Linköping University

# Automated Planning

## Introduction to Planning

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# **One** way of defining planning:

*Using* ***knowledge*** *about the world,*

*including possible actions and their results,*

*to* ***decide*** *what to do and when*

*in order to achieve an* ***objective****,*

***before*** *you actually start doing it*

# Applications of Planning

# Towers of Hanoi



**Some applications are simple, well-structured, almost *toy problems***

**Simple structure**

**Single agent acting**

**Possible actions**

- **Move** topmost disk from *x* to *y*, **without** placing larger disks on smaller disks

**Objective**

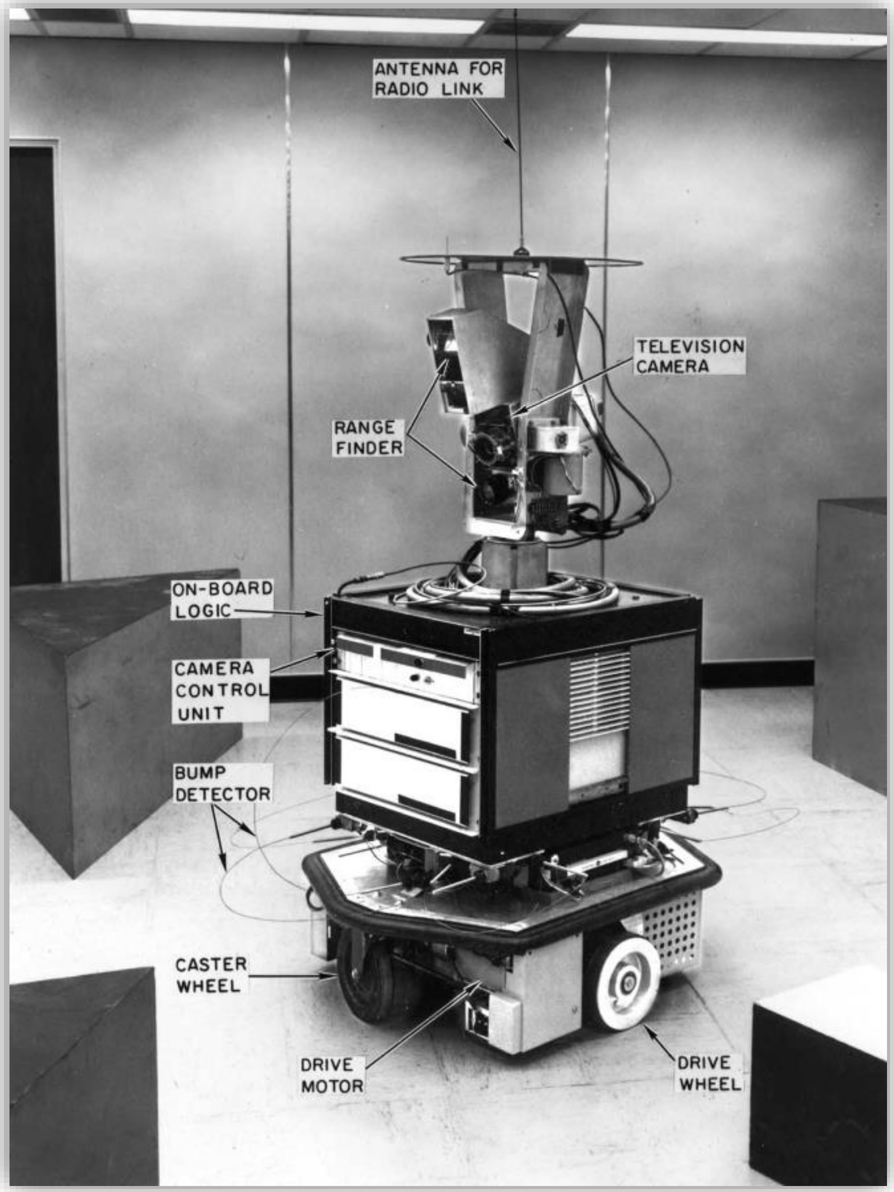
- All disks on the *third* peg, in order of increasing size

# Shakey



- Classical robot example: **Shakey** (1969)
  - Available **actions**:
    - *Moving* to another location
    - *Turning* light switches on and off
    - *Opening* and *closing* doors
    - *Pushing* movable objects around
    - …
  - **Goals**:
    - *Be in room 4 with objects A,B,C*

    - http://www.youtube.com/watch?v=qXdn6ynwpiI

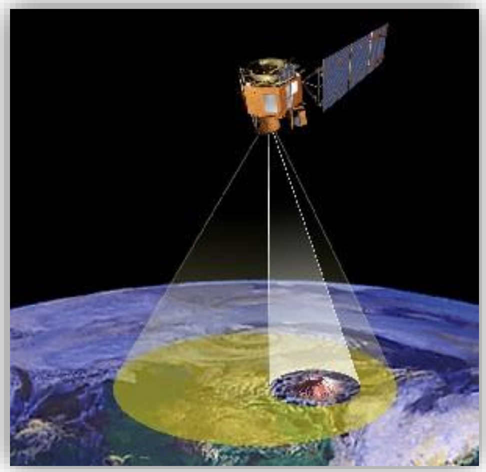


# Miconic 10 Elevators

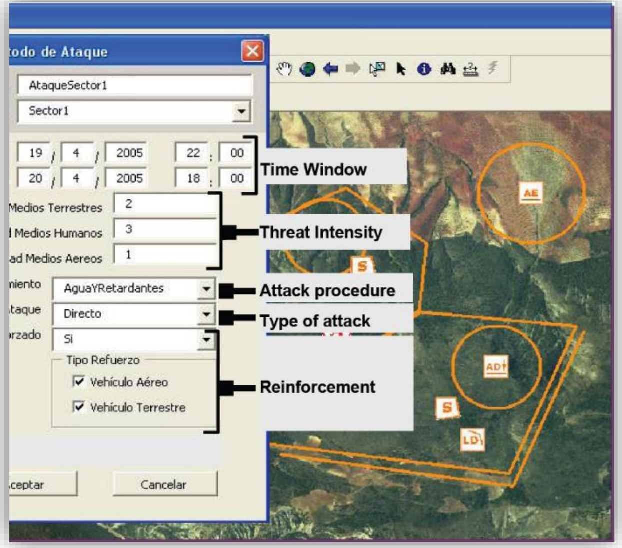


- **Schindler Miconic 10 system**
  - Tall buildings, multiple elevators
  - Enter destination *before* you board
  - System creates a *plan*:
    - Which elevator goes to which floor
    - In which order
  - Saves time!
    - 3 elevators could serve as much traffic as 5 elevators with earlier algorithms

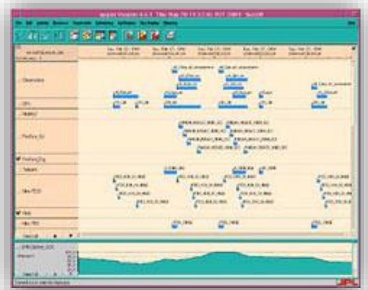
# Earth and Space



**On-board planning**
to view interesting natural events:
http://ase.jpl.nasa.gov/




**SIADEX** –
plan for firefighting
Limited resources
Plan execution is dangerous!



**NASA Mapgen / Mars Rovers**

Primary platform for creating daily activity plans for Spirit, Opportunity

Mixed-initiative tool:
Human in the loop

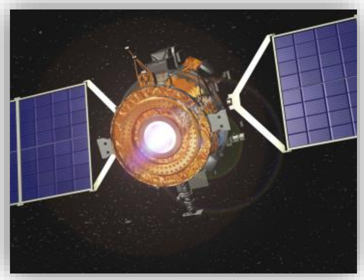
# Why should Computers Plan?



- And why should **computers** create plans?
  - Manual planning can be **boring** and **inefficient**

  - Automated planning may **create higher quality plans**
    - Software can systematically optimize


  - Automated planning can be applied **where the agent is**
    - Satellites cannot always communicate with ground operators
    - Spacecraft or robots on other planets
      may be hours away by radio



# Distinction:
# Planning vs. Reacting

# Context: Unmanned Aerial Vehicles



- A modern **context** for planning:
  - Autonomous
    Unmanned Aerial Vehicles (UAVs)


*Using **knowledge** about the world,*
*including possible actions and their results,*
*to **decide** what to do and when*
*in order to achieve an **objective**,*
***before** you actually start doing it*

# Actions for UAVs



- General knowledge about the world
  - **Locations** of UAVs and objects
  - **Fuel** levels, …
- Available actions:
  - **Take off**
    - Before: The UAV must be on the ground
    - Result: The UAV is flying
  - **Fly to a point**
    - Before: Must have sufficient fuel
    - Result: Will end up at the indicated point
  - **Land**
  - **Fly a trajectory curve**
  - **Point camera, take picture**
  - **Start/stop video recording**
  - **Transmit information to operator**
  - **…**

