

COMP219: Artificial Intelligence

Lecture 24: Scheduling in Real World Planning

Real World Planning



- Classical planning decides **what to do** and **in what order**
- Planners used in the real world for planning and scheduling operations for spacecraft, factories and military campaigns need to talk about **time (scheduling)**:
 - **how long** an action takes
 - **when** an action occurs
 - e.g. an airline schedule assigning planes to flights needs to know departure and arrival times
- The real world also imposes many **resource constraints**
 - e.g. there is a limit on the number of pilots employed, and a pilot can only fly one plane at any one time

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Overview

- Last time
 - Classical planning; PDDL; planning as a SAT problem
- Today
 - Planning in the real world
 - Time and resource constraints
- Learning outcomes covered today:

Identify or describe approaches used to solve planning problems in AI and apply these to simple examples

Time



- In classical planning we assumed that:
 - actions are instantaneous
 - preconditions must hold before an action is taken
 - the effects of an action persist
- Real world planning domains are more complex:
 - actions take time to execute; how long an action takes to execute may depend on the preconditions
 - preconditions may need to hold during an action's execution as well as before it starts
 - effects may not be true immediately or may persist for only a limited time
 - an action may have multiple effects on a fluent at different times
- In scheduling we usually require a goal to be true **at a given time** or **over a given time interval**

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Planning with Time

- Examples:
 - If I hire a carpet cleaning machine to clean my carpets, I need to **continue to have the machine** while I am cleaning my carpets
 - If I push a lift button, the lift may take **time to arrive** and the doors will only open for **a limited time**
 - If I share a printer, my print job will have to **wait until the printer is available** if someone else is currently printing
- Some actions may have to be taken concurrently:
 - If a fuse blows, I have to strike a match and walk to the fusebox **while the match is burning**

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Resources

- A resource is a set of objects whose value or availability determines whether an action can be taken
 - e.g. money, drivers, trucks, surgeons, power
 - **time** is a resource which PDDL treats as a special case
- Resources can be **consumable** (e.g. fuel) or **reusable** (e.g. a plane)
- Resources can be produced by actions (e.g. hire a car, refuel a plane, grow a potato)



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Planning with Resources

- A **solution** is a plan that achieves the **goals** while **allocating resources** to actions such that all **resource constraints** are satisfied
- A **satisficing plan** achieves the goals without violating any temporal and resource constraints
 - e.g. deliver all packages by 09.00
- An **optimal plan** achieves the goals while minimising (or maximising) a cost function, often defined in terms of resource usage
 - e.g. deliver all packages by 09.00, minimising the number of planes and fuel required

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Scheduling Approach

- One approach to scheduling is to **plan first and schedule later**
- Divide the overall problem into
 - **Planning phase**: select actions (with some ordering constraints) to meet the goals: partially ordered plan
 - **Scheduling phase**: add temporal information to ensure it meets resource and deadline constraints
- This approach is common in real-world manufacturing and logistical domains, where the planning phase is often done by human experts



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Example: Assembly of Cars



```
Jobs({AddEngine1 < AddWheels1 < Inspect1 },
      {AddEngine2 < AddWheels2 < Inspect2 })
Resources(EngineHoists(1), WheelStations(1), Inspectors(2),
          LugNuts(500))
Action(AddEngine1, DURATION: 30, USE: EngineHoists(1))
Action(AddEngine2, DURATION: 60, USE: EngineHoists(1))
Action(AddWheels1, DURATION: 30, CONSUME: LugNuts(30),
       USE: WheelStations(1))
Action(AddWheels2, DURATION: 15, CONSUME: LugNuts(20),
       USE: WheelStations(1))
Action(Inspecti, DURATION: 10, USE: Inspectors(1))
```

- Each job has a set of actions with **ordering constraints**
- A < B means that action A must precede action B
- Each action has a duration and a set of **resource constraints**
- Each constraint specifies **type, number** and **consumable/reusable**

Example from Chapter 11 of AIAMA

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Aggregation

- If all objects are indistinguishable w.r.t. the purpose of the plan, complexity can be reduced by grouping individual objects into quantities – called **aggregation**
 - e.g. *Inspectors(2)* instead of *Inspector(Bob), Inspector(Jane)* because it does not matter *which* inspector inspects the car in our problem, so we don't need to make the distinction
- Consider a schedule proposing 10 concurrent inspections when there are only 9 available inspectors:
 - Inspectors represented as quantities – failure detected immediately, backtrack and try another schedule
 - Inspectors as individuals – algorithm backtracks to try all 10! ways of assigning inspectors to actions

