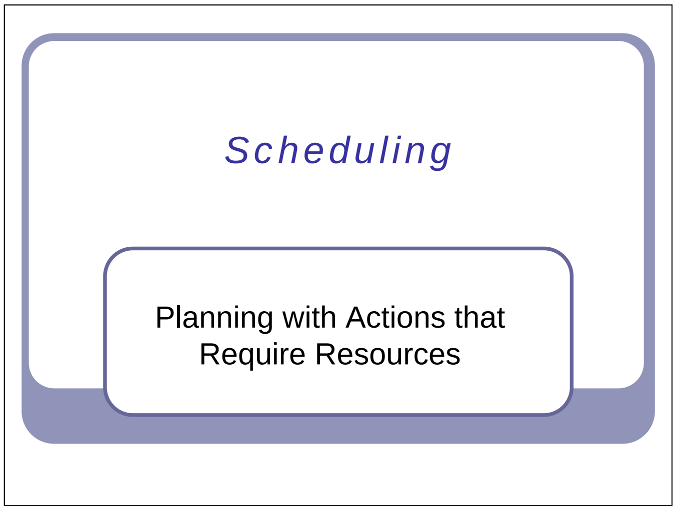
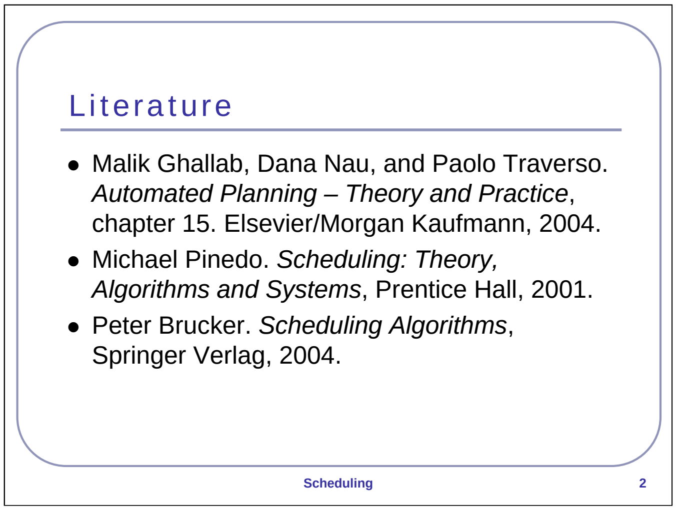


Scheduling

•Planning with Actions that Require Resources

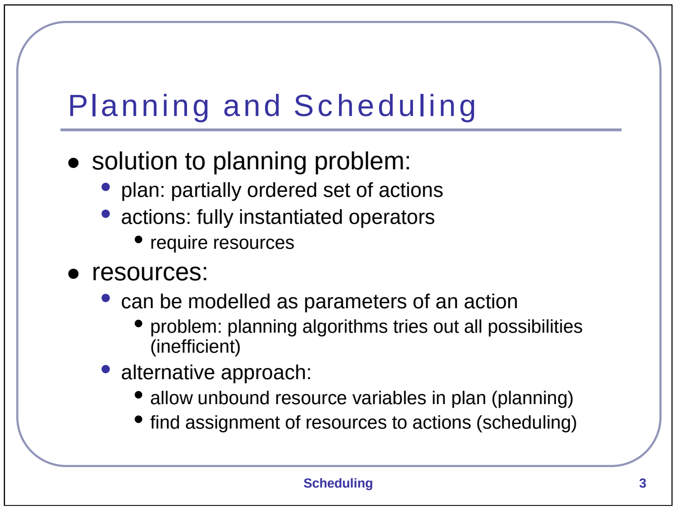


Literature

•Malik Ghallab, Dana Nau, and Paolo Traverso. *Automated Planning – Theory and Practice*, chapter 15. Elsevier/Morgan Kaufmann, 2004.

•Michael Pinedo. *Scheduling: Theory, Algorithms and Systems*, Prentice Hall, 2001.

•Peter Brucker. *Scheduling Algorithms*, Springer Verlag, 2004.



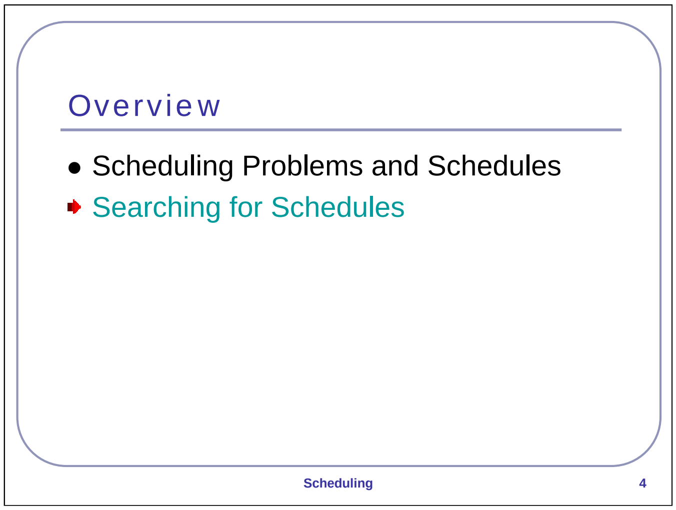
Planning and Scheduling

•solution to planning problem:

- **•plan: partially ordered set of actions**
- **•actions: fully instantiated operators**
  - **•require resources**

•resources:

- **•can be modelled as parameters of an action**
  - **•problem: planning algorithms tries out all possibilities (inefficient)**
- **•alternative approach:**
  - **•allow unbound resource variables in plan (planning)**
    - •planning focuses on causal reasoning (what to do)
  - **•find assignment of resources to actions (scheduling)**
    - •scheduling: resource and time allocation (how and when to do it)
  - •planning before scheduling (not optimal approach)

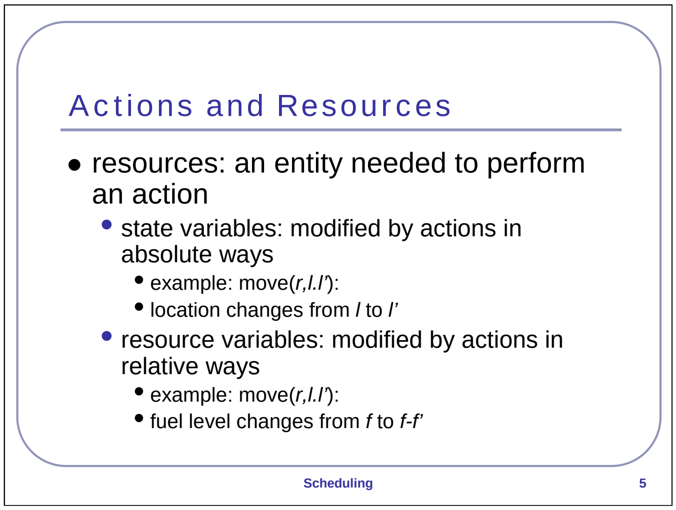


Overview

•Scheduling Problems and Schedules

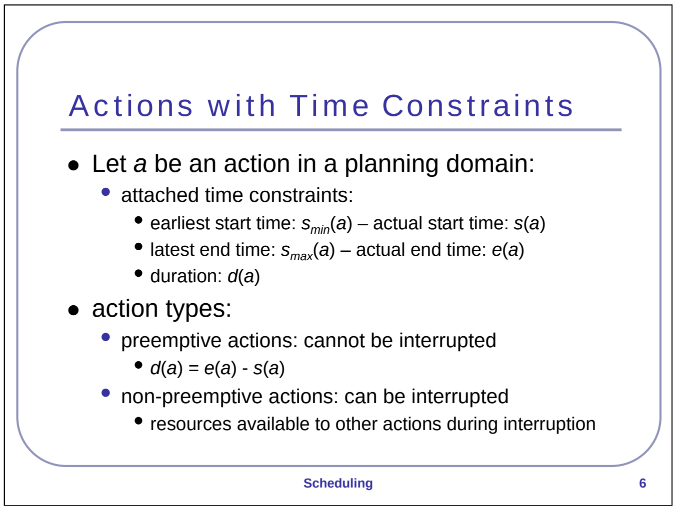
•now: an overview of different types of scheduling problems

Searching for Schedules



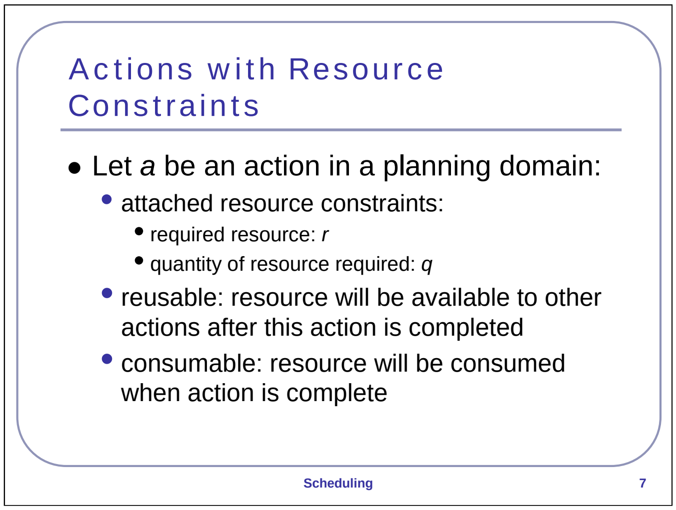
Actions and Resources

- **resources: an entity needed to perform an action**
  - **state variables: modified by actions in absolute ways**
    - **example: move(*r,l.l'*):**
    - **location changes from *l* to *l'***
  - **resource variables: modified by actions in relative ways**
    - **example: move(*r,l.l'*):**
    - **fuel level changes from *f* to *f-f'***



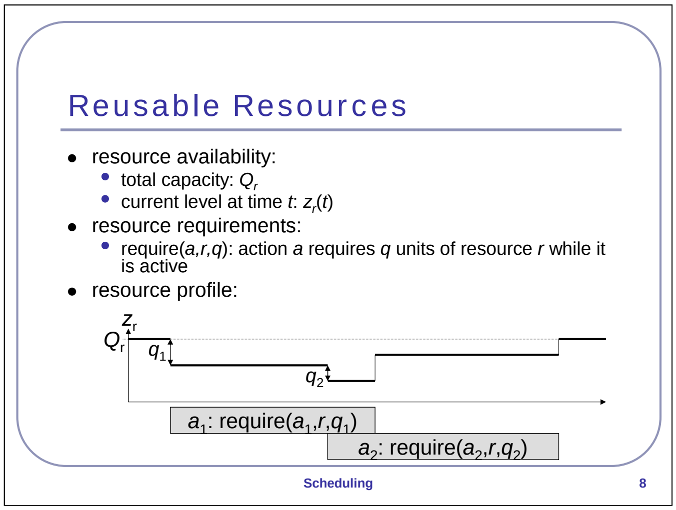
Actions with Time Constraints

- **Let *a* be an action in a planning domain:**
  - **attached time constraints:**
    - **earliest start time: $s_{min}(a)$ – actual start time: $s(a)$**
    - **latest end time: $s_{max}(a)$ – actual end time: $e(a)$**
    - **duration: $d(a)$**
- **action types:**
  - **preemptive actions: cannot be interrupted**
    - $d(a) = e(a) - s(a)$
  - **non-preemptive actions: can be interrupted**
    - **resources available to other actions during interruption**
    - cost: interruption usually has cost associated
- further constraints: examples:
  - action must be performed at night
  - interruptions must be at least 30 minutes long