**Informal!**
**Incomplete!**

More later…

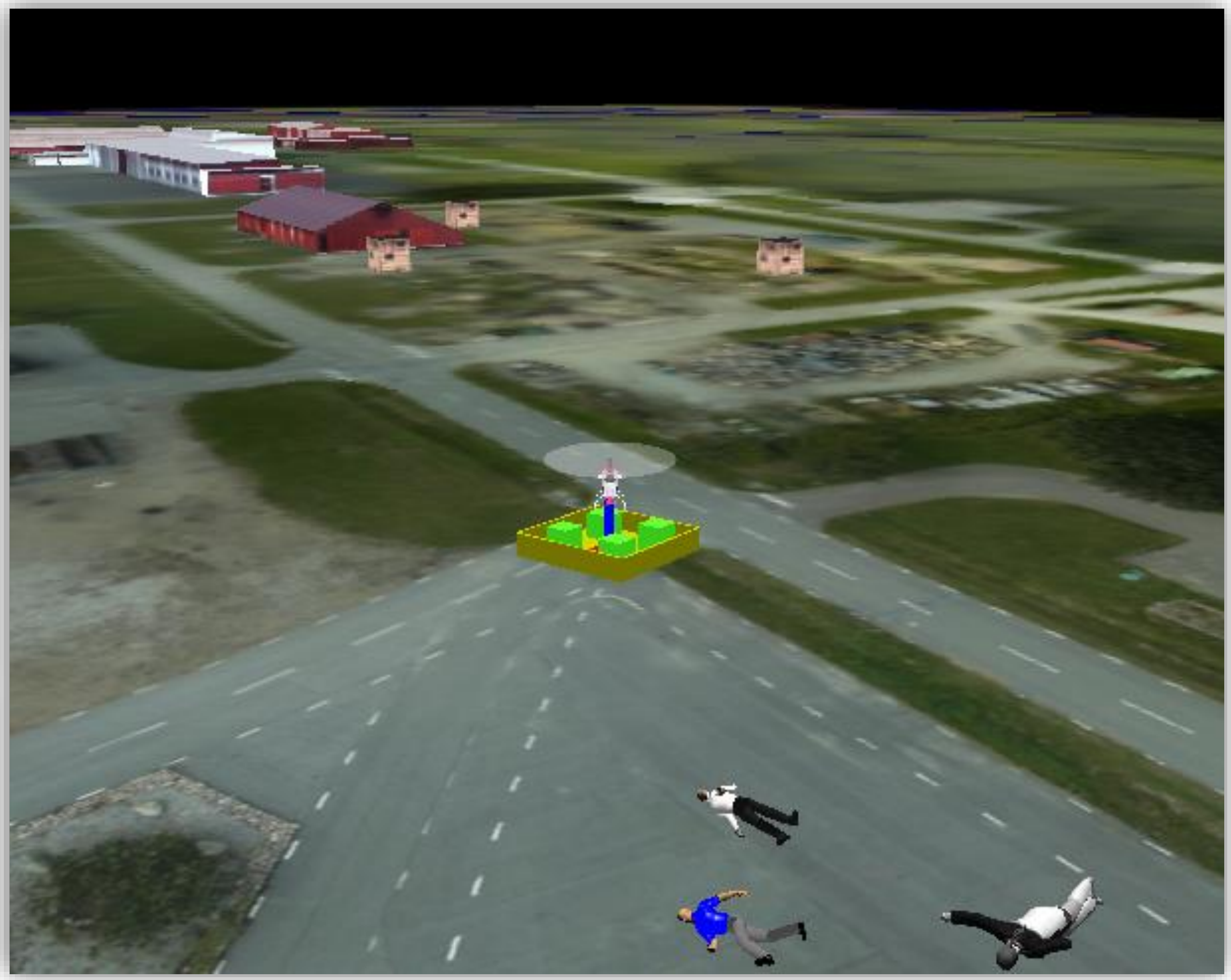
*Using **knowledge** about the world,*
*including possible actions and their results,*
*to **decide** what to do and when*
*in order to achieve an **objective**,*
***before** you actually start doing it*

# UAV Objective 1: Emergency Services Logistics



- Assist in emergency situations
  - Deliver packages of food, medicine, water

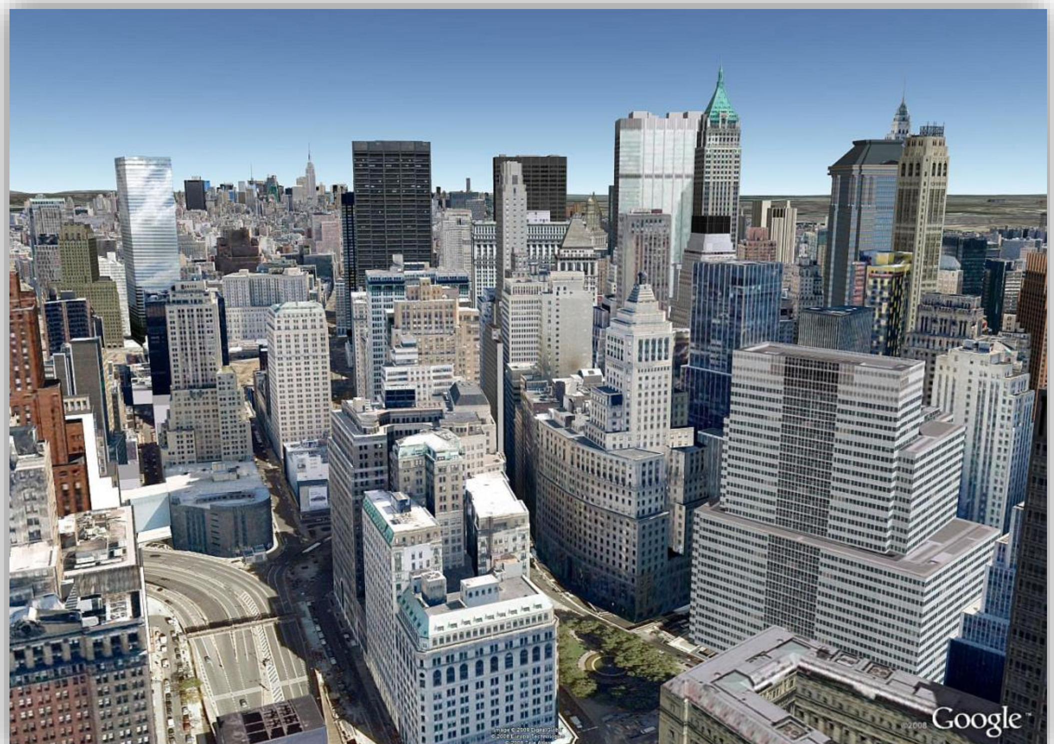


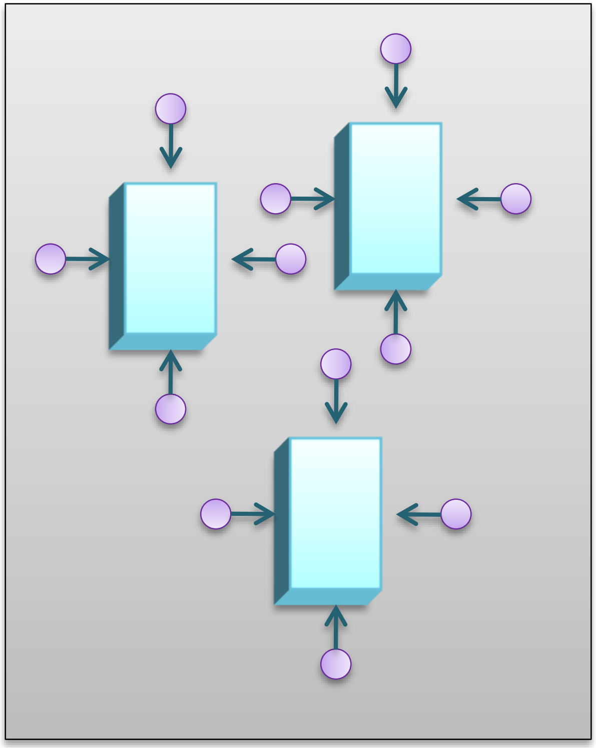



# UAV Objective 2: Photogrammetry



- A specific **photogrammetry problem** with a single UAV:
  - Photograph buildings – generate realistic 3D models
  - Problem:  Find best way of taking pictures
    - From specificed locations
    - In the specified directions





*Using **knowledge** about the world,*

*including possible actions and their results,*

*to **decide** what to do and when*

*in order to achieve an **objective**,*

***before** you actually start doing it*

# Method 0: Reactive + Stupid



- Method 0: Let's be **reactive** and **stupid**
  - Reactive: *No planning, don't explicitly consider the future*
  - Very fast *decision + execution algorithm:*

```
while (exists unvisited position) {
    pos ← some random unvisited position
    flyto(pos)
    aim()
    take-picture()
}
```

