Karlsruhe Institute of Technology

Automated Planning and Scheduling

Lecture 1

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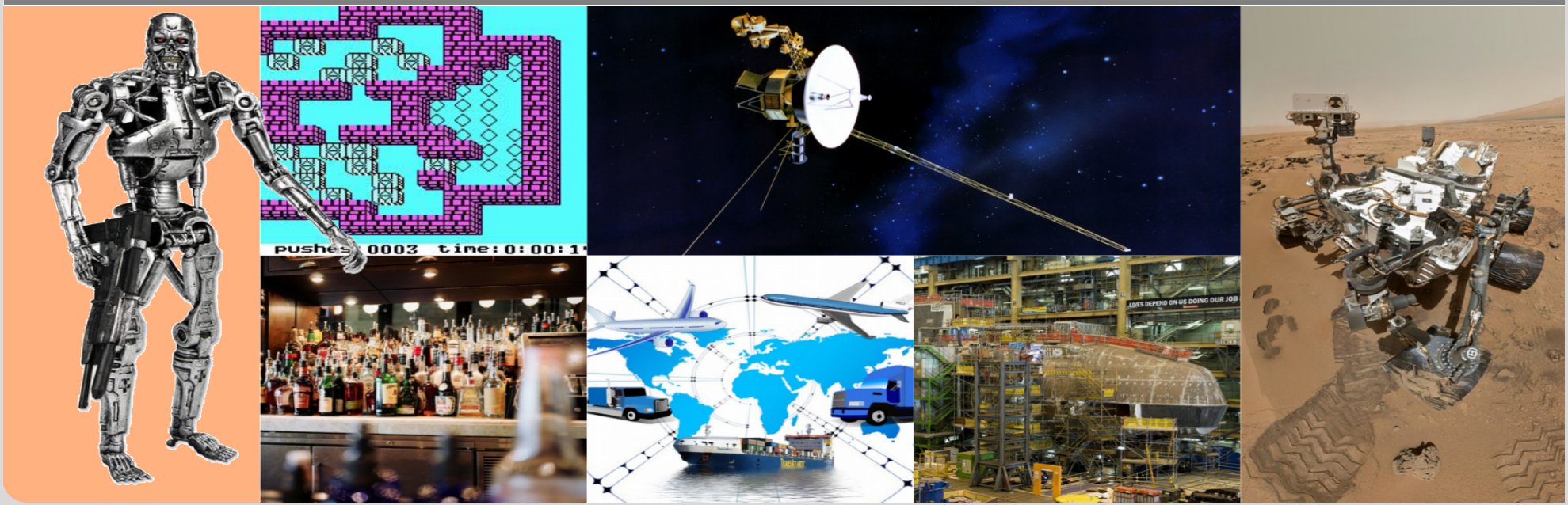
INSTITUTE OF THEORETICAL INFORMATICS



Events

- Lectures
  - Room 301
  - Every Thursday at 14:00
  - Please enroll to the lecture on `http://campus.studium.kit.edu`
- Exercises
  - Room -119
  - Every second Wednesday (starting 31.10.) at 14:00
- Exams
  - Oral/Written examination
  - Bonus points for homework improve the grade
  - Dates are flexible

Homeworks and Lecture Notes

- You get homework points for doing homework and showing up with them on the exercises
- You will have the possiblity to collect at least 120 points for homeworks during the semester (plus a lot more bonus points)
- You must collect at least 60 points to pass the exercises and be allowed to participate in the oral exam.
- Extra points improve your grade:
  - $\geq$ 70 points improves grade by 0.3
  - $\geq$ 90 points improves grade by 0.7
  - $\geq$ 110 points improves grade by 1.0

Contact

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- Dominik Schreiber
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- Homepage
  - https://baldur.iti.kit.edu/plan/
  - Contains all the slides and homework assignments

