))}}$ A3), (A2 $\xrightarrow{\text{at(a(x))}}$ A3), (A3 $\xrightarrow{\text{at(a(y))}}$ A4), (A4 $\xrightarrow{\text{at(y)}}$ A∞)}

Basic HTN Procedure

1. Input a planning problem P
2. If P contains only *primitive* tasks, then resolve the conflicts and return *solution*. If the conflicts cannot be resolved, return *failure*
3. Choose a *non-primitive* task *t* in P
4. Choose an expansion for *t*
5. Replace *t* with the expansion
6. Find interactions among the tasks in P and suggest ways to handle them
7. Choose one way and apply it
7. Go to step 2

total ordering primitives satisfying constraints

Find conflicts and suggest ways to resolve them

Properties of HTN planning

Sound, *complete* and has formal semantics [Erol et al 94]

- Strictly more expressive than classical planning
- Encode expert knowledge essential to task reasoning
- Handle actions and propositions with variables

The idea of *task decomposition* is critical

- Efficient ways to represent complex task knowledge
- Practical planner applied to real-world problems
- Critical applications in large-scale intelligent systems

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Classical planning

- Most advances seen *first* in classical planning
- Many practical environments don't satisfy classical planning *assumptions*
  - Possible to handle *minor* assumption *violations* through re-planning and execution monitoring
  - Advantageous to rely on *widely-used* (and efficient) classical planning techniques
- Classical planning techniques often shed light on the effective ways of handling *non-classical* planning problems
  - Most of the efficient techniques for handling non-classical scenarios are based on classical ideas/advances

Classical planning assumptions

- Discrete time
- All effects are immediate
- Fully observable environment
- Deterministic effects
- No dynamic changes in plan execution
- Planning agent is the sole agent of changes

…… ……

Classical planning assumptions

- Discrete time
- All effects are immediate
- **Fully observable environment**
- **Deterministic effects**
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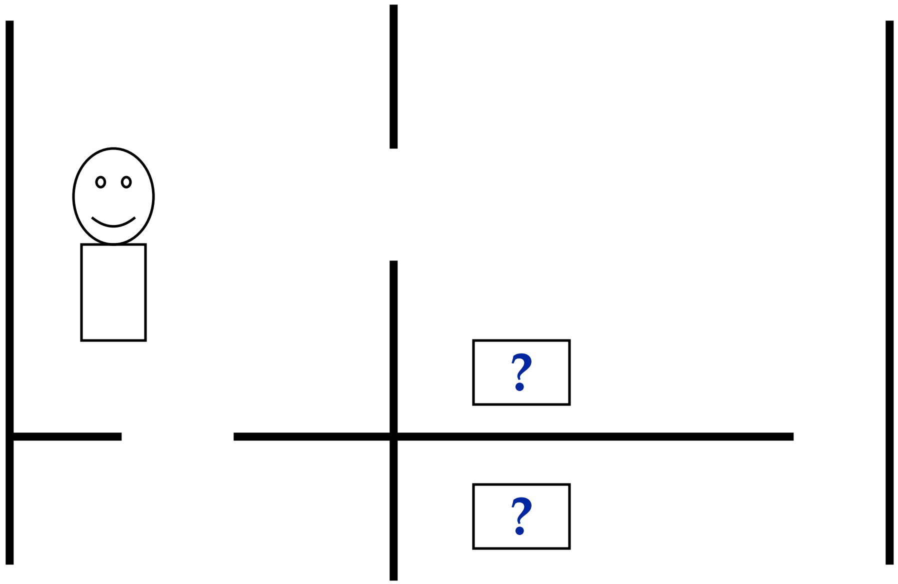
Uncertainty

. . . . . .

Sources of uncertainty

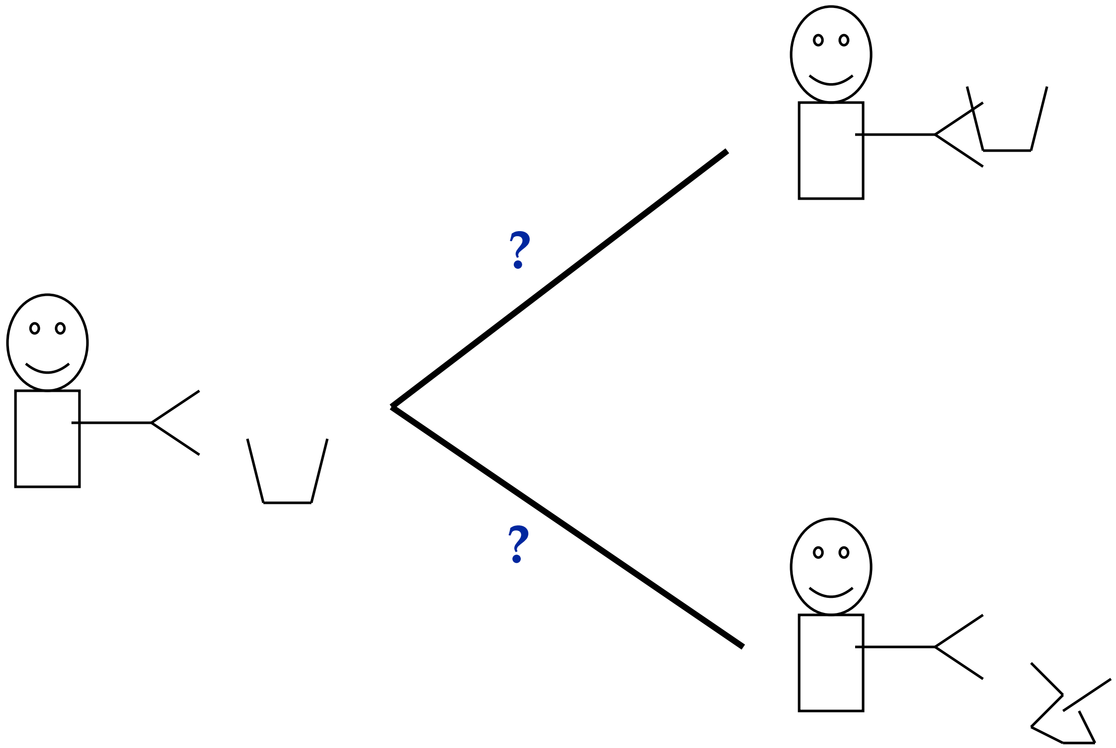
When we try to execute plans, uncertainty from several different sources can affect plan success.