  - Somewhat suboptimal for *flight…*

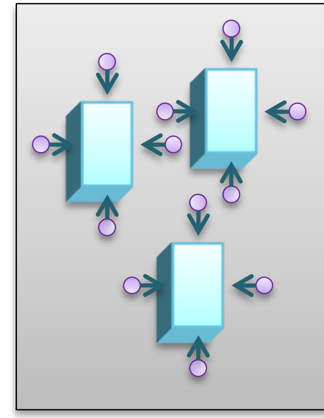
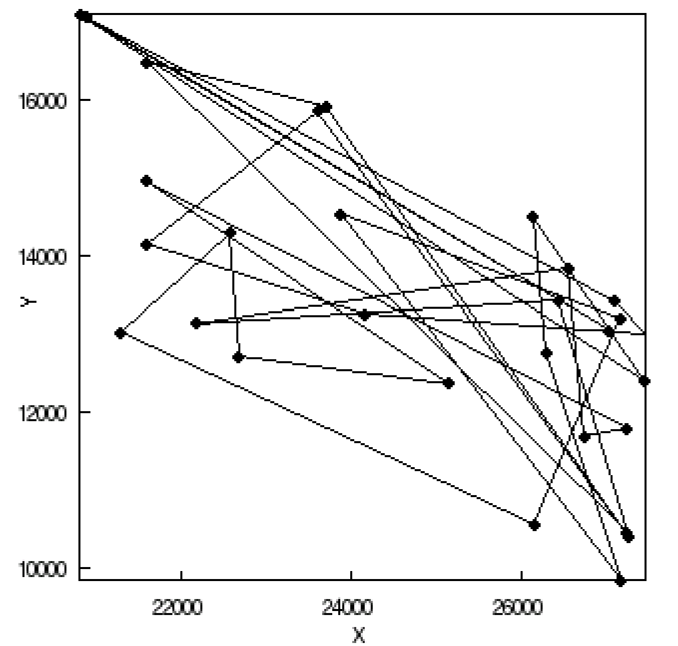


Figure 3.1. Western Sahara: example of random initial tour




http://nfrac.org/felix/publications/tsp/

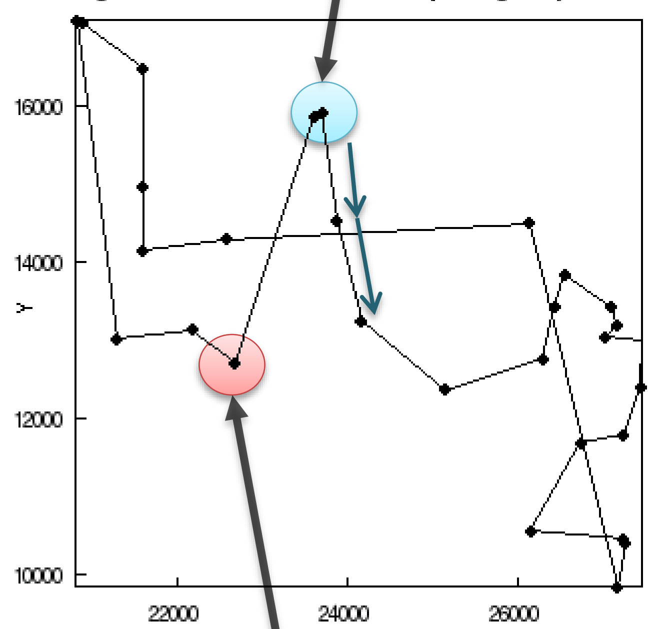
# Method 1: Reactive + Greedy



- Method 1: Let's be **reactive** and **greedy**
  - **Greedy heuristic** chooses next location
    - "Least expensive extension to the plan"
  - **while** (exists unvisited position) {
    *pos* ← the **nearest** unvisited position
    **flyto**(*pos*)
    **aim**(); **take-picture**()
    }
  - *Seems* good for this task; not optimal
    - Least expensive *right now*, more expensive in the long run
  - For many other tasks: Still *really bad*

Start here; generate actions incrementally

Figure 3.2. Western Sahara: example of greedy initial tour




Run out of fuel here?

**Often, *not thinking ahead* means you can't even solve the problem!**

**(Fly too far → run out of fuel; crack an egg → can't uncrack it; …)**

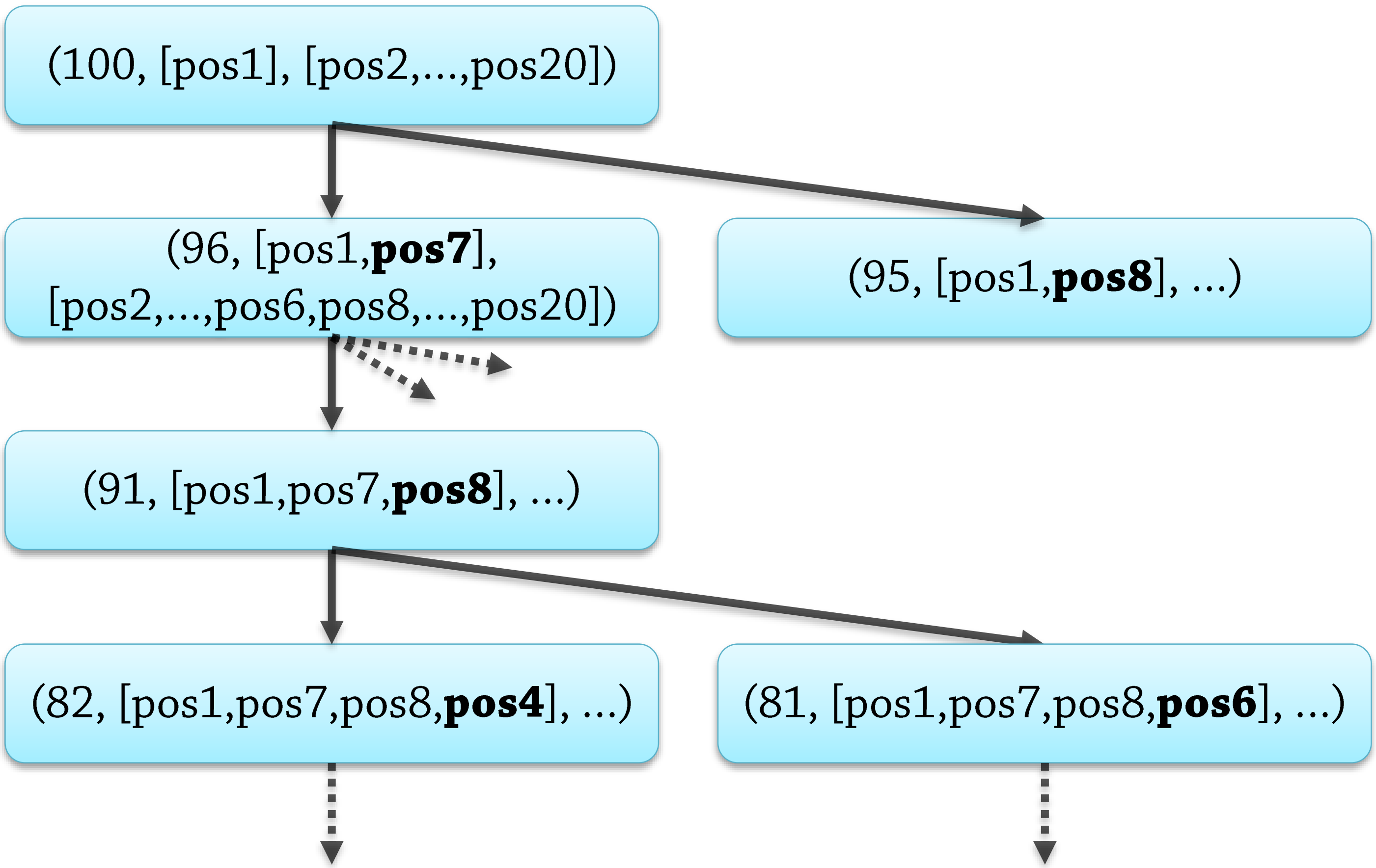
*Using **knowledge** about the world,*
*including possible actions and their results,*
*to **decide** what to do and when*
*in order to achieve an **objective**,*
***before** you actually start doing it*

# Method 2: Think ahead





- Method 2: Let's **think ahead**
  - *First* create a complete plan, considering multiple choices
  - Keeping track of [**fuel** left, **visited** positions, **remaining** positions]



# Method 2: Think ahead – planning




- Method 2, *first step*: **<u>Search</u>** (for example, depth first)
  - **call solve**(100, [pos1], {pos2,…,pos20})
  - **solve**(*fuel-before*, *plan*, *remaining*) {

```
solve(fuel-before, plan, remaining) {
    if (remaining == ∅) return plan;
    currpos = last(plan)
    foreach position nextpos in remaining
                in order of increasing
                distance(currpos, nextpos)
    {
        after = fuel-before – fuel-usage(currpos, nextpos);
        if (after > 0) {
            plan2 = solve(after, plan+[nextpos],
                          remaining–[nextpos])
            if (plan2 ≠ null) return plan2;
        }
    }
    return null;
}
```

Have we already achieved the goal?

