COIN-OR: Software Tools for Implementing Custom Solvers

Ted Ralphs
Lehigh University

László Ladányi
IBM T. J. Watson Research Center

Matthew Saltzman
Clemson University

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Agenda

• Overview of COIN-OR

• Overview of COIN-OR branch, cut, and price toolbox
  – BCP
  – OSI
  – CGL
  – CLP
  – VOL

• Developing an application
  – Basic concepts
  – Design of BCP
  – User API

• Example
What is COIN-OR?

• The COIN-OR Project
  – A consortium of researchers in both industry and academia dedicated to improving the state of computational research in OR.
  – An initiative promoting the development and use of interoperable, open-source software for operations research.
  – Soon to become a non-profit corporation known as the COIN-OR Foundation

• The COIN-OR Repository
  – A library of interoperable software tools for building optimization codes, as well as a few stand alone packages.
  – A venue for peer review of OR software tools.
  – A development platform for open source projects, including a CVS repository.
What is Open Source Development?

• *Open source development* is a coding paradigm in which development is done in a cooperative and distributed fashion.

• Strictly speaking, an open source license must satisfy the requirements of the *Open Source Definition*.

• A license cannot call itself “open source” until it is approved by the *Open Source Initiative*.

• Basic properties of an open source license
  
  – Access to source code.
  – The right to redistribute.
  – The right to modify.

• The license may require that modifications also be kept open.
Our Agenda

• **Accelerate the pace of research** in computational OR.
  – Reuse instead of reinvent.
  – Reduce development time and increase robustness.
  – Increase interoperability (standards and interfaces).

• **Provide for software what the open literature provides for theory.**
  – Peer review of software.
  – Free distribution of ideas.
  – Adherence to the principles of good scientific research.

• **Define standards and interfaces** that allow software components to interoperate.

• **Increase synergy** between various development projects.

• **Provide robust, open-source tools for practitioners.**
Components of the COIN-OR Library

- **Branch, cut, price toolbox**
  - **OSI**: Open Solver Interface
  - **CGL**: Cut Generator Library
  - **BCP**: Branch, Cut, and Price Library
  - **VOL**: Volume Algorithm
  - **CLP**: COIN-OR LP Solver
  - **SBB**: Simple Branch and Bound
  - **COIN**: COIN-OR Utility Library

- **Stand-alone components**
  - **IPOPT**: Interior Point Optimization
  - **NLPAPI**: Nonlinear Solver interface
  - **DFO**: Derivative Free Optimization
  - **MULTIFARIO**: Solution Manifolds
  - **OTS**: Open Tabu Search


**Overview of BCP Toolbox**

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BCP Overview

• **Concept:** Provide a *framework* in which the user has only to define the core relaxation, along with classes of dynamically generated variables and constraints.
  
  – Branch and bound ⇒ core relaxation only
  – Branch and cut ⇒ core relaxation plus constraints
  – Branch and price ⇒ core relaxation plus variables
  – Branch, cut, and price ⇒ the whole caboodle

• **Existing frameworks**
  
  – SYMPHONY (parallel, C)
  – COIN/BCP (parallel, C++)
  – ABACUS (sequential, C++)

• **Components**
  
  – Framework (BCP)
  – LP Solver (OSI)
  – Cut Generator (CGL)
  – Utilities (COIN)
OSI Overview

Uniform interface to LP solvers, including:

- CLP (COIN-OR)
- CPLEX (ILOG)
- DyLP (BonsaiG LP Solver)
- GLPK (GNU LP Kit)
- OSL (IBM)
- SoPlex (Konrad-Zuse-Zentrum für Informationstechnik Berlin)
- Volume (COIN-OR)
- XPRESS (Dash Optimization)
- MOSEK (under construction)
CGL Overview

• Collection of cut generation routines integrated with OSI.

• Intended to provide robust implementations, including computational tricks not usually published.

• Currently includes:
  – Simple rounding cut
  – Gomory cut
  – Knapsack cover cut
  – Rudimentary lift-and-project cut
  – Odd hole cut
  – Probing cut
VOL Overview

- Generalized subgradient optimization algorithm.

- Compatible with branch, cut, and price:
  - provides approximate primal and dual solutions,
  - provides a valid lower bound (feasible dual solution), and
  - provides a method for warm starting.
CLP Overview

- A full-featured, open source LP solver.
- Has interfaces for primal, dual, and network simplex.
- Can be accessed through the OSI.
- Reasonably robust and fast.
SBB Overview

- A lightweight generic MIP solver.
- Uses OSI to solve the LP relaxations.
- Uses CGL to generate cuts.
- Optimized for CLP.
COIN Utility Library Overview

• Contains classes for
  - Storage and manipulation of sparse vectors and matrices.
  - Factorization of sparse matrices.
  - Storage of solver warm start information.
  - Message handling.
  - Reading/writing of MPS files.
  - Other utilities (simultaneous sorting, timing, . . .).