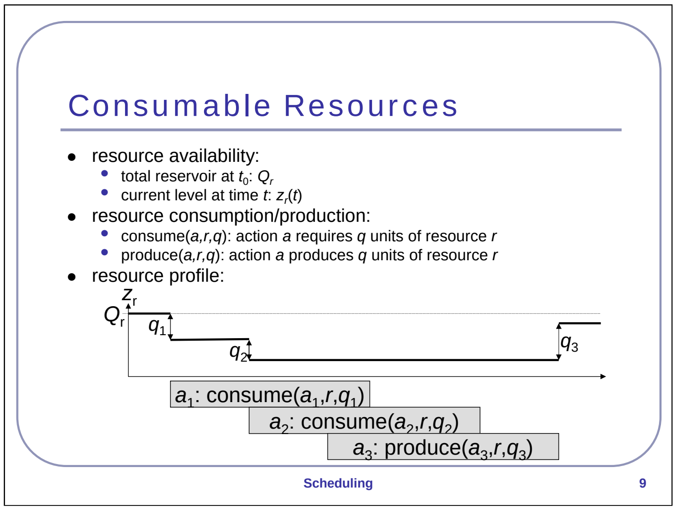
Actions with Resource Constraints

- **Let *a* be an action in a planning domain:**
  - **attached resource constraints:**
    - **required resource: *r***
    - **quantity of resource required: *q***
  - **reusable: resource will be available to other actions after this action is completed**
    - tools, machines, HD space, helicopters, docks
  - **consumable: resource will be consumed when action is complete**
    - petrol, electricity, CPU time, credit
      - time is usually treated differently, as a special case



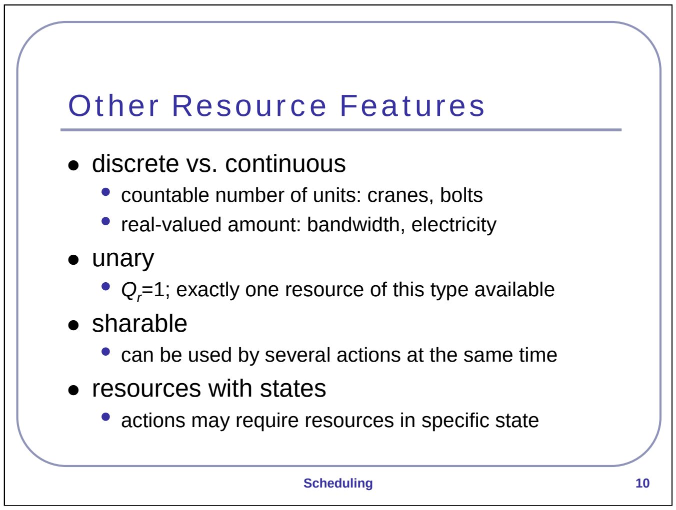
Reusable Resources

- **resource availability:**
  - **total capacity: Q_r**
  - **current level at time t: $z_r(t)$**
- **resource requirements:**
  - **require(a,r,q): action a requires q units of resource r while it is active**
- **resource profile:**
  - **[figure]**
  - actions are overlapping (temporally)
  - profile shows availability of resource to other actions
    - returns to full capacity when all actions are completed



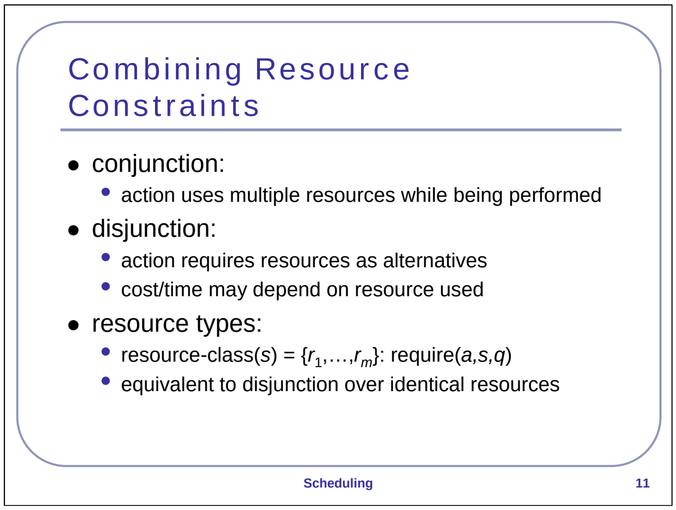
Consumable Resources

- **resource availability:**
  - **total reservoir at t_0: Q_r**
  - **current level at time t: $z_r(t)$**
- **resource consumption/production:**
  - **consume(*a*,*r*,*q*): action *a* requires *q* units of resource *r***
  - **produce(*a*,*r*,*q*): action *a* produces *q* units of resource *r***
- **resource profile:**
  - **[figure]**
  - actions are overlapping (temporally)
  - profile shows availability of resource to other actions
    - availability at end usually different from beginning
  - resource profile as step function: usually not accurate