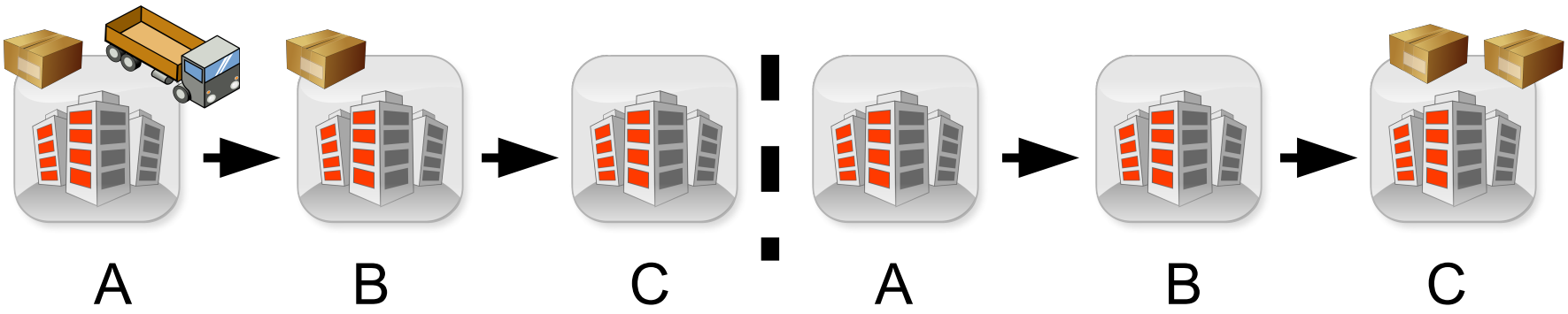
Goals of this lecture

- What is planning and scheduling?
  - Why is it important?
- How to use a Planner efficiently
  - How to encode your problems into PDDL
- How do Planners work
  - Algorithms
- How to make a Planner
  - Implementation techniques
- How do scheduling algorithms work

Planning vs Scheduling

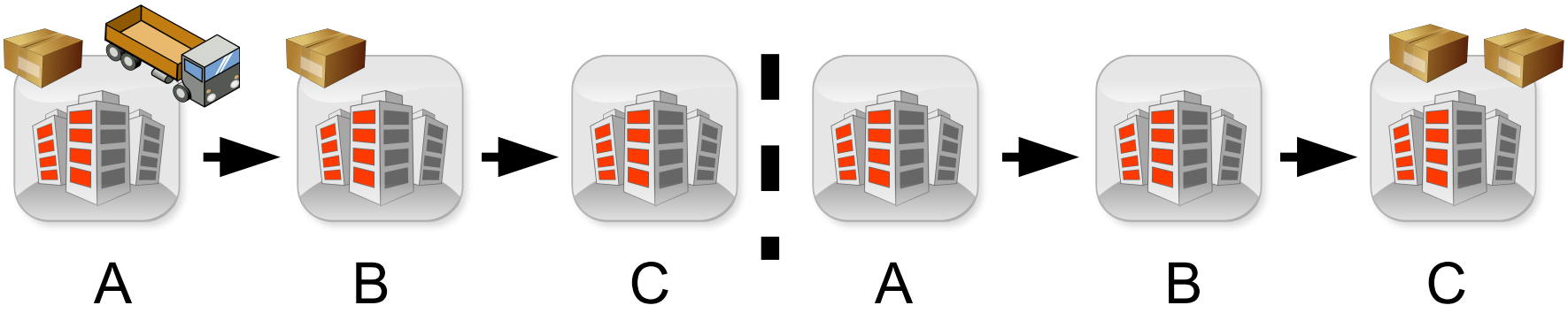
- Planning
  - given a description of the **current state**, a set of **possible actions**, and a **desired state** come up with a **sequence of actions = plan** that one can take to achieve the desired state.
  - belongs to the category of Artificial Intelligence.
  - high complexity, P-SPACE hard or even Undecidable.
- Scheduling
  - given a collection of **actions** and restricted **resources** decide how to execute **all the actions** in an efficient manner (create a schedule).
  - belongs to the category of operations research.
  - complexity typically in P and NP

Planning Problem Example – Trucking



- Initial State
  - There is a truck and a package in city A
  - There is a package in city B
- Goal
  - There are two packages in city C
- Possible Actions
  - (Un)loading packages from/on the truck, driving between cities

