technische universität dortmund

fakultät für informatik

Evaluation and Validation

Jian-Jia Chen
(Slides are based on
Peter Marwedel)
TU Dortmund, Informatik 12
Germany

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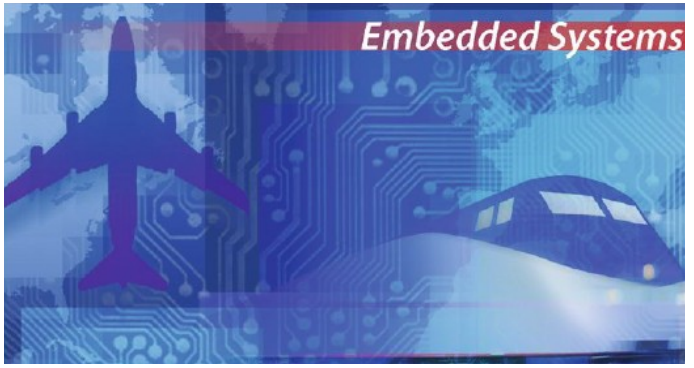
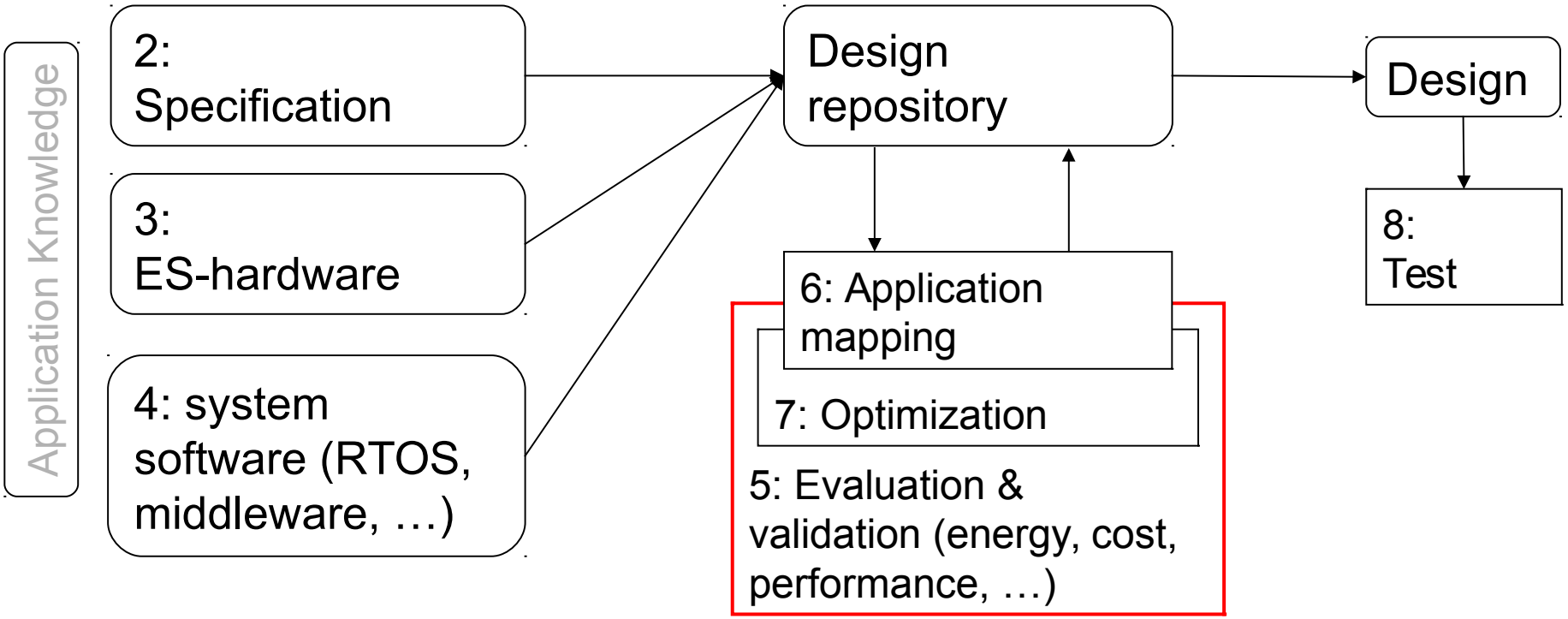


Structure of this course



Numbers denote sequence of chapters

Validation and Evaluation

Definition: *Validation* is the process of checking whether or not a certain (possibly partial) design is appropriate for its purpose, meets all constraints and will perform as expected (yes/no decision).

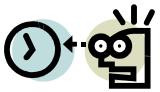
Definition: Validation with mathematical rigor is called *(formal) verification*.

Definition: *Evaluation* is the process of computing quantitative information of some key characteristics of a certain (possibly partial) design.

How to evaluate designs according to multiple criteria?

Many different criteria are relevant for evaluating designs:

- Average & worst case delay
- power/energy consumption
- thermal behavior
- reliability, safety, security
- cost, size
- weight
- EMC characteristics
- radiation hardness, environmental friendliness, ..





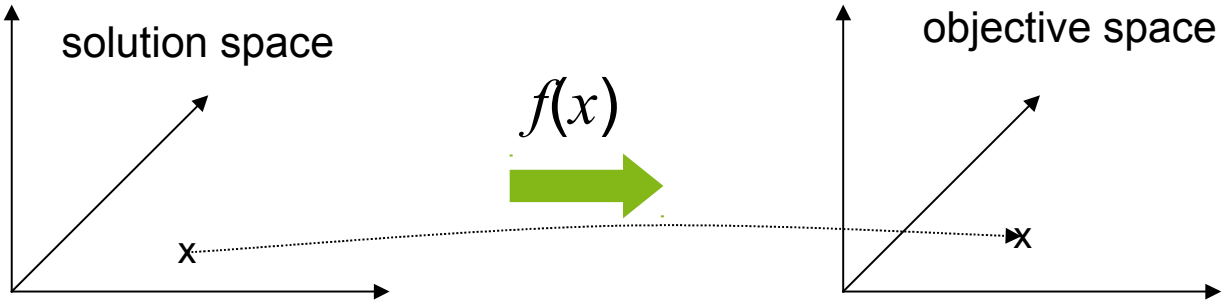




How to compare different designs?
(Some designs are “better” than others)

Definitions

- Let X: m-dimensional **solution space** for the design problem. Example: dimensions correspond to # of processors, size of memories, type and width of busses etc.
- Let F: n-dimensional **objective space** for the design problem. Example: dimensions correspond to average and worst case delay, power/energy consumption, size, weight, reliability, …
- Let $f(x)=(f_1(x),\ldots,f_n(x))$ where $x \in X$ be an **objective function.** We assume that we are using $f(x)$ for evaluating designs.