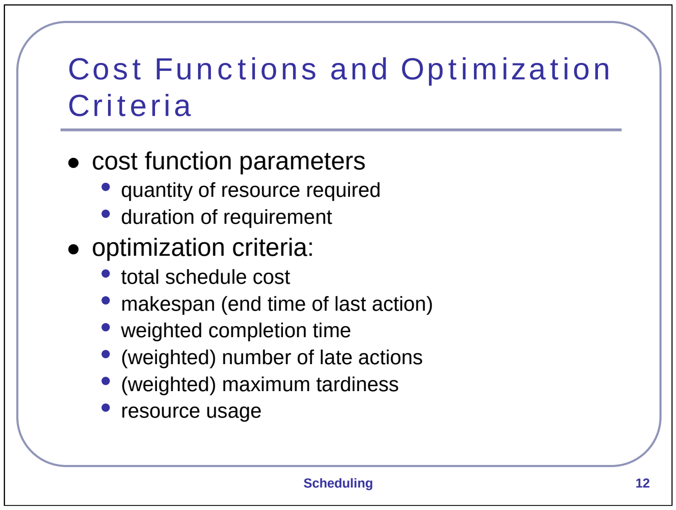
Other Resource Features

- **discrete vs. continuous**
  - **countable number of units: cranes, bolts**
  - **real-valued amount: bandwidth, electricity**
- **unary**
  - **Q_r=1; exactly one resource of this type available**
- **sharable**
  - **can be used by several actions at the same time**
- **resources with states**
  - **actions may require resources in specific state**
    - example: freezer with temperature setting



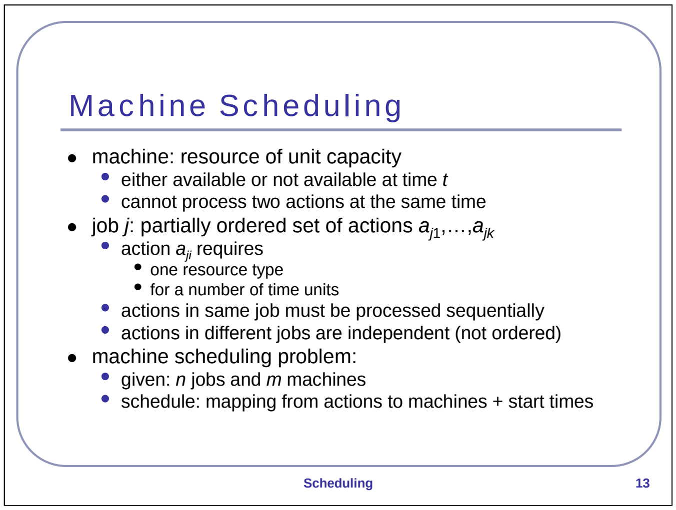
Combining Resource Constraints

- **conjunction:**
  - **action uses multiple resources while being performed**
- **disjunction:**
  - **action requires resources as alternatives**
  - **cost/time may depend on resource used**
- **resource types:**
  - **resource-class(*s*) = {r_1,…,r_m}: require(*a*,*s*,*q*)**
  - **equivalent to disjunction over identical resources**



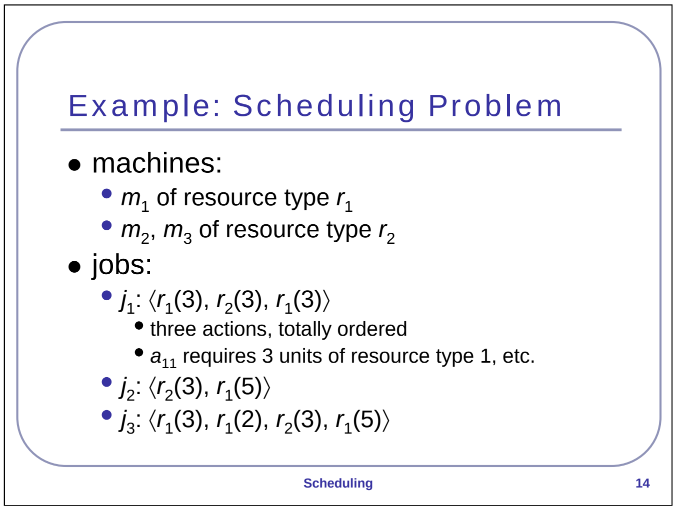
Cost Functions and Optimization Criteria

- **cost function parameters**
    - **quantity of resource required**
    - **duration of requirement**
- **optimization criteria:**
    - **total schedule cost**
    - **makespan (end time of last action)**
    - **weighted completion time**
    - **(weighted) number of late actions**
    - **(weighted) maximum tardiness**
    - **resource usage**



