

Constraint Satisfaction Problems

Constraint Optimization

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based on a slideset by
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Hard and Soft Constraint

Real-life problems often contain **hard** and **soft constraints**:

Hard constraints: must be satisfied;

Soft constraints: should be satisfied, but may be violated.

Example: In time-tabling problems,

- resource constraints such as “a teacher can teach only one class at a time” must be satisfied;
- a request such as “the schedule of teacher should be concentrated in two days” is simply a preference, but not essential for the solution.

What to do with soft constraints?

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Constraint Optimization

Formalizing problems with soft and hard constraints leads to constraint networks augmented with a **global cost function** (also called **criterion function** or **objective function**), based on the satisfaction of soft constraints.

A **constraint optimization problem** (COP) is the problem of finding a variable assignment to all variables that satisfies all hard constraints and at the same time optimizes the global cost function.

Note: Every constraint satisfaction problem can be viewed as a constraint optimization problem – when not all constraints are satisfiable. Try to find an assignment that maximizes the number of satisfied constraints: **MAX-CSP** problem.

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Example 1: Power Plant Maintenance

Given

- 1 a number of power generators,
- 2 preventive maintenance intervals,
- 3 time for maintenance,
- 4 accurate estimates for plant's power demands,

determine a maintenance schedule respecting (2) that minimizes operating and maintenance costs.

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Example 2: Combinatorial Auctions

In **combinatorial auctions**, bidders can give bids for sets of items. The auctioneer then has to generate an optimal selection, e.g., one that maximizes revenue.

Definition

The **combinatorial auction problem** is specified as follows:

Given: A set of items $Q = \{q_1, \dots, q_n\}$ and a set of bids $B = \{b_1, \dots, b_m\}$ such that each bid is $b_i = (Q_i, r_i)$, where $Q_i \subseteq Q$ and r_i is a strictly positive real number.

Task: Find a subset of bids $B' \subseteq B$ such that any two bids in B' do not share an item maximizing
$$\sum_{(Q_i, r_i) \in B'} r_i.$$

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From Constraint to Cost Networks

- We will extend **constraint networks** to **cost networks**.
- **Hard constraint** are modelled as ordinary constraints, we know already.
- **Soft constraints** are modelled by **cost functions**, which assign particular costs to variable assignments.
- The costs are aggregated by a **global cost function**

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Global Cost Functions

A constraint optimization problem (COP) is a constraint network extended by a **global cost function**.

Definition

Given a set of variables $V = \{v_1, \dots, v_n\}$, a set of real-valued functions F_1, \dots, F_l over scopes S_1, \dots, S_l , $S_j \subseteq V$, and assignments a over V . The **global cost function** F is defined by

$$F(a) = \sum_{j=1}^l F_j(a),$$

where $F_j(a)$ means F_j applied to assignments in a restricted to the scope of F_j , i.e., $F_j(a) = F_j(\bar{a}[S_j])$.

Cost Networks

Constraint optimization problems can be viewed as defined over an extended constraint network called **cost network**.

Definition

A **cost network** is a 4-tuple $\mathcal{O} = \langle V, \text{dom}, C_h, C_s \rangle$, where $\langle V, \text{dom}, C_h \rangle$ is a constraint network (elements of C_h are called **hard constraints**), and $C_s = \{F_1, \dots, F_l\}$ is a set of real-valued functions defined over scopes S_1, \dots, S_l (elements of C_s are called **soft constraints**).

Definition

A **solution to a constraint optimization problem** given by a cost network $\mathcal{O} = \langle V, \text{dom}, C_h, C_s \rangle$, is an assignment a^* that maximizes (minimizes) $F(a)$ among all assignments a that satisfy $\langle V, \text{dom}, C_h \rangle$.

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Example: Cost Network for Combinatorial Auction

For a combinatorial auction given by item set $Q = \{q_1, \dots, q_n\}$ and bids $B = \{b_1, \dots, b_m\}$ with $b_i = (Q_i, r_i)$ define a cost network as follows:

- **Variables** b_i with domain $\{0, 1\}$; 1 for selecting the bid, 0 otherwise;
- For each pair b_i, b_j such that $Q_i \cap Q_j \neq \emptyset$ a **constraint** R_{ij} prohibiting that b_i and b_j are assigned 1 simultaneously;
- **Cost functions** F_i with $F_i(a) = r_i$ if $a(b_i) = 1$, $F_i(a) = 0$ otherwise, for an assignment a .