Firstly, we might have uncertainty about the *state of the world*.

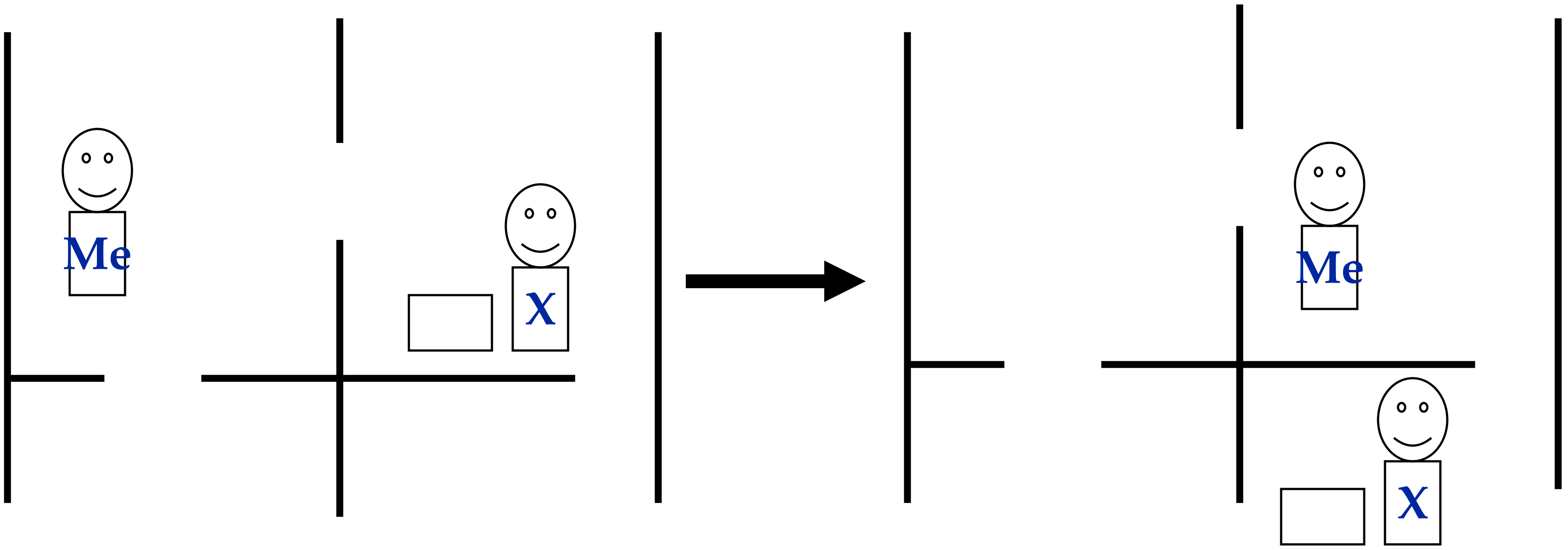
Sources of uncertainty

Actions we take might have *uncertain effects* even when we know the world state.



Sources of uncertainty

External agents might be changing the world while we execute our plan.



Dealing with uncertainty: Re-planning

- Make a plan assuming nothing bad will happen
- Monitor for problems during execution
- Build a *new plan* if a problem is found
  - Either re-plan to the goal state
  - Or try to amend the existing plan

Dealing with uncertainty: Conditional planning

- Deal with *contingencies* (偶发事情、意外) at planning time before they occur
- Utilize *conditional planning*（条件规划）to address every possible contingency in the policy

E.g. if <*test1*> then *plan_A*
else if <*test2*> then *plan_B*
else if <*test3*> then *plan_C*
else …

Trade-offs in strategies for uncertainty

- Re-planning: Can’t predict the plan steps are needed *before* the contingency is discovered
  - Re-planning agent: “Why are you taking an umbrella? It’s not raining!”
- Conditional planning: Impossible to plan for *every* contingency
  - Conditional planning agent: “Why are you leaving the house? Class may be cancelled. It might rain. You might have won the lottery. Was that an earthquake?…”

Probabilistic planning: The middle ground

- Partial knowledge about *uncertainty*: different contingencies have different probabilities of occurring
- Plan ahead for *likely* contingencies that may need steps taken before they occur
- Use probability theory to judge plans that address some contingencies:

  seek a plan that is above some minimum probability of *success*

Some issues to think about

- How to represent the occurrence of *likely* contingencies in action representation?
- How do we figure out the probability of *plan success*? What are the representations to support this?
- Can we distinguish bad *outcomes* (e.g. not holding the glass) from *really* bad outcomes (e.g. broken the glass, spilled the sulfuric acid..)?