Pareto points

- We assume that, for each objective, an order < and the corresponding order ≤ are defined.
- **Definition**:
  Vector $u=(u_1,...,u_n)\in F$ **dominates** vector $v=(v_1,...,v_n)\in F$
  $\Leftrightarrow$
  u is "better" than v with respect to one objective and not worse than v with respect to all other objectives:

$$\forall i \in \{1,...,n\} : u_i \leq v_i \wedge$$
$$\exists i \in \{1,...,n\} : u_i < v_i$$

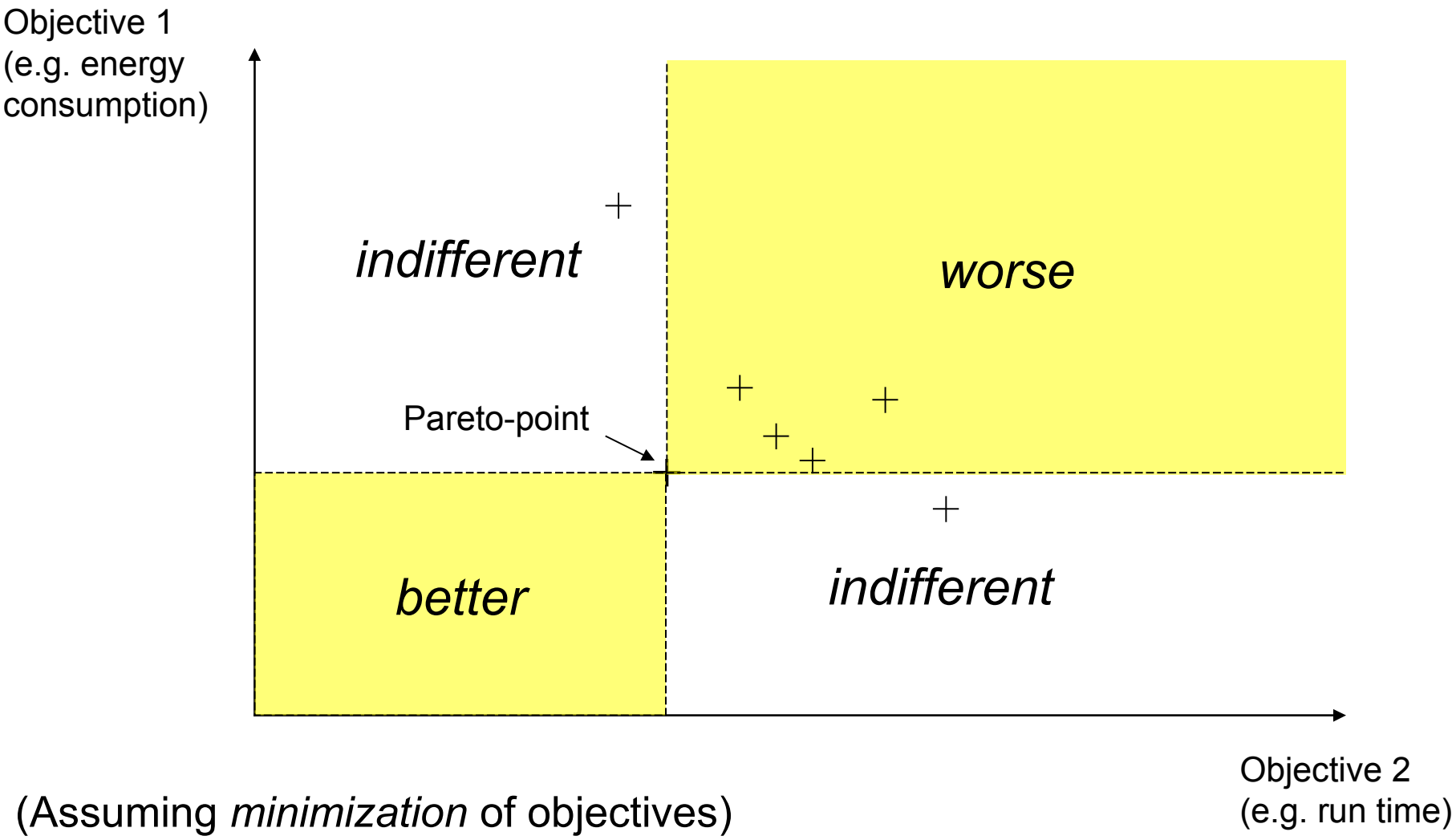
- **Definition:**
  Vector $u\in F$ is **indifferent** with respect to vector $v\in F$
  $\Leftrightarrow$ neither u dominates v nor v dominates u

Pareto points

- A solution $x \in X$ is called **Pareto-optimal** with respect to X $\Leftrightarrow$ there is no solution $y \in X$ such that $u=f(x)$ is dominated by $v=f(y)$. x is a **Pareto point**.
- **Definition**: Let $S \subseteq F$ be a subset of solutions. $v \in F$ is called a **non-dominated solution** with respect to S $\Leftrightarrow$ v is not dominated by any element $\in S$.
- v is called **Pareto-optimal** $\Leftrightarrow$ v is non-dominated with respect to all solutions F.
- A **Pareto-set** is the set of all Pareto-optimal solutions