Planning Problem Example – Trucking



World State

- Truck at A, packages at A and B
- Truck at A with one package ...
- Truck at B ...
- Truck at B with both packages
- Truck at C with both packages
- both packages delivered to C

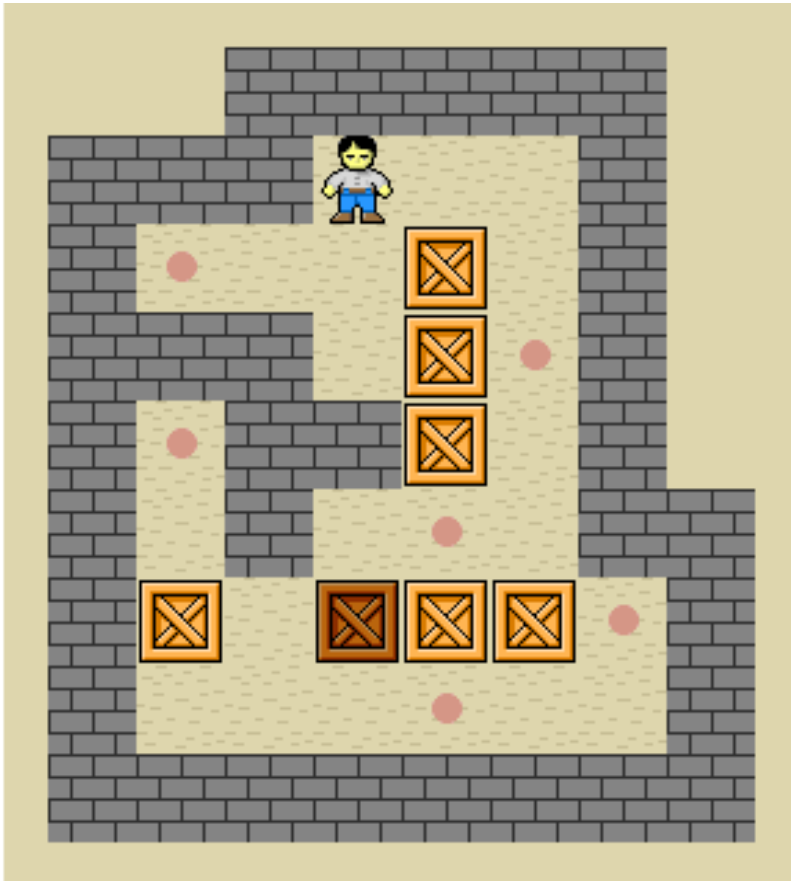
The Plan

- load package at A
- drive truck to B
- load the second package
- drive truck to C
- unload both packages

Another Planning Problem Example

Sokoban

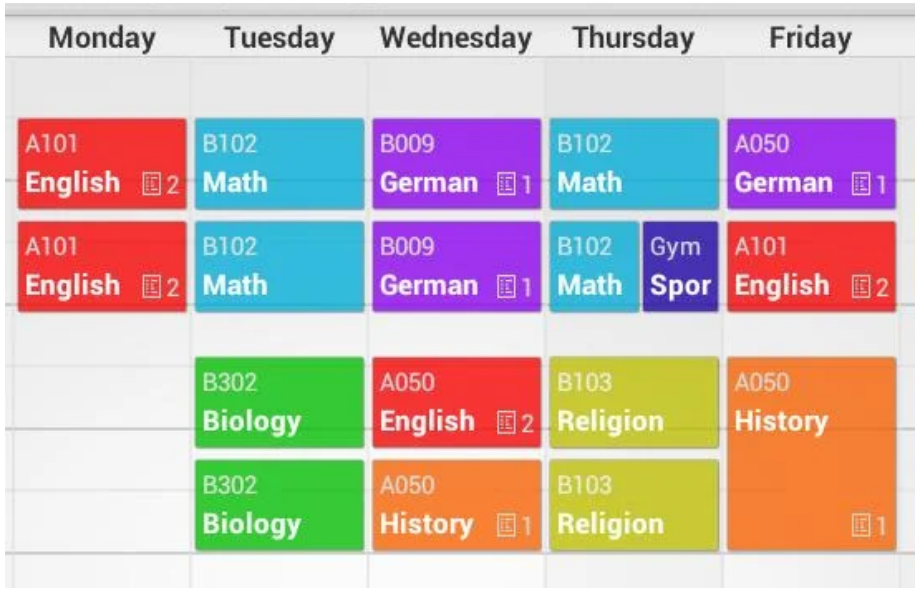
- Initial State
  - There is a worker and a bunch of boxes
- Goal
  - All the boxes must be in goal positions
- Possible Actions
  - moving with the worker
  - pushing a box
- Forbidden
  - to pull boxes
  - move through walls or boxes