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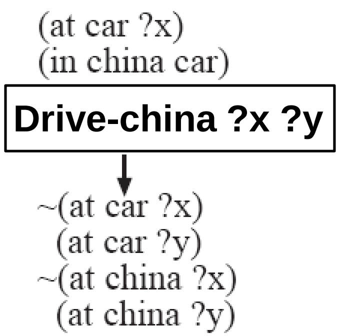
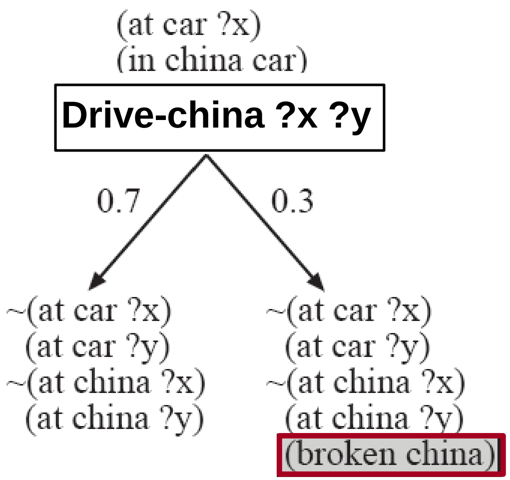
  - Probabilistic action representation
  - Probability of plan success
  - Plan utility

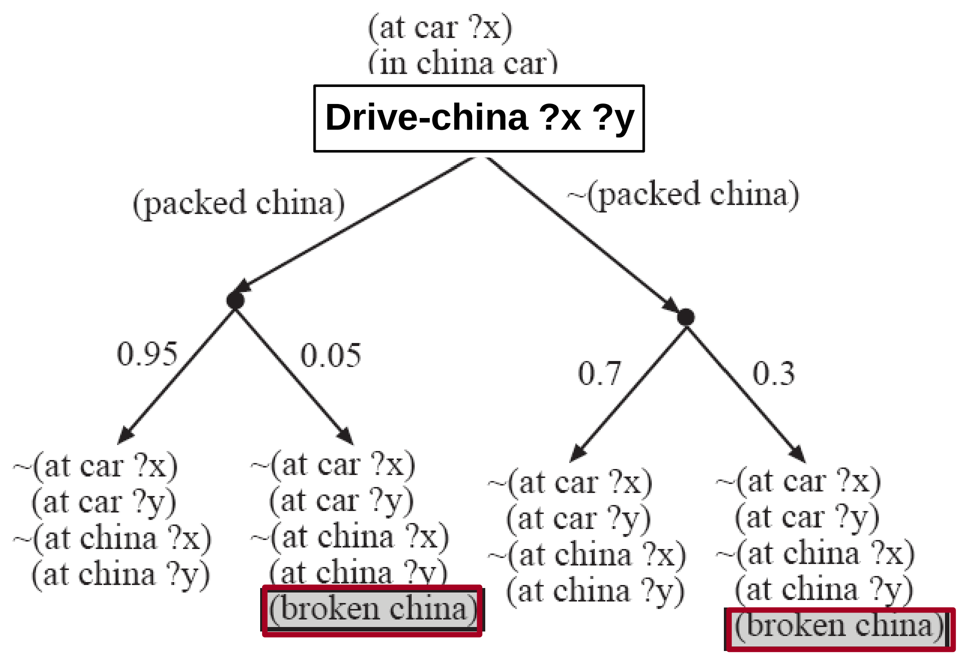
Representing actions with uncertain outcomes