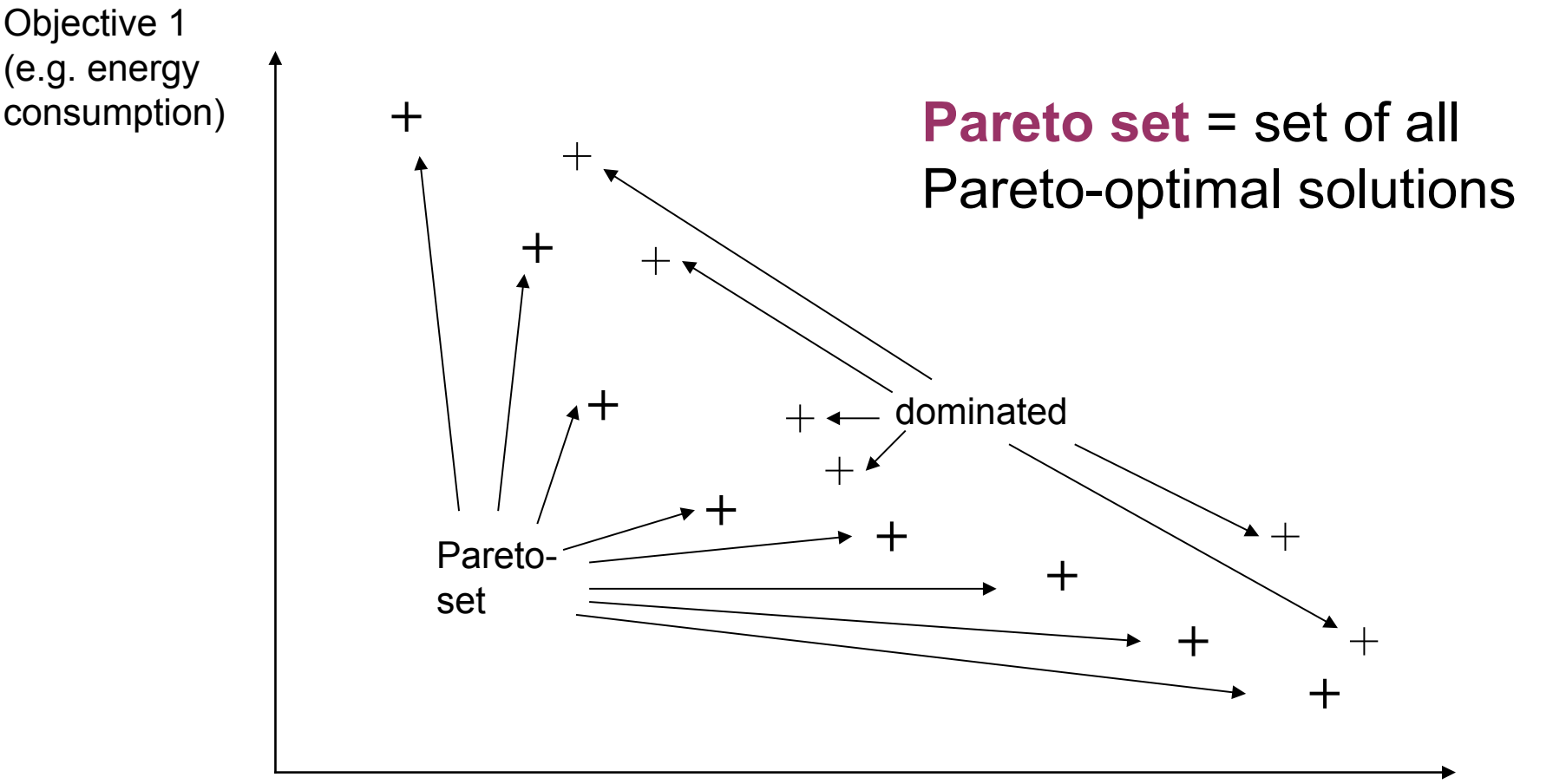
Pareto-sets define a **Pareto-front**
(boundary of dominated subspace)

Pareto Point



(Assuming *minimization* of objectives)