`www.sokobanonline.com`

Scheduling Problem - School Timetable

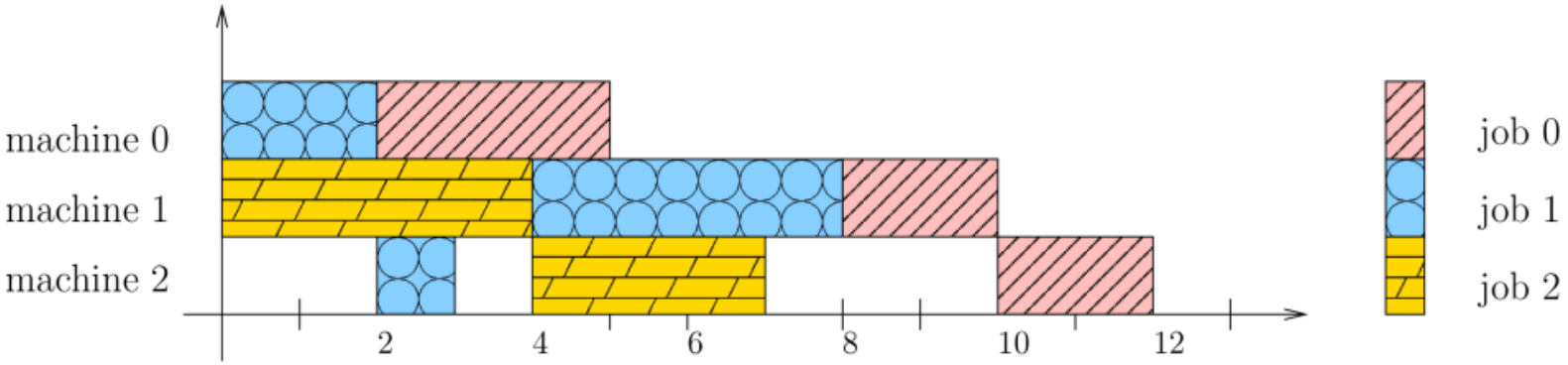
- Actions
  - There is given number of each kind of lesson that needs to take place
- Constraints
  - Teachers can teach certain subjects, only one at a time
  - Students need to take certains subjects
  - It must fit in a week
- Optimization Goals
  - Finish early each day (especially on fridays)
  - No holes in the schedule



Job Shop Scheduling

- Actions
  - A job is a sequence of tasks, each task has a certain duration and must be executed on a specific machine.
- Constraints
  - A machine works on one task at a time uninterrupted
  - The tasks of a job are executed in the correct order without overlap
- Optimization Goal = finish as soon as possible