Deterministic effects



Non-deterministic effects

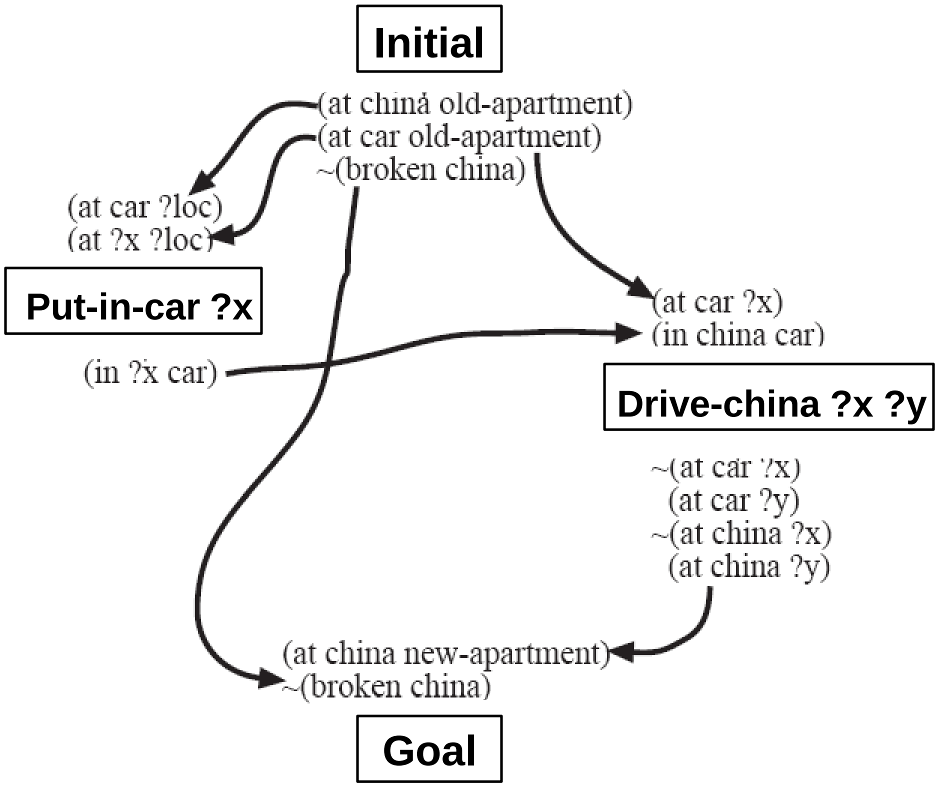


Non-deterministic effects with conditional probabilities

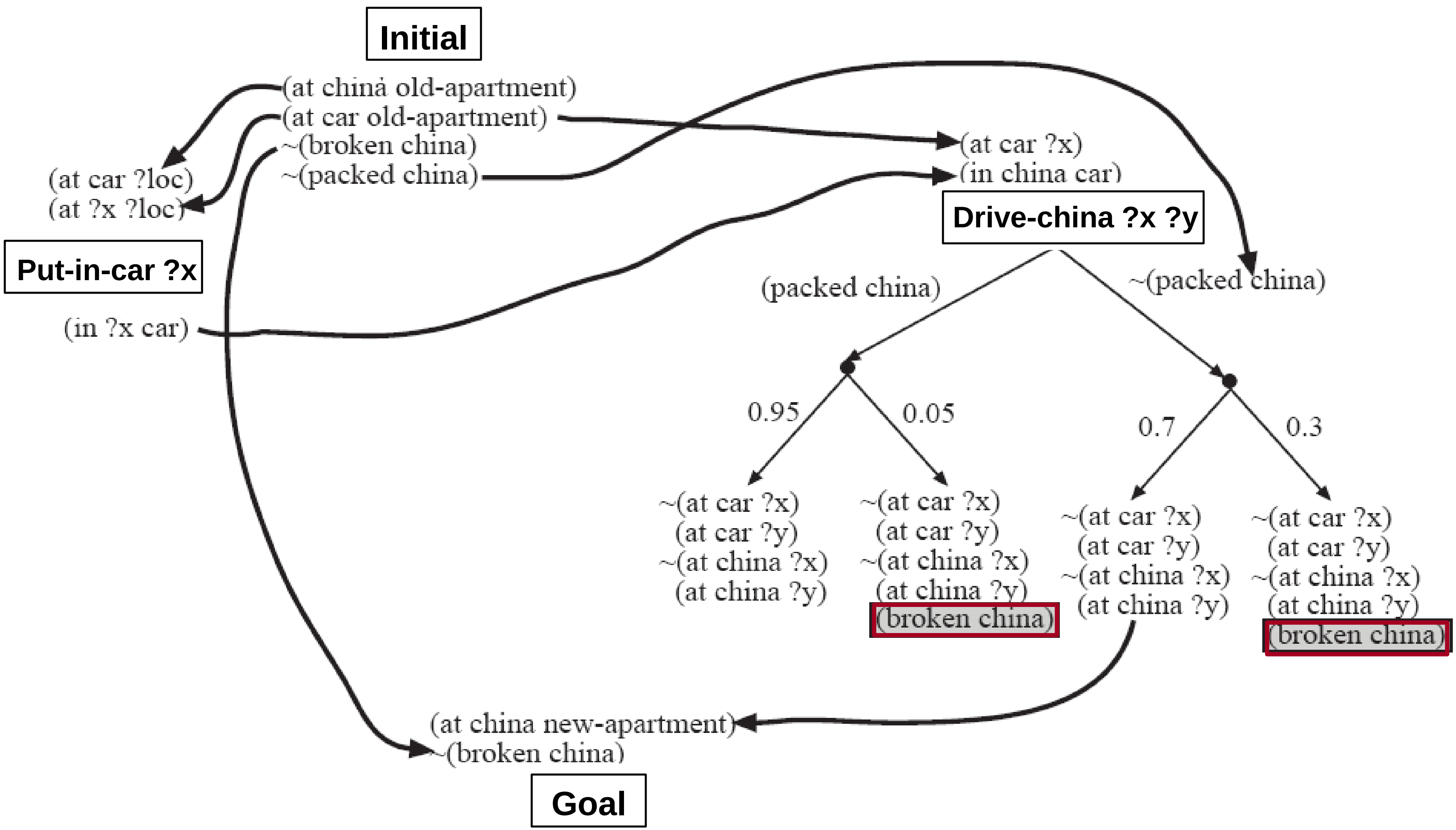
“~”表示否定，同“¬”

A partial-order plan to move china

- An POP-based planner might come up with this plan for deterministic action representation:



A plan that works 70% of the time…



Recall: POP algorithm

POP((A, O, L), agenda, actions)

Initial plan: {*Start*, *Finish*} and preconditions in *Finish* as open conditions

1. If **agenda** is empty, then **return** (A, O, L) 结束条件
2. Pick (Q, A_{need}) from **agenda** （子）目标
3. **Choose** an action A_{add} that adds effect Q 动作选择
   - If no such action exists, **fail**
   - Add the link $A_{add} \xrightarrow{Q} A_{need}$ to **L** and the ordering $A_{add}<A_{need}$ to **O**
   - If A_{add} is new, add it to **A** 规划扩充
4. Remove (Q, A_{need}) from **agenda**. If A_{add} is new, for each of its preconditions P add (P, A_{add}) to **agenda** 更新（子）目标
5. For every action A_t in A that threatens any causal link $A_p \longrightarrow A_c$ in **L**
   - **Choose** to add $A_t<A_p$ or $A_c<A_t$ to **O**
   - If neither choice is consistent, **fail**
6. POP((A, O, L), **agenda**, actions)

保护因果连接：
- 降级(Demotion): $\mathbf{A_t < A_p}$
- 升级(Promotion): $\mathbf{A_c < A_t}$