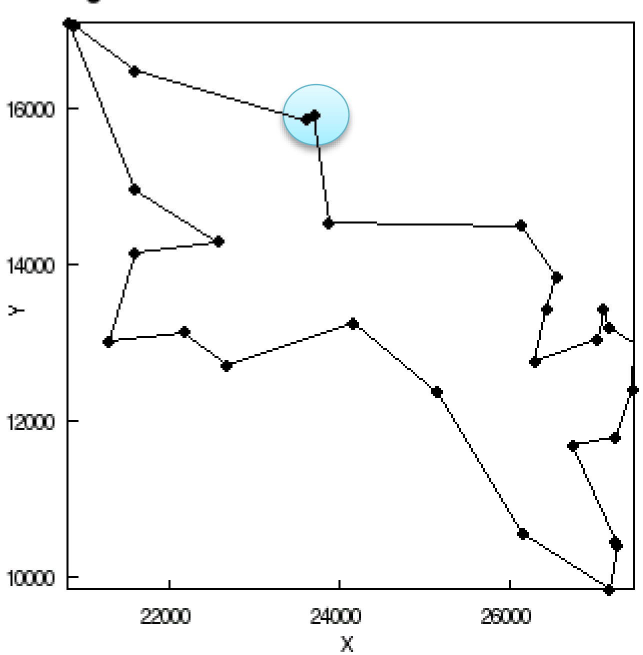
First choice: As before (*greedy heuristic*)
**If not feasible: Try the *next nearest* pos**
Usually won't have to try *each* position

Check fuel "in simulation", not in reality

*Backtrack* if there is no feasible continuation

**This is (one form of) planning!**

Figure 3.8. Western Sahara: solution tour

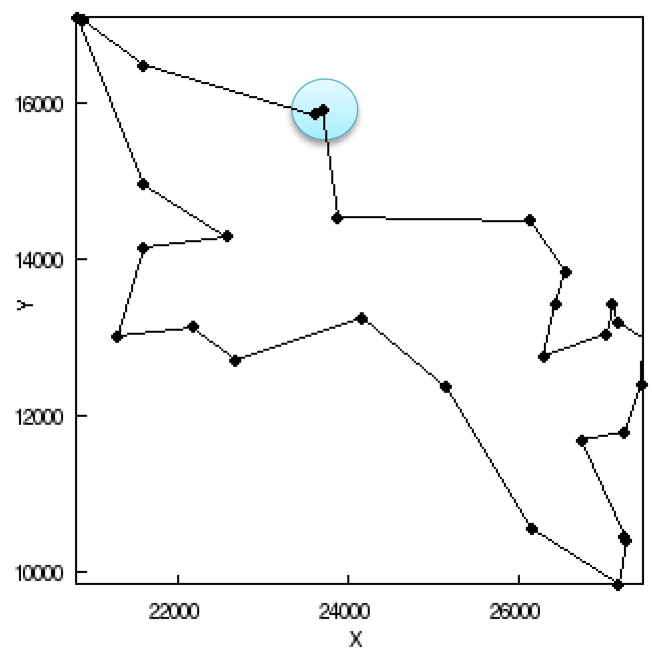


# Method 2: Think ahead – execution



- Method 2: Let's think ahead – *second step*, execute the plan
  - seq = **solve**(100, [pos1], [pos2,...,pos20])
  - **if** seq == null:
    **signal** error
  - **foreach** (position *pos* in seq) {
    **flyto**(*pos*)
    **aim**()
    **take-picture**()
    }

Figure 3.8. Western Sahara: solution tour




**Execution after verifying the plan!**

# Distinction:
# Domain-specific vs. domain-independent planning

# Domain-Specific Planning 1



- Our solver is **domain-specific** – only photogrammetry
  - **Strong assumptions**:
    - Interesting aspects of the world:
      **fuel** left, **visited** positions, **remaining** positions
    - Objective:
      Take a **single** picture at **every** position (no more, no less)
    - Available actions:
      **flyto, aim, take-picture**
      (executed *in that order* at *each position*)
    - Executability conditions:
      Having **fuel**, being in the right **place**
      (no more, no less)
  - **Positive**: Allows efficient code
    - *Adapted* to the exact problem, "hardcoded"
    - Can even use Traveling Salesman algorithms…

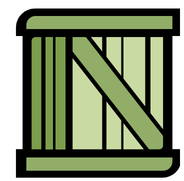
```
solve(fuel-before, plan, remaining) {
  if (remaining == ∅) return order;
    currpos = last(plan)
    foreach position nextpos in remaining
              in order of increasing
              distance(currpos, nextpos)
    {
      after = fuel-before – fuel-usage(currpos, nextpos);
      if (after > 0) {
        plan2 = solve(after, plan+[nextpos],
                      remaining–[nextpos])
        if (plan2 ≠ null) return plan2;
      }
    }
    return null;
}
```

# Domain-Specific Planning 2



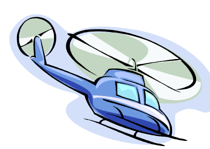
- But some domains are **less straight-forward!**
  - Writing an efficient solver from scratch is *difficult*

- Specialization means **less flexibility!** What if…
  - you want to **deliver** a couple of crates at the same time?
    - Need to modify the code of the planner



PG + Delivery Planner

  - you have **two UAVs** and a **UGV** (ground vehicle)?
    - Different algorithm: *Multiple TSP*



Multi-TSP planner

  - you want to survey an **area** (send video feed of the ground)?
  - you have dynamic no-fly-zones (”don’t fly there at 15:00-16:00”)?

# Generalization



| Many hardcoded assumptions |
|---|
| **Interesting aspects of the world:** **fuel** left, **visited** positions, **remaining** positions **Objective:** Take a **single** picture at **every** position (no more, no less) **Available actions:** **flyto, aim, take-picture** (executed *in that order* at *each position*) **Executability conditions:** Having **fuel**, being in the right **place** (no more, no less) |

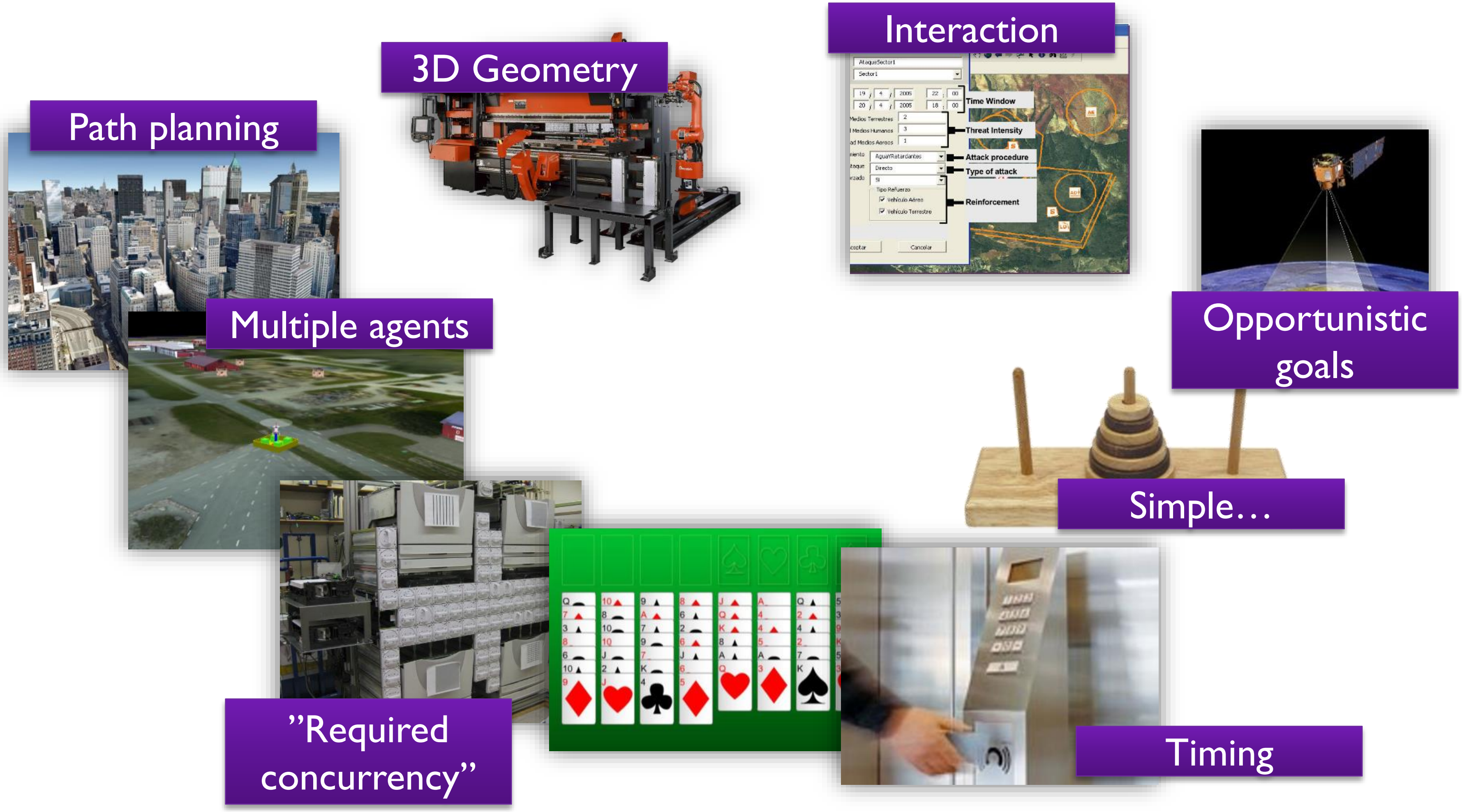
| Little input |
|---|
| Initial fuel level<br>List of positions |

↓

| Few assumptions |
|---|
| ??? |

| As much as possible specified in the input |
|---|
| ?? (should *define* fuel, taking pictures, …) |

# Can we find a **single** set of **common modeling concepts** sufficient for **all** of these **very different** domains?




Can we – and **should** we?