• These are the classes common to many of the other algorithms.
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Basic Concepts

• We consider problem \( P \):

\[
\begin{align*}
\text{min} & \quad c^T x \\
\text{s.t.} & \quad Ax \leq b \\
& \quad x_i \in \mathbb{Z} \quad \forall i \in I
\end{align*}
\]

where \( A \in \mathbb{R}^{m \times n} \), \( b \in \mathbb{R}^m \), \( c \in \mathbb{R}^n \).

• Let \( P = \text{conv}\{x \in \mathbb{R}^n : Ax \leq b, x_i \in \mathbb{Z} \ \forall i \in I\} \).

• Basic Algorithmic Approach
  
  – Use \( LP \) relaxations to produce lower bounds.
  – \( Branch \) using hyperplanes.
  – The LP relaxations are built up from a core relaxation with dynamically generated \( objects \) (variables and constraints).
Object Generation

- The efficiency of BCP depends heavily on the size (number of rows and columns) and tightness of the LP relaxations.

- **Tradeoff**
  - Small LP relaxations $\Rightarrow$ faster LP solution.
  - Big LP relaxations $\Rightarrow$ better bounds.

- The goal is to keep relaxations small while not sacrificing bound quality.

- We must be able to easily move constraints and variables in and out of the active set.

- This means dynamic generation and deletion.

- Defining a class of objects consists of defining methods for
  - generating new objects, given the primal/dual solution to the current LP relaxation,
  - representing the object (for storage and/or sharing), and
  - adding objects to a given LP relaxation.
Getting Started

- The source can be obtained from www.coin-or.org as “tarball” or using CVS.

- Platforms/Requirements
  - Linux, gcc 2.95.3/2.96RH/3.2/3.3
  - Windows, Visual C++, CygWin make (untested)
  - Sun Solaris, gcc 2.95.3/3.2 or SunWorkshop C++
  - AIX gcc 2.95.3/3.3
  - Mac OS X

- Editing the Makefiles
  - Makefile.location
  - Makefile.<operating system>

- Make the necessary libraries. They’ll be installed in ${CoinDir}/lib.
  - Change to appropriate directory and type make.
BCP Modules

• The BCP library is divided into three basic modules:

  – **Tree Manager** Controls overall execution by maintaining the search tree and dispatching subproblems to the node processors.

  – **Node Processor** Perform processing and branching operations.

  – **Object Generation** Generate objects (cuts and/or variables).

• The division into separate modules is what allows the code to be parallelizable.
The User API

- The user API is implemented via a C++ class hierarchy.
- To develop an application, the user must derive the appropriate classes and override the appropriate methods.
- Classes for customizing the behavior of the modules
  - BCP_tm_user
  - BCP_lp_user
  - BCP_cg_user
  - BCP_vg_user
- Classes for defining user objects
  - BCP_cut
  - BCP_var
  - BCP_solution
- Allowing BCP to create instances of the user classes.
  - The user must derive the class USER_initialize.
  - The function BCP_user_init() returns an instance of the derived initializer class.
Objects in BCP

• Most application-specific methods are related to handling of objects.
• Since representation is independent of the current LP, the user must define methods to add objects to a given subproblem.
• For parallel execution, the objects need to be packed into (and unpacked from) a buffer.

• Object Types
  – Core objects are objects that are active in every subproblem (BCP_xxx_core).
  – Indexed objects are extra objects that can be uniquely identified by an index (such as the edges of a graph) (BCP_xxx_indexed).
  – Algorithmic objects are extra objects that have an abstract representation (BCP_xxx_algo).
## Forming the LP Relaxations in BCP

The current LP relaxation looks like this:

```
<table>
<thead>
<tr>
<th>core vars</th>
<th>extra vars</th>
</tr>
</thead>
<tbody>
<tr>
<td>core cuts</td>
<td></td>
</tr>
<tr>
<td>core matrix</td>
<td></td>
</tr>
<tr>
<td>extra cuts</td>
<td></td>
</tr>
</tbody>
</table>
```

Reason for this split: efficiency.
Developing an Application

BCP Methods: Initialization

Solver Initialization (Tree Manager)

create_root() initialize_core() xx_init() pack_module_data()

Create and initialize the user’s data structures
Set the core and extra variables and cuts
Send data to the modules
BCP Methods: Steady State

Tree Manager
- (un)pack_xxx_algo()
- display_feasible_solution()
- compare_tree_nodes()

