# Building a Custom Solver with the COIN-OR Branch, Cut, and Price Frameworks

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# Agenda

- Introduction to BCP Frameworks
- Introduction to SYMPHONY
  - Callable library API
  - OSI interface
  - User callbacks
- Introduction to COIN/BCP
  - Basic concepts
  - Design of COIN/BCP
  - User API
  - Example

# Concept

- Concept: Provide a *framework* in which the user has only to define the core relaxation, along with classes of dynamically generated variables and constraints.
- SYMPHONY and COIN/BCP are two frameworks that can be used to implement solvers for mixed-integer programs.
- They have similar design concepts and state-of-the-art implementations of branch, cut and price.
- SYMPHONY
  - is a callable library with C and OSI interfaces,
  - works out of the box as a generic MIP solver,
  - employs callbacks for customization,
  - is a bit easier for the novice.
- COIN/BCP
  - has more power for implementing column generation and integrating cut and column generation,
  - employs C++ inheritance for customization,
  - is a bit more difficult to learn.

# SYMPHONY Overview

- Description
  - A callable library for solving mixed-integer linear programs with a wide variety of customization options.
  - Fully integrated with the Computational Infrastructure for Operations Research (COIN-OR) libraries (soon to be in the repository).
  - Outfitted as a generic MILP solver, with cut generation from the CGL.
  - Extensive documentation available.
  - Source can be downloaded from `www.branchandcut.org`
- SYMPHONY Solvers
  - Generic MILP
  - Traveling Salesman Problem
  - Vehicle Routing Problem
  - Mixed Postman Problem
  - Set Partitioning Problem
  - Matching Problem
  - Network Routing

# Supported Formats and Architectures

- Input formats
  - MPS (COIN-OR parser)
  - GMPL/AMPL (GLPK parser)
  - User defined
- Output/Display formats
  - Text
  - IGD
  - VbcTool
- Supported architectures
  - Single-processor Linux, Unix, or Windows
  - Distributed memory parallel (message-passing)
  - Shared memory parallel (OpenMP)

# C Callable Library

- Primary subroutines
  - `sym_open_environment()`
  - `sym_parse_command_line()`
  - `sym_load_problem()`
  - `sym_find_initial_bounds()`
  - `sym_solve()`
  - `sym_mc_solve()`
  - `sym_resolve()`
  - `sym_close_environment()`
- Auxiliary subroutines
  - Accessing and modifying problem data
  - Accessing and modifying parameters
  - User callbacks

# Implementing a MILP Solver with SYMPHONY

- Using the callable library, we only need a few lines to implement a solver.
- The file name and other parameters are specified on the command line.
- The code is exactly the same for all architectures, even parallel.
- Command line would be

```
symphony -F model.mps
```

```
int main(int argc, char **argv)
{
   sym_environment *p = sym_open_environment();
   sym_parse_command_line(p, argc, argv);
   sym_load_problem(p);
   sym_solve(p);
   sym_close_environment(p);
}
```

# OSI interface

- For each method in OSI, SYMPHONY has a corresponding method.
- The OSI interface is implemented as wrapped C calls.
- The constructor calls `sym_open_environment()` and the destructor calls `sym_close_environment()`.
- The OSI `initialSolve()` method calls `sym_solve()`.
- The OSI `resolve()` method calls `sym_resolve()`.
- There is also a multicriteria solve method.

```
int main(int argc, char **argv)
{
   OsiSymSolverInterface si;
   si.parseCommandLine(argc, argv);
   si.loadProblem();
   si.branchAndBound();
}
```

# Customizing

- The main avenues for advanced customization are the parameters and the user callback subroutines.
- There are more than 50 callbacks and over 100 parameters.
- The user can override SYMPHONY's default behavior in a variety of ways.
  - Custom input
  - Custom displays
  - Branching
  - Cut/column generation
  - Cut pool management
  - Search and diving strategies
  - LP management

# Resources

- SYMPHONY 5.0 will be released soon and can be downloaded from

  `http://www.branchandcut.org/SYMPHONY`

- SYMPHONY is well-documented, and includes sample codes and tutorials.
- There is a mailing list, but it is better to just send me e-mail directly to me.
- SYMPHONY will be added to the COIN-OR repository once it moves to INFORMS.