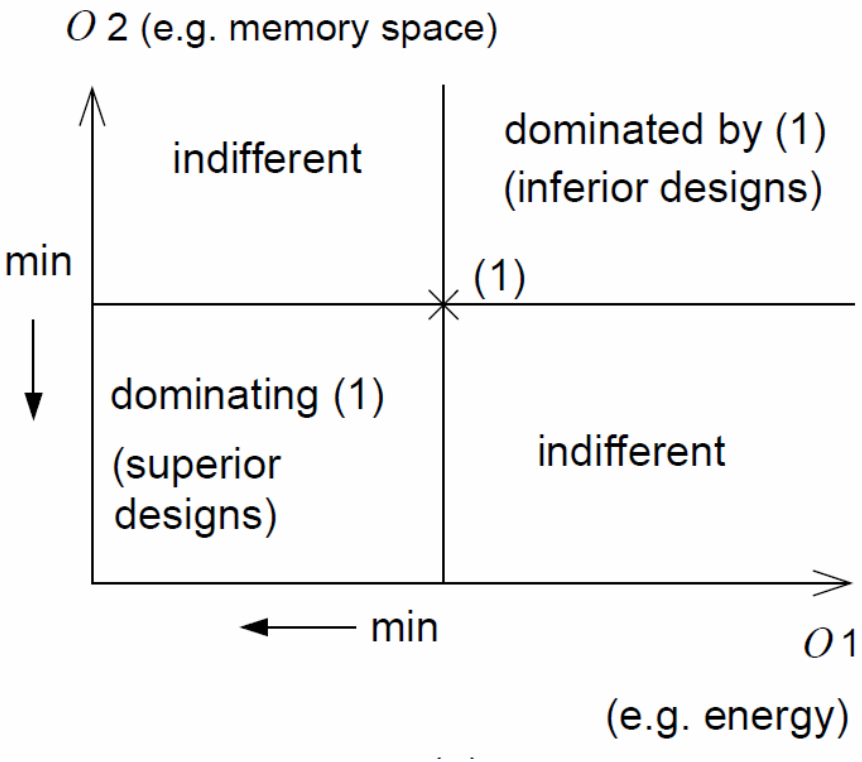
Pareto Set



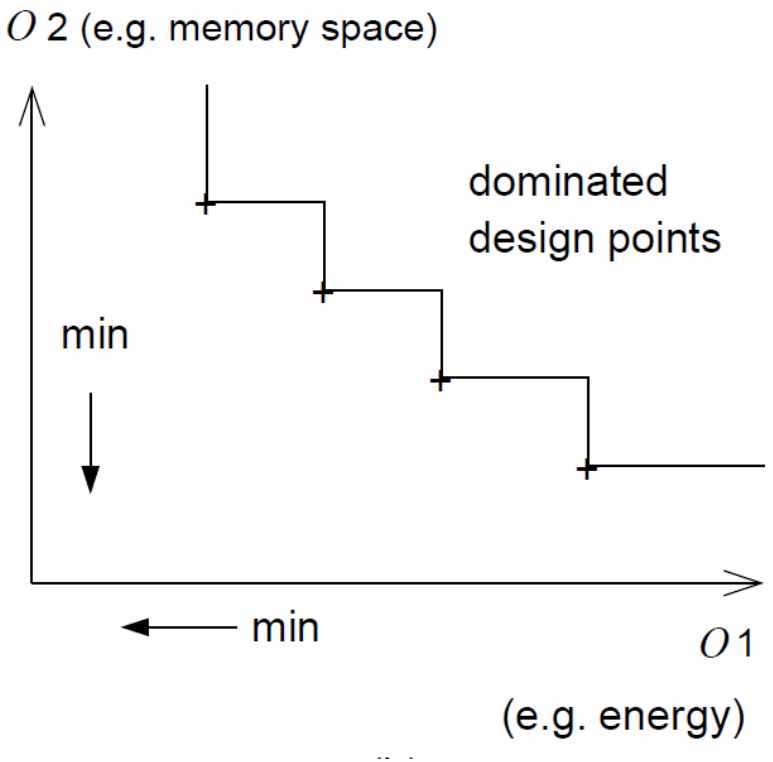
(Assuming *minimization* of objectives)

One more time …

Pareto point



Pareto front



Design space evaluation

Design space evaluation (DSE) based on Pareto-points is the process of finding and returning a set of Pareto-optimal designs to the user, enabling the user to select the most appropriate design.

How to evaluate designs according to multiple criteria?

Many different criteria are relevant for evaluating designs:

- Average & worst case delay
- power/energy consumption
- thermal behavior
- reliability, safety, security
- cost, size
- weight
- EMC characteristics
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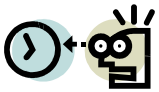






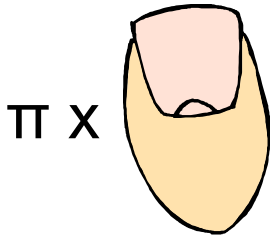




How to compare different designs?
(Some designs are “better” than others)

Average delays (execution times)

- **Estimated** average execution times **:**
  Difficult to generate sufficiently precise estimates;
  Balance between run-time and precision

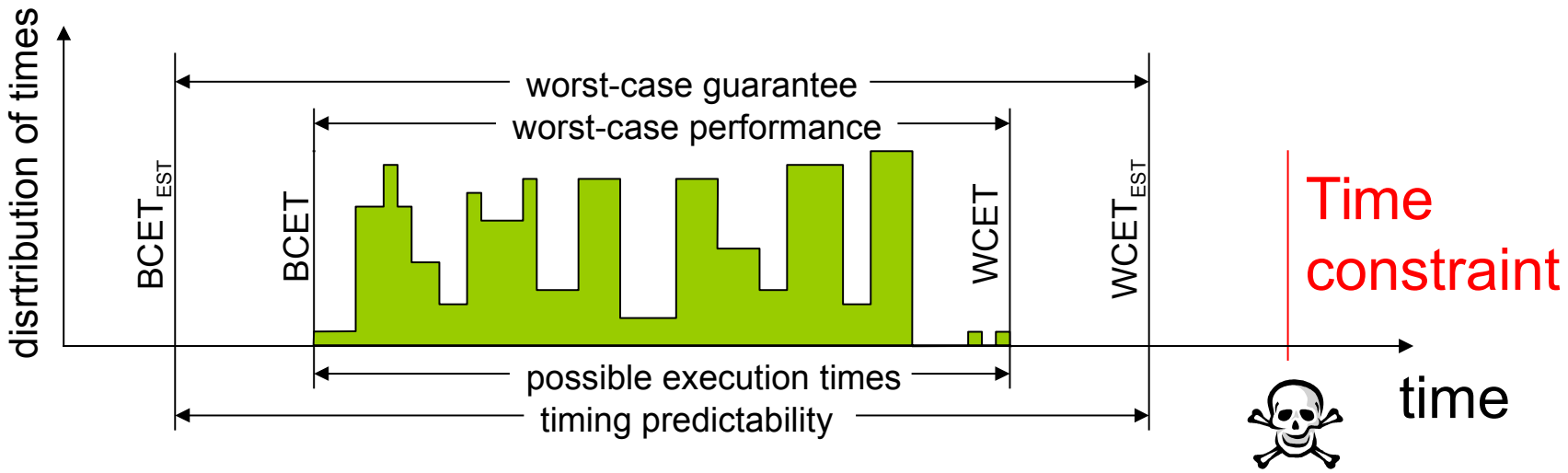


- **Accurate** average execution times**:**
  As precise as the input data is.

We need to compute **average** and **worst case** execution times

Worst case execution time (1)

Definition of worst case execution time:



$WCET_{EST}$ must be

1. safe (i.e. ≥ WCET) and
2. tight ($WCET_{EST}$-WCET≪$WCET_{EST}$)

Worst case execution times (2)