# Different Requirements





## Increasing model expressivity:

- Can be **necessary**
  - Can't model fuel usage constraints?
    ➔ create non-executable plans!
- Can **improve quality**
  - Want plans that execute quickly
    ➔ requires a model of time!
- Can **simplify our job**
  - More expressivity
    ➔ easier to express the problem

## Decreasing model expressivity:

- Can improve **performance**
  - (By many orders of magnitude)
  - We can exploit problem structure
    - Allows different heuristics
    - Allows different plan structures
    - …
- Simplifies development
- …

**Conflicting desires – we need trade-offs!**

Decide what "kind" of domains your planner should be able to accept
Write a planner for this **expressivity**

# Degrees of Expressivity



*Except for standard Turing-complete programming languages, which don't count…

**“Truly domain-independent”**

Handles *everything* – does not exist*

Partial order of expressivity, "coverage"…

…

…

Temporal planning

MDP planning

Some classes *subsume* others, some are simply *different*

Classical planning

…

…

**Domain-specific (photogrammetry)**

Can specialize the planner for very high performance
Must write an entire planner

# What is Classical Planning?

# Classical Planning



- Many early planners made **similar tradeoffs**
  - **At the time**, simply called "*planning*" or "*problem solving*"
    - **Later** grouped together, called "**classical planning**"
  - Restricted, but a **good place to start**
    - Forms the basis of most non-classical planners as well

# Classical Planning: Disagreements



- So **exactly** what is classical planning?
  - Some disagreements…
    - Inevitable: Just a group of *similar* techniques, formalisms
  - Where to draw the line?

We'll use the book's definitions
You can go outside those boundaries and still be "*kind of classical*"!

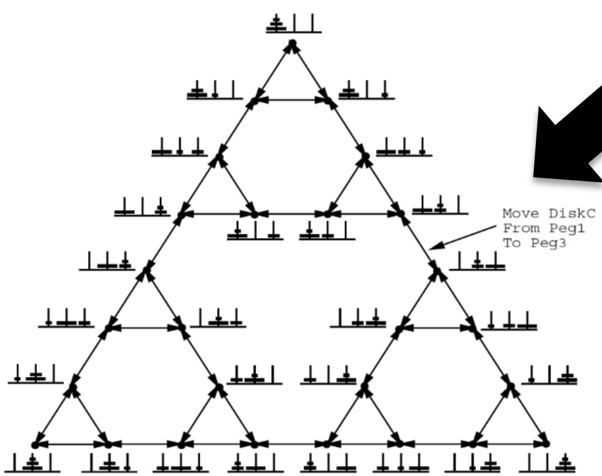
# Modeling Assumptions
# and
# State Transition Systems
# for classical planning

# Intro



**Now: Formal classical model**

$$(\Sigma, s_0, S_g)$$
where
$$\Sigma = (S, A, \gamma)$$




**Next time:**
**Language for describing models**

```
;; The Towers of Hanoi problem
;; (formalisation by Hector Geffner).

(define (domain hanoi)
  (:requirements :strips)
  (:predicates (clear ?x) (on ?x ?y) (smaller ?x ?y))

  (:action move
    :parameters (?disc ?from ?to)
    :precondition (and (smaller ?to ?disc)
                       (on ?disc ?from)
                       (clear ?disc) (clear ?to))
    :effect  (and (clear ?from) (on ?disc ?to)
                  (not (on ?disc ?from))
                  (not (clear ?to))))
  )
```

**A0: *Finite* number of states**

Can't model continuous positions of disks in ToH

OK – we're only interested in some discrete alternatives:

On peg 1, on peg 2, above disk 3, …

**The world is always in a given <u>state</u>, which we want to <u>affect</u>**

**<u>Photogrammetry</u> state:**

**fuel** left,

**visited** positions,

**remaining** positions

- We need **<u>states of the world</u>**
  - $S = \{s_1, s_2, \ldots, s_n\}$ is a set of states

**A3: The world can only be affected by executing an action**

No random changes in the world

No other agents acting in the world

*At least not in the part of the world we model!*

**The world is always in a given state, which we want to affect**

- We need **actions**
  - $A = \{a_1, a_2, \ldots, a_m\}$ is a set of actions; this set is also finite

- We must know **when an action is executable** and **what it achieves**
  - $\gamma: S \times A \rightarrow 2^S$ — $\gamma(s,a)$ ➔ the *set* of states you *may end up in* if you execute *a* in state *s*
  - $\gamma(s,a) = \emptyset$ — means *a* cannot be executed in *s*
  - $\gamma(s,a) = \{s'\}$ — means executing *a* in *s* leads to s'

**The world is always in a given state, which we want to affect** → **Another possible state**

**A6: Every action results in a discrete state transition**

No concept of time

No concept of continuous change (crane swinging from A to B), only:

**Before** *pickup*, the container is on truck *y*;

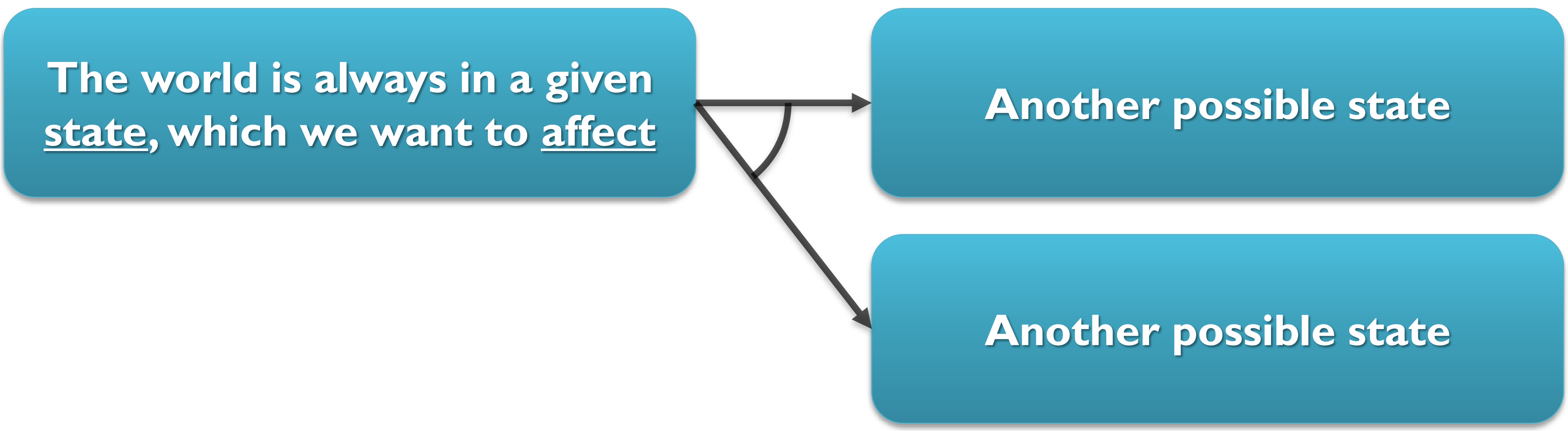
**after**, the container is carried by crane z

**Many planners do model time in some way ➔ "semi-classical"**

# Non-determinism?



- $\gamma(s,a) = \{s_1, s_2, \dots\}$ is possible in some **<u>non-classical planners</u>**




**Non-deterministic actions**
**Complicated due to explosion of possibilities!**

# Classical Planning 4





- We must know **when an action is executable** and **what it achieves**
  - $\gamma: S \times A \to 2^S$ — $\gamma(s,a)$ ➔ returns the set of states you *may end up in*
  - $\gamma(s,a) = \emptyset$ — means *a* cannot be executed in *s*
  - $\gamma(s,a) = \{s'\}$ — means executing *a* in *s* leads to s'
  - $|\gamma(s,a)| > 1$ — impossible in classical planning, due to A2

**The world is always in a given state, which we want to affect** → **Another possible state**

**A2: Deterministic actions**
If we know the current state and the action that is executed, we *know in advance* exactly which state we will end up in