# COIN/BCP Overview

- COIN/BCP is focused on the implementation of full-blown branch, cut, and price algorithms.
- The framework centers around the management of classes of dynamically generated cut and variables, generically called *objects*.
- Subproblems are composed of dynamic lists of these objects.
- The goal is to keep the lists as small as possible, while not sacrificing bound quality.
- 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`.

# COIN/BCP Modules

- The COIN/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

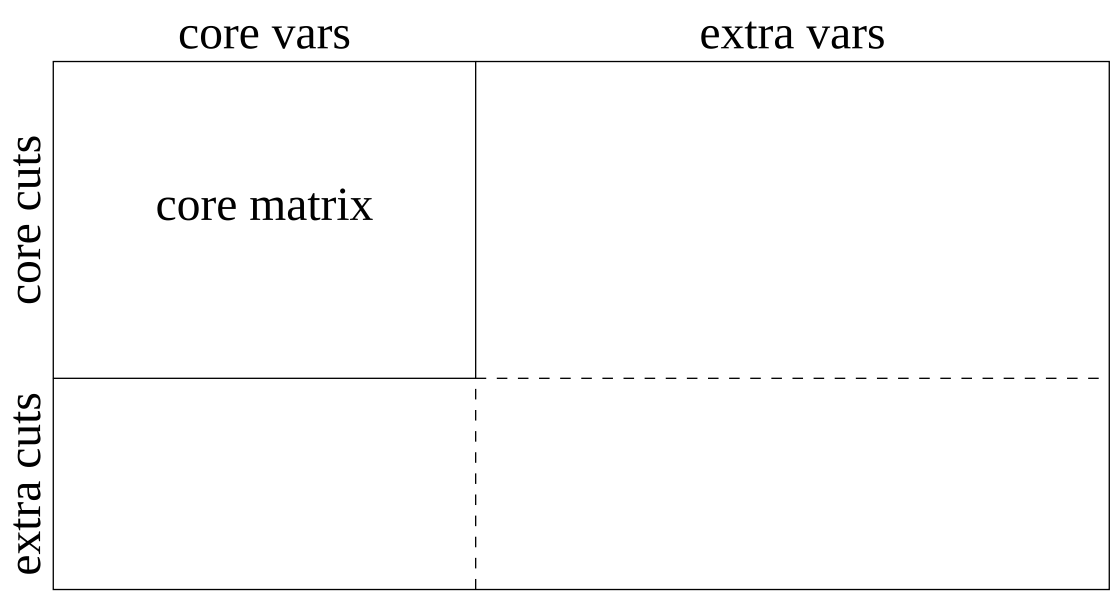
- The user API is implemented via a C++ class hierarchy.
- To develop an application, the user must derive the appropriate classes and override the appropriate methods.
- Classes for customizing the behavior of the modules
  - BCP_tm_user
  - BCP_lp_user
  - BCP_cg_user
  - BCP_vg_user
- Classes for defining user objects
  - BCP_cut
  - BCP_var
  - BCP_solution
- Allowing COIN/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 COIN/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).