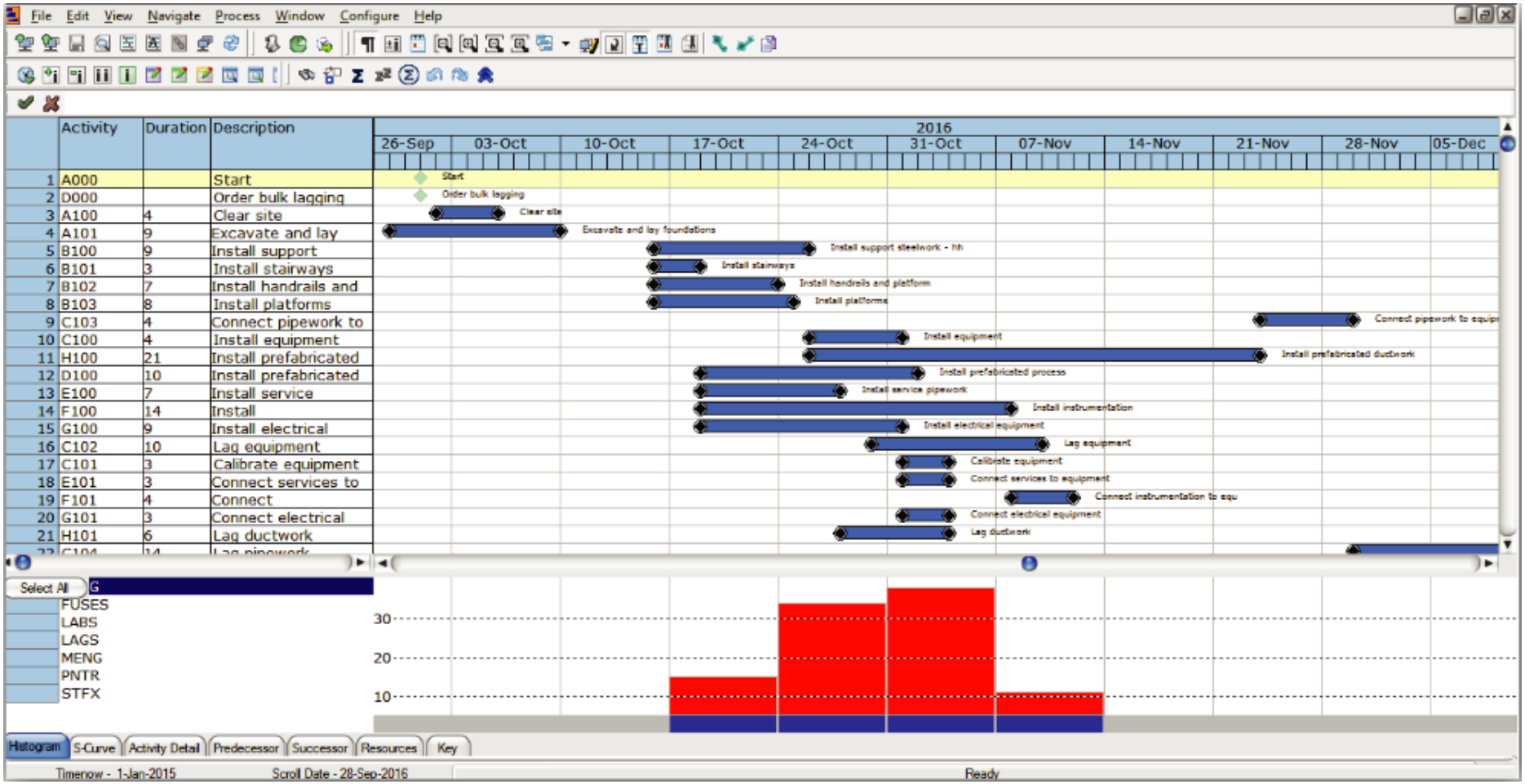
Example: job0 = [(0,3),(1,2),(2,2)], job1=[(0,2),(2,1),(1,4], job2=[(1,4),(2,3)]



Motivation - Aircraft Assembly

- 570 tasks, 17 resources
- A traditonal approach:
  - ARTEMIS
  - 20 hours to produce a schedule
- Intelligent Planning and Scheduling:
  - ARTEMIS substituted by a CSP
  - 30 minutes to generate an optimal schedule
  - 10-15% shorter makespan
- Savings:
  - 4 to 6 days shorter schedules
  - 200 000$ –1 000 000$ per day

Artemis Scheduler



Motivation - Submarine Construction

- 7000 tasks per boat, 125 resource classes
- A traditonal approach:
  - ARTEMIS
  - 6 weeks to produce a schedule (very non uniform)
- Intelligent Planning and Scheduling:
  - ARTEMIS substituted by a CSP
  - 2 days per schedule
  - uniform resource profile
- Savings:
  - 30% less overtime and sub-contracts