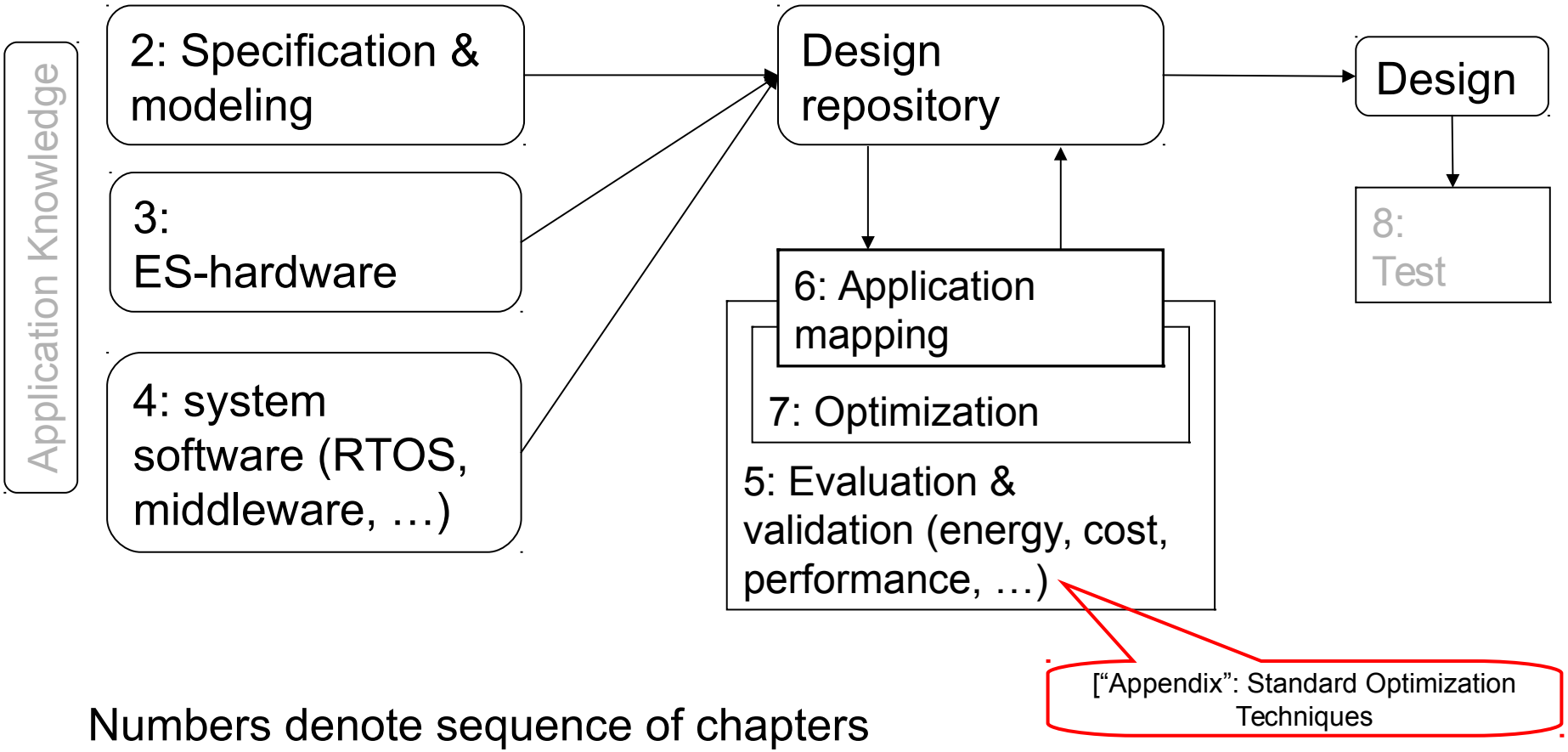
Complexity:

- in the general case: undecidable if a bound exists.
- for restricted programs: simple for “old“ architectures, very complex for new architectures with pipelines, caches, interrupts, virtual memory, etc.

Approaches:

- for hardware: requires detailed timing behavior
- for software: requires availability of machine programs; complex analysis (see, e.g., www.absint.de)

Structure of this course



Numbers denote sequence of chapters

Integer linear programming models

Ingredients:

- Cost function
- Constraints

} Involving linear expressions of integer variables from a set X

Cost function $$C = \sum_{x_i \in X} a_i x_i \text{ with } a_i \in \mathbb{R}, x_i \in \mathbb{N} \quad (1)$$

Constraints: $$\forall j \in J : \sum_{x_i \in X} b_{i,j}\, x_i \geq c_j \text{ with } b_{i,j}, c_j \in \mathbb{R} \quad (2)$$

Def.: The problem of minimizing (1) subject to the constraints (2) is called an **integer linear programming (ILP) problem**.

If all x_i are constrained to be either 0 or 1, the ILP problem is said to be a **0/1 integer linear programming problem**.

Example

$$C = 5x_1 + 6x_2 + 4x_3$$

$$x_1 + x_2 + x_3 \geq 2$$

$$x_1, x_2, x_3 \in \{0,1\}$$

x_1	x_2	x_3	C	
0	1	1	10	
1	0	1	9	← Optimal
1	1	0	11	
1	1	1	15	

Remarks on integer programming

- Maximizing the cost function: just set C‘=-C
- Integer programming is NP-complete.
- Running times depend exponentially on problem size, but problems of >1000 vars solvable with good solver (depending on the size and structure of the problem)
- The case of $x_i \in \mathbb{R}$ is called *linear programming* (LP). Polynomial complexity, but most algorithms are exponential, in practice still faster than for ILP problems.
- The case of some $x_i \in \mathbb{R}$ and some $x_i \in \mathbb{N}$ is called *mixed integer-linear programming.*
- ILP/LP models good starting point for modeling, even if heuristics are used in the end.
- Solvers: lp_solve (public), CPLEX (commercial), …

Petri Net: Matrix $\underline{N}$ describing all changes of markings

$$\underline{t}(p) = \begin{cases} -W(p,t) \text{ if } p \in {}^\bullet t \setminus t^\bullet \\ +W(t,p) \text{ if } p \in t^\bullet \setminus {}^\bullet t \\ -W(p,t) + W(t,p) \text{ if } p \in t^\bullet \cap {}^\bullet t \\ 0 \end{cases}$$

Def.: Matrix $\underline{N}$ of net N is a mapping

$$\underline{N}: P \times T \rightarrow \mathbb{Z} \text{ (integers)}$$

such that $\forall\ t \in T : \underline{N}(p,t) = \underline{t}(p)$

Component in column t and row p indicates the change of the marking of place p if transition t takes place.

For pure nets, $(\underline{N}, M_0)$ is a complete representation of a net.