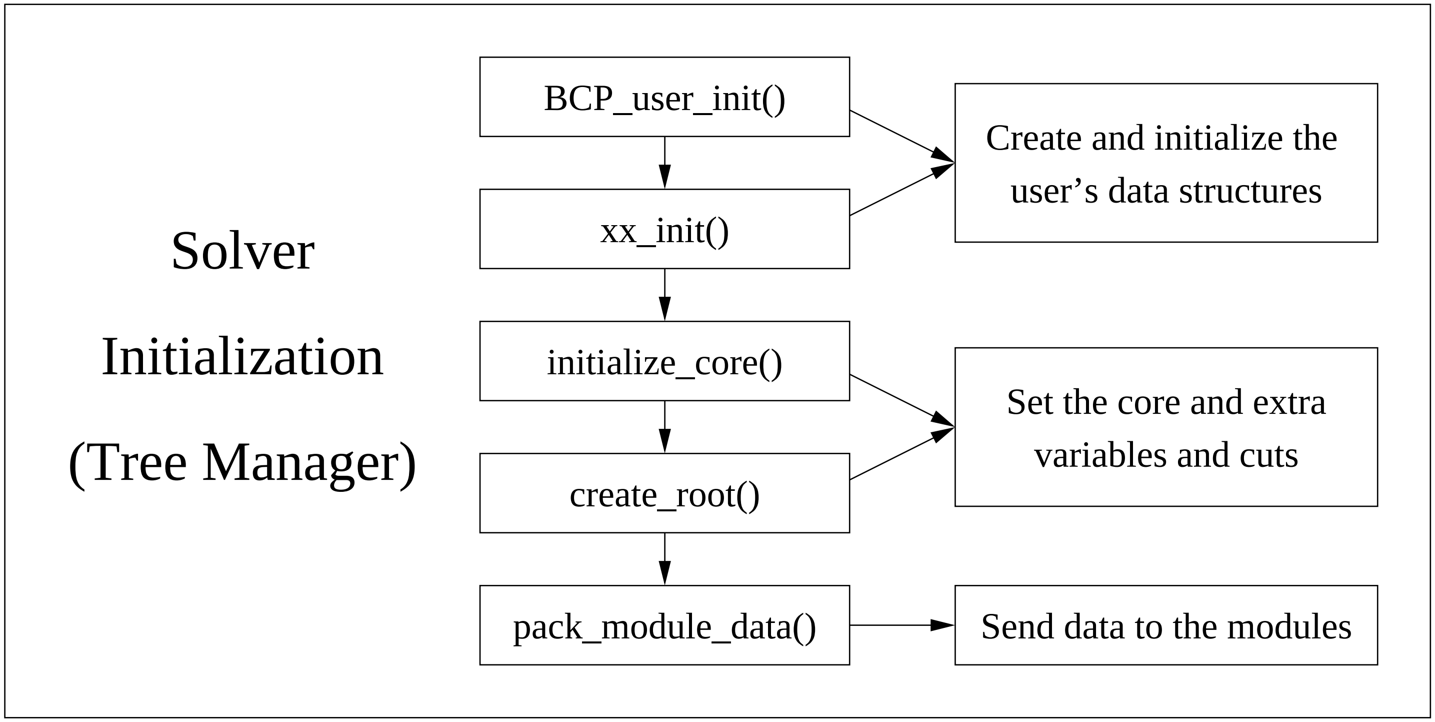
# Forming the LP Relaxations in COIN/BCP

The current LP relaxation looks like this:

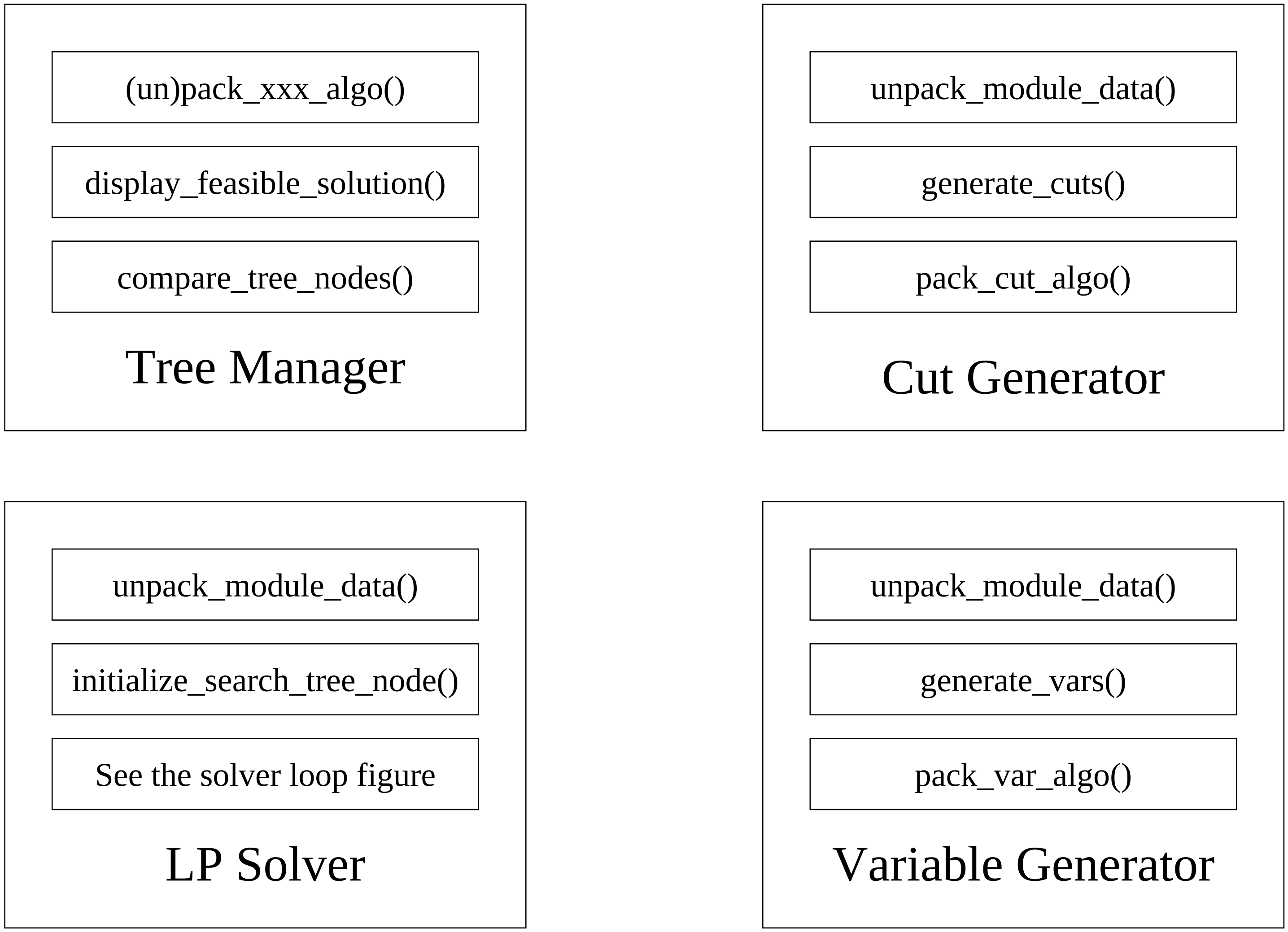



Reason for this split: efficiency.