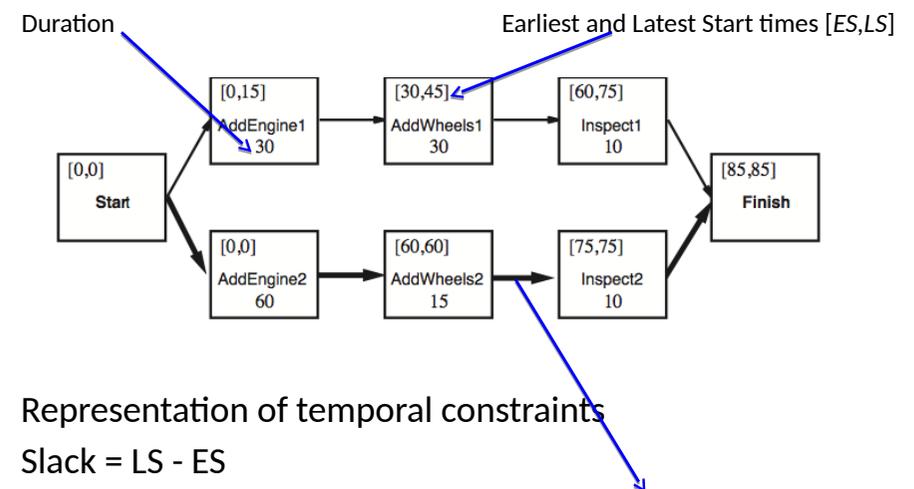
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Time Constraints: Critical Path Method

- To minimise the plan duration, must find the **earliest start times** for all actions consistent with the ordering constraints
- **Critical path method** can find the possible start and end times for each action
- A path is a linearly ordered sequence of actions beginning with *Start* and ending with *Finish*
- The **critical path**: path with the longest total duration; 'critical' because it determines the duration of the entire plan:
 - Shortening other paths does not shorten the whole plan, **BUT** delaying the start of *any action* on the critical path slows down the entire plan
- Actions not on the critical path have a window of time in which they can be executed: **LS - ES** is known as the **slack** for the action (ES earliest possible start time, LS latest possible start time)
- A **schedule** is the ES and LS times for all the actions

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Example: Assembly of Cars



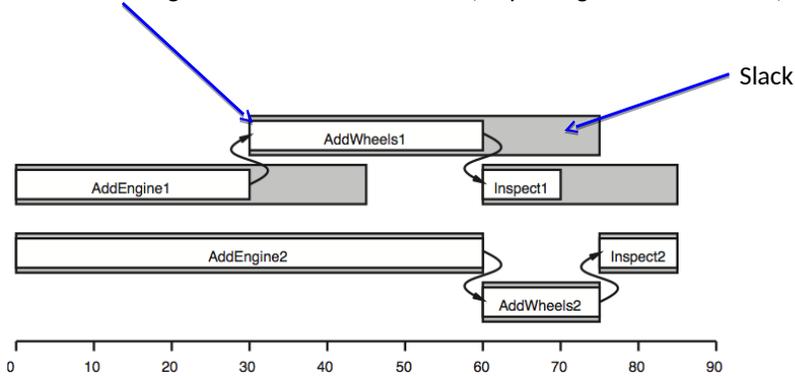
- Representation of temporal constraints
- Slack = LS - ES
- Actions with zero slack are on critical path

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Example: Assembly of Cars



Time interval during which action can be taken (respecting order constraints)



- Solution as a timeline

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Resource Constraints

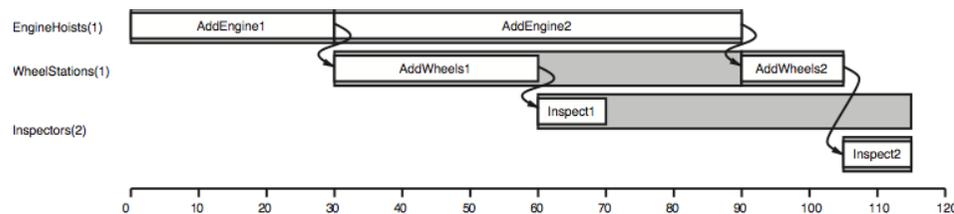
- Finding a minimum-duration schedule given a partial ordering on actions and no resource constraints is easy:
 - Any action can be executed in parallel with any other unless this is prohibited by the partial order specified in the plan
- Resource constraints impose additional restrictions on the ordering of actions – actions which require the same resources can't be executed at the same time
 - e.g. two *AddEngine* actions begin at the same time but both require the same *EngineHoist* and so a constraint "cannot overlap" must be added
- Scheduling with resource constraints is complex

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Example: Assembly of Cars with Resource Constraints