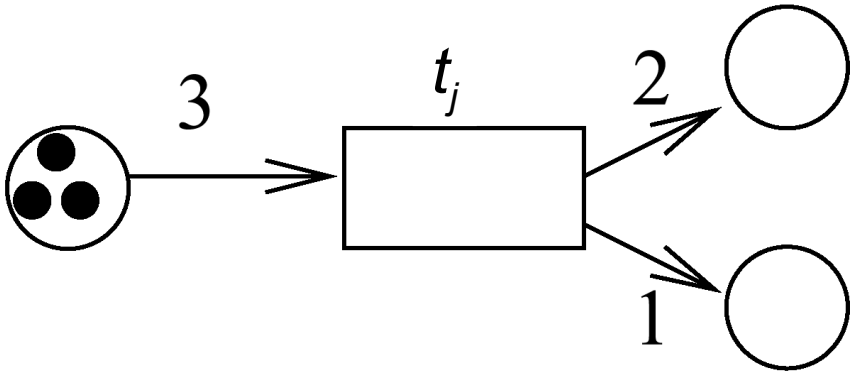
Petri Net: Place – invariants

Standardized technique for proving properties of system models

For any transition $t_j \in T$ we are looking for sets $R \subseteq P$ of places for which the accumulated marking is constant:

$$\sum_{p \in R} \underline{t}_j(p) = 0$$

Example:



Characteristic Vector

$$\sum_{p \in R} \underline{t}_j(p) = 0$$

Let: $$\underline{c}_R(p) = \begin{cases} 1 \text{ if } p \in R \\ 0 \text{ if } p \notin R \end{cases}$$

$$\Rightarrow \; 0 = \sum_{p \in R} \underline{t}_j(p) = \sum_{p \in P} \underline{t}_j(p)\, \underline{c}_R(p) = \underline{t}_j \cdot \underline{c}_R$$

Scalar product

Condition for place invariants

$$\sum_{p \in R} \underline{t}_j(p) = \sum_{p \in P} \underline{t}_j(p)\, \underline{c}_R(p) = \underline{t}_j \cdot \underline{c}_R = 0$$

Accumulated marking constant for **all** transitions if

$$\begin{aligned} \underline{t}_1 \cdot \underline{c}_R &= 0 \\ \ldots \quad \ldots &\quad \ldots \\ \underline{t}_n \cdot \underline{c}_R &= 0 \end{aligned}$$

Equivalent to $\underline{N}^T \boldsymbol{c_R} = \mathbf{0}$ where $\underline{N}^T$ is the transposed of $\underline{N}$

More detailed view of constraints

$$\begin{pmatrix} \underline{t}_1(p_1)\ldots\underline{t}_1(p_n) \\ \underline{t}_2(p_1)\ldots\underline{t}_2(p_n) \\ \ldots \\ \underline{t}_m(p_1)\ldots\underline{t}_m(p_n) \end{pmatrix} \begin{pmatrix} \underline{c}_R(p_1) \\ \underline{c}_R(p_2) \\ \ldots \\ \underline{c}_R(p_n) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

System of linear equations.

Solution vectors must consist of zeros and ones.

Put Things Together: Maximum Place Invariants

$$\text{maximize} \sum_{p \in P} x_p$$

$$\text{such that} \sum_{p \in P} \underline{t}_j(p) x_p = 0$$

$$x_p \in \{0, 1\}, \forall p \in P$$

Another Example: Knapsack Problem

Example IP formulation:
The Knapsack problem:

I wish to select items to put in my backpack.

There are *m* items available.
Item *i* weights w_i kg,
Item *i* has value v_i.
I can carry Q kg.

$$\text{Let } x_i = \begin{cases} 1 & \text{if I select item } i \\ 0 & \text{otherwise} \end{cases}$$

$$\max \quad \sum_i x_i v_i$$

$$\text{s.t.} \quad \sum_i x_i w_i \le Q$$

$$x_i \in \{0, 1\}$$

Variance of Knapsack Problem

- ***Given*** a set of periodic tasks with implicit deadlines
  - Task τ_i: period T_i,
    - Options: Execution without/with scratchpad memory (SPM)
    - Without SPM: Worst-case execution time $C_{i,1}$
    - With SPM: required m_i scratchpad memory size and Worst-case execution time $C_{i,2}$
    - $U_{i,1} = C_{i,1}/Ti$, $U_{i,2} = C_{i,2}/Ti$
- ***Objective***
  - Select the tasks to be put into the SPM
  - Minimize the required SPM size
  - The task set should be schedulable by using EDF

$$\min \quad \sum_i x_i m_i$$

$$\text{s.t.} \quad \sum_i x_i U_{i,2} + \sum_i (1 - x_i) U_{i,1} \le 1$$

$$x_i \in \{0, 1\}$$

Evolutionary Algorithms (1)

- ***Evolutionary Algorithms*** *are based on the collective learning process within a population of individuals, each of which represents a search point in the space of potential solutions to a given problem.*
- *The population is arbitrarily initialized, and it evolves towards better and better regions of the search space by means of randomized processes of*
  - ***selection*** *(which is deterministic in some algorithms),*
  - ***mutation****, and*
  - ***recombination*** *(which is completely omitted in some algorithmic realizations).*

[Bäck, Schwefel, 1993]

Evolutionary Algorithms (2)

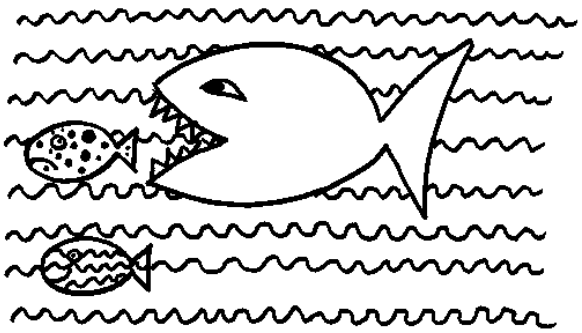
- *The environment (given aim of the search) delivers a quality information (**fitness value**) of the search points, and the selection process favours those individuals of higher fitness to reproduce more often than worse individuals.*
- *The recombination mechanism allows the mixing of parental information while passing it to their descendants, and mutation introduces innovation into the population*

[Bäck, Schwefel, 1993]