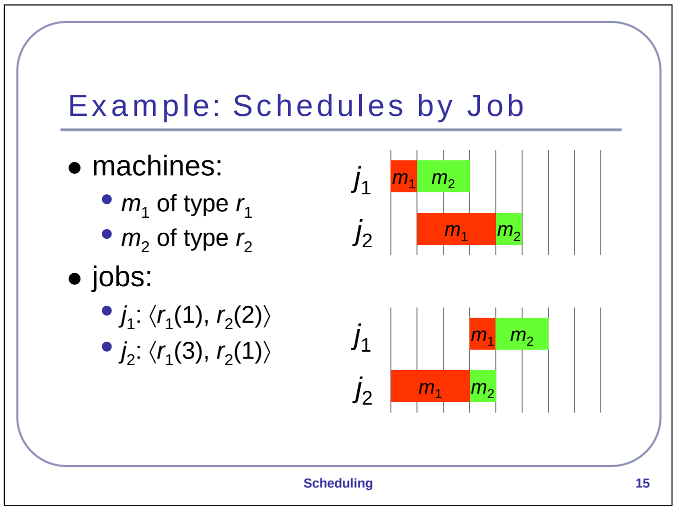
Machine Scheduling

- class of problems
- **machine: resource of unit capacity**
  - **either available or not available at time *t***
  - **cannot process two actions at the same time**
- **job *j*: partially ordered set of actions $a_{j1},\ldots,a_{jk}$**
  - in general, jobs can have different numbers of activities
  - **action a_{ji} requires**
    - **one resource type**
    - **for a number of time units**
  - **actions in same job must be processed sequentially**
    - even if they are only partially ordered: object that is being worked on
  - **actions in different jobs are independent (not ordered)**
- **machine scheduling problem:**
  - **given: *n* jobs and *m* machines**
  - **schedule: mapping from actions to machines + start times**



Example: Scheduling Problem

- **machines:**
  - **m_1 of resource type r_1**
  - **m_2, m_3 of resource type r_2**
- **jobs:**
  - **j_1: $\langle r_1(3), r_2(3), r_1(3)\rangle$**
    - **three actions, totally ordered**
    - **a_{11} requires 3 units of resource type 1, etc.**
  - **j_2: $\langle r_2(3), r_1(5)\rangle$**
  - **j_3: $\langle r_1(3), r_1(2), r_2(3), r_1(5)\rangle$**



Example: Schedules by Job

•machines:

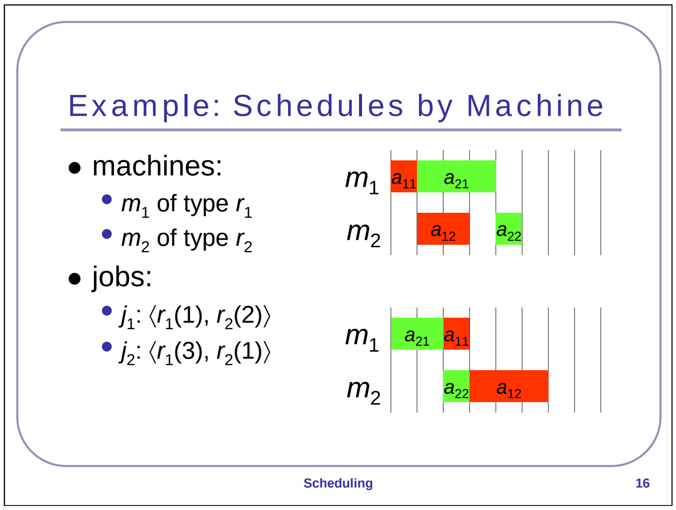
- **•m_1 of type r_1**
- **•m_2 of type r_2**

•jobs:

- **•j_1: $\langle r_1(1), r_2(2)\rangle$**
- **•j_2: $\langle r_1(3), r_2(1)\rangle$**

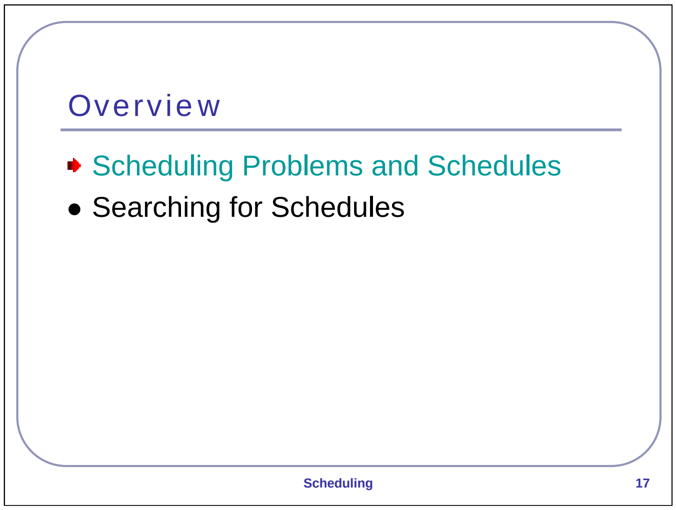
•[figures]

- •schedules showing machines assigned to actions in jobs



Example: Schedules by Machine

- **machines:**
    - m_1 **of type** r_1
    - m_2 **of type** r_2
- **jobs:**
    - j_1: $\langle r_1(1), r_2(2)\rangle$
    - j_2: $\langle r_1(3), r_2(1)\rangle$
- [figures]
    - schedules showing actions assigned to machines



Overview

- **Scheduling Problems and Schedules**
  - just done: an overview of different types of scheduling problems
- **Searching for Schedules**
  - now: search algorithms that generate schedules

Assignable Actions

- Let *P* be a machine scheduling problem. Let *S* be a partially defined schedule.
- An action a_{ji} of some job j_l in *P* is unassigned if it does not appear in *S*.
- An action a_{ji} of some job j_l in *P* is assignable if it has no unassigned predecessors in *S*.