Modifications to the UCPOP algorithm

- Allow more than one causal link for each condition in the plan
- Confront a threat by decreasing the probability of an outcome in which the threatened condition is negated
- Terminate when sufficient probability reached (may still have threats)

Finding plans for moving china

- Goals:

  (at china new-apartment)

  ~(broken china)

- Initial states:

  (at china old-apartment)

  (at car old-apartment)

  ~(broken china)

  ~(packed china)

- Actions:

(at car ?loc)
(at ?x ?loc)

Put-in-car ?x

(in ?x car)

(at car ?x)
(in china car)

Drive-china ?x ?y

(packed china)

~(at car ?x)
(at car ?y)
~(at china ?x)
(at china ?y)
(broken china) 0.05

~(packed china)

~(at car ?x)
(at car ?y)
~(at china ?x)
(at china ?y)
(broken china) 0.3

~(packed china)

Pack-china

(packed china)

- Plans:

  Start → {Pack-china, Put-in-car china} → Drive-china → *Finish* (Prob: 0.95)

  Start → Put-in-car china → Drive-china → *Finish* (Prob: 0.70)

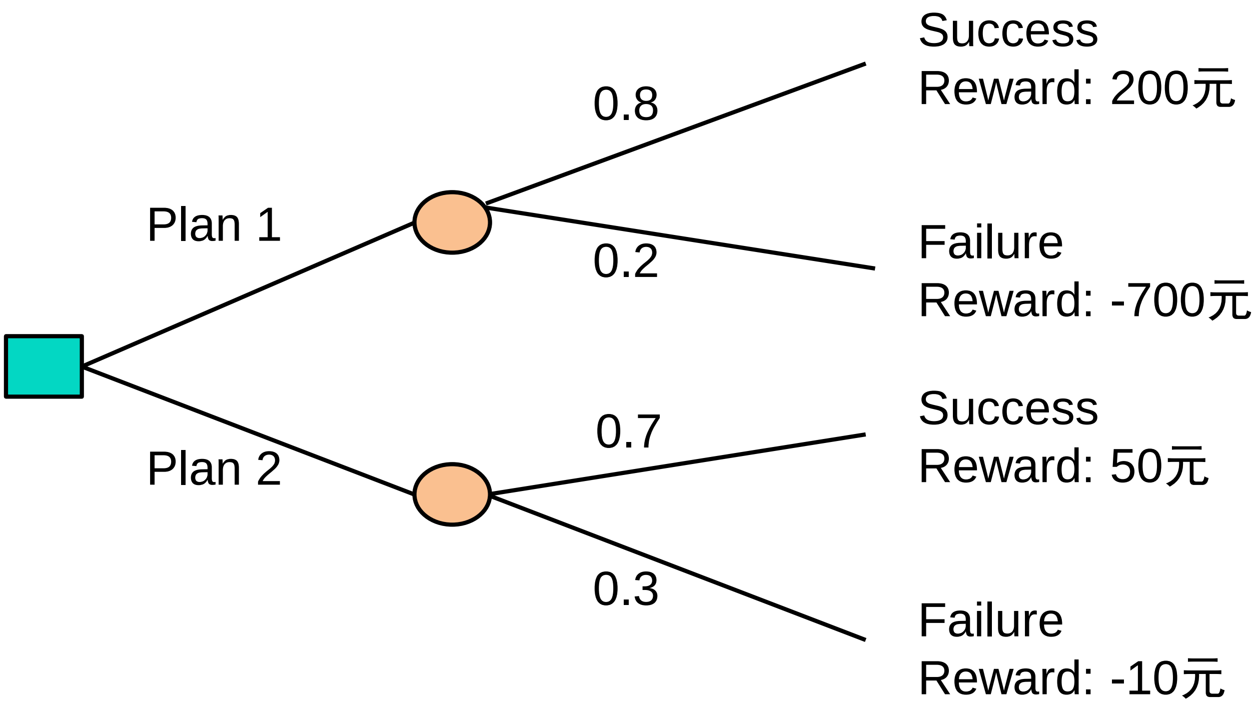
  … …

DRIPS: Decision-theoretic Refinement Planner

- Consider plan *utility*, taking into account action costs and benefits of different states
- Search for a plan with *Maximum Expected Utility* (*MEU*), not just above a threshold
- A skeletal planner, makes use of utility ranges of alternative plans in order to search efficiently
- Prune alternatives whose utility ranges are completely below the range of some *dominated plan*