Exercise



- Solution incorporates "cannot overlap" constraint
- Fastest solution takes 115 mins (30 mins longer)
- No time when both inspectors needed, so only need one for this solution

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Reducing Complexity

- Complexity of scheduling with resource constraints is often seen in practice
 - e.g. challenge posed in 1963 to find the optimal schedule for a problem involving 10 machines and 10 jobs of 100 actions went unsolved for 23 years (Lawler *et al.* 1993)
- **Minimum slack algorithm** heuristic

```
REPEAT
IF (unscheduled(A) AND all_predec_scheduled(A)
AND least_slack(A))
THEN schedule A for earliest possible start;
UPDATE ES and LS for all affected actions;
UNTIL solution produced
```

 - But for car assembly problem, solution longer (130 mins)
- Integrating planning and scheduling is active area of research

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Managing Complexity: Hierarchical Decomposition

- State-of-the art planning algorithms can generate plans with thousands of actions
- However some planning tasks involve millions of actions, e.g.
 - Planning military operations
 - Plans executed by the human brain: to move about, if this is planned at the level of muscle activations (about 10^3 muscles, activation can be modulated 10 times per second, so planning for just one hour may involve more than 3 million actions)
- Solution: plan at a **higher level of abstraction**, e.g. instead of muscle activations, just an action 'walk to the shop', then **refine** if necessary

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Example: Holiday

- A reasonable plan might be
[Go to Manchester Airport; Take Emirates Air flight 778 to Dubai; Do holiday stuff for 2 weeks; Go to Dubai Airport; Take Emirates Air flight 779 to Manchester; Go home]
- Each action in the plan is a planning task in itself
 - e.g. 'Go to Manchester Airport' may have a solution [Drive to the airport car-park; park; take the shuttle bus to the terminal]
- Each of these actions may then be *decomposed* further until we reach the right level of actions
- **Hierarchical decomposition**
 - call discussion about 'right' level of abstraction w.r.t. search



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Hierarchical Decomposition

- **Software:** Hierarchy of subroutines or object classes
- **Armies:** hierarchy of units
- **Government and corporations:** hierarchy of departments, subsidiaries, branch offices
- **Key benefit:** at each level of the hierarchy a computational task, military mission or administrative function is reduced to a smaller number of activities at the next lower level
 - Computational cost of solving a planning problem is small

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Hierarchical Task Networks

- HTN similar to classical planning:
 - States are sets of fluents (ground atomic formulae)
 - Actions correspond to deterministic state transitions
- Planning domain description extended: methods for decomposing tasks into subtasks
- **Primitive actions**: set of possible actions
- **High-level actions**: higher level abstraction of actions

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High-Level Actions

- Each HLA has one or more possible **refinements** into a sequence of actions
- Each refinement may include HLAs or primitive actions
- Primitive actions by definition have no refinements
- Refinements may be recursive
- An HLA refinement that contains only primitive actions is called an **implementation** of the HLA

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Example Refinement: Holiday

- The action 'Go to Manchester Airport' represented as $Go(Home, MAN)$ might have two possible refinements:

$Refinement(Go(Home, MAN),$
 $STEPS: [Drive(Home, MANLongStayParking),$
 $Shuttle(MANLongStayParking, MAN)])$

$Refinement(Go(Home, MAN),$
 $STEPS: [Taxi(Home, MAN)])$



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Example Refinement: Vacuum World

$Refinement(Navigate([a, b], [x, y]),$
 $PRECOND: a=x \wedge b=y$
 $STEPS: [])$

$Refinement(Navigate([a, b], [x, y]),$
 $PRECOND: Connected([a, b], [a - 1, b]),$
 $STEPS: [Left, Navigate([a - 1, b], [x, y])]$

$Refinement(Navigate([a, b], [x, y]),$
 $PRECOND: Connected([a, b], [a + 1, b]),$
 $STEPS: [Right, Navigate([a + 1, b], [x, y])]$

- **Recursive** refinement: to get to a destination, take a step, and then go to the destination
- $[Right, Right, Down]$ and $[Down, Right, Right]$ are both implementations of the HLA $Navigate([1, 3], [3, 2])$



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High-Level Plan

- A high-level plan is a sequence of HLAs
- An implementation of a high-level plan is the concatenation of implementations of each HLA in the sequence
- A high-level plan achieves the goal from a given state if *at least one* of its implementations achieves the goal from that state
 - Not all implementations need to achieve the goal
- If a HLA has exactly one implementation, can compute preconditions and effects as if it were a primitive action

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Summary

- Planning in the real world
 - Time constraints, critical path method, minimum slack
 - Resource constraints, abstraction, Hierarchical Task Networks
- This concludes our consideration of the topic Planning
- *Next time*
 - Machine learning

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