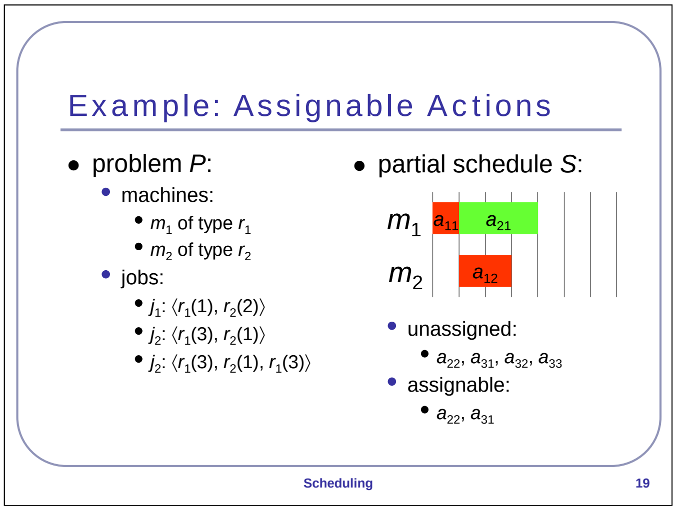
Assignable Actions

•Let *P* be a machine scheduling problem. Let *S* be a partially defined schedule.

•An action a_{ji} of some job j_l in *P* is unassigned if it does not appear in *S*.

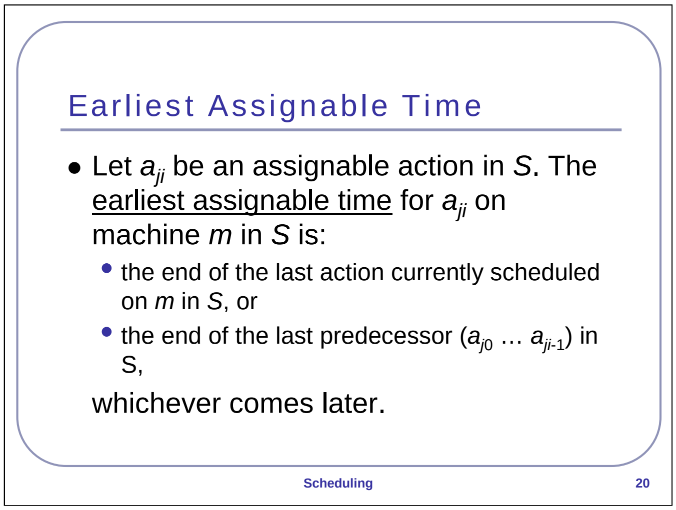
•An action a_{ji} of some job j_l in *P* is assignable if it has no unassigned predecessors in *S*.

- all predecessors in schedule; action is ready to be executed



Example: Assignable Actions

- **problem *P*:**
  - **machines:**
    - m_1 **of type** r_1
    - m_2 **of type** r_2
  - **jobs:**
    - j_1: $\langle r_1(1), r_2(2)\rangle$
    - j_2: $\langle r_1(3), r_2(1)\rangle$
    - j_2: $\langle r_1(3), r_2(1), r_1(3)\rangle$
- [figure]
  - **unassigned:**
    - $a_{22}, a_{31}, a_{32}, a_{33}$
  - **assignable:**
    - a_{22}, a_{31}



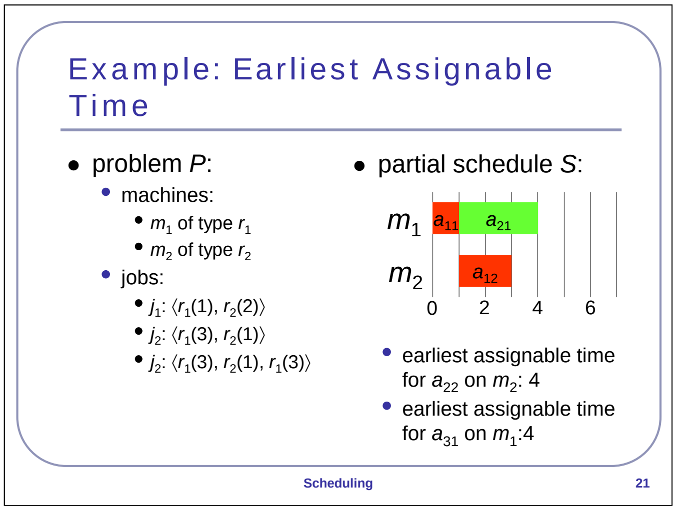
Earliest Assignable Time

•Let a_{ji} be an assignable action in *S*. The <u>earliest assignable time</u> for a_{ji} on machine *m* in *S* is:

- **•the end of the last action currently scheduled on *m* in *S*, or**
- **•the end of the last predecessor (a_{j0} … a_{ji-1}) in S,**

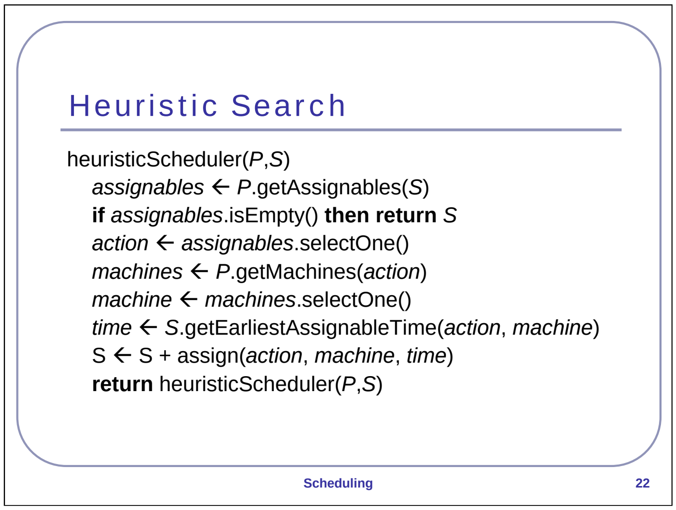
•whichever comes later.