**Some planners support non-determinism**
**Complicated due to explosion of possibilities!**

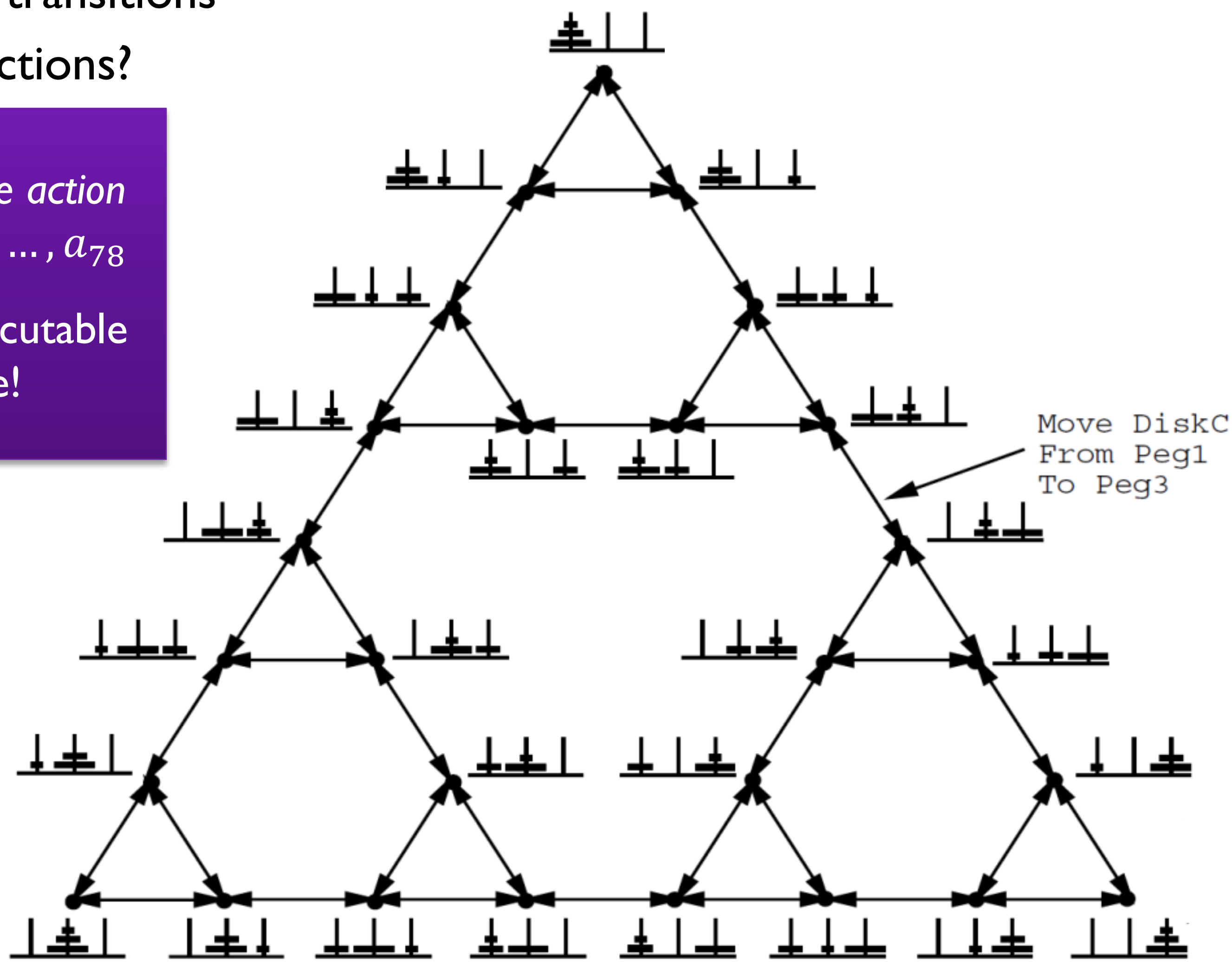
Together: $\Sigma = (S, A, \gamma)$ is a **state transition system (STS)**

# Classical Planning 5: STS Example

- **Part** of an **STS** for a Hanoi problem, **illustrated**:
  - 27 states, 78 transitions
  - How many actions?

Can **always** have *one action per transition:* $a_1, a_2, \ldots, a_{78}$

Each action only executable in a single state!




# Classical Planning 6: STS Example, cont.

jonkv@ida

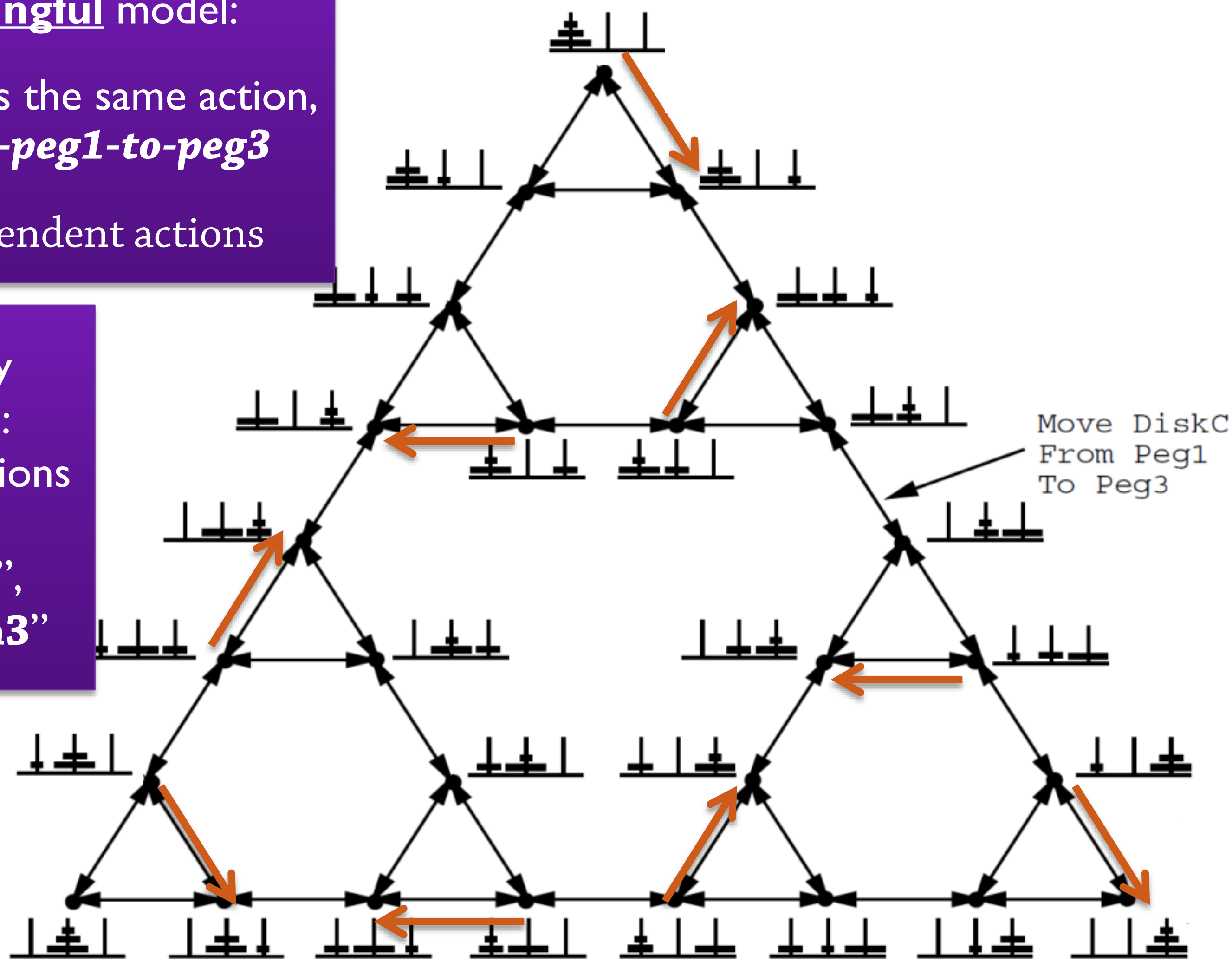
- **Part** of an **STS** for a Hanoi problem, **illustrated**:

Common **meaningful** model:

Every orange arrow is the same action, ***move-diskA-from-peg1-to-peg3***

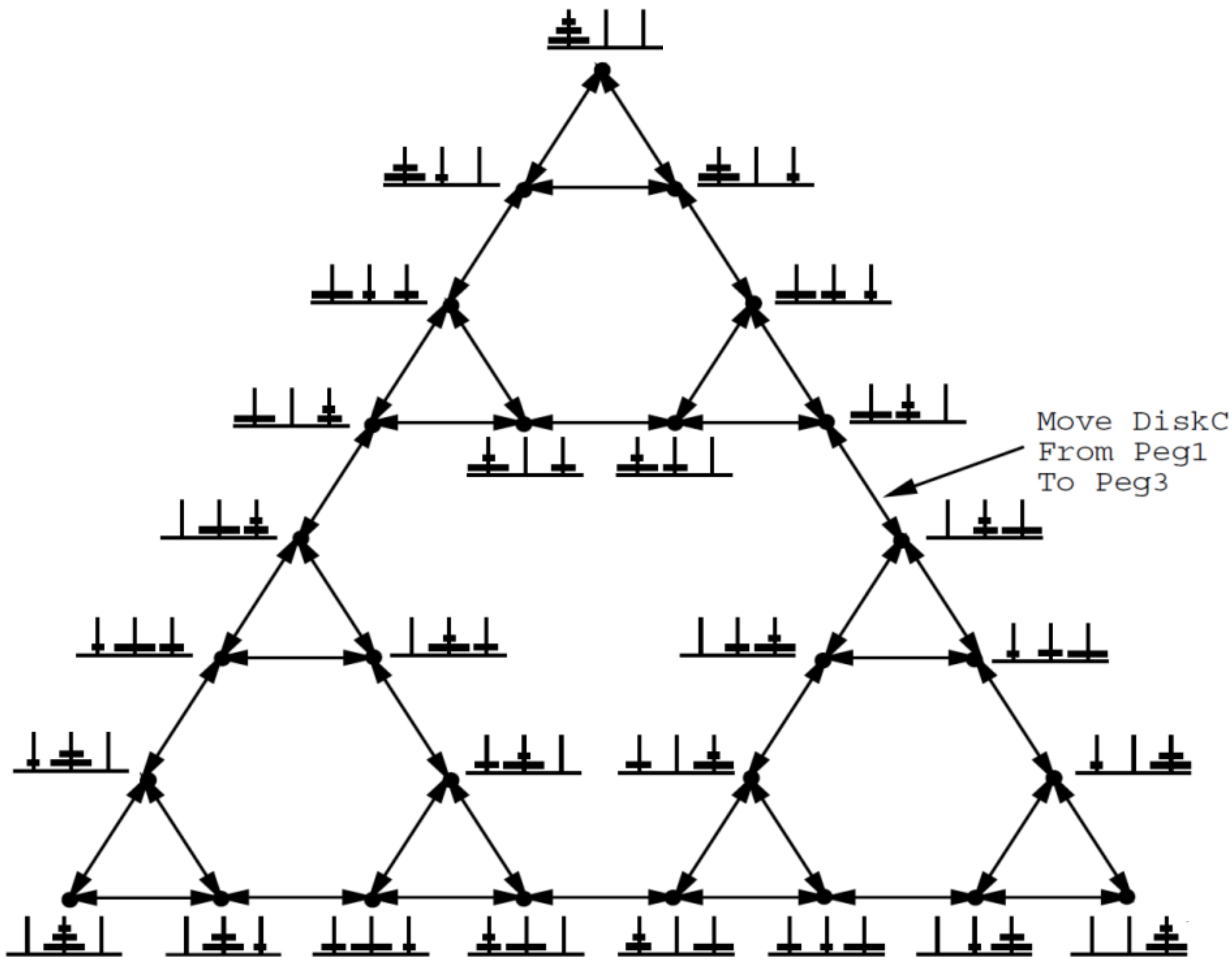
➔ 18 context-dependent actions

Or we *could* get by using *three* actions: At most three transitions from any state ➔ Actions "**option1**", "**option2**", "**option3**"