Example of decision theory

- People are utility maximizers



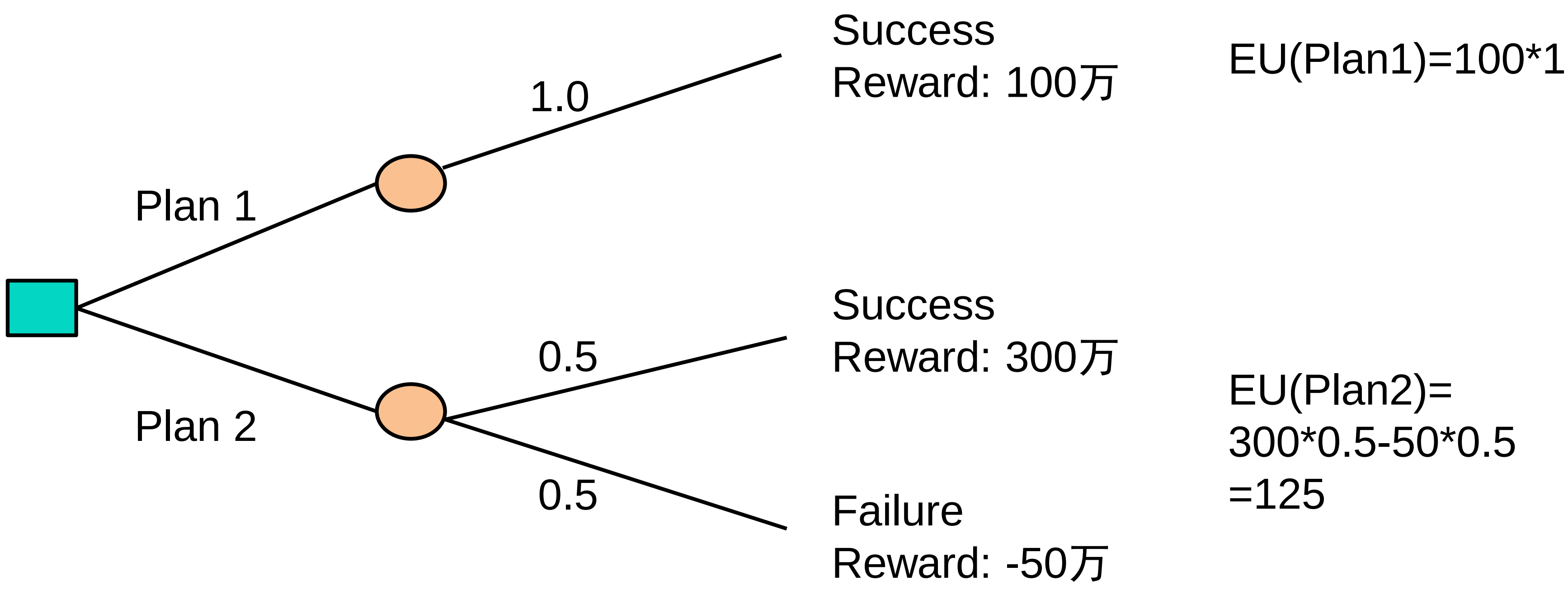
EU(Plan1)=
200*0.8-700*0.2
=20

EU(Plan2)=
50*0.7-10*0.3
=32 ✓

Decision node: Agent plays

Chance node: Nature plays

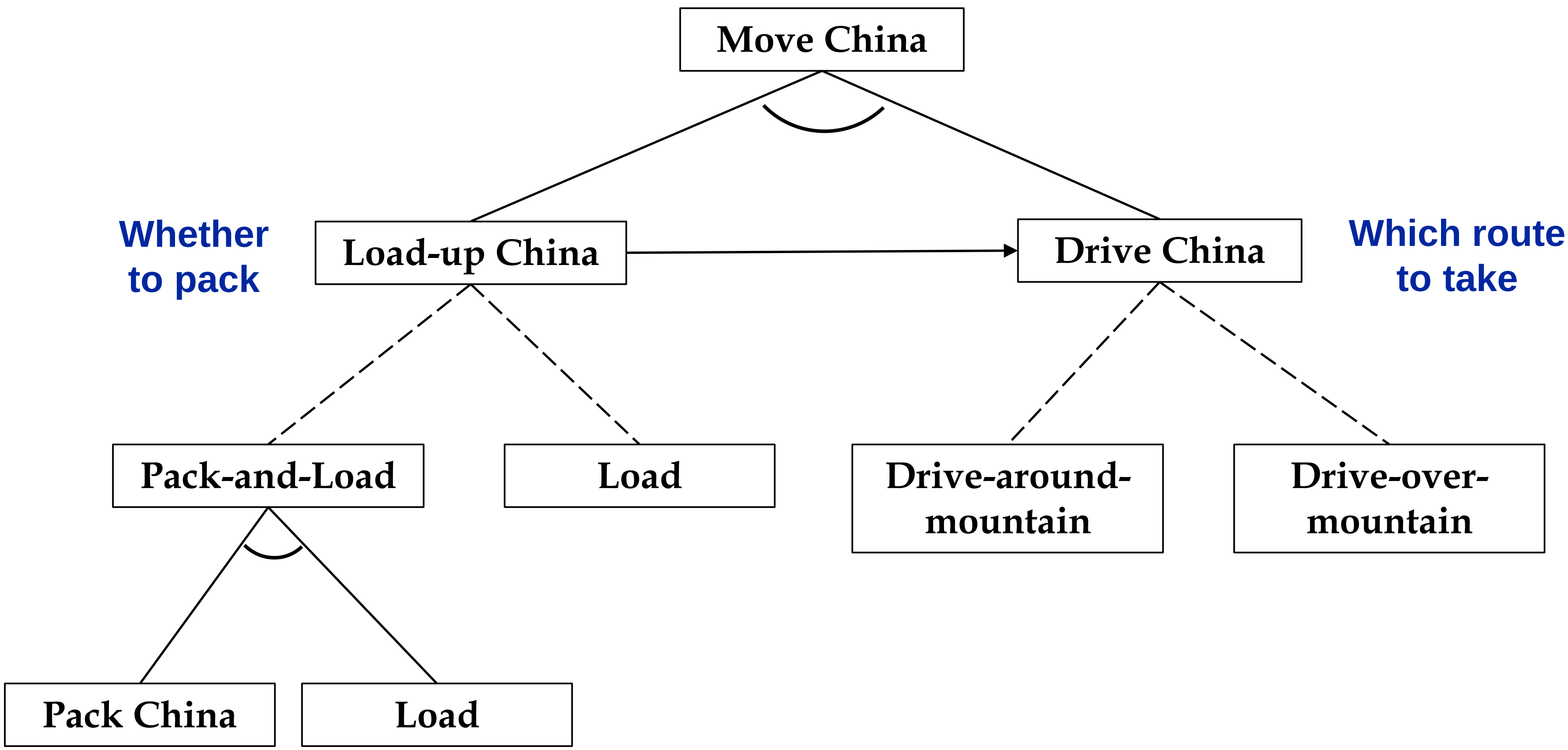
Example of decision theory



- Money is not necessarily equal to preferences …
  - Utility theory does not assume money is people's utility function
  - People assign utility to money. Different people have different utility functions