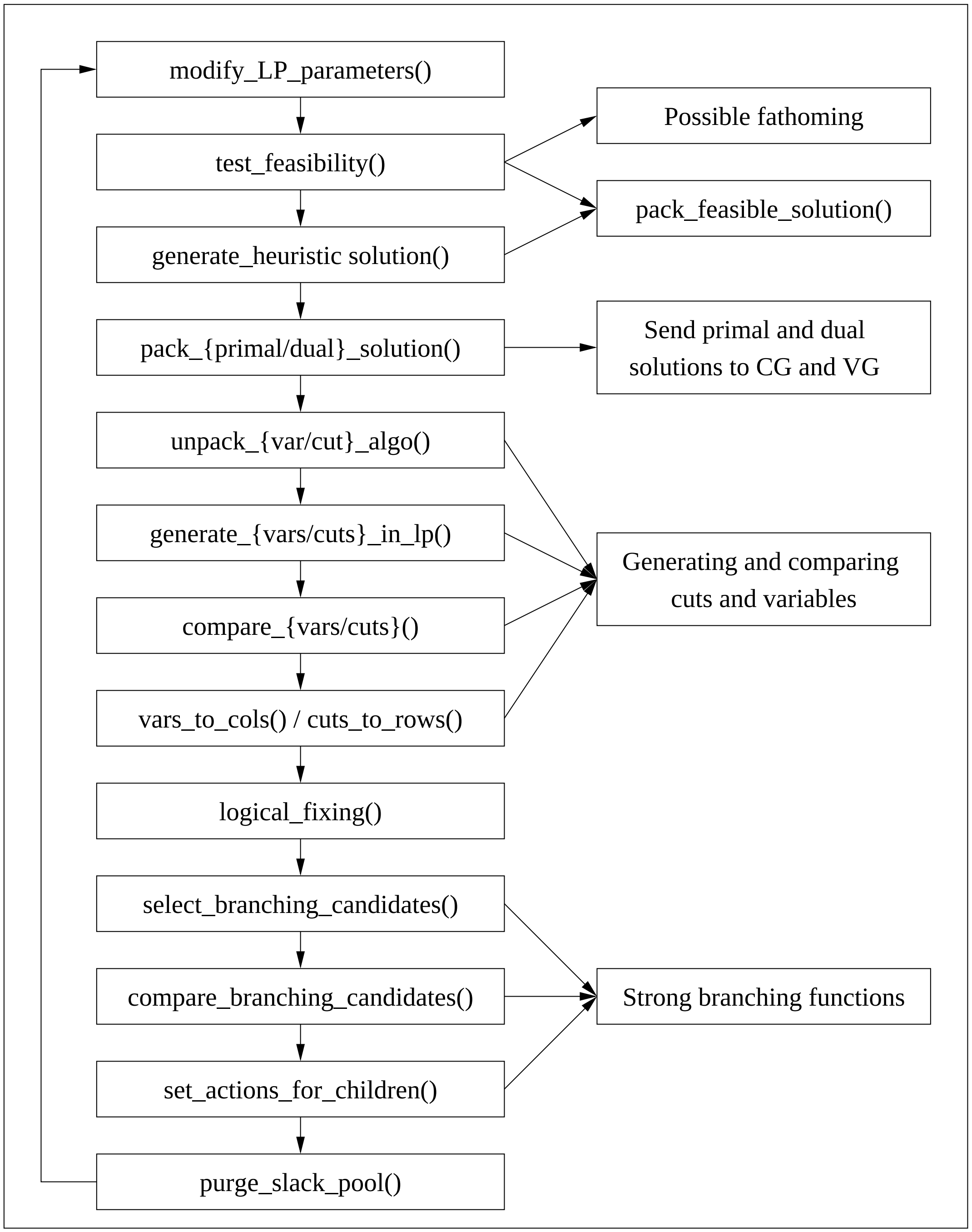
# COIN/BCP Methods: Initialization



# COIN/BCP Methods: Steady State



# COIN/BCP Methods: Node Processing Loop



# 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 COIN/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.

# 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

$$
\begin{array}{llr}
\min \sum_{i \in M} \sum_{j \in N} \frac{c_{ij}}{d_i} x_{ij} + \sum_{j \in N} f_j y_j & & \\
s.t. & \sum_{j \in N} x_{ij} = d_i & \forall i \in M, \\
& \sum_{i \in M} x_{ij} \leq (\sum_{i \in M} d_i) y_j & \forall j \in N, \\
& y_j \in \{0, 1\} & \forall j \in N \\
& 0 \leq x_{ij} \leq d_i & \forall i \in M, j \in N
\end{array}
$$

# UFL: Solution Approach

- The code for this example is available at

  http://sagan.ie.lehigh.edu/coin/uflBCP.tar.gz

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

$$x_{ij} \leq d_j y_j, \ \forall i \in M, j \in N \tag{1}$$

- 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;
}
```

# COIN/BCP Buffers

- One construct that is pervasive in COIN/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:

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

buf.pack(i).pack(j);
buf.unpack(i).unpack(j);
```

# UFL: Module Data

- Because COIN/BCP is a parallel code, there is no shared memory 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.

```
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 COIN/BCP know what solver we want to use.
- Here is what that looks like:

```
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.

```
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 COIN/BCP.

```
//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.

```
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 COIN/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 today at 1:00.
- There are also two other sessions revolving around COIN software.

# Final advice

## Use the source, Luke...

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