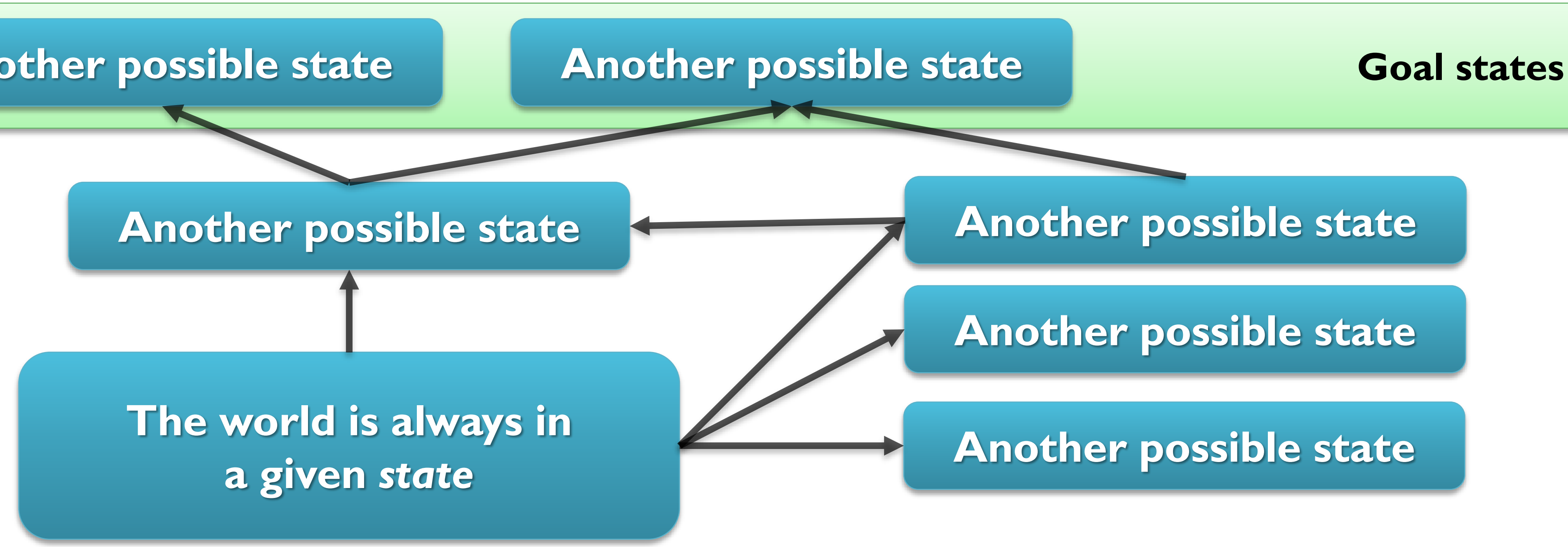

# STS: How the world works **in general**

# Now: What's the (formal) **problem** to solve?



# Problem, part 1: Objectives






**A4: Restricted objectives**

The *objective* is always to *end up in* a *goal state* $s \in S_g$
(No constraint on cost, time requirements, states to avoid on the way, …)

**Many planners support more complex objectives**

# Problem, part 2: Initial State



**A1: We can always <u>detect</u> the current state**

**The world is always in a given *state***

**A7: Offline planning**
No need to consider changes that may happen *while generating plans.*

We know **now** what the state of the world **will be** when we start executing a plan!

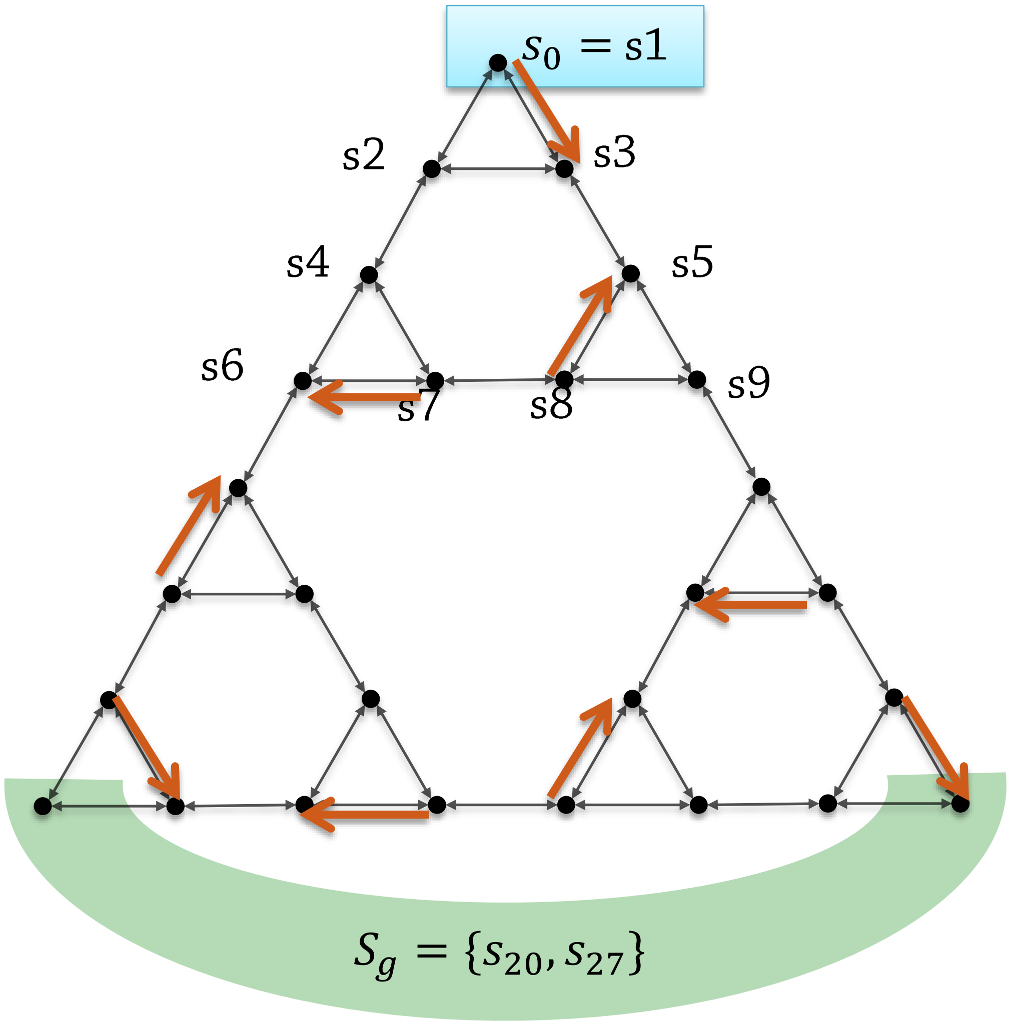
**Initial state**: $s_0$

# Problem Definition





- Result: A complete **classical planning problem** $(\Sigma, s_0, S_g)$



# Transition System and Problem



Real World

Abstraction
Approximation
Simplification

**State Transition System**
**$\Sigma = (S, A, \gamma)$**

Tells us: **How the world works**
(Only those aspects
that we *need* in our model
in order to solve
interesting problems!)