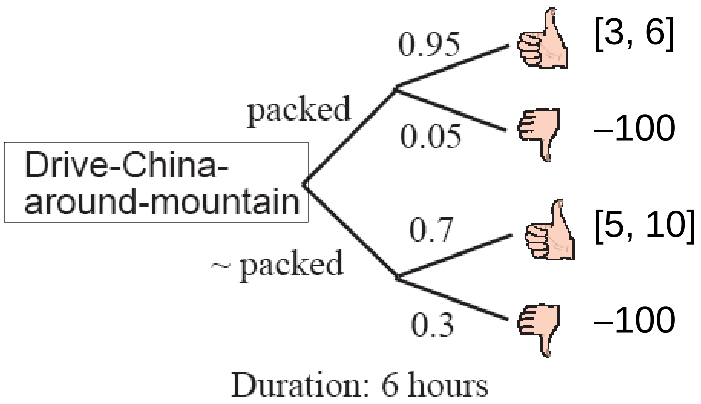
Abstract plan for moving china

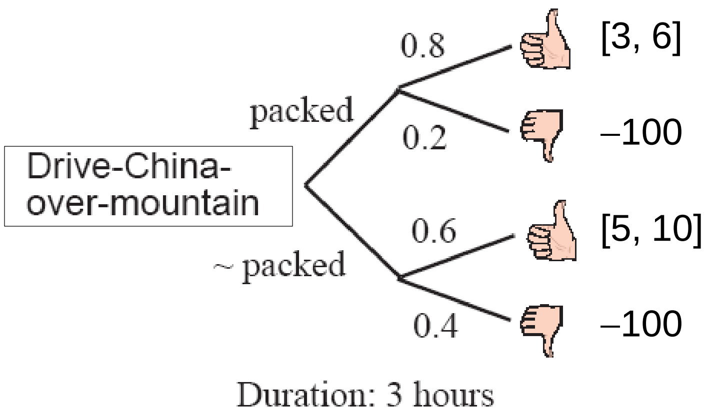
- Use an *abstraction-decomposition network* to describe all possible specializations of an abstract plan to move china

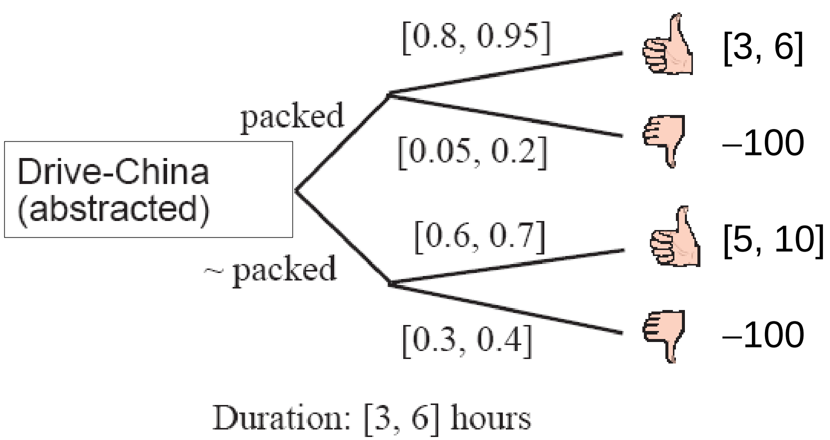


Utilities of action outcomes

- Use utility to represent the costs / benefits of action *outcomes*







Refining abstract action Load-up-china

- Use utility ranges to compute the *dominance* between *alternative* plans

Plan A: Pack and load china

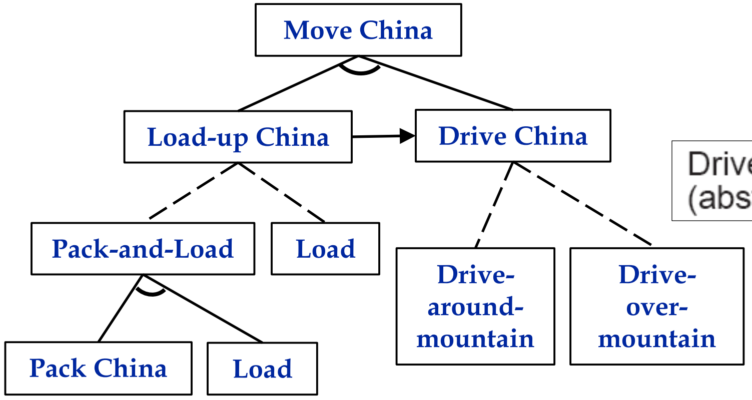
Outcome	Duration	Utility	Probability
Not broken	[3 6]	[3 6]	[0.8 0.95]
Broken	[3 6]	–100	[0.05 0.2]

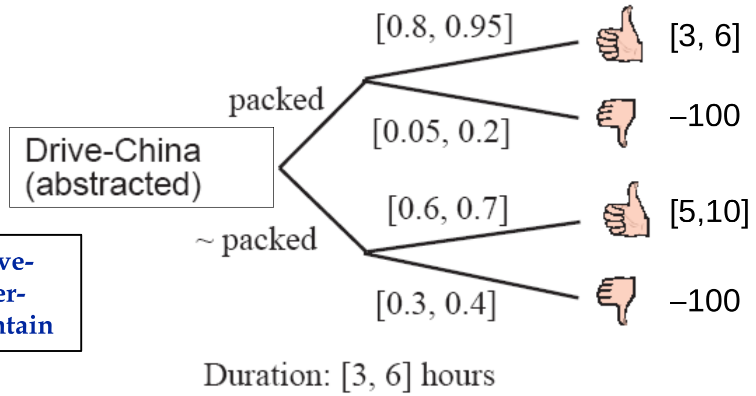
Plan utility:
[-20+2.4, -5+5.7]