Find a consistent assignment a to the b_i s that **maximizes** $F(a) = \sum_i F_i(a)$.

Note: cost network = constraint network, because all cost components are unary.

Example Auction

Consider the following auction:

$$\begin{aligned} b_1 &= \{1, 2, 3, 4\}, & r_1 &= 8, \\ b_2 &= \{2, 3, 6\}, & r_2 &= 6, \\ b_3 &= \{1, 4, 5\}, & r_3 &= 5, \\ b_4 &= \{2, 8\}, & r_4 &= 2, \\ b_5 &= \{5, 6\}, & r_5 &= 2. \end{aligned}$$

What is the optimal assignment?

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Reduction of COP-Solving to CSP-Solving

We can always reduce COP-solving to solving a **sequence of CSPs**.

Given a COP \mathcal{O} which we want to maximize. Consider a sequence of CSPs \mathcal{C}_i , s. t. each contains the constraint part of \mathcal{O} and an additional constraint $\sum_j F_j(a) \geq c_i$, where $c_1 \leq \dots \leq c_i \leq \dots$

Solve the CSPs with increasing cost bounds c_i until no solution can be found. Then the previous step is the optimal solution – provided the difference between the steps is not larger than the smallest difference between different values of the global cost function.

As a variation, one could think of **binary search** approaches.

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Example: Solving the Auction Problem

Assumption: Step size 1 and static variable ordering
 b_1, b_2, b_3, b_4, b_5 .

For cost bounds from $c_1 = 0$ to $c_9 = 8$, $a(b_1) = 1$ and all others 0 is satisfying.

For cost bound $c_{10} = 9$ and $c_{11} = 10$, $a(b_1) = 1$ and $a(b_5) = 1$ (and all others 0) is satisfying.

For cost bound $c_{12} = 11$, $a(b_2) = 1$ and $a(b_3) = 1$ (and all others 0) is satisfying.

For cost bound $c_{13} = 12$, there is no satisfying assignment.

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Branch and Bound: First idea

When solving a COP using a sequence of CSPs, one could use all CSP techniques. However, instead of solving multiple CSPs, one may instead want to integrate the optimization process into the search process.

First **idea**:

- 1 Set bound $c = 0$.
- 2 Use any systematic search technique to find an assignment that satisfies the constraint part.
- 3 Remember solution in a and global cost in c if global cost $> c$.
- 4 Return a and c if no further solutions can be found, otherwise continue with next solution at (3).

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Pruning

Of course, often it is possible to **prune** the search, even if no inconsistency has been detected yet.

Main idea behind **depth-first branch-and-bound (BnB)**:

If the best solution so far is c , this is a **lower bound** for all other possible solutions. So, if a partial solution has led to costs of x for all cost components of fully instantiated variables and **the best we can achieve** for all other cost components is y with $x + y < c$, then we do not need to continue in this branch.

How can we find out what is the best we can achieve?

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Bounding Evaluation Function

In the following, we will write \vec{a}_i for partial instantiations of the first i variables, assuming a static variable ordering.

Definition

A **bounding evaluation function** for a **maximizing (minimizing) constraint optimization problem** is a function f over partial assignments such that $f(\vec{a}_i) \geq \max_a F(a)$ ($f(\vec{a}_i) \leq \min_a F(a)$) for all satisfying assignments a that extend \vec{a}_i .

Note:

- If $f(\vec{a}_i) < c$ for some already found solution c , then \vec{a}_i cannot be extended to a maximal solution.
- f can also be used as a heuristic for choosing a value of the next variable!

Branch and Bound (BnB) Algorithm

BnB(\mathcal{O}, f):

Input: cost network \mathcal{O} and evaluation bounding function f

Output: an optimal assignment a' (possibly empty) and costs c'

$\forall i D'_i \leftarrow D_i, i \leftarrow 1, c' \leftarrow 0, a' \leftarrow \emptyset, a \leftarrow \emptyset$

while ($i \neq 0$)

while ($1 \leq i \leq n$)

 remove ($v_i \mapsto _$) from a // remove old assignment to v_i

$x \leftarrow \text{SELECTVALUE}(i, c')$

if ($x = \text{null}$) $D'_i \leftarrow D_i$ // no value for x_i : reset domain

$i \leftarrow i - 1$ // backtrack

else $a \leftarrow a \cup \{v_i \mapsto x\}$

$i \leftarrow i + 1$ // step forward

if ($i = n + 1$) // one solution found

if ($F(a) > c'$) // better solution

$a' \leftarrow a$ // remember best solution found so far

$c' \leftarrow F(a)$

$i \leftarrow n$ // search for next solution

return(a', c')