Motivation - Gulf War 1991 Logistics

- A traditonal approach:
  - hundreds of human planners
  - months to generate the plans
- Intelligent Planning and Scheduling:
  - O-PLAN2 (a system combining planning and scheduling)
- Savings:
  - faster background creation
  - less flight missions
  - Financial savings that highly exceed all AI research supported by US government since 1956

Motivation - Mars Rovers

- Why automated planning and scheduling?
  - Communication delay 3-22 minutes one way
  - Comm. opportunity via orbiter only once a sol for about 8 minutes
  - Direct comm. to Earth only possible for few hours a day
- CASPER (Continuous Activity Scheduling, Planning, Execution and Re-planning) is the NASA's automated planning and scheduling component of OASIS (Onboard Autonomous Science Investigation System)
- Capabilities:
  - generation of a rover activity plan based on science priorities
  - handling of opportunistic science
  - modifying the rover activity plan in response to problems or other state and resource changes

Restrictive assumptions of Planning

Compared to the “Real World” in Classical Planning

- There are finitely many states and actions
- The world state is fully observable, the agent knows the current state
- Actions are deterministic, they only have one outcome
- The world is static, it only changes by the agents actions
- Goal is defined as a set of states
- Plan is defined as a sequence of actions

Three Kinds of Planners

- Domain–specific
  - A planner designed and developed for a specific planning domain.
  - Won't work well or at all for other planning domains.
  - Examples: Path finding algorithms, sokoban puzzle solver
- **Domain–independent**
  - A planner that works on any planning domain (given the restrictions on the previous slide).
  - Correctness and completeness is guaranteed, but performance may be worse than a domain-spefic planner on its respective domain.
- Configurable
  - Domain independent engine, input includes info about efficient solving.
  - One example of this HTN (Hierarchical Task Network) Planning.

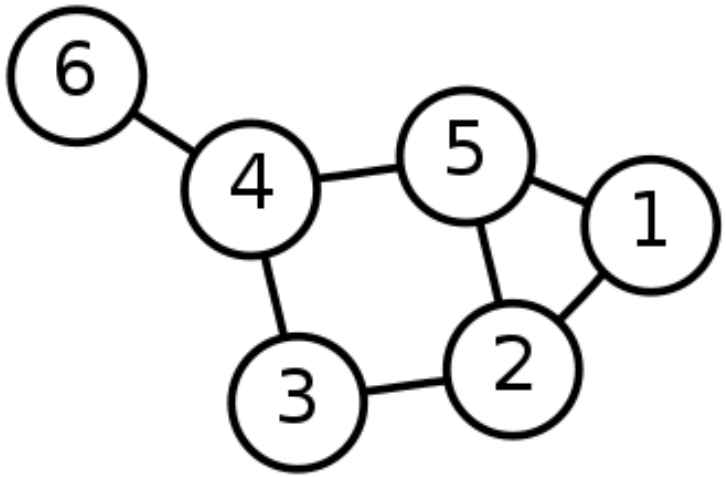
Representation of Planning Problems

A classical planning problem $\pi = (\mathcal{S}, \mathcal{A}, s_I, s_G)$ is a tuple where

- $\mathcal{S}$ represents the final set of world states
- $\mathcal{A}$ represents the final set of actions
- $s_I \in \mathcal{S}$ represents the initial state
- $s_G \subset \mathcal{S}$ represents the set of goal states

A plan $P = [a_1, a_2, ..., a_n]$ is a sequence of actions where $a_i \in \mathcal{A}$ that transforms the world state from s_I to a state $s \in s_G$.

Example: pathfinding in a graph



$\pi = (\mathcal{S}, \mathcal{A}, s_I, s_G)$ Explicit representation:

- $\mathcal{S} = \{at_1, at_2, at_3, at_4, at_5, at_6\}$
- $\mathcal{A} = \{move(at_6, at_4), move(at_4, at_6), move(at_4, at_5), ...\}$
- $s_I = at_1$
- $s_G = \{at_6\}$

Plan $P = [move(at_1, at_5), move(at_5, at_4), move(at_4, at_6)]$

Representation of World States

- In general far too many states to represent explicitly
- We represent states as a set of features
  - a set of propositions that are true (PR – Propositional rep.)
  - vector of values of finite domain variables (FDR – finite dom. rep.)