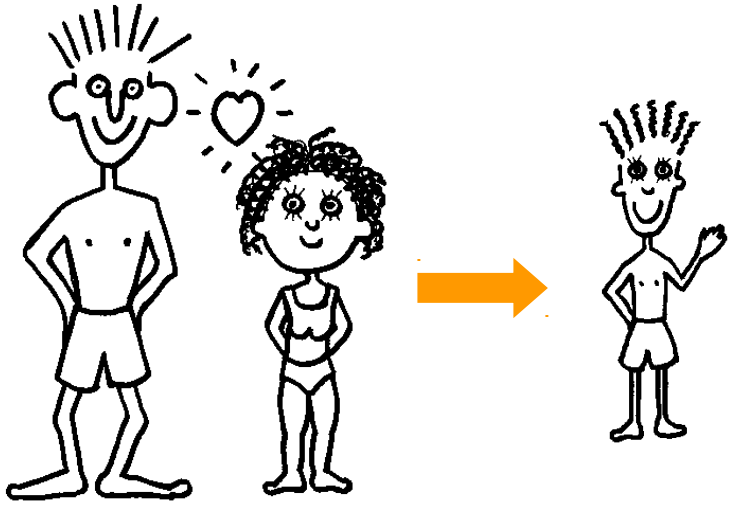
Evolutionary Algorithms

Principles of Evolution

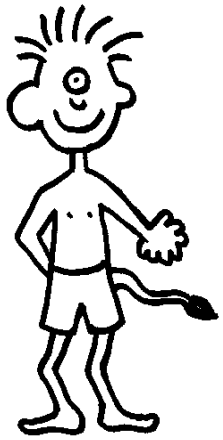
❶ Selection



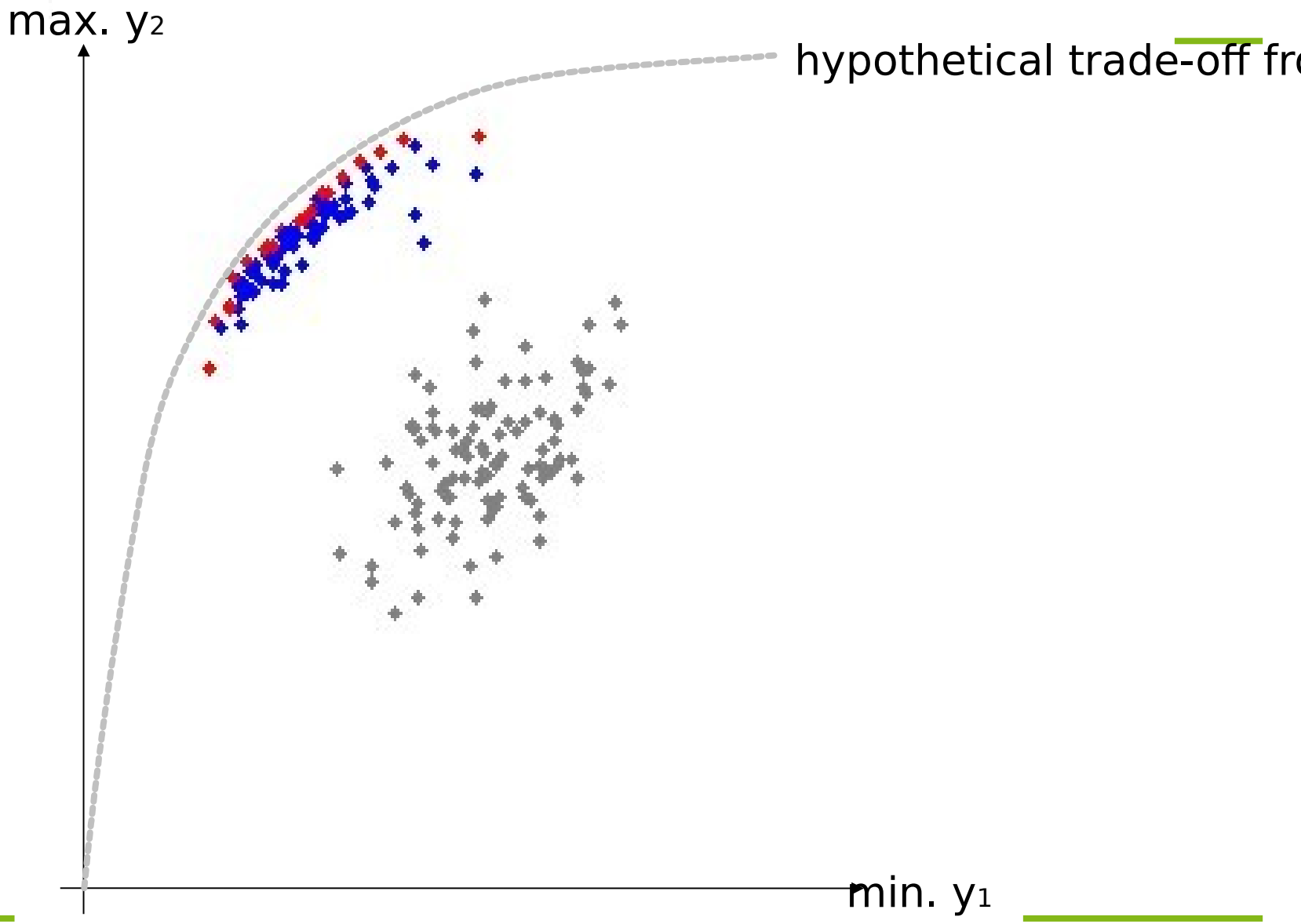
❸ Cross-over



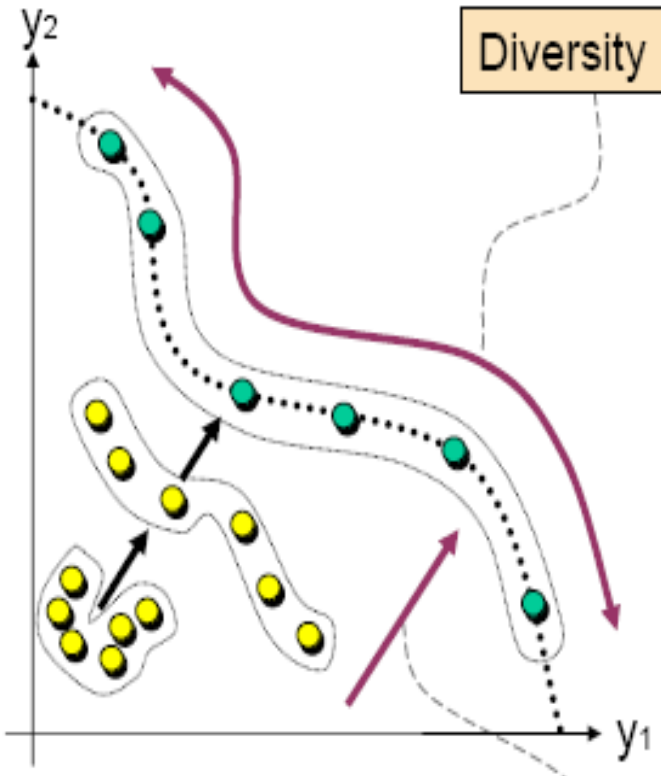
❷ Mutation



An Evolutionary Algorithm in Action



Issues in Multi-Objective Optimization



Diversity

Convergence

- How to maintain a diverse Pareto set approximation?

  ❷ **density estimation**

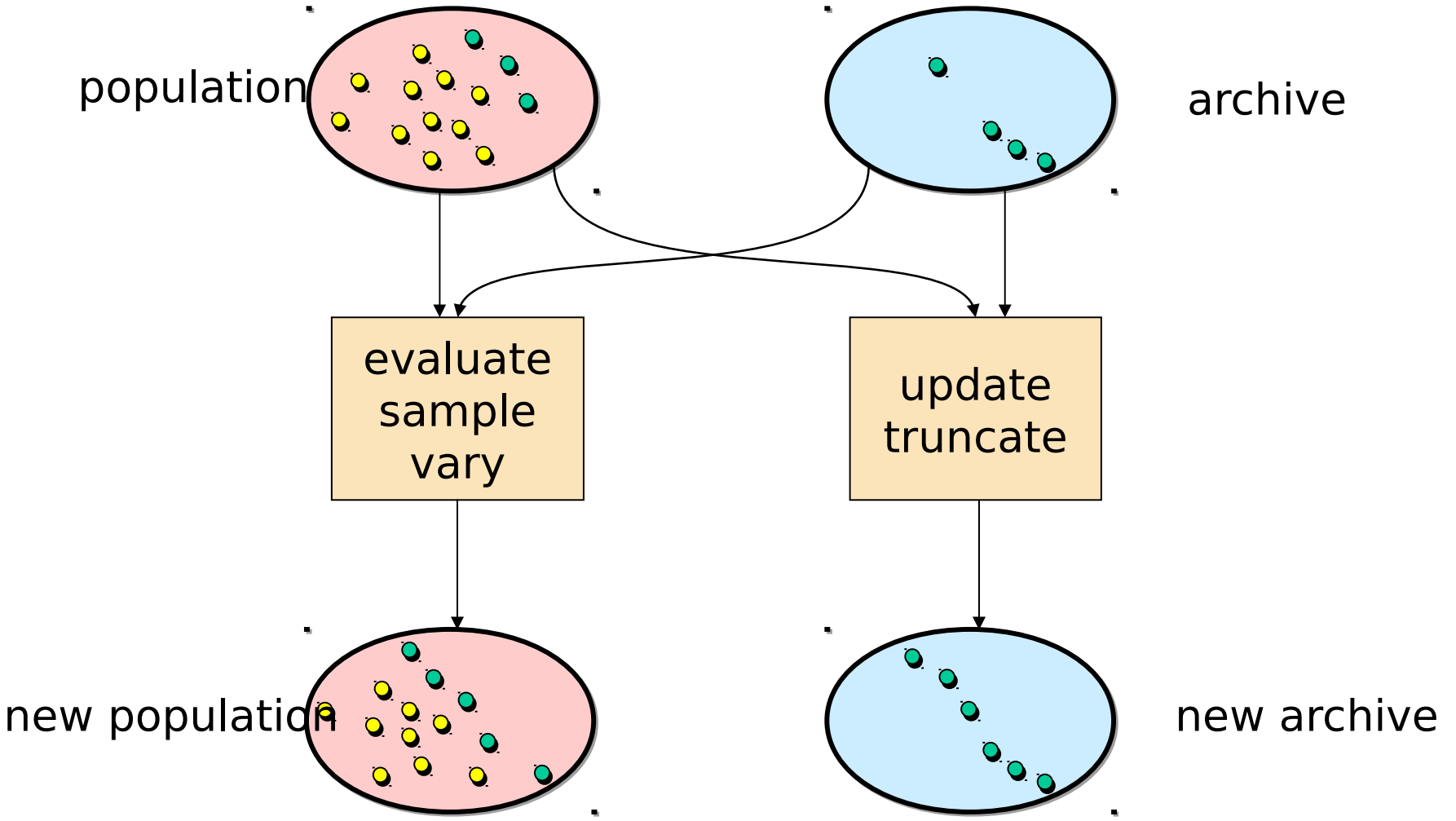
- How to prevent nondominated solutions from being lost?

  ❸ **environmental selection**

- How to guide the population towards the Pareto set?

  ❶ **fitness assignment**

A Generic Multiobjective EA



Example: SPEA2 Algorithm

Step 1:	Generate initial population P0 and empty archive (external set) A_0. Set t = 0.
Step 2:	Calculate fitness values of individuals in P_t and A_t.
Step 3:	A_{t+1} = nondominated individuals in P_t and A_t. If size of A_{t+1} > N then reduce A_{t+1}, else if size of A_{t+1} < N then fill A_{t+1} with dominated individuals in P_t and A_t.
Step 4:	If t > T then output the nondominated set of A_{t+1}. Stop.
Step 5:	Fill mating pool by binary tournament selection.
Step 6:	Apply recombination and mutation operators to the mating pool and set P_{t+1} to the resulting population. Set t = t + 1 and go to Step 2.

Summary

Integer (linear) programming

- Integer programming is NP-complete
- Linear programming is faster
- Good starting point even if solutions are generated with different techniques

Simulated annealing

- Modeled after cooling of liquids
- Overcomes local minima

Evolutionary algorithms

- Maintain set of solutions
- Include selection, mutation and recombination