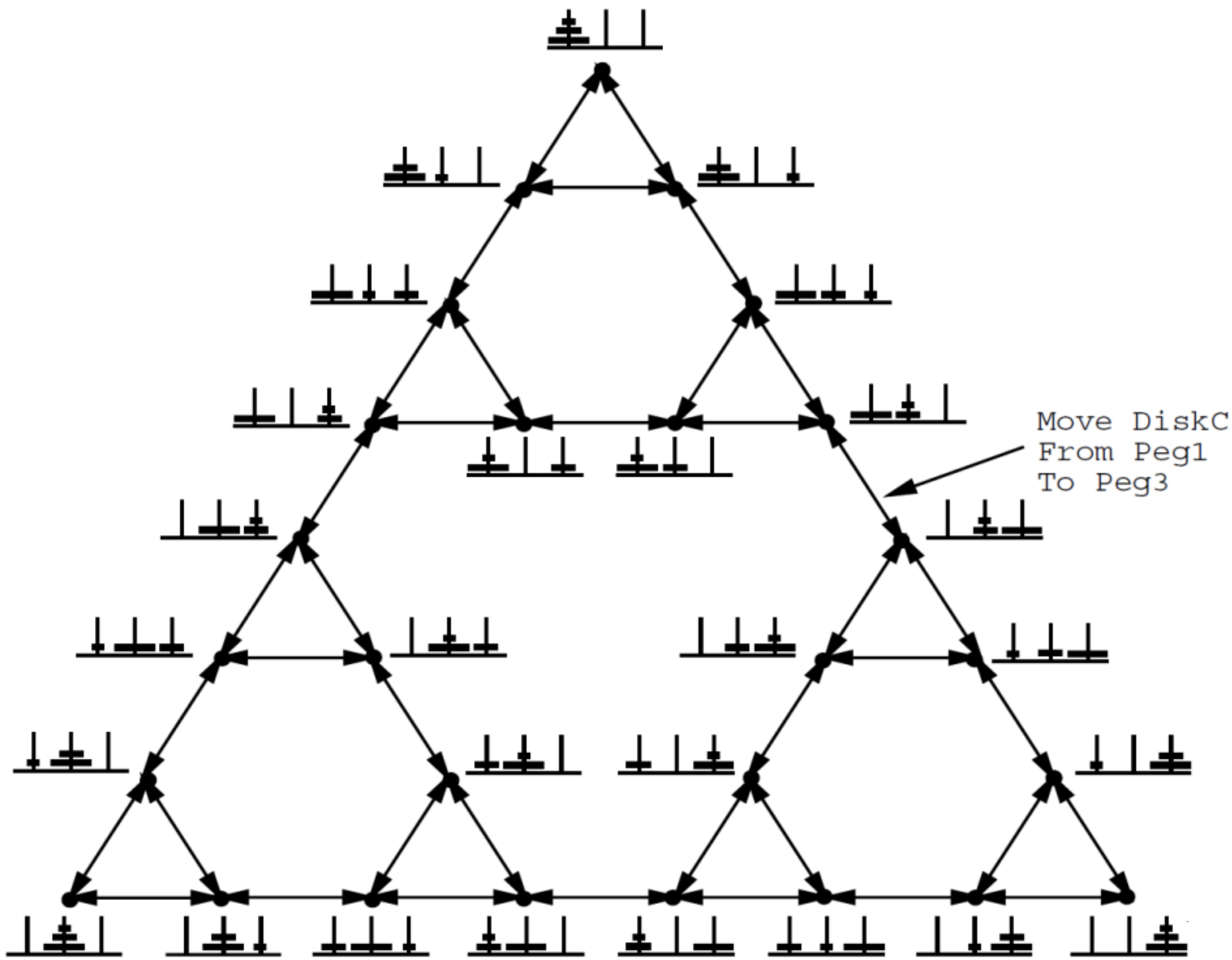
Real World
+ current
problem

Abstraction
Approximation
Simplification

**Planning Problem**
**$\mathcal{P} = (\Sigma, s_0, S_g)$**

Tells us:
**Which specific problem to solve**

# And what **is** a solution?



# Action Sequences




**A5: Sequential execution**
A solution never executes two actions concurrently
(Many planners do allow concurrency ➔ "semi-classical")

- **Action sequence**: $\boldsymbol{\sigma} = \langle \boldsymbol{a_1}, \boldsymbol{a_2}, \ldots, \boldsymbol{a_n} \rangle$, where $\{a_1, \ldots, a_n\} \subseteq A$
  - *Sometimes called "plan"*

- An action sequence is **executable** in state $s \in S$ if $\exists s_1, \ldots, s_n \in S$ such that:
  - $\gamma(s, a_1) = \{s_1\}$
  - $\gamma(s_1, a_2) = \{s_2\}$
  - $\ldots$
  - $\gamma(s_{n-1}, a_n) = \{s_n\}$
  - *Sometimes called "executable action sequence", "plan", "executable plan", …*

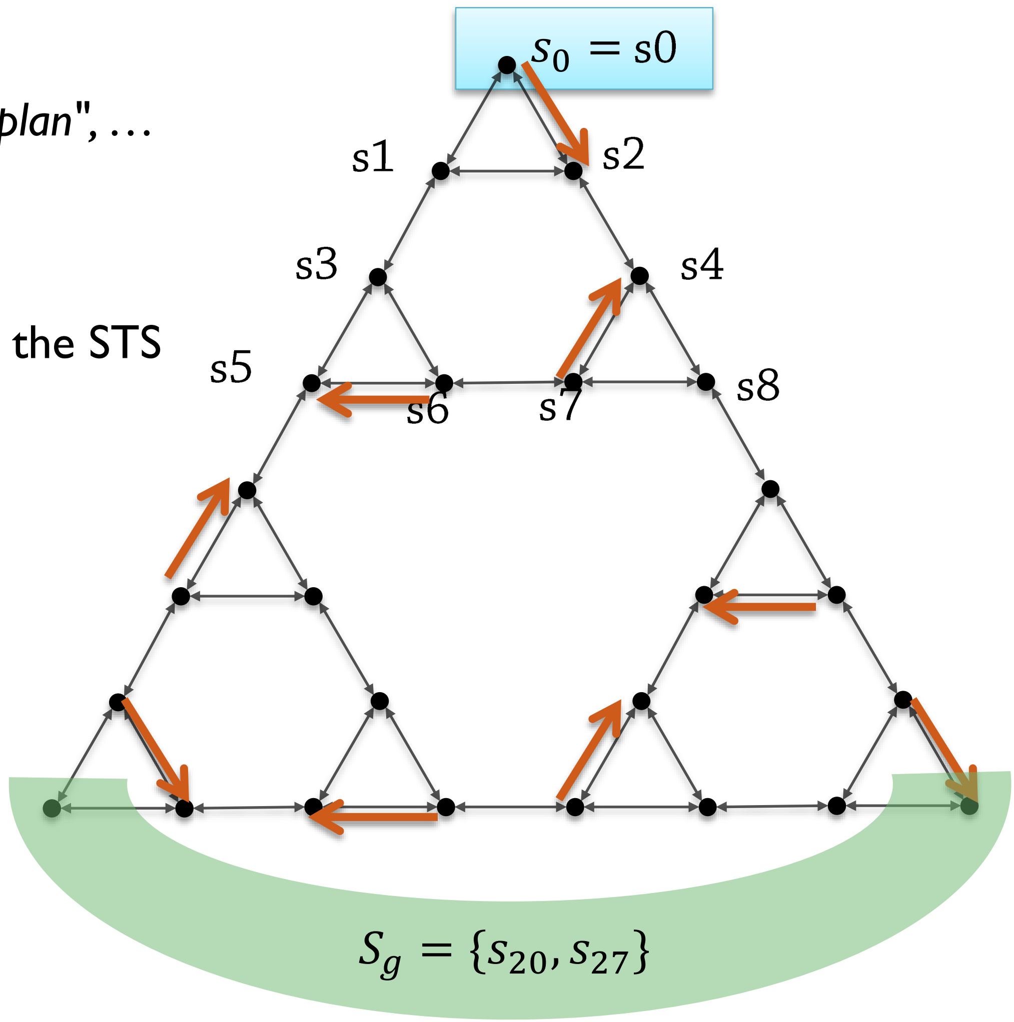
**In the exam questions, the terminology will be unambiguous!**

# Solution

- An action sequence is a **solution** to $(\Sigma, s_0, S_g)$ if:
  - It is executable in $s_0$
  - It results in a state $s_n \in S_g$
  - *Sometimes called "plan", "solution plan", ...*

- A **good** solution:
  - Add a cost function $c: A \to \mathbb{R}$ to the STS
  - Minimize total plan cost:

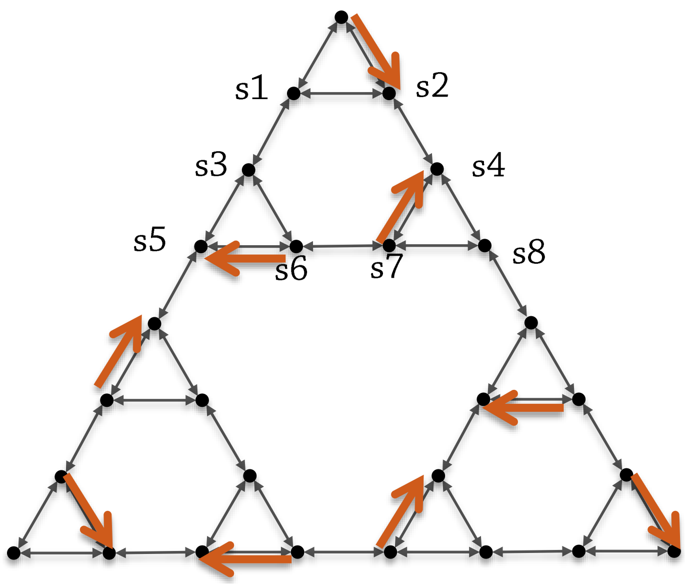
$$\sum_{a \in \pi} c(a)$$



# Plan Generation (2)



- Is classical planning simply **graph search**?
  - *Can* be, but:
    - **Graphs are enormous**
      Requires advanced heuristics, adapted to planning
      Requires advanced search methods
    - **Alternatives to searching the STS**
      can be used to "indirectly" find paths!
    - Many forms of **non-classical** planning
      do **not** map into searching an STS



# STS 8: Useful ?





- Very useful:
  - As a conceptual model, explaining important concepts
  - To analyze expressivity, clarify restrictions
  - To prove properties
- Very useless:
  - As a way of actually **writing down** realistic planning problems (enumerate all possible states?)
  - As an implementation structure for planners
  - → Next time!