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Branch and Bound Algorithm: SELECTVALUE

SELECTVALUE(i, c'):

```
while ( $D'_i \neq \emptyset$ )  
    select  $a_i^* \in D'_i$  such that  
         $a_i^* = \text{pick one } \arg \max_{a_i \in D'_i} f(a \cup \{v_i \mapsto a_i\})$   
    remove  $a_i^*$  from  $D'_i$   
    if ( $a \cup \{v_i \mapsto a_i^*\}$ ) is consistent and  
         $f(a \cup \{v_i \mapsto a_i^*\}) > c'$  return( $a_i^*$ )  
return(null)
```

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First-Choice Bounding Function

How to come up with a good **bounding evaluation function**?

In *Operation Research*, one often uses **Linear Programming** to come up with bounds for **Integer Programming Problems**.

Let us consider what we can achieve for all soft constraints in isolation subject to the partial assignment we have already.

This function is called **first-choice** (*fc*) bounding function:

$$f_{fc}(\vec{a}_i) = \sum_{F_j \in C_s} \max_{a_{i+1}, \dots, a_n} F_j(\vec{a}_i \cup \{v_{i+1} \mapsto a_{i+1}, \dots, v_n \mapsto a_n\})$$

How could one improve on that?

- Only allow locally consistent partial assignments.
- Do not consider all soft constraints in isolation, but combine them!

Example: Auction again

Let us consider **BnB** with the **first-choice** bounding function on our auction example:

$$① \quad f_{fc}(\{b_1 \mapsto 1\}) = 8 + (6 + 5 + 2 + 2) = 23$$

$$② \quad f_{fc}(\{b_1 \mapsto 1, b_2 \mapsto 0\}) = 8 + (5 + 2 + 2) = 17$$

$$③ \quad f_{fc}(\{b_1 \mapsto 1, b_2 \mapsto 0, b_3 \mapsto 0\}) = 8 + (2 + 2) = 12$$

$$④ \quad f_{fc}(\{b_1 \mapsto 1, b_2 \mapsto 0, b_3 \mapsto 0, b_4 \mapsto 0\}) = 8 + (2) = 10$$

$$⑤ \quad \dots$$

Russian Doll Search: Idea

One way to get more accurate bounding functions is to solve subproblems and store the optimal results, reusing them for larger problems.

Solve a sequence of n problems using **BnB**, where in the i th run the last i variables, i.e., v_{n-i+1} up to v_n , (and the relevant hard and soft constraints) are considered.

The results of the previous runs can be used:

- 1 as an initial lower bound,
- 2 in a heuristic for choosing values, and
- 3 to generate a more accurate bounding function.

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Improving the Evaluation Function

- Solve n COPs \mathcal{O}_i , ($i = 1, \dots, n$) over the last i variables v_{n-i+1}, \dots, v_n using BnB and store maximal costs as c_i^* .
- In the $(n - i + 1)$ th run, variables v_i, \dots, v_n are considered.
- Assume that the variables v_i, \dots, v_{i+j} are instantiated, denoted by the partial assignment \vec{a}_j^i , and that $C_{i,j}$ are all those soft constraints F such that their scopes have a non-empty intersection with $\{v_i, \dots, v_{i+j}\}$.
- Then we use the optimal costs from the $n - i - j$ th run to improve on the first-choice function:

$$f(\vec{a}_j^i) = c_{n-i-j}^* + \sum_{F \in C_{i,j}} \max_{a_{i+j+1}, \dots, a_n} F(\{v_i \mapsto a_i, \dots, v_n \mapsto a_n\}).$$

Conclusion & Outlook

- Problems with hard and soft constraints lead to **constraint optimization problems**
- These are formalized using **cost functions** and **cost networks**
- They can be solved using a reduction to a sequence of CSP problems
- More efficiently, one can search for optimal solutions during the backtracking search
- **Branch and Bound** is the method of choice
- Its pruning power depends on the accuracy of the **bounding evaluation function**
- **Russian doll search** can boost its performance
- Further enhancements are possible using **constraint inference** techniques (such as **bucket elimination**).

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Rina Dechter.
Constraint Processing,
Chapter 13, Morgan Kaufmann, 2003

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