•note: assignment not necessarily optimal!

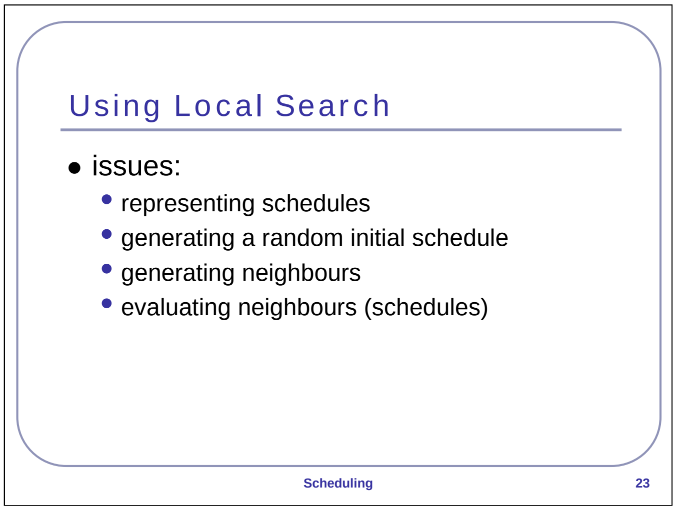


Example: Earliest Assignable Time

- **problem *P*:**
  - **machines:**
    - **m_1 of type r_1**
    - **m_2 of type r_2**
  - **jobs:**
    - **j_1: $\langle r_1(1), r_2(2)\rangle$**
    - **j_2: $\langle r_1(3), r_2(1)\rangle$**
    - **j_2: $\langle r_1(3), r_2(1), r_1(3)\rangle$**
- [figure]
  - **earliest assignable time for a_{22} on m_2: 4**
  - **earliest assignable time for a_{31} on m_1:4**

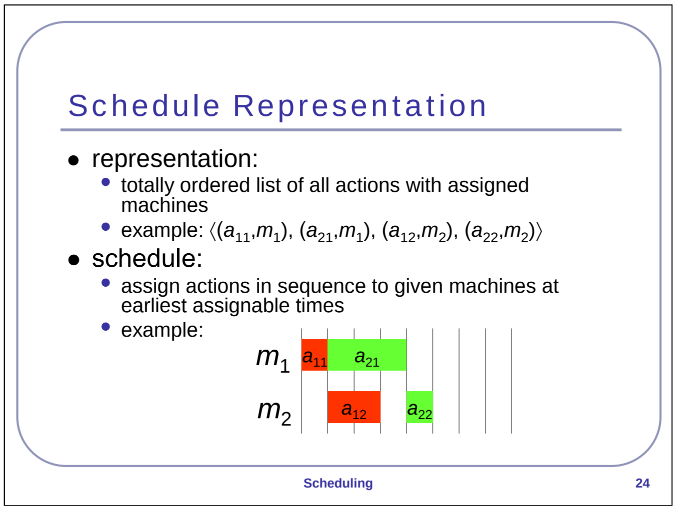


- **Heuristic Search**
- **heuristicScheduler(*P*,*S*)**
- ***assignables* ← *P*.getAssignables(*S*)**
- **if *assignables*.isEmpty() then return *S***
- ***action* ← *assignables*.selectOne()**
- ***machines* ← *P*.getMachines(*action*)**
- ***machine* ← *machines*.selectOne()**
- ***time* ← *S*.getEarliestAssignableTime(*action*, *machine*)**
- **S ← S + assign(*action*, *machine*, *time*)**
- **return heuristicScheduler(*P*,*S*)**



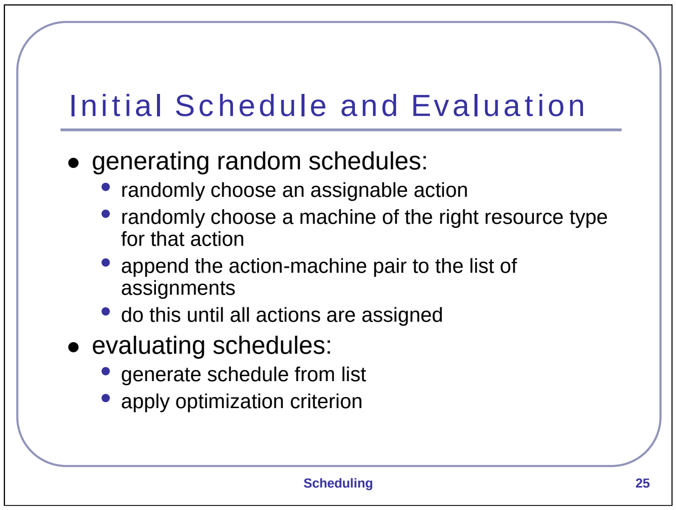
Using Local Search

- **issues:**
    - **representing schedules**
    - **generating a random initial schedule**
    - **generating neighbours**
    - **evaluating neighbours (schedules)**