Example

- PR propositions: `Tr@A, Tr@B, Tr@C, P1@A, P2@A, P1@B, P2@B, P1@C, P2@C, P1-in-Truck, P1-in-Truck`
- FDR variables: `TruckLocation = {A|B|C}, Package1Location = {A|B|C|T}, Package2Location = {A|B|C|T}`

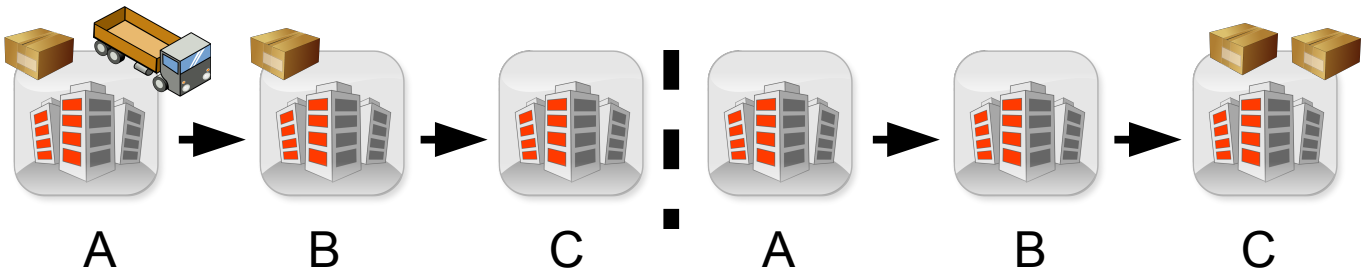
Representation of Initial State

Representing the Initial state is same as any other state

- A full description of a world state
- PR: set of all true propositions
- FDR: each variable has a value assigned from its domain

Example

- PR: `Tr@A, P1@A, P2@B`
- FDR: `TruckLocation = A, Package1Location = A, Package2Location = B`



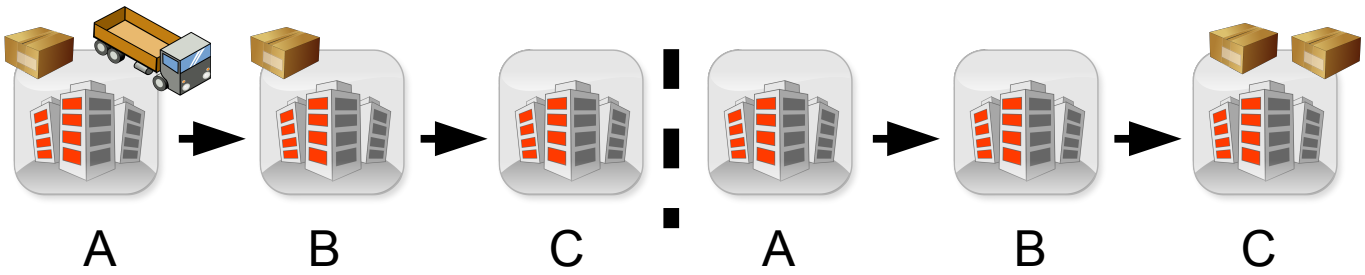
Representation of Goal Conditions

Goal conditions are represented as a partial state

- PR: set of true propositions – same as any state
- FDR: some variables have a value assigned from their domains
- A state s is goal state if $s \subseteq s_G$

Example

- PR: `P1@C, P2@C`
- FDR: `Package1Location = C, Package2Location = C`



Representation of an Action

An action $A = (pre, eff)$ is 2-tuple where

- *pre* represents the **preconditions** of the action, i.e., the conditions that must hold before the action is executed.
- *eff* represents the **effects** of the action, i.e., the conditions that must hold after the action is executed.
- PR: both *pre* and *eff* are sets of propositions
- FDR: both *pre* and *eff* are partial assignments to the FD variables

