Tutorial on CPLEX
Linear Programming

Combinatorial Problem Solving (CPS)

Enric Rodríguez-Carbonell

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Among other things, CPLEX allows one to deal with:

- **Real linear progs (all vars are in $\mathbb{R}$)**
  
  \[
  \begin{align*}
  \min & \quad c^T x \\
  A_1 x & \leq b_1 \\
  A_2 x & = b_2 \\
  A_3 x & \geq b_3 \\
  x & \in \mathbb{R}^n
  \end{align*}
  \]

- **Mixed integer linear progs (some vars are in $\mathbb{Z}$)**
  
  \[
  \begin{align*}
  \min & \quad c^T x \\
  A_1 x & \leq b_1 \\
  A_2 x & = b_2 \\
  A_3 x & \geq b_3 \\
  \forall i & \in I : x_i \in \mathbb{Z} \\
  \forall i & \not\in I : x_i \in \mathbb{R}
  \end{align*}
  \]
Cplex Toolkit

- Cplex allows one to work in several ways. Cplex is...

  - An IDE that uses the OPL modeling language
  - An interactive command-line optimizer that reads MPS/LP input
  - A callable library in several languages
    - Java
    - C
    - C++ (concert technology)
    - ...

Concert Technology

- Two kinds of objects:

  - **Modeling objects** for defining the optimization problem (constraints, objective function, etc.)

    They are grouped into an `IloModel` object representing the complete optimization problem (recall: here, `model = problem`).

  - **Solving objects** for solving problems represented by modeling objects.

    An `IloCplex` object reads a model, extracts its data, solves the problem and answers queries on solution.
Creating the Environment: IloEnv

- The class IloEnv constructs a CPLEX environment.

- The environment is the first object created in an application.

- To create an environment named env, you do this:

  ```cpp
  IloEnv env;
  ```

- The environment object needs to be available to the constructor of all other Concert Technology classes

- IloEnv is a handle class: variable env is a pointer to an implementation object, which is created at the same time

- Before terminating destroy the implementation object with

  ```cpp
  env.end();
  ```

  for just ONE of its IloEnv handles
Creating a Model: IloModel

- After creating the environment, a Concert application is ready to create one or more optimization models.

- Objects of class IloModel define a complete model (which can be solved by passing it to an IloCplex object).

- To construct a modeling object named model, within an existing environment named env, call:

  ```
  IloModel model(env);
  ```

- One can get the environment of a given optimization model by calling:

  ```
  IloEnv env = model.getEnv();
  ```
Creating a Model: IloModel

After an IloModel object has been constructed, it can be populated with objects of classes:

- IloNumVar, representing modeling variables;
- IloRange, which define constraints of the form $l \leq E \leq u$, where $E$ is a linear expression;
- IloObjective, representing an objective function.

Any object `obj` can be added to the model by calling:

```cpp
model.add(obj);
```

No need to explicitly add the variable objects to a model, as they are implicitly added when they are used in range constraints (instances of IloRange) or in the objective.

At most one objective function can be added to a model.
Creating a Model: IloModel

- Modeling variables are constructed as objects of class IloNumVar, e.g.:

```cpp
IloNumVar x(env, 0, 40, ILOFLOAT);
```

This definition creates the modeling variable `x` with lower bound 0, upper bound 40 and type ILOFLOAT.

- Variable types:
  - ILOFLOAT: continuous variable
  - ILOINT: integer variable
  - ILOBOOL: Boolean variable

- Note that even for variables of type ILOBOOL, the lower bound (0) and the upper bound (1) have to be specified.

- One may have arrays of variables: IloNumVarArray
Creating a Model: IloModel

- After all the modeling variables have been constructed, they can be used to define the objective function (objects of class IloObjective) and constraints (objects of class IloRange).

- To create `obj` of type IloObjective representing an objective function (and direction of optimization):

  ```cpp
  IloObjective obj = IloMinimize(env, x+2*y);
  ```

  or

  ```cpp
  IloObjective obj = IloMaximize(env, x+2*y);
  ```

- Creating constraints and adding them to the model:

  ```cpp
  model.add(-x + 2*y + z <= 20);
  ```

  `-x + 2*y + z <= 20` creates implicitly an object of class IloRange that is immediately added to the model.
Creating a Model: IloModel

- Actually in

```cpp
model.add(-x + 2*y + z <= 20);
```

an object of class IloExpr (a linear expression) is also implicitly created before the object of class IloRange is created

- Sometimes it is convenient to create objects of class IloExpr explicitly. E.g., when expressions cannot be spelled out in source code but have to be built up dynamically. Operators like += provide an efficient way to do this.