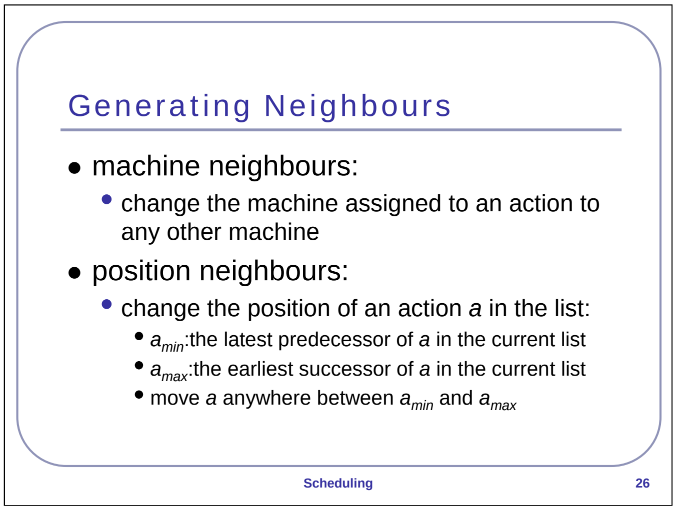
Schedule Representation

- **representation:**
  - **totally ordered list of all actions with assigned machines**
  - **example: ⟨(a_{11},m_1), (a_{21},m_1), (a_{12},m_2), (a_{22},m_2)⟩**
- schedule:
  - **assign actions in sequence to given machines at earliest assignable times**
  - **example:**
    - **[figure]**



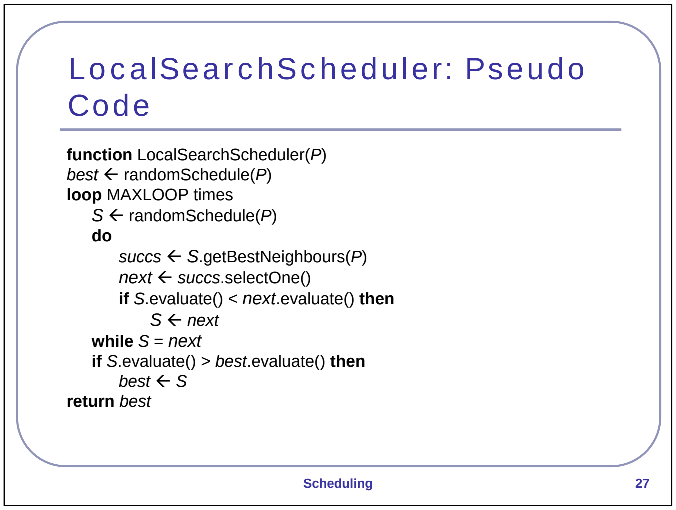
Initial Schedule and Evaluation

- **generating random schedules:**
  - **randomly choose an assignable action**
  - **randomly choose a machine of the right resource type for that action**
  - **append the action-machine pair to the list of assignments**
  - **do this until all actions are assigned**
- **evaluating schedules:**
  - **generate schedule from list**
  - **apply optimization criterion**

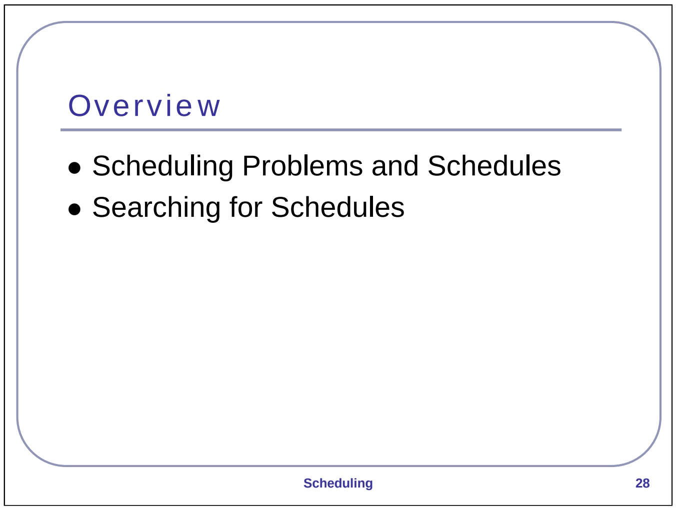


Generating Neighbours

- **machine neighbours:**
  - **change the machine assigned to an action to any other machine**
- **position neighbours:**
  - **change the position of an action *a* in the list:**
    - **a_{min}:the latest predecessor of *a* in the current list**
    - **a_{max}:the earliest successor of *a* in the current list**
    - **move *a* anywhere between a_{min} and a_{max}**



- LocalSearchScheduler: Pseudo Code
- **function LocalSearchScheduler(*P*)**
- ***best* ← randomSchedule(*P*)**
  - will contain best schedule found
- **loop MAXLOOP times**
- ***S* ← randomSchedule(*P*)**
  - best schedule for local search
- **do**
- ***succs* ← *S*.getBestNeighbours(*P*)**
  - returns set of neighbours with highest value for evaluation function
- ***next* ← *succs*.selectOne()**
  - randomly select a (best) neighbour
- **if *S*.evaluate() < *next*.evaluate() then**
- ***S* ← *next***
  - remember best local neighbour
- **while *S* = *next***
  - stop local search when no uphill move possible
- **if *S*.evaluate() > *best*.evaluate() then**
- ***best* ← *S***
  - remember best overall
- **return *best***



Overview

•Scheduling Problems and Schedules

➧Searching for Schedules

- ➧just done: search algorithms that generate schedules