Cut Generator
- unpack_module_data()
- generate_cuts()
- pack_cut_algo()

LP Solver
- unpack_module_data()
- initialize_search_tree_node()
- See the solver loop figure

Variable Generator
- unpack_module_data()
- generate_vars()
- pack_var_algo()
**BCP Methods: Node Processing Loop**

- **modify_LP_parameters()**
- **test_feasibility()**
- **generate_heuristic_solution()**
- **pack_{primal/dual}_solution()**
- **unpack_{var/cut}_algo()**
- **generate_{vars/cuts}_in_lp()**
- **compare_{vars/cuts}()**
- **vars_to_cols() / cuts_to_rows()**
- **logical_fixing()**
- **select_branching_candidates()**
- **compare_branching_candidates()**
- **set_actions_for_children()**
- **purge_slack_pool()**

Possible fathoming

Send primal and dual solutions to CG and VG

Generating and comparing cuts and variables

Strong branching functions
Parameters and using the finished code

• Create a parameter file

• Run your code with the parameter file name as an argument (command line switches will be added).

• BCP_ for BCP’s parameters

• Defined and documented in BCP_tm_par, BCP lp_par, etc.

• Helper class for creating your parameters.

• Output controlled by verbosity parameters.
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Example: Uncapacitated Facility Location

- **Data**
  - a set $N$ of facilities and a set $M$ of clients,
  - transportation cost $c_{ij}$ to service client $i$ from depot $j$,
  - fixed cost $f_j$ for using depot $j$, and
  - the demand of $d_i$ of client $i$.

- **Variables**
  - $x_{ij}$ is the amount of the demand for client $i$ satisfied from depot $j$
  - $y_j$ is 1 if the depot is used, 0 otherwise

\[
\begin{align*}
\text{min} & \sum_{i \in M} \sum_{j \in N} \frac{c_{ij}}{d_i} x_{ij} + \sum_{j \in N} f_j y_j \\
\text{s.t.} & \sum_{j \in N} x_{ij} = d_i \quad \forall i \in M, \\
& \sum_{i \in M} x_{ij} \leq (\sum_{i \in M} d_i) y_j \quad \forall j \in N, \\
& y_j \in \{0, 1\} \quad \forall j \in N \\
& 0 \leq x_{ij} \leq d_i \quad \forall i \in M, j \in N
\end{align*}
\]
UFL: Solution Approach

- We use a simple branch and cut scheme.
- We dynamically generate the following class disaggregated logical cuts

\[ x_{ij} \leq d_j y_j, \forall i \in M, j \in N \]  \hspace{1cm} (1)

- These can be generated by complete enumeration.
- The indices \( i \) and \( j \) uniquely identify the cut., so we will use this to create the packed form.
- The core relaxation will consist of the LP relaxation.
UFL: User classes

User classes and methods

- **UFL_init**
  - tm_init()
  - lp_init()

- **UFL_lp**
  - unpack_module_data()
  - pack_cut_algo()
  - unpack_cut_algo()
  - generate_cuts_in_lp()
  - cuts_to_rows()

- **UFL_tm**
  - read_data()
  - initialize_core()
  - pack_module_data()

- **UFL_cut**
UFL: Initialization Methods

USER_initialize * BCP_user_init()
{
    return new UFL_init;
}

BCP_lp_user *
UFL_init::lp_init(BCP_lp_prob& p)
{
    return new UFL_lp;
}

BCP_tm_user * UFL_init::tm_init(BCP_tm_prob& p, const int argnum,
const char * const * arglist)
{
    UFL_tm* tm = new UFL_tm;
    tm->tm_par.read_from_file(arglist[1]);
    tm->lp_par.read_from_file(arglist[1]);
    return tm;
}
BCP Buffers

- One construct that is pervasive in BCP is the BCP_buffer.
- A BCP_buffer consists of a character string into which data can be packed for storage or communication (parallel code).
- The usual way of adding data to a buffer is to use the pack() method.
- The pack method returns a reference to the buffer, so that multiple calls to pack() can be strung together.
- To pack integers \( i \) and \( j \) into a buffer and then unpack from the same buffer again, the call would be:

```c
int i = 0, j = 0;
BCP_buffer buf;

buf.pack(i).pack(j);
buf.unpack(i).unpack(j);
```
**UFL: Module Data**

- Because BCP is a parallel code, there is no shared between modules.
- The `pack_module_data()` and `unpack_module_data()` methods allow instance data to be broadcast to other modules.
- In the UFL, the data to be broadcast consists of the number of facilities \(N\), the number of clients \(N\), and the demands.
- Here is what the pack and unpack methods look like.

```cpp
void UFL_tm::pack_module_data(BCP_buffer& buf, BCP_process_t pty) {
    lp_par.pack(buf);
    buf.pack(M).pack(N).pack(demand,M);
}

void UFL_lp::unpack_module_data(BCP_buffer& buf) {
    lp_par.unpack(buf);
    buf.unpack(M).unpack(N).unpack(demand,M).unpack(capacity,N);
}
```
UFL: Initializing the Core

- The core is specified as an instance of the `BCP_lp_relax` class, which can be constructed from
  - either a vector of `BCP_rows` or `BCP_cols`, and
  - a set of rim vectors.