- Example:

```cpp
IloEnv env;
IloModel model(env);
IloNumVarArray V(env, n, 0, 1, ILOBOOL);
IloExpr expr(env);
for (int i = 0; i < n; ++i) expr += V[i];
model.add(expr == 1);
expr.end();
```
Creating a Model: IloModel

```plaintext
IloEnv env;
IloModel model(env);
IloNumVarArray V(env, n, 0, 1, ILOBOOL);
IloExpr expr(env);
for (int i = 0; i < n; ++i) expr += V[i];
model.add(expr == 1);
expr.end(); // Notice this!
```

- IloExpr objects are handles.
  So if an IloExpr object has been created explicitly,
  then method end() must be called when it is no longer needed.

- Example of explicitly defining an IloRange object
  ```plaintext
  IloRange c(env, -IloInfinity, -x1 + x2 + x3, 0);
  ```

- One may have arrays of constraints: IloRangeArray
Solving the Model: IloCplex

- The class IloCplex solves a model.

- After the optimization problem has been stored in an IloModel object (say, model), it is time to create an IloCplex object (say, cplex) for solving the problem:

  ```
  IloCplex cplex(model);
  ```

- To solve the model, call:

  ```
  cplex.solve();
  ```

- This method returns an IloBool value, where:
  - IloTrue indicates that CPLEX successfully found a feasible (yet not necessarily optimal) solution
  - IloFalse indicates that no solution was found
Solving the Model: IloCplex

- More precise information about the outcome of the last call to the method `solve` can be obtained by calling:

```java
IloCplex getStatus();
```

- Returned value tells what CPLEX found out: whether
  - it found the optimal solution or only a feasible one; or
  - it proved the model to be unbounded or infeasible; or
  - nothing at all has been proved at this point.

- More info is available with method `getCplexStatus`. 
Querying Results

- Query methods access information about the solution.
- Numbers in solution, etc. are of type IloNum (= double)

To query the solution value for a variable:

```c
IloNum v = cplex.getValue(x);
```

**Warning!** Sometimes for integer variables the value is not integer but just “almost” integer (e.g. 1e-9 instead of 0). Explicit rounding necessary (use functions round of <math.h> or IloRound).

To query the solution value for an array of variables:

```c
IloNumVarArray x(env);
...
IloNumArray v(env);
cplex.getValues(v, x);
```
Querying Results

- To get the values of the slacks of an array of constraints:

```cpp
IloRangeArray c(env);
...
IloNumArray v(env);
cplex.getSlacks(v, c);
```

- To get the values of the dual variables (simplex multipliers) of an array of constraints:

```cpp
IloRangeArray c(env);
...
IloNumArray v(env);
cplex.getDuals(v, c);
```
Querying Results

- To get the values of the reduced costs of an array of variables:

```java
IloNumVarArray x(env);
...
IloNumArray v(env);
cplex.getReducedCosts(v, x);
```

- To avoid logging messages by CPLEX on screen:

```java
cplex.setOut (env.getNullStream());
cplex.setError(env.getNullStream());
```
Querying Results

- Output operator « is defined for type IloAlgorithm::Status returned by getStatus, as well as for IloNum, IloNumVar, ...

« is also defined for any array of elements if the output operator is defined for the elements.

- Default names are of the form IloNumVar(n)[ℓ..u] for variables, and similarly for constraints, e.g.,

\[
\text{IloNumVar(1)[0..9] + IloNumVar(3)[0..\text{inf}] \leq 20}
\]

- One can set names to variables and constraints:

```cpp
x.setName("x");
c.setName("c");
```
Writing/Reading Models

- CPLEX supports reading models from files and writing models to files in several languages (e.g., LP format, MPS format)

- To write the model to a file (say, model.lp):

  ```
  cplex.exportModel ("model.lp");
  ```

- IloCplex decides which file format to write based on the extension of the file name (e.g., .lp is for LP format)

- This may be useful, for example, for debugging
Languages for Linear Programs

- **MPS**
  - Very old format (≈ age of punched cards!) by IBM
  - Has become industry standard over the years
  - Column-oriented
  - Not really human-readable nor comfortable for writing
  - All LP solvers support this language

- **LP**
  - CPLEX specific file format
  - Row-oriented
  - Very readable, close to mathematical formulation
  - Supported by CPLEX, GUROBI, GLPK, LP_SOLVE, ..
    (which can translate from one format to the other!)
Example: Product Mix Problem

- A company can produce 6 different products $P_1, \ldots, P_6$
- Production requires labour, energy and machines, which are all limited
- The company wants to maximize revenue
- The next table describes the requirements of producing one unit of each product, the corresponding revenue and the availability of resources:

<table>
<thead>
<tr>
<th></th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1050</td>
</tr>
<tr>
<td>Labour</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1050</td>
</tr>
<tr>
<td>Energy</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1080</td>
</tr>
</tbody>
</table>
Example: Product Mix Problem

MODEL:

\[ x_i = \text{quantity of product } P_i \text{ to be produced.} \]

\[
\begin{align*}
\text{max Revenue} &: \quad 5x_1 + 6x_2 + 7x_3 + 5x_4 + 6x_5 + 7x_6 \\
\text{Machine} &: \quad 2x_1 + 3x_2 + 2x_3 + x_4 + x_5 + 3x_6 \leq 1050 \\
\text{Labour} &: \quad 2x_1 + x_2 + 3x_3 + x_4 + 3x_5 + 2x_6 \leq 1050 \\
\text{Energy} &: \quad x_1 + 2x_2 + x_3 + 4x_4 + x_5 + 2x_6 \leq 1080 \\
\end{align*}
\]

\[ x_1, x_2, x_3, x_4, x_5, x_6 \geq 0 \]
Product-mix problem (LP format)

\[
\text{max} \\
\text{revenue: } 5 \, x_1 + 6 \, x_2 + 7 \, x_3 + 5 \, x_4 + 6 \, x_5 + 7 \, x_6
\]

subject to

\[
\text{machine: } 2 \, x_1 + 3 \, x_2 + 2 \, x_3 + x_4 + x_5 + 3 \, x_6 \leq 1050
\]
\[
\text{labour: } 2 \, x_1 + x_2 + 3 \, x_3 + x_4 + 3 \, x_5 + 2 \, x_6 \leq 1050
\]
\[
\text{energy: } 1 \, x_1 + 2 \, x_2 + x_3 + 4 \, x_4 + x_5 + 2 \, x_6 \leq 1080
\]

end
MPS Format

* Product-mix problem (Fixed MPS format)
*
* Column indices
*0000000011111111112222222223333333334444444445555555556666666666
*23456789012345678901234567890123456789012345678901234567890123456789
*
* mrevenue stands for -revenue
*
NAME PRODMIX
ROWS
N mrevenue
L machine
L labour
L energy
COLUMNS
  x_1  mrevenue   -5  machine     2
  x_1  labour      2  energy      1
  x_2  mrevenue   -6  machine     3
  x_2  labour      1  energy      2
  x_3  mrevenue   -7  machine     2
  x_3  labour      3  energy      1
  x_4  mrevenue   -5  machine     1
  x_4  labour      1  energy      4
  x_5  mrevenue   -6  machine     1
  x_5  labour      3  energy      1
  x_6  mrevenue   -7  machine     3
  x_6  labour      2  energy      2
RHS
  RHS1 machine  1050  labour  1050
  RHS1 energy  1080
ENDATA
LP Format

- Intended for representing LP’s of the form

\[
\begin{align*}
\text{min / max} & \quad c^T x \\
A^T_i x & \mathbin{\bigtriangledown}_i b_i \quad (1 \leq i \leq m, \quad \mathbin{\bigtriangledown}_i \in \{\leq, =, \geq\}) \\
\ell & \leq x \leq u \quad (-\infty \leq \ell_k, u_k \leq +\infty)
\end{align*}
\]

- Comments: anything from a backslash \ to end of line
- In general blank spaces are ignored (except for separating keywords)
- Names are sequences of alphanumeric chars and symbols ( , ) _ etc. Careful with e, E: troubles with exponential notation!
LP Format

1. Objective function section

   (a) One of the keywords: \textit{min}, \textit{max} \\
   (b) Label with colon: e.g. \textit{cost:} (optional) \\
   (c) Expression: e.g. $-2 \times x_1 + 2 \times x_2$

2. Constraints section

   (a) Keyword \textit{subject to} (or equivalently: \textit{s.t.}, \textit{st}, \textit{such that}) \\
   (b) List of constraints, each in a different line \\
      i. Label with colon: e.g. \textit{limit:} (optional) \\
      ii. Expression: e.g. $3 \times x_1 + 2 \times x_2 \leq 4$ \\
          Senses: $\leq$, $\leqslant$ for $\leq$; $\geq$, $\geqslant$ for $\geq$; $=$ for $=$
LP Format

3. Bounds section (optional)
   (a) Keyword **Bounds**
   (b) List of bounds, each in a different line

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l \leq x \leq u$</td>
<td>sets lower and upper bounds</td>
</tr>
<tr>
<td>$l \leq x$</td>
<td>sets lower bound</td>
</tr>
<tr>
<td>$x \geq l$</td>
<td>sets lower bound</td>
</tr>
<tr>
<td>$x \leq u$</td>
<td>sets upper bound</td>
</tr>
<tr>
<td>$x = f$</td>
<td>sets a fixed value</td>
</tr>
<tr>
<td>$x$ free</td>
<td>specifies a free variable</td>
</tr>
</tbody>
</table>

   (c) Infinite bounds $-\infty$, $+\infty$ are represented $-\text{inf}$, $+\text{inf}$
   (d) Default bounds: lower bound 0, upper bound $+\infty$

4. Generals section: Keyword **Generals** + list of integer variables (optional)
5. Binary section: Keyword **Binary** + list of binary variables (optional)
6. End section: File should end with keyword **End**
IloCplex supports reading files with importModel

A call to importModel causes CPLEX to read a problem from a file and add all data in it as new objects.

```cpp
void IloCplex::importModel (  
    IloModel& m,  
    const char* filename,  
    IloObjective& obj,  
    IloNumVarArray vars,  
    IloRangeArray rngs) const;
```
Example 1

Let us see a program for solving:

\[
\begin{align*}
\text{max} & \quad x_0 + 2x_1 + 3x_2 \\
-x_0 + x_1 + x_2 & \leq 20 \\
x_0 - 3x_1 + x_2 & \leq 30 \\
0 & \leq x_0 \leq 40 \\
0 & \leq x_1 \leq \infty \\
0 & \leq x_2 \leq \infty \\
x_i & \in \mathbb{R}
\end{align*}
\]
Example 1

```cpp
#include <ilcplex/ilcplex.h>
ILOSTLBEGIN
int main () {
    IloEnv        env;
    IloModel      model(env);
    IloNumVarArray x(env);
    x.add(IloNumVar(env, 0, 40));
    x.add(IloNumVar(env)); // default: between 0 and +\infty
    model.add(- x[0] + x[1] + x[2] <= 20);
    model.add( x[0] - 3 * x[1] + x[2] <= 30);
    model.add(IloMaximize(env, x[0]+2*x[1]+3*x[2]));
    IloCplex cplex(model);
    cplex.solve();
    cout << "Max=" << cplex.getObjValue() << endl;
    env.end();
}
```
Example 2

Let us see a program for solving:

\[
\begin{align*}
\text{max} & \quad x_0 + 2x_1 + 3x_2 + x_3 \\
-x_0 + x_1 + x_2 + 10x_3 & \leq 20 \\
x_0 - 3x_1 + x_2 & \leq 30 \\
x_1 - 3.5x_3 & = 0 \\
0 & \leq x_0 \leq 40 \\
0 & \leq x_1 \leq \infty \\
0 & \leq x_2 \leq \infty \\
2 & \leq x_3 \leq 3 \\
x_0, x_1, x_2 & \in \mathbb{R} \\
x_3 & \in \mathbb{Z}
\end{align*}
\]
Example 2

```cpp
#include <ilcplex/ilocplex.h>
ILOSTLBEGIN
int main () {
    IloEnv env;
    IloModel model(env);
    IloNumVarArray x(env);
    x.add(IloNumVar(env, 0, 40));
    x.add(IloNumVar(env));
    x.add(IloNumVar(env));
    x.add(IloNumVar(env, 2, 3, ILOINT));
    model.add( x[0] - 3 * x[1] + x[2] <= 30);
    model.add( x[1] - 3.5* x[3] == 0);
    model.add(IloMaximize(env, x[0]+2*x[1]+3*x[2]+x[3]));
    IloCplex cplex(model); cplex.solve();
    cout << "Max=" << cplex.getObjValue() << endl;
    env.end();
}
```
More information

- You can find collection of examples in lab’s machines at:
  /opt/ibm/ILOG/CPLEX_Studio124/cplex/examples/src/cpp
  /opt/ibm/ILOG/CPLEX_Studio124/cplex/examples/data

- You can find a template for Makefile and the examples shown here at:
  www.cs.upc.edu/~erodri/webpage/cps/lab/lp/tutorial-cplex-code/tutorial-cplex-code.tgz