Plan B: Load china, don't pack

Outcome	Duration	Utility	Probability
Not broken	[3 6]	[5 10]	[0.6 0.7]
Broken	[3 6]	–100	[0.3 0.4]

Plan utility:
[-40+3, -30+7]





Other approaches

MaxPlan (Inspired by SATPLAN):

- Given a boolean formula with variables (either *choice* variables or *chance* variables), find an assignment to the choice variables that maximizes the probability that the formula is true
- We have control to *choice* variables:
  - e.g. which actions to use
- We cannot control *chance* variables:
  - e.g. the weather, the outcome of each action …
- Then use standard algorithm to compute and *maximize* probability of *success*

Other approaches

MDPs and POMDPs:

- MDP-based approaches can find optimal solutions and deal elegantly with costs
- However,
  - They use rather compact action representation
  - Need to control potential state space explosion
  - Complexity issue and tractability

Recent trends in planning research

Trends:

- Combining *planning* with *learning* technique
  - Bridging the Gap between AI Planning and Reinforcement Learning (PRL) Workshop @ *ICAPS 2020-2023*
  - Bridging the Gap between AI Planning and Reinforcement Learning (PRL) Workshop @ *IJCAI 2022*
- *Explainable* automated *planning* and decision making
  - Explainable AI Planning (XAIP) Workshop @ *ICAPS 2018-2022*
  - Explainable AI (XAI) Workshop @ *IJCAI 2017-2020*, *2022*
  - Explainable AI Workshop 2021 Organized by *NIST*
  - Explainable and Transparent AI and MAS (EXTRAAMAS) Workshop @ *AAMAS 2019-2023*

小结：关于规划

偏序规划（POP）

图规划（GraphPlan）

约束满足规划（SATPlan）

时序规划（TLPlan）

Classical planning

Hierarchical extension

层次任务网络规划（HTN）

Probabilistic extension

概率规划

Probabilistic planning

Multi-agent extension

多智能体规划

Multi-Agent planning

Multi-agent planning

- *Collective* effort of multiple agents to combine their knowledge, information and capabilities so as to develop solution(s) to the planning problem that each agent could not have solved as well alone
- Assume that agents are *cooperative*: each agent must formulate plans for what it will do that take into account (sufficiently well) the plans of other agents

What aspects are multi-agent?

- Multi-agent planning could refer to just the *results* of the planning process:

  A centralized planning process formulates plans that specify how each of the multiple agents should do

  - Centralized planning for distributed plans

- Multi-agent planning could refer to the *process* of formulating plans:

  Multiple agents participate in the construction of a single joint plan

  - Distributed planning for centralized plans

What aspects are multi-agent?

- Both the planning process and results are multi-agent:
  - Each agent applies its local expertise and awareness to develop its local plan
  - Agents use communication and/or shared knowledge to shape their local plans and conform better to others' plans, in order to work together effectively
  - ➢ Distributed planning for distributed plans

Levels of working together

	As a process	As a result
Coordination	Decision-making takes others into account	Individuals are not thwarted by others
Cooperation	Individual decisions further the collective welfare	Individuals appear to be “working together”
Collaboration /Teamwork	Individuals work toward shared goals	Common goals are achieved well and/or efficiently

Coordinating multiple agents

- Social conventions（协定）
- Flocking behavior in nature
  - Cohesion（凝聚）: get closer to the average position of neighbors
  - Separation（分离）: avoid getting too close to any one neighbor
  - Alignment（对齐）: get closer to the average heading of neighbors
- Agent communication
- Agent modeling
  - Build mind model of other agents
  - Intention/goal recognition

Agent modeling

- Representing and reasoning about *other* agents
  - Other agents' capabilities, skills, responsibilities
  - Other agents' mental states, plans, goals, actions
  - Other teams' goals, plans, states

    …
- *Explicitly* model other agents
  - *Implicit* modeling if all coordination with other agents compiled in without actual representation and reasoning about other agents

Modeling other agents: A critical technique

- In dynamic, complex, multi-agent environments:
  - Agents respond unpredictably to the environment
  - Interactions with other agents not always feasible

    E.g. communications failures, opponent behavior, etc
  - State of other agents not known at design time
- Agents must model other agents at *execution time*
  - To detect failures in their execution (leading to diagnosis, recovery)
  - To coordinate with others, render assistance
  - To visualize, ascertain progress
  - To compete against other agents

  ...

Plan recognition（规划/意图识别）

- *Key* agent modeling technique
  - Infer other agent's current plans and goals based on the available *observations*
  - Other agents may be unable to *communicate* directly for a variety of reasons
- Major challenge: *Ambiguity*
  - There may be multiple plans to explain the observed actions

Resources

- UCPOP Planner:

  https://www.swmath.org/software/20687
- GraphPlan Planner:

  https://en.wikipedia.org/wiki/Graphplan (External links)
- UMCP Planner:

  http://www.cs.umd.edu/projects/plus/umcp
- SHOP/SHOP2 Planner:

  http://www.cs.umd.edu/projects/shop
- Planning Domain Definition Language (PDDL):

  https://planning.wiki/guide/whatis/pddl

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