Example: action load package 1 in the truck at location A

- PR: $\texttt{Load1A} = (\{\texttt{Tr@A}, \texttt{P1@A}\}, \{\texttt{P1-in-Truck}, \neg\texttt{P1@A}\})$
- FDR: $\texttt{Load1A} = (\{\texttt{TruckLocation} = \texttt{A}, \texttt{Package1Location} = \texttt{A}\}, \{\texttt{Package1Location} = \texttt{T}\})$

Valid Plan

Let $\pi = (\mathcal{S}, \mathcal{A}, s_I, s_G)$ be a planning problem
A plan $P = [a_1, a_2, ..., a_n]$ is a valid plan for π if

- $\forall i : a_i \in \mathcal{A}$
- let $s_1 = s_i$ and $s_{i+1} = \mathit{apply}(s_i, a_i)$
- $\forall i : a_i$ is applicable in s_i, i.e., $\mathit{pre}(a_i) \subseteq s_i$
- $s_G \subseteq s_n$

where $s' = \mathit{apply}(s, a)$ is the world state after applying action a in state s.
The state s' is identical to s except for changes implied by the effects of a.

Representation of all possible Actions

- List all the actions – Explicit Representation
  - Can be a huge amount, but most of the time it's fine
  - Requires some script to generate the list, cannot be done by hand
  - Usually used with FDR
- Operators – Action Templates – Implicit Representation
  - Using objects, types and predicates define Action Templates

Example: operator for loading a package at some location

Types: `location, package`

Objects: `P1, P2 - package, A,B,C - location`

Predicates: `at(P - package, L - location),`
`TruckAt(L - location), InTruck(P - package)`

Operator:

`loadPackage(P - package, L - location) = ({at(P,L),`
`TruckAt(L)}, {¬at(P,L), InTruck(P)})`

Actions from Operators

Types: `location, package`
Objects: `P1, P2 - package, A,B,C - location`
Predicates: `PackageAt(P - package, L - location), TruckAt(L - location), InTruck(P - package)`
Operator:
`loadPackage(P - package, L - location) = ({PackageAt(P,L), TruckAt(L)}, {¬PackageAt(P,L), InTruck(P)})`

- The operator and objects generate these actions:

`loadPackage(P1,A), loadPackage(P1,B), loadPackage(P1,C), loadPackage(P2,A), loadPackage(P2,B), loadPackage(P2,C),`

PDDL – Planning Domain Description Language – domain file

```
(define (domain trucking)
  (:requirements :strips :typing)
  (:types
        location - object
        package - object
  )
  (:constants )

  (:predicates
     (road ?l1 - location ?l2 - location)
     (truck-at ?l - location)
     (package-at ?p - package ?l - location)
     (in-truck ?p - package)
  )
```

PDDL – Planning Domain Description Language – domain file 2

```
(:action loadPackage
  :parameters (?l - location ?p - package)
  :precondition (and
      (package-at ?p ?l)
      (truck-at ?l)
  )
  :effect(and
      (not (package-at ?p ?l))
      (in-truck ?p)
  )
)
```

PDDL – Planning Domain Description Language – domain file 3

```
(:action unloadPackage
  :parameters (?l - location ?p - package)
  :precondition (and
      (in-truck ?p)
      (truck-at ?l)
  )
  :effect(and
      (not (in-truck ?p))
      (package-at ?p ?l)
  )
)
```

PDDL – Planning Domain Description Language – domain file 4

```
  (:action drive
    :parameters (?l1 ?l2 - location)
    :precondition (and
        (road ?l1 ?l2)
        (truck-at ?l1)
    )
    :effect(and
        (not (truck-at ?l1))
        (truck-at ?l2)
    )
  )
)
```

PDDL – Planning Domain Description Language – problem file

```
(define (problem trucking-3-cities-2-packages)
 (:domain trucking)
 (:requirements :strips :typing)
 (:objects
  l1 l2 l3 - location
  p1 p2 - package
 )
```

PDDL – Planning Domain Description Language – problem file 2

```
 (:init
    (road l1 l2)
    (road l2 l3)
    (truck-at l1)
    (package-at p1 l1)
    (package-at p2 l2)
 )
 (:goal (and
    (package-at p1 l3)
    (package-at p2 l3)
 ))
)
```

The End

Next Week: Complexity of Planning