- In the `initialize_core()` method, the user must also construct a vector of `BCP_cut_core` and `BCP_var_core` objects.
UFL: Initializing the Solver Interface

• In the BCP_lp_user class, we must initialize the solver interface to let BCP know what solver we want to use.

• Here is what that looks like:

```cpp
OsiSolverInterface* UFL_lp::initialize_solver_interface(){
#if COIN_USE_OSL
    OsiOslSolverInterface* si = new OsiOslSolverInterface();
#endif
#if COIN_USE_CPX
    OsiCpxSolverInterface* si = new OsiCpxSolverInterface();
#endif
#if COIN_USE_CLP
    OsiClpSolverInterface* si = new OsiClpSolverInterface();
#endif
    return si;
}
```
UFL: Cut Class

class UFL_cut : public BCP_cut_algo{
public:
    int i,j;

public:
    UFL_cut(int ii, int jj):
        BCP_cut_algo(-1 * INF, 0.0), i(ii), j(jj) {
    }
    UFL_cut(BCP_buffer& buf):
        BCP_cut_algo(-1 * INF, 0.0), i(0), j(0) {
            buf.unpack(i).unpack(j);
        }
    void pack(BCP_buffer& buf) const;
};

inline void UFL_cut::pack(BCP_buffer& buf) const{
    buf.pack(i).pack(j);
}
UFL: Generating Cuts

• To find violated cuts, we simply enumerate, as in this code snippet.

```c++
double violation;
vector< pair<int,int> > cut_v;
map<double,int> cut_violation; //map keeps violations sorted
map<double,int>::reverse_iterator it;

for (i = 0; i < M; i++){
    for (j = 0; j < N; j++){
        xind = xindex(i,j);
        yind = yindex(j);
        violation = lpres.x()[xind]-(demand[i]*lpres.x()[yind]);
        if (violation > tolerance){
            cut_v.push_back(make_pair(i,j));
            cut_violation.insert(make_pair(violation,cutindex++));
        }
    }
}
```
**UFL: Constructing Cuts**

- Next, we pass the most violated cuts back to BCP.

```cpp
//Add the xxx most violated ones.
maxcuts = min((int)cut_v.size(),
              lp_par.entry(UFL_lp_par::UFL_maxcuts_iteration));
it = cut_violation.rbegin();
while(newcuts<maxcuts){
    cutindex = it->second;
    violation = it->first;
    new_cuts.push_back(new UFL_cut(cut_v[cutindex].first,
                                    cut_v[cutindex].second));
    newcuts++;
    it++;
}
```
UFL: Adding Cuts to the LP

- Here is the `cuts_to_rows` function that actually generates the rows to be added to the LP relaxation.

```cpp
void UFL_lp::cuts_to_rows(const BCP_vec<BCP_var*>& vars,
                          BCP_vec<BCP_cut*>& cuts,
                          BCP_vec<BCP_row*>& rows,
                          const BCP_lp_result& lpres,
                          BCP_object_origin origin, bool allow_multiple){
    const int cutnum = cuts.size();
    rows.reserve(cutnum);
    for (int c = 0; c < cutnum; ++c) {
        UFL_cut* mcut = dynamic_cast<const UFL_cut*>(cuts[c]);
        if (mcut != 0){
            CoinPackedVector cut;
            cut.insert(xindex(mcut->i,mcut->j), 1.0);
            cut.insert(yindex(mcut->j), -1.0 * demand[mcut->i]);
            rows.push_back(new BCP_row(cut,-1.0 * INF, 0.0));
        }
    }
}
```
Resources

• Documentation
  – There is a user’s manual for BCP, but it is out of date.
  – The most current documentation is in the source code—don't be afraid to use it.

• Other resources
  – There are several mailing lists on which to post questions and we make an effort to answer quickly.
  – Also, there is a lot of good info at www.coin-or.org.
  – There are some basic tutorials and other information, including the example you saw today at sagan.ie.lehigh.edu/coin/.

• There is a user’s meeting Monday at 12:00 in International Ballroom A.

• There are three other sessions revolving around COIN software, including a tutorial on OSI.
Final advice

Use the source, Luke...

...and feel free to ask questions either by